EFFECTS OF CONSERVATION AGRICULTURE ON SOIL PHYSICO-CHEMICAL PROPERTIES AND SOIL MICROBIAL BIOMASS UNDER A RAIN-FED MAIZE PRODUCTION SYSTEM IN LAIKIPIA EAST, KENYA

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Effects of Conservation Agriculture on Soil Physico-Chemical Properties and Soil Microbial Biomass under a Rain-Fed Maize Production System in Laikipia East, Kenya

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

I dedicate this work to my late Mother Nyambura, a great lady who was passionate about education, and to my wife Elizabeth, my children Neil, Neville and Nella.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ACRONYMS AND ABBREVIATIONS

AC	Aeration capacity
AS	Aggregate stability
ASAL	Arid and semi-arid lands
BD	Bulk density
CA	Conservation Agriculture
CEC	Cation exchange capacity
CSA	Climate smart agriculture
CT	Conventional tillage
FAO	Food and agricultural organization
IPCC	Intergovernmental Panel on Climate Change
MacPOR	Macro porosity
MatPOR	matric porosity
MB	Maize beans
MD	Maize dolichos
MWD	Mean Weight Diameter
NT	No till
PAWC	Plant available water capacity
RWC	Relative water content
RWUE	Rain water use efficiency
SI	Stability index
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub-Saharan Africa
SMC	Soil moisture content
SWRC	Soil water retention curve

ABSTRACT

There is reduced crop yield due to soil degradation and climate change. Conservation agriculture (CA) is being advocated to address land degradation and low productivity among small-scale farmers. However, contrasting results on the effects of the CA practices such as tillage, mulching and herbicide application on yield and soil properties have been reported. Thus, the need to carry out more research to appropriately describe the effects of CA components on soil physicochemical properties, soil microbial biomass and crop yield. The study was conducted for three years using split plot experimental design. The main treatments were tillage management (conventional tillage: CT, no tillage: NT and no tillage herbicide: NTH) and four sub-treatments. The sub-treatments were maize intercropped with (a) common beans (MB), (b) dolichos beans (MD), (c) common beans and 1.5 Mg ha^{-1} of mulch and (d) common beans and leucaena. The rainfall for 1st, 2nd and 3rd seasons was 685, 538 and 270 mm, respectively. The 1st and 2nd years growing seasons were wet while the 3rd year was a dry season. The tillage, mulching and herbicide application only significantly affected a selected physical property; namely saturated hydraulic conductivity and bulk density and had no significant effect on Ca, Mg, Fe, Cu, Mn and Zn. Tillage significantly affected yield, soil moisture and water use efficiency during the dry year, with CT showing significantly lower 33.9% and 33% maize yield and rain water use efficiency (RWUE) respectively than NT. Similarly, mulching significantly affected soil macronutrients, soil microbial biomass carbon (SMBC), soil hydraulic conductivity and increased maize yield and RWUE but had no significant effect on micronutrients and soil physical properties. Maize yield, soil moisture and RWUE were significantly increased in agroforestry treatments. The study found that NT and mulch are critical aspects of CA in that they avoid drought stress of maize during dry seasons while enhancing maize yield. Agroforestry showed potential to further improve CA in semi-arid zones resulting in higher yield in dry years. Even though the dry growing season under study corresponded with a meteorological drought, practicing two or three CA practices avoided agricultural drought due to conservation of soil moisture which became available to the crops during dry periods. The 'best' practice (no till with maize, beans and mulch), resulted in up to 74% higher yield in the dry year and still up to 24% higher yield in the wet growing season compared to the conventional practice. The study concluded that NT, mulching and agroforestry had a significant effect on soil moisture, macro nutrients, SMBC, maize yield and RWUE especially in season with rainfall below normal average and mulching is a critical component of CA. There was no significant effect of NT, mulching and agroforestry on soil physical properties. The application of CA practices is recommended to improve the soil physico chemical and microbial properties, improve maize yield and enhance rain water use efficiency.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Agriculture is the mainstay of the Kenyan economy directly contributing 24% of the national gross domestic product (GDP) per annum (MOA, 2021). It provides more than 80% of informal employment in the rural areas (KNBS, 2018). It is therefore, not only the driver of Kenyan economy but also the means of livelihood for the majority of Kenyan people (Branca *et al.*, 2011). There is near total reliance on rain-fed agriculture in the sub-Saharan Africa (SSA) countries including Kenya (Kalele *et al.*, 2021). However, this form of agriculture is disproportionately affected by climate change despite playing a dominant role in providing food and livelihoods for an increasing human population (Tofu & Wolka, 2023).

Climate change affects different world regions varyingly; for instance, semi-arid areas are global hotspots, in terms of water related constraints to food production, high prevalence of malnourishment and poverty, and rapidly increasing food demands (Connolly-Boutin & Smit, 2016). These factors are made worse by climate change. Its noteworthy that yield gaps are large in these regions, at times not due to lack of water, but rather due to inefficient management of water, soils, and crops (Rockström *et al.*, 2010). The world is facing a water crisis with little room for further expansion of large-scale irrigation. Therefore, there is a need for water management in rain-fed agricultural systems; not only to secure the water required for food production, but also to build resilience to cope with future water related risks and uncertainties (Ingrao *et al.*, 2023).

The medium to low potential agriculture counties of Kenya are reeling from the effects of global warming with prolonged droughts and unexpected shift in normal weather patterns (Obwocha *et al.*, 2022). This has resulted in the reduction of crop production by approximately 30% (NEMA, 2007).

Laikipia East sub-county is located in the semi-arid region of Rift Valley in Kenya. Half of the human population in the sub-county suffer from regular and prolonged droughts which increases by the day. Crop and livestock production dominate the sub-county economic activities (Kaumbutho and Kienzle, 2007). Variable rainfall and dry spells cause high risks and lead to low and unpredictable yields. The production is mainly reliant on rainfall with negligible number of farms being irrigated (Kaumbutho and Kienzle, 2007). Improving productivity of rain-fed agriculture is therefore, of major importance to improve food security and reduce the vulnerability of poor people in the county (Makurira *et al.,* 2007).

There are a variety of tested technologies that can be used to increase crop productivity especially in areas of low precipitation. Conservation agriculture (CA) has been proposed as a technology that can lead to stable and increased farm yield in dry areas. The technology is a crop management system based on three practices: minimum soil movement (no soil inversion by tillage), soil surface cover with crop residues and/or living plants and crop rotations to avoid pest and diseases (CYMMYT, 2011). The Food and Agriculture Organization (FAO) endorsed CA as the key step to meeting the long-term global demand for food, feed and fibre for the projected 9 billion people by 2050 (Kopittke, *et al.,* 2019; Mackenzie, 2009). Stroosnijder (2009) observes that due to the increasing population more food is required. Therefore, there exists a need for more scientific research to improve and make rain-fed agriculture more efficient.

Rain-fed crop production uses infiltrated rainwater that forms soil moisture in the root zone (green water resource), which accounts for most of the crop water consumption in agriculture (Lamptey, 2022). This highlights the potential role conservation agriculture farming system can play in improving crop production as it enhances water infiltration into the soil. It improves wetting root zone volume, by breaking soil hardpans, but also protecting rainfall losses through evaporation and runoff, by soil surface cover (Araya *et al.,* 2024). Furthermore, Rockström *et al.* (2010) proposes two strategies for increasing yields in rain-fed agriculture when water availability in the root zone constrains crop growth. These are: capturing more water and allowing it to infiltrate into the root zone; and using the available moisture more efficiently by increasing the plant water uptake capacity and/or reducing non-productive soil evaporation. Previous studies indicate that adoption of conservation agriculture in place of ploughing results in yield and water productivity improvement in SSA (Araya *et al.,* 2021; Mutuku *et al.,* 2020). The conservation agriculture is relatively cheap to implement and it can be practiced on all soils furthermore, it does not require water storage devices. As a result, the approach is quite important for supporting rain-fed agriculture, which often is constrained by lack of investment capital.

1.2 Problem Statement

The advocates of conservation agriculture claim that it increases yields by as much as 25% (Mosquera, *et al.*, 2019), reduces labour requirements by 50% (Kassam *et al.*, 2018) in production systems, improves soil moisture holding capacity, soil fertility and reduces erosion. However, the impact of conservation agriculture on crop yields due to these incremental benefits within smallholder farmers’ environment in semi-arid regions like Laikipia East sub-county and in Kenya in general are not well established. Furthermore, the techniques to apply the practices depend on climate, livestock ownership, type of crops grown, soil type and its nutrient status, and farmer circumstances (wealth, land size, traction owned, labour availability and many more). Therefore, there is need to determine how to manage conservation agriculture under particular conditions in order to optimize its usability.

This is supported by Giller *et al.* (2009) who advocates for studies to gain more empirical evidence about the functioning of conservation agriculture under a variety of ecological and socio-economic conditions. These authors further noted that surface cover is a major challenge in implementing conservation agriculture due to the competing uses of crop residues, namely as livestock fodder and source of fuel. Thus, the need to explore other sources of organic materials for surface cover. This alternative may include agroforestry which can offer organic mulch that may reduce competition with crop residue. However, inclusion of agroforestry in conservation agriculture requires evaluating its effects on the soil properties and the crop yield.

To control weed in conservation agriculture there is intense use of herbicides. The increased use of herbicide has raised conerns on its effects on soil microbial properties. Despite these concerns, comprehensive information on effect of herbicice on soil biology is scanty and not well documented (Rose *et al.,* 2016). Thus, the need to investigate the effect of herbicides on soil properties and crop yield under conservation agriculture.

1.3 Justification

Rain-fed agriculture is the major form of food production system in Kenya (Kalele *et al.,* 2021). However, it is faced with many production and market risks. Currently, the main challenge is climate change that results to agricultural drought which negatively affect crop yields and livestock productivity which increases food and nutritional insecurity. Therefore, any strategy, technology, innovation or practice that reduces the negative impact on climate change in food production should be considered.

Various innovative agricultural technologies that reduce the impact of climate change on agriculture have been studied and recommended for adoption in crop and animal production systems. The effect conservation agriculture technologies such as tillage practices, mulching and herbicide application on soil properties and crop yield have been tested and shown to positively affect important soil properties that support crop yield (Sairam *et al.,* 2023). It is important to test such technologies in different production systems to determine the extent to which the soil properties and yields are affected. This study determined the impact of conservation agriculture technologies in a rain-fed mixed farming system in a semiarid area of Kenya. The findings provide an understanding of the effects of individual conservation agriculture components and their interactions on soil physicochemical properties, soil microbial biomass and maize yield under a rain-fed maize production system.

1.4 Objectives

The main objective of the study was to evaluate the effects of tillage, mulching, herbicide application and agroforestry on soil physicochemical properties and soil microbial biomass under a rain-fed maize production system in a semi-arid zone.

The specific objectives were to:

(a) Evaluate the effects of tillage, mulching, herbicide application and agroforestry on soil physicochemical properties.
(b) Evaluate the effects of tillage, mulching, herbicide application and agroforestry on soil microbial biomass; and
(c) To assess the effects of using different conservation agriculture strategies on maize yield in a rain-fed production system.

1.5 Research Hypothesis

(i) Tillage, mulching, agroforestry and herbicide application have no significant effect on soil physicochemical properties.

(ii) Tillage, mulching, agroforestry and herbicide application have no significant effect on soil microbial biomass.

(iii) Tillage, mulching, agroforestry and herbicide application have no significant effect on maize crop yields and water productivity under rain-fed agriculture.

1.6 Scope

The study was conducted in a farmer’s field at Michuiri village in Laikipia East sub-county. The key areas under investigation were the effects of conservation agriculture technologies namely tillage, mulching, herbicide application and agroforestry on soil physicochemical properties, soil microbial biomass and maize yield under a rain-fed cropping system in a semiarid zone. The reason for conducting it in the farmer’s field was to ensure that the evaluated conservation agriculture technologies were as they are practiced by small-scale farmers under rain-fed agriculture.

1.7 Limitation

The study was carried out within three years. This was a short period for some of the soil properties to be significantly influenced by the conservation agriculture practices. However, the three-year period provided some insights on trends on the conservation agriculture effects on the physicochemical properties of the soil.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The dry lands of Kenya, Laikipia County included, are vulnerable to climate change phenomenon due to the fragile nature of the environment. This has been exacerbated by encroachment of agricultural activities associated with increasing human population and accompanied by unsustainable land-use activities (Ojwang *et al.*, 2010). The frequency and severity of both droughts and floods is already high and is expected to increase in coming years. In these areas, smallholder farming and pastoral livestock production are dominant, but are dependent on the availability of rainfall (Ronner, 2011). The major impact of droughts on smallholder activities is increased food and nutritional insecurity and loss of livelihoods.

Conventional agriculture, which often involves intensive tillage, has been shown to cause soil degradation, particularly when practised in areas of marginal productivity (Huho & Mugalavai, 2010). The effects of recurrent droughts, combined with the low productivity of small and uneconomical land holdings, have further aggravated the severity of land degradation, with repercussion on the livelihoods of many local communities. Therefore, the smallholder farmers in these areas must embrace practices such as environmental conservation, as an integral part of sustainable agricultural production system in order to improve food and nutritional insecurity (Ojwang *et al.,* 2010). Arid and semi-arid lands (ASALs) are expected to see an overall decrease in precipitation due to climate change (IPCC, 2007). Therefore, sustainable methods of food production, such as conservation agriculture, are crucial in mitigating climate change which negatively affect food and nutrition security.

2.2 Rain-Fed Agriculture

Rain-fed agriculture produces 69% of all cereal area globally with developing nations producing more that 80% cereals through rain-fed system. These statistics are in line with the Kenyan situation with cereal area accounting for 98% of the agricultural output (GoK, 2017). However, rain-fed agriculture is increasingly vulnerable to risks, especially to extreme and growing weather variability (D’Alessandro *et al.,* 2015).

Nelson et al. (2009) observes that this will result into likelihood of short-run crop failures and long-run production declines. This is despite the fact that developing world, where much of the food production is reliant on rainfall, has eight hundred million people who are considered as food/nutrition-insecure (Wudil *et al.*, 2022). This is projected to worsen with increasing human population. To alleviate the situation, there is need for advocacy to promote soil and water conservation measures in rain-fed agriculture as coping strategy to climate change as well as making the production system sustainable (Huho, 2011). Such strategies would include practices such as conservation agriculture. However, the adoption of conservation agriculture is slow and gradual and depends on financial, human or land resources, benefits and risks or costs of conservation agriculture (Giller *et al.*, 2011). Furthermore, farmers practice diverse aspects of conservation agriculture due to various reasons because of conflicting uses of crop residuals such as choosing feeding livestock instead of using it as mulch (Gowing & Palmer, 2008). This necessitates the need to evaluate the effects of conservation agriculture components on soil quality and crop yield.

2.3 Conservation Agriculture

Tillage dates back to when humans changed from hunting and gathering to more sedentary and settled agriculture. The reasons for using tillage in agriculture can broadly be summarised to include softening of the soil and prepare a seedbed to kill the weeds, help release soil nutrients through mineralization and oxidation after exposure of soil organic matter to air, incorporate crop residues and amendments (fertilizers, organic or inorganic) into the soil and reduction of soil compaction (Hobbs *et al.,* 2011). However, tilling benefits come at a cost both to the farmer and the environment. A good example is the dust bowl in the mid United States in 1930s that illustrated how human interventions in soil management and ploughing had led to unsustainable agricultural systems. In some cases, intensive tillage has been found to adversely affect soil structure and cause excessive breakdown of aggregates, leading to soil erosion in higher rainfall areas. Intensive tillage can also have a negative effect on environmental quality by accelerating soil carbon loss and greenhouse gas emissions (Hussain et al., 2021).

The identifiable tillage detriments led to campaign for reduced tillage systems that use less fossil fuel, reduce run-off and erosion of soils and reverse the loss of soil organic matter. Its other objectives include retention of 30% surface cover by residues, conservation of time, fuel, earthworms, soil water, soil structure and nutrients (FAO, 2015). Conservation agriculture is based on three practices namely minimum mechanical soil disturbance, maintenance of permanent soil cover and diversified crop rotation systems which include legumes (Kassam *et al.,* 2009). The three practices, as shown in Figure 2.1, have effect on soil properties that in turn affect rain water use and crop yield.

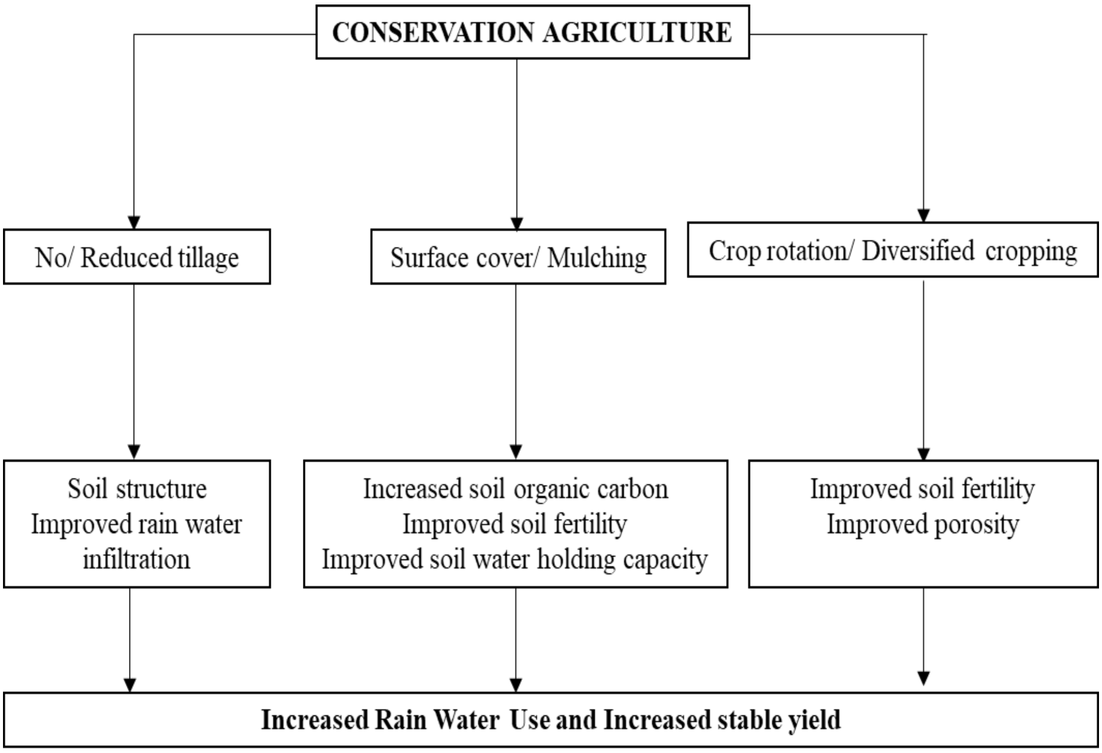

Figure 2.1: Relationship between Conservation Agriculture Practices and Soil Properties

2.3.1 Minimal Soil Disturbance

Tillage practices result in decline of soil organic matter (SOM) due to increased oxidation over time, leading to soil degradation, loss of soil biological fertility and resilience (Lal, 1994). Baker *et al.* (2002) defines reduced tillage in terms of practices that include no-tillage, direct-drilling, minimum-tillage and/or ridge-tillage. No-tillage minimizes SOM losses and especially in semiarid regions (Almagro *et al.*, 2016) and is a promising strategy to maintain or even increase soil carbon (C) and nitrogen (N) stock. It also promotes soil aggregation and sustainable crop production systems (Bayer *et al.*, 2000).

The effects of reduced/no till practices on soil erosion control has been documented by Carretta et al. (2021) and consider no till/reduced till as an efficient way of maintaining and improving soil quality. The combination of no-till and mulch reduces surface soil crusting, increases water infiltration, reduces runoff and gives higher yields than tilled soils (Thierfelder *et al.,* 2005). Some challenges of no-till management have also been observed such as compaction in subsoil and weed management that may decrease crop yield (Martinez-Mena *et al.,* 2013). To address these challenges Singh, (2014) advocates the combination of no-till with other management practices (i.e., cover crop, crop rotation, and organic amendments). These are expected to increase SOC and N storage and promote soil structure.

2.3.2 Crop Diversification

Crop diversification assist in optimizing crop production and improving soil health through improving nutrient use efficiency and balancing soil biodiversity (Barbieri et al., 2019). Diversified cropping enhances soil physicochemical properties resulting to better soil health and crop yields (Maron et al., 2011). Crop diversification is considered an integral component of conservation agriculture and it has been shown to accrue benefits (Thierfelder & Wall, 2010; Volsi *et al.,* 2022). It has been demonstrated it leads to increased rainfall/water use efficiency as well as higher crop yields. It also increases microbial diversity, reduces risk of pests and disease outbreaks from pathogenic organisms. The biological diversity characterised by crop rotation helps in keeping the pathogenic organisms in check (Leake, 2003; Tang *et al.,* 2020). This reduces chemical application in disease and pest control.

The diversification of crops is not only necessary to offer a diverse diet to the soil microorganisms, but as they root at different soil depths, they are capable of exploring different soil layers for nutrients. Nutrients that have been leached to deeper layers and that are no longer available for some of the crops can be "recycled" by the crops in rotation. This way the rotation of crops function as biological pumps. Furthermore, diversity of crops in rotation leads to a diverse soil flora and fauna, as the roots excrete different organic substances that attract different types of bacteria and fungi, which in turn, play an important role in the transformation of these substances into plant available nutrients (Srinivas, 2006). Through their rooting cover, crops help promote biological soil tillage. The surface mulch provides food, nutrients and energy for earthworms, arthropods and micro-organisms below the ground that biologically till the soils. Use of deep-rooted cover crops and biological agents, such as earthworms, can also help to relieve compaction under zero-tillage systems (Hobbs *et al.,* 2011). However, the effect of diversified cropping uniform and this necessitates more research on effect of diversified cropping on soil quality and crop yield sin various farming systems (Roscher *et al.,* 2013).

2.3.3 Crop Rotation

Crop rotation plays important roles in crop production by promoting soil health, reducing pests and disease outbreaks (Barbieri *et al.,* 2019). The efficiency of a crop rotation is affected by including crop types in the rotation, and the farm agronomic history on farmland (Li *et al.,* 2019). The choice of crop sequence in the crop rotation is a challenge due to the varying effect of crops used on soil properties and crop yield (Yang *et al.,* 2013).

Crop rotation enhance soil structure through rotating different plants whose roots reach various soil depths instead of leaving the soil in its compressed state. This will improve the moisture holding capacity and create conducive root environment for crop growth (Zheng *et al.,* 2023). The soil fertility is boosted by crop rotation through putting some of those lost nutrients back into the ground (Mosier *et al.,* 2021). The cover crops used in crop rotation protect the top soil from erosion and provide roots to the soil for optimal conditions (Sharma *et al.,* 2018). Koropeckyj-Cox et al. (2021) notes that crop rotation allows plants to receive optimal nutrients from the soil through nutrient recycling. This reduces the fertilizer application which reduce pollution. Crop rotation allows plenty of crops to grow, and creates less space for weeds to inhabit the soil. This becomes an effective weed control method. The reduced weed in the field will lead to reduced herbicide application in conservation agriculture (Gamage *et al.,* 2023). Crop rotation leads to more yield and better income. This is due to the improved nutrients input from crop rotation systems compared to monocropping which depletes the soil of nutrients. Decreased input costs associated with crop rotation lowers crop production cost (Shah *et al.,* 2021).

2.3.4 Mulching

One of the practices of conservation agriculture is surface cover which is attained by maintaining of permanent covering of the soil surface by at least 30% either by using crop residues and/or cover crops (FAO, 2015). Therefore, mulching is a critical aspect of conservation agriculture. Mulching has mainly been attributed with positive effects on crop yield in conservation agriculture systems. The benefits of mulching on grain yields have been documented especially during the seasons characterized with several extended dry spells (Kodzwa *et al.,* 2020).

The positive effect of mulch on crop yield is attributed to its effect of reducing evaporation and runoff and therefore increasing infiltration thus retaining soil moisture. This is achieved through increased yields in farms adopting mulch technology which could be attributed to the building up of soil organic matter through organic matter (mulch) that provides energy and nutrients to soil micro and macro-organisms. This improves the soil biophysical and chemical environment (Mupangwa *et al.,* 2012). Ahmad *et al.* (2015) further note that weed suppression that reduce competition between weed and crops for nutrients, light and water, improves crop yield. Kodzwa *et al.* (2020) found that mulch had the greatest effect on maize yield when evaluating the effect of individual conservation agriculture practices on maize yield in Zimbabwe. They ranked mulching as the most critical component among the three conservation agriculture practices. However, the adoption of this aspect of conservation agriculture is inhibited by the competing uses of crop residues in crop-livestock farming systems (Rusinamhodzi *et al.,* 2011).

2.4 Agroforestry

There has been limited adoption of conservation agriculture in SSA especially for mixed smallholder farms. This has been due to the difficulties farmers face to simultaneously apply all the three components of conservation agriculture, particularly permanent soil cover (Rockström *et al.,* 2009). There is competition of cover crops with food crops (Giller, 2001), inadequate amounts of crop residues in infertile fields (Guto *et al.,* 2011) and the presence of stall-fed dairy cows (Tittonell *et al.,* 2010) that create a huge demand for crop residues as livestock feed (Rufino *et al.,* 2009). This can partially be addressed by integration of agroforestry in farming systems.

Agroforestry is a set of land use practice that involve the deliberate combination of woody perennials including trees, shrubs, palms and bamboos, with agricultural crops and/or animals on the same land management unit in some form of spatial arrangement or temporal sequence such that there are significant ecological and economic interactions among the woody and non-woody components (Sinclair, 1999). It can include planting trees on contours, intercropping, multiple cropping, riparian zones/buffer strips and many more (Branca *et al.,* 2011). These assist in improving land productivity by providing favourable micro-climate, permanent cover, improved soil structure and organic carbon content, increased infiltration and enhanced soil fertility (WOCAT, 2011).

Agroforestry plays important roles of providing food for human, feed, fodder, and bedding materials (litter) to livestock (Neupane *et al.,* 2002). Kang and Akinnifesi (2000) indicate that agroforestry plays a role in increasing agricultural productivity by nutrient recycling, reducing soil erosion, and improving soil fertility and enhancing farm income compared with conventional crop production. The plants used play a crucial role in maintaining and regenerating soil fertility through the action of their roots and litter. Agroforestry practices have been shown to influence chemical, physical and biological components of soil fertility (Schroth & Sinclair, 2003). Pastoralists value trees for the high nutritional value of the fodder from their leaves and fruits. In the dry season the trees are still available when the grasses dry out (Cajas-Giron & Sinclair, 2001). This encourages the integration of agroforestry among small scale farmers who keep animals apart from just growing crops. It also promotes sustainable farming systems (Cooper *et al.*, 1996).

A study done by Schroth and Sinclair (2003) indicated the importance of matching agroforestry technique with the fertility problems observed at a given site, rather than assuming that every type of agroforestry will improve soil fertility in general. While studying the effect of minimum tillage and vegetative barrier effects on crop yields, Guto et al. (2011) found that leucaena extracted more water from deeper soil layers during dry periods. They further observed that leucaena had deep roots that exploited different soil layers than shallow rooted crops thereby posing limited water and nutrients competition. The resource use pattern between crops and leucaena barriers implies a complementary and facilitative relationship. Additionally, leucaena trees fix nitrogen thereby sparing soil nitrogen (Giller, 2001) as well as restricting nutrient leaching by capturing and transporting leached nutrients from deep soil horizons to topsoil hence facilitating overall nutrient capture and its utilization efficiency (Teixeira *et al.*, 2003).

Woody shrubs are effective in their biological drilling in the soil because of their perennial nature and their known ability to penetrate hard soil horizons and may be useful at sites with compact sub-soil horizons (Grimaldi *et al.,* 2003). Based on these facts the application of agroforestry in conservation agriculture would be a beneficial strategy as it would help in improving the soil conditions and at the same time provide fodder for the animals and reduce the competition for the crop residues which can be used as mulch in crop production systems.

2.5 Herbicide Application in Weed Control

Weed management is an important aspect in crop production. Weeds are a significant constraint and cost to agricultural production worldwide and can lead to yield losses (Oerke, 2005). Weed control has mainly been done manually or mechanically through soil cultivation and though it is effective for reducing weed it has a number of detrimental effects such as increasing soil erosion risk and loss of soil organic matter (Six et al., 1999). Manual weed control is labour intensive and therefore limits the production area. It has become increasingly difficult to hire labour for weeding and other farming activities mainly due to a dwindling labour force as a consequence of out-migration of the young and energetic population (Steiner *et al.,* 2003). Weed control in conventional tillage is through tillage to produce a clean seedbed. This gives the planted crop an advantage in emerging before most weeds come out. However, tillage has detrimental effects on soil quality as shown by Nichols *et al.* (2015).

In farming systems that adopt conservation agriculture technologies, the weed control by ploughing/tilling is not used. Therefore, when adopting conservation agriculture, farmers must have a carefully planned weed control strategy, especially in the early years when weed levels are high, as they are no longer controlled by primary tillage. Weed control in conservation agriculture can be achieved through a number of approaches including cover crops, crop residues, crop rotations, planting density, in-row slashing of weeds, superficial weeding (hoeing, ridging), pulling out, and/or slashing even at crop maturity and post-harvest to prevent seed production, and also through herbicide application (Baijukya *et al.*, 2020). Inadequate weed control in farming systems using conservation agriculture has in the past caused losses in crop production resulting into the low adoption of this practice by farmers (Sims *et al.,* 2018). However, the advent of effective herbicides in weed control has provided an opportunity to implement conservation agriculture without yield losses due to weeds (Vishwakarma *et al.*, 2023).

The farm scale economic impacts of labour use for tillage, weeding, and inputs of fertilizer and herbicide, need to be assessed in relation to the benefits for production (Giller *et al.*, 2011). To realize the benefits of conservation agriculture practices, herbicides are often needed but not available to smallholders (Gowing & Palmer, 2008). Unfortunately, the impact of increased herbicide use on soil biota and the ecosystem services they provide is not well understood or documented (Rose *et al.*, 2016). There is thus need for the assessment of the economic impact of using herbicides in relation to the benefits gained in the agricultural production by small scale farmers (Giller *et al.,* 2011).

2.6 Effects of Conservation Agriculture on Soil Physicochemical Properties

Conservation agriculture is an approach to manage agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (FAO, 2007). It supposedly results to higher and more stable yields and reduced vulnerability to climatic variability (Kassam *et al.,* 2009). conservation agriculture protects and enhances sustainability whereas conventional tillage agriculture adversely affects soil quality and farm productivity (Shaxson *et al.,* 2008). They further, note that soil plays a central role in agricultural production as it not only determines the production, but also the efficiency of much other production factors and inputs.

This is through the dynamic interaction of four components in space and over time. These are: (i) **physical** which include aspects such as soil structure and depth, (ii) **hydric** which involves soil's capacity to absorb, transmit and retain water received at the surface and the supply of soil water to plants, (iii) **chemical** which deals with dissolved substances which serve as plant nutrients, and (iv) **biological** which relates with soil-inhabiting organisms such as bacteria, fungi, plants, animals, and their non-living residues. All these four components interact under the influences of climate, gravity, available species, and the stability of soil care and management. The dynamic equilibrium of these components is crucial for soil productivity. However, some operations like tillage offset this equilibrium. Technologies such as the conservation agriculture would play an important role in preserving the equilibrium and maintaining sustainable soil productivity.

Soil water is a medium for plant nutrition and its conservation and availability determines the crop growth and productivity. This is more pronounced in semi-arid region where seasonal variation in yield is largely determined by the amount of water available for transpiration (Kironchi *et al.,* 1995). It represents a balance between processes that add water to the soil, such as infiltration of rainfall, and processes through which water is lost from the soil, such as plant water use (transpiration), evaporation, runoff and drainage. The efficiency of using rainfall to produce food especially where water is scarce is of fundamental importance to sustaining a global balance between food supply and demand because 75% of human use of fresh water is consumed in agriculture (Schroth & Sinclair, 2003). Soil water storage and availability vary with soil type and management. Soil properties such as particle size distribution, clay mineralogy, organic carbon and bulk density influence soil water retention. Soil structure, which plays an important role on soil pore distribution, strongly relates to soil water retention (Williams *et al.,* 1983).

Soil water retention curve (SWRC) is defined as the relationship between volumetric water content and matric potential (McKenzie and Cresswell, 2002). It is important in simulating soil water balance. The relationship between hydraulic conductivity and water content has an important role in the control of local soil water regime. Hydraulic conductivity depends on soil water content. The selection of the method used to determine hydraulic conductivity depends on several factors that include the soil to be measured, purpose of measurement and the available resources. The two most important factors in increasing water availability are reducing evaporation and enhancing infiltration.

The amount of water infiltrated in the soil depends on the duration of the rainfall and the soil's infiltration capacity (Stroosnijder, 2009). Land degradation such as destruction of soil structure leads to increased bulk density, reduced soil porosity, reduced water infiltration, surface crusting and reduced water-holding capacity (Grimaldi *et al.,* 2003). The destruction of soil structure leads to decreased infiltration rates and increased runoff, hence reducing the amount of water that get into the soil that is available for crop production. Through mulching, processes such as surface sealing and crusting of the soil by rainfall are prevented and infiltration is enhanced (Scopel *et al.,* 2004). Moreover, mulching triggers activities of soil macro fauna, such as termites, which loosen the soil and create pores, thereby enabling water to infiltrate more rapidly which improve soil water availability (Stroosnijder, 2009).

Another way to increase rain water use efficiency is to improve the storage capacity of the soil. Soil structure is an important factor in this regard, as well as the depth of the root zone. No-tillage and introduction of cover crops technologies may contribute to enlargement of the root zone (up to 30%), while the soil moisture holding capacity of the soil may increase in the long term because of the build-up of organic matter in the root zone (Tittonell *et al.*, 2012). In addition, mulching may prevent loss of fertile top soil through erosion, which also contributes to increased storage capacity of the root zone (Stroosnijder, 2009). The ability of standing stubble and surface residues to enhance water conservation and reduce wind erosion has been well documented by Smika and Unger (1986).

The positive benefits have been documented for no-till production systems on crop production and energy use efficiency (Lafond *et al.*, 2006). No-till has the potential for soils carbon (C) sequestration due to increased macro-aggregation (>0.25 mm) and mean weight diameter of soil aggregates (Franzluebbers and Arshad, 1996). Further work indicates potential of no-till to sequester carbon (C) (McConkey *et al.*, 2003). Water retention and infiltration can be increased due to a redistribution of pore size classes into more small pores and fewer large pores having the potential to improve crop water use and crop production. Because of their positive impact on soil carbon, no-till production systems are seen as a necessary component to sustaining and enhancing the global soil resource (den Biggelaar *et al.*, 2004).

2.7 Effects of Conservation Agriculture on Soil Biological Properties

Biological properties influence of the living organisms habiting a particular soil. These properties are important in soil quality and reflect how well-suited a soil is to support life (Jones *et al*., 2019). Soil microbial biomass (SMB) are crucial in ecosystem processes like nutrient and carbon cycling (Jia *et al.*, 2020). There is a relationship between physicochemical properties and soil microbial biomass. Thus, management practices such as tillage, mulching, herbicide application and agroforestry which has effect on soil physicochemical properties are expected to influence soil microbial biomass (Wang *et al*., 2018).

Soil management practices have effect soil chemical properties such as pH and soil organic carbon which influence soil microbial biomass (Li *et al*., 2018; Vazquez *et al*., 2019). Muchabi *et al.* (2014) found significantly highe soil organic carbon, nodulation, biological nitrogen fixation, soil microbial biomass and soil respiration under conservation agriculture than conventional tillage after seven years of practice. Farmers awareness about the importance of soil for sustaining crop production and providing beneficial ecosystem services has increased over time (Rose *et al.*, 2016). The global herbicide use has increased as farmers have shifts to more sustainable conservation tillage practices and have adopted herbicide tolerant crop cultivars. Ith the increased use of herbicide their effects on soil biology are being questioned. However, comprehensive information on efect of herbicice on soil biology is scanty and not well documented (Rose *et al.*, 2016). Management practices have varying effect on soil microbial proprties and thus, the need to evaluate the effect of diffrenet management practices on soil microbial biomass. This will assist in identifying the soil management practices that have a positive effect on soil microbial biomass.

2.8 Soil Quality Indicators

Some of the soil quality indicators are bulk density, stability index, matric and macro porosity, aeration capacity, relative water content and plant available water content. Soil bulk density is one of the most prominent indicators of soil structure and is a good indicator of the effect of soil management practices (Rabot *et al.,* 2018). Macro-porosity is considered an excellent indicator of soil degradation and is widely used in soil management studies due to its relation with compaction **(**Stolf *et al.,* 2011). Air capacity is related to root-zone aeration, the diffusion of gases and the respiration of soil fauna and is a critical aspect in evaluation of management practices. The plant available water content is a critical soil physical property because it indicates the amount of water available to the plants and determines crop growth and yield. Dexter (2004) noted that stability index (S) is mostly affected by microstructural porosity and therefore it directly influences many of the principal soil physical properties. This shows that it can be used to assess the effects of different conservation agriculture practices directly.

Soil physical properties are important as they affect crop growth and take time to be affected by soil management practices. This implies that it takes a long time for significant differences to be realized under management practices. Under a given research study, it may be therefore important to consider the mean of the management treatments, which may show trends indicating the effect of various conservation agriculture practices (Amrhein *et al.,* 2019). In the case of this study, these would be; tillage, mulching and agroforestry.

Soil biological activity is highly sensitive to changes caused by environmental and management factors (David *et al.,* 2007). Aziz *et al.* (2013) noted that soil biological activity is a sensitive soil quality indicator as compared to other soil properties such as porosity, soil aggregate stability and total soil carbon in response to management practices like tillage, cropping systems, surface cover management and weed control methods such as herbicide application.

2.9 Rain Water Use Efficiency

The importance of water use efficiency in crop production in semi-arid areas is based on the fact that the available water is the most limiting factor influencing crop production. It measures the cropping system's capacity to convert water into plant biomass or grain. Thus, any crop production practice that has a better water use efficiency is best suited in these areas (Kröbel *et al.,* 2021). Study by Ruggiero *et al.* (2017) report that the focus in plant breeding has been selection or development of seeds that are drought tolerant and have high water use efficiency in order to relieve scarcity of water and ensure food security.

Management practices in crop production with improved soil fertility have also been adopted to achieve higher crop yields under less water (Farmaha *et al.,* 2022). There is greater variation in water use efficiency between crops. Moreover, the supply of water has been significant on water use efficiency by crops with some studies reporting rising water use efficiency with decreasing water supply (Chibarabada *et al.,* 2015).

2.10 Research Gaps

Conservation agriculture has been billed as the key to unlock production potential among the small-scale farmers in areas constrained by moisture and plant nutrients. The need for crop water use efficiency has been identified as a key in the face of climate change. However, impact of conservation agriculture on crop yields due to these incremental benefits within smallholder farmers' environment in semi-arid regions like Laikipia are not well established in general. Thus, there is need to evaluate the effectiveness of various conservation agriculture practices on soil properties and ultimately the crop yield. This will assist in determining the optimal application in particular conditions (dry areas of Kenya) in order to improve its suitability among the small-scale farmers. Furthermore, adoption of conservation agriculture practices is low due to the competing uses of crop residues especially feeding to livestock. This study endeavoured to close in on these gaps by evaluating the effect of each conservation agriculture components; tillage and mulching, and agroforestry on soil physicochemical properties, soil microbial biomass and maize yield at a small-scale farmer's field.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Site

Laikipia East sub-County is located about 200 km north of Nairobi (Figure 3.1) and lies on the leeward side of Mt. Kenya between latitudes 0°17'S and 0°45'N and longitudes 36°15'E and 37°20'E. The altitude ranges between 1962 m above sea level on a dry land and semi-arid plateau (Ojwang’ *et al.*, 2010). It has semi-arid climate with reduced temperatures (CETRAD, 2008). Rainfall is bimodal with long rainy season between the months of April to July while the short season occurs from October to December (Kaumbutho and Kienzle, 2007). However, the length of the season as well as the onset of the rains is highly variable and unreliable (CETRAD, 2008). On average, annual rainfall in this area is around 750 mm. Potential evaporation is 1425 mm (Mutonga *et al.*, 2019) and, in most months, higher than the rainfall (Ronner, 2011). The area is under agroecological zone IV, semi-arid climate.

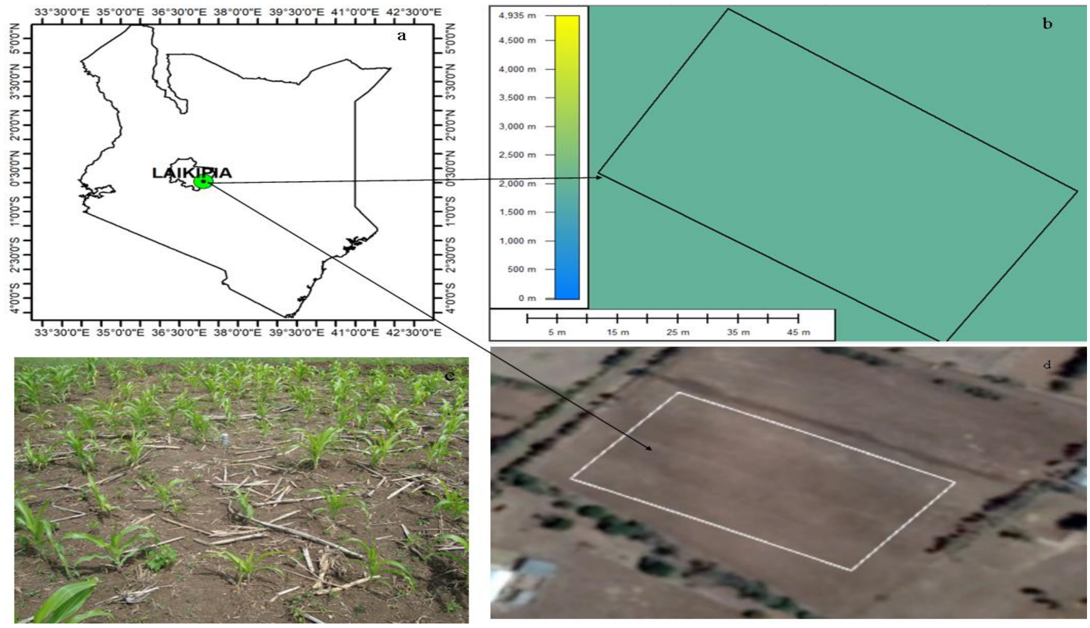

Figure 3.1: Location of the Research Site Plate (a) Study area location on map

of Kenya, (b) the study area elevation, (c) Plot of growing maize under mulch and (d) Google earth image at the end of the study period.

This makes the study site representative of similar agroecological zones in Kenya where crop production is done. The soil in the study site is classified as Vertic Phaeozem. The base research soil characteristics are given in Table 3.1.

Table 3.1: Soil Characteristics at the Research Site Prior to the Field Trials

Soil characteristic[1]	
pH	6.4
N (%)	0.14
OC (g kg^{-1})	14
P (ppm)	74.7
K (ppm)	322
EC_e (dS m^{-1})	0.15
CEC (cmol kg^{-1})	12.4
BD (Mg m^{-3})	1.24
Clay (%)	60
Silt (%)	17
Sand (%[1])	23
Textural class	Clay

[1] N is nitrogen, OC is organic carbon content, P is phosphorous, K is potassium, EC_e is electrical conductivity of a saturated paste, CEC is cation exchange capacity, and BD is bulk density

Rain-fed agriculture is one of many other activities and source of income in the study area. Arable agriculture occupies 26.5% of the total area of the county (Ojwang' et al., 2006). In this area, agriculture is practiced both by smallholder commercial and subsistence farmers and largescale commercial farmers. Agricultural practice in the region is mainly rain-fed which accounts for approximately 26.0% of the livelihood activities. The main rain-fed crops grown in the area include maize (about 51% of the cultivated area), beans, potatoes, sorghum, wheat, barley, fruit trees, and a range of horticultural crops (Kaumbutho and Kienzle, 2007). Large-scale farmers commonly grow wheat, barley and horticultural crops. The average maize yield in Laikipia is about 1,800 kg ha^{-1} which lies around the national average in Kenya of 1,900 kg ha^{-1} as of 2007 (FAOSTAT, 2011).

3.2 Experimental Design and Treatments

The research was carried out for three years (year 1 (2012), year 2 (2013) and year 3 (2014)) in farmers' field already practicing conservation agriculture in Laikipia East sub-County. The experimental design was split-plot with the three main-treatments and four sub-treatments, replicated three times. The three main treatments were: conventional tillage (CT), no tillage (NT) and no tillage with herbicides (NTH). In each of the treatments the following sub-treatments were included: (a) Maize and beans (MB), (b) maize and dolichos (MD), (c) maize beans and leucaena (MBL) and (d) maize, beans and maize residue mulch (1.5 tonnes Ha^{-1}) (MBMu) (See Table 3.2).

The common beans and dolichos beans were selected for intercropping because they are the legumes farmers in the study area use for intercropping with maize. The plots were 5 metres wide and 10 metres long. Under no tillage with herbicides there was no tilling of the fields. The weeds were controlled through the use of herbicides. In the no tillage with no herbicides there was no tilling, and weeds were controlled using a scrap weeder. However, in both treatments, planting of the seeds was in the holes through direct drilling of the ground. For the conventional tillage the normal practices that involve tilling the land and weed control using a hoe, was carried out. More information on the treatments and their combination is presented in Table 3.2.

Table 3.2: Research Treatments

Treatment	Number of conservation agriculture practices applied			Specific practice tested		
	one	two	three	herbicide	agroforestry	mulch
CTMB	x					
CTMD	x					
CTMBL	x				+	
CTMBMu		x				+
NTMB		x				
NTMD		x				
NTMBL		x			+	
NTMBMu			x			+
NTHMB		x		+		
NTHMD		x		+		
NTHMBL		x		+	+	
NTHMBMu			x	+		+

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

3.3 Crop Establishment and Field Management

The maize variety SC Duma 43 was used in this study due to its early maturing, drought and diseases tolerance besides possessing friendly intercropping characteristics. The variety is recommended for areas such as Laikipia sub-County besides being commercially available. The maize was sown at the onset of the rains at a spacing of 0.75 m between the rows and 0.30 m within the rows. Sowing was done manually by placing two maize seeds per planting hole dug at a depth of 0.04 m. Dolichos beans and common bean seeds were sown in between the maize rows at a spacing of 0.75 m between the rows and 0.30 m within the rows. Seed gapping was done after emergence. Common beans and dolichos beans were sown same time with maize, while leucaena spacing was 0.6 m within the rows and 1 m between the rows.

After harvesting the mature dry dolichos pods, the plants were left to continue growing in the field as it is a perennial crop.

Fertilizer was applied at the rate of 50 kg ha^{-1} NPK fertilizer (17-17-17, N: P_2O_5:K_2O) at planting and was applied to all treatments by placing it next to the seeds. Top dressing was done when the maize crop was knee high using calcium ammonium nitrate (27% N) at the rate of 50 kg ha^{-1} with the placement method. Weeds were controlled by use of a superficial shallow scrape weeder for the NT treatment and using Paraquat herbicide (Gramaxone®) at an application rate of 2 litres ha^{-1} in the NTH treatment. The herbicide was applied three times per growing season, that is, at the beginning of the season before emergence and two other times in between depending on the weed population. The herbicide was applied using a zam-wipe to avoid crop damage.

3.4 Soil Physical Properties

3.4.1 Soil Moisture Content (SMC)

Soil moisture content (SMC) was measured at depths of 0.15, 0.30, 0.45, 0.60, 0.75, 0.90, 1.05, 1.20, 1.35, 1.50 m using a neutron probe (Hydroprobe® model 503, CPN Corporation, Martinez CA USA). Two access tubes were installed in each plot, 2 m from the edge of the plot and with 6 m between them as shown in Figure 3.2. Soil moisture content was measured every week and after a rainfall event up to 120 days after planting.

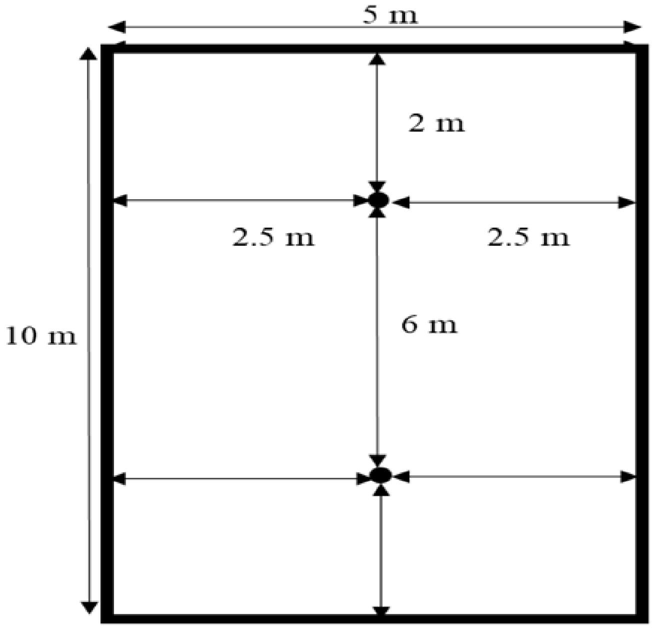

Figure 3.2: Research Plot Dimensions and Position of Neutron Probe Access Tubes Shown by the Two Black Dots

The neutron probe was calibrated by installing three access tubes outside but adjacent to the experimental plots. To have a wide range of moisture conditions, the soil surrounding these access tubes were wetted differently (wetting to field capacity, intermediate wetting, no wetting) in dry weather (Evett *et al.*, 2003). During the reading of the neutron probe at various soil depth increments, both disturbed and undisturbed soil samples were also taken at the corresponding depths. Gravimetric water content was determined from the disturbed samples and bulk density from the undisturbed (Grossman and Reinsch, 2002) as shown in Equation 3.1.

$$BD = \frac{M_s}{V_b}$$ **Equation 3.1**

where BD is bulk density, M_s (Kg) is oven-dry soil mass, and V_b (m^{-3}) is the corresponding bulk (undisturbed) soil volume. Gravimetric soil-water content was multiplied by the measured bulk density (from the undisturbed samples) to obtain volumetric soil moisture content C [(Mw/Ms)xBD where Mw is mass of water], which was then regressed against the count ratio (CR) to get the neutron probe calibration equation. Count ratio is the count rate in the soil at a given point divided by count rate in the standard absorber (i.e., the shield of the probe). Equation 3.2 shows how count ratio was calculated.

$$CR = \frac{\text{count rate in soil} M_s}{\text{count rate in standard}} = \frac{N}{N_S} \qquad \textbf{Equation 3.2}$$

where N is the count rate in the soil (count per minute; cpm) and Ns the count rate in the standard absorber (cpm). Standard counts are counts taken when detector/source tube is locked in the polypropylene shielding positioned at the top of the transport case. The calibration equation was used to obtain soil moisture content as shown in equation 3.3.

$$SMC = MCR - X \qquad \textbf{Equation 3.3}$$

where SMC is soil moisture content, CR is count ratio, M and X are calibration constants, namely the slope of the calibration curve and the x-intercept respectively.

Undisturbed soil core samples were taken from depth of 15 cm using a 100 cm^3 soil metal core rings for determination of soil water retention and bulk density. The soil water retention curves per treatment were determined using a combination of sand box and pressure plates following the procedure outlined in Cornelis *et al.* (2005).

The critical moisture storage at which maize starts to experience drought stress was determined using a matric potential of -500 kPa which was taken during the vegetative period and -800 kPa during the reproductive period, which includes ripening, the latter value being the upper limit in case of a high evaporative demand (Taylor and Ashcroft, 1972) as in the study location. Water retention curves measured per treatment on undisturbed 100 cm^3 soil cores taken in the 3rd year of the experiment using a combination of sand box and pressure plates following the procedure outlined in Cornelis *et al.* (2005), was used to convert critical matric potential to critical soil moisture content. The latter was multiplied by the depth of interest to get the critical soil moisture storage. Likewise, soil moisture storage at -33 kPa and -2400 kPa was calculated to assist in the interpretation of the results. Soil moisture storage at matric potentials above -500 kPa during the vegetative period and

-800 kPa during the reproductive period was considered as readily available, while that above -2400 kPa as totally available at the dates of measurements. Taylor and Ashcroft (1972) suggested permanent wilting of maize at -2400 kPa rather than the more commonly used value of -1500 kPa. However, given the very small changes in soil moisture content between -1500 kPa and -2400 kPa, the choice of that value hardly affects the corresponding S-index (S) which is the slope of the soil water retention curve (SWRC).

3.4.2 Soil Physical Quality Indicators

Undisturbed samples were taken after three years of experimentation at a depth of 0 m to 0.15 m in all the plots. Several soil quality indicators were used to evaluate of the effect of tillage, mulching and herbicide application on soil physical properties. They were derived from the Water Retention Curve (WRC) as described by Dexter, (2004) and Renolds *et al.* (2007).

Soil physical quality (SPQ) indicators were calculated and compared to optimal or critical values to evaluate the effects of the treatments on the soil quality. Soil physical quality index (S) is a parameter used in assessing physical soil quality based on the shape of the Soil Water Retention Curve (SWRC) (Dexter, 2004) and was calculated as shown in Equation 3.4:

$$S = -n(\theta_s - \theta_r)\left[\frac{2n-1}{n-1}\right]^{\left[\frac{1}{n}-2\right]}$$

Equation 3.4

where θ_r is the residual water content (m^3 m^{-3}) and θ_s is the saturated water content (m^3 m^{-3}). Parameters α (kPa^{-1}) and n were estimated using the Levenberg-Marquardt algorithm and it is the curve's slope at its inflection point.

The soil physical quality indicators were calculated as suggested by Reynolds *et al.* (2007 and 2009) using Equations 3.5 to 3.12, with indicators related to porosity derived from soil water retention curve:

Soil structural stability index (SI) expressed in %

$$\mathrm{SI} = \frac{1.72\mathrm{XOC}(\mathrm{wt}\%)}{\mathrm{clay} + \mathrm{silt}(\mathrm{wt}\%)} \mathrm{x}100$$ **Equation 3.5**

where OC is organic carbon (%weight). Macro-porosity (MacPOR, m^3 m^{-3}) and matric-porosity (MatPOR, m^3 m^{-3}) which are the expression of the volume of soil macro-pores (MatPOR) and matric-pores (MacPOR), respectively, were calculated as follows:

$$MatPOR = \theta_v$$ **Equation 3.6**

$$MacPOR = \theta_v - MatPOR$$ **Equation 3.7**

where θ_v (m^3 m^{-3}) is the saturated volumetric water content of the soil matrix exclusive of the macro-pores. Macro-pores are defined as pores having an equivalent diameter larger than 300 µm (Dexter and Czyz, 2007), which corresponds to a tension of (0-10cm) 0.98 kPa according to the capillary equation. Soil aeration is represented by soil aeration capacity (AC, m^3 m^{-3}) defined as:

$$AC = \theta_{vs} - \theta_{vfc}$$ **Equation 3.8**

where θ_{vs} (m^3 m^{-3}) is the saturated volumetric water content and θ_{vfc} (m^3 m^{-3}) is the volumetric water content at field capacity (FC) taken at -10kPa. The water that is available to the plant is given by plant available water capacity (PAWC, m^3 m^{-3}):

$$PAWC = \theta_{vfc} - \theta_{\mathrm{vpwp}}$$ **Equation 3.9**

where θ_{vpwp} is permanent wilting point (PWP). The capacity of soil to store water relative to the soil's pore volume is relative water capacity (RWC) which was calculated as:

$$RWC = \frac{\theta_{vfc}}{\theta_{vs}} = \left(1 - \frac{AC}{\theta_{vs}}\right)$$ **Equation 3.10**

The S-Index is derived from the relationship between the gravimetric soil water content and the natural log of matric tension. This was calculated as the slope of the soil water retention curve (SWRC).

$$S = -n\left(\theta_{gs} - \theta_{gr}\right)[2n-1]^{\left(\frac{1}{n}\right)-2}$$ **Equation 3.11**

where θ_{gs} and θ_{gr} are gravimetric saturated and gravimetric residual water contents respectively, the n was estimated using the Levenberg-Marquardt algorithm which was taken from curve's slope at its inflection point.

Aggregate stability was determined based on the Yoder method modified by Kemper and Rosenau (1986) using a wet sieving apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands). Results were expressed as Mean Weight Diameter (MWD):

$$\mathrm{MWD} = \frac{dW_S}{W_t}$$

Equation 3.12

where W_S is mass of the stable aggregate fraction (g), d mean diameter of fraction (mm), W_t total weight of the sample (g).

3.4.3 Soil Hydraulic Conductivity

The soil hydraulic conductivity was determined using tension infiltrometer (Model 2825K1, Soil moisture Equipment). The K(h) was calculated using non-linear regression method (Logsdon & Jaynes, 1993) (Equation 3.13) based on the theoretical analysis of the steady-state water flux under the infiltrometer (Wooding, 1968):

$$\frac{Qx(h)}{\pi R^2} = K_s \exp(\alpha h) + \frac{[4K_s \exp(\alpha h)]}{\pi R \alpha}$$ **Equation 3.13**

where Qx (h) is the steady infiltration rate under pressure head of h (-m), R is the radius of the disc, and α is the Gardner constant which characterizes the soil pore size distribution. The parameters K_s and α were determined by curve-fitting, using the Levenberg-Marquardt algorithm, allowing for the determination of the hydraulic conductivity K(h) under any other pressure head, h, from Gardner's (1958) exponential function, thus:

$$K(h) = K_s \exp(\alpha h)$$ **Equation 3.14**

where K_s is the field saturated hydraulic conductivity (m s^{-1}).

3.5 Soil Chemical Properties

Samples were taken from 0.15m depth once per year at crop maturity for the three years of the experimentation. The samples were taken to the laboratory for air drying, grinding and sieving using 2 mm sieve. The sieved air-dried soil was used for the analysis of soil chemical properties. The soil total organic carbon content (SOC) was determined using the Organic carbon Walkley and Black method (Walkley & Black, 1934). The pH was determined with a pH meter (Model inolab pH720, WTW, Germany) where soil was mixed with water in the ratio of 1:2.5 of soil and distilled water, respectively. Cation exchange capacity (CEC) was determined using ammonium acetate pH 7 method by Schollenberger (1927). Total nitrogen content was determined using the Kjeldahl extraction method while phosphorous was determined by the Mehlich double acid method (Mehlich, 1953). The available K, Ca and Mg were extracted by the Mehlich method. Potassium was determined using the flame photometer (Corning M400, UK), while the macro-Ca and Mg and micronutrients (Cu, Mn, Fe, and Zn) were determined using atomic absorption spectrophotometer (210VGP Atomic Absorption Spectrophotometer, Buck Scientific, USA).

3.6 Soil Microbial Biomass

Soil samples were collected from a depth of 0-0.15 m at random points between the maize rows in all plots at the end of the experiment using an auger. From each plot, five soil samples were composited, put in a polyethylene bag and placed in a cool box at 4 ^{o}C for transportation and storage in the laboratory.

The soil microbial biomass was determined using CO_2 burst (Franzluebbers *et al.*, 2000) using Solvita analysis kit (Woods End Laboratories, Inc. Mt. Vernon ME USA) where a 100 g per soil sample was dried in a laboratory convection oven at 50 ^{o}C for 24 hours. The soils were ground and sieved through a 2 mm sieve and 40 g per sample was put in a perforated 50 ml plastic beaker which was placed in a 250 ml glass jar. Twenty-five (25) mm of de-ionised water was placed onto the bottom of the glass jar to facilitate wicking of moisture into the sample so as to bring the soils to full water capacity by capillarity.

The Solvita probe was carefully placed into the glass jar alongside the plastic beaker using plastic tweezers. Care was taken to avoid touching the gel surface while ensuring that the soil was not touched. The colour of the gel was checked to ensure that it was blue at the beginning. The lids of the glass jars were tightly screwed and kept under stable room temperature conditions of 25 ^{o}C for a period of 24 hours. At the end of the 24 hours period the colour of the probes was read by inserting them into a Digital Colour Reader (DCR). The DCR number was converted to CO_2-C using the formula (Equation 3.15) derived by Haney *et al.* (2008), thus:

$$y = 20.6 * (\text{DCR number}) - 16.5 \qquad \textbf{Equation 3.15}$$

3.7 Crop Yield Data

Yield data was collected during long rain season each year for the three years of study. The maize was harvested at physiological maturity and its water content was measured using a digital moisture meter (GMK-303**,** G-won Hitech Co. Ltd. Korea).

Grain yield was converted to standard water content of 12% using the formula in Equation 3.16.

$$Y_f = \frac{Y_i \times DM_i}{DM_f}$$ **Equation 3.16**

where Y_f is final grain wt at 12% m.c, Y_i is original grain wt. from the field, DM_i initial dry matter wt of grains from field (100 – % measured mc), DM_f is the final grain wt at desired storage mc (100- 12%).

Two grids of 2 m by 2 m next to the access tubes was used for harvesting the maize (See Figure 3.3). The harvesting was done manually, after which it was threshed and the grain weight taken.

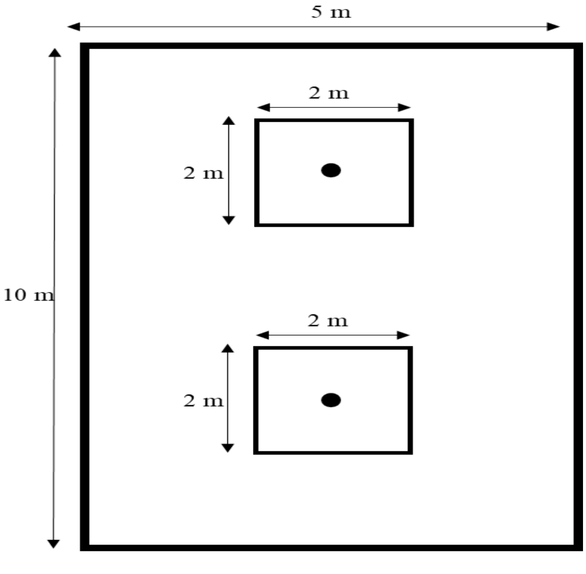

Figure 3.3: Sampling Grid for Maize Harvesting with the Two Black Dots Indicating the Position of Neutron Probe Access Tubes

Yield stability index was applied to evaluate effect of tillage, mulching, herbicide application and agroforestry on sustainable maize production. Yield stability is how stable the yield of an agricultural system is over time from one year to another. A management practice with high yield stability will output about the same amount of food each year. Stability analysis was done using linear regression of treatment yield on the environment means (Grover *et al.,* 2009). Environment mean was calculated as the annual mean yield of all treatments being compared (Eberhart & Russell, 1966). Environmental means were then ranked by yield level to produce a quantitative gradient of environmental productivity irrespective of the cause of variability in yield (Hildebrand, 1984). The individual treatment means were regressed on the environment means and regression lines were compared among treatments. The assumption for stability analysis was that year-to-year variability in yield was due mainly to environmental variability. For a valid stability analysis, therefore, change in yield over time should not differ among the treatments being compared (Guertal *et al.,* 1994). The treatments with a smaller slope indicate greater yield stability (Sileshi *et al.,* 2011).

Rain water use efficiency (RWUE) is defined as the ratio between aboveground and rainfall and increasingly used to diagnose land degradation (Dardel *et al.,* 2014). For a given ecosystem with no degradation, the rain water use efficiency is expected to be stable over time (Dardel *et al.,* 2014). It has been increasingly used to analyse the variability of vegetation production in arid and semi-arid biomes, where rainfall is a major limiting factor for plant growth (Bai *et al.,* 2008). It indicates yield attained by a treatment per millimetre of rain water received during the specified period. Since there is no irrigation to the crop other than rain water, rain water use efficiency would also indicate the water productivity or water use efficiency of a treatment under rainfed conditions (Sharma *et al.,* 2013). Rainfall was measured using a manual rain gauge installed at the research site.

The rain water use efficiency was calculated by dividing the total grain yield (GY, in kg ha^{-1}) by total rainfall (mm) from planting to harvest:

$$\text{RWUE}\left(\text{Kg ha}^{-1}\ \text{mm}^{-1}\right) = \frac{\text{Grain yield}\left(\text{Kg ha}^{-1}\right)}{\text{Total rainfall (mm)}}$$ **Equation 3.17**

3.8 Data Analysis

The data was analysed using IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, IL). Data was tested for normality and analyses of variances (ANOVA) conducted following the General Linear Model (GLM) to check the effect of number of conservation agriculture practices applied. Significant difference between the treatments was tested using least significant difference (LSD) at 5% probability level. To check the effect of tillage, herbicide application, agroforestry and mulching, a t-test was applied at 5% probability level.

Data was pooled following the categories shown in Table 3.2. The effect of tillage was tested by comparing CT treatments with NT treatments. The effect of herbicides was tested by comparing all no till combinations with herbicides against those without. To test the effect of mulching, comparison was done between all treatments of maize and common bean with and without mulch. To compare the effect of the pulse bean species used in intercropping, all treatments of maize with common beans were compared to that with dolichos bean. Where significant differences were detected, means were separated using the Fisher’s LSD (Least Significant Difference) test (0.1 probability level).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Rainfall

The variation in the amount of rainfall received in the different growing seasons and within the season was substantial. The recorded rainfall for the 1st (2012), 2nd (2013) and 3rd (2014) years' seasons was 685 mm, 538 mm and 270 mm, respectively (See Figure 4.1). An 18-years (1993-2011) average seasonal rainfall (470 mm) at Kenya Meteorological Department, Laikipia County office was used for comparison. Frequency analysis of the data shows that the 1st and 2nd years growing seasons were wetter than the 3rd year which was generally drier than average. The return period and probability of exceedance for the three years' seasons were 6.4 years and 15%, 5.3 years and 18%, and 1.1 years and 92% respectively.

Periods with continuous rainy days with high rainfall amount were followed by extended periods of dry days resulting into meteorological and agricultural dry spells. Meteorological drought is a reduction in seasonal rainfall mainly below normal or crop water requirements over a certain period of time and region, while agricultural drought is soil moisture deficiency for crop production (Alam *et al.,* 2014). Dry spells are prolonged periods of dry weather (10 days or more) during crop critical growth stages (Barron *et al.*, 2004). Periods with 10 days or more without rain occurred once in all the years of the experiment as shown in Fig. 4.1. The effects of these dry periods on soil moisture are discussed in section 4.2.1

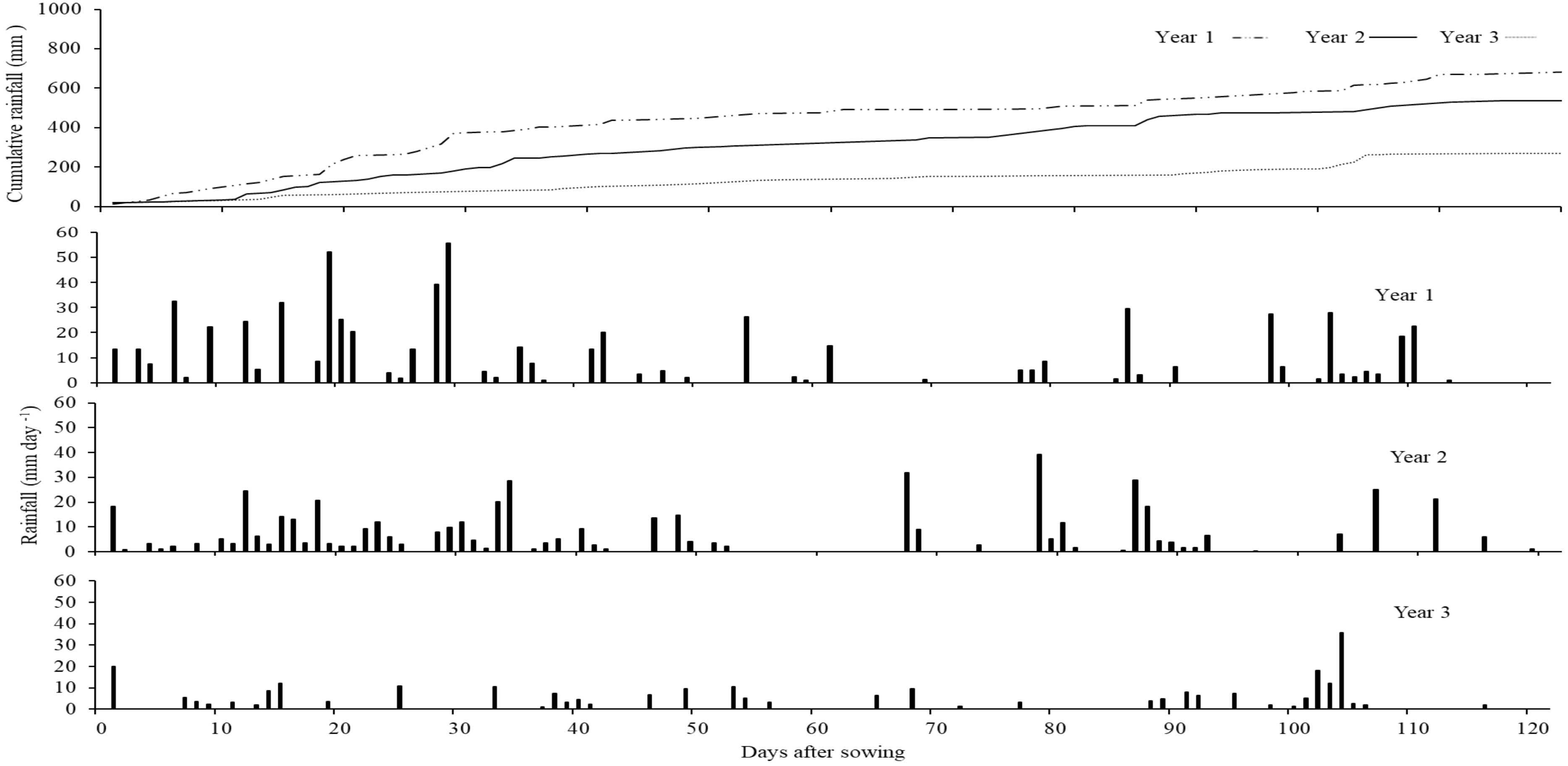

Figure 4.1: Cumulative Rainfall Distribution and Daily Rainfall during Research Period Year 1-Year 3.

Crop water requirements (ET_c) calculated with FAO's AquaCrop model for the maize variety used in the study under the local climate conditions and the results are given in Table 4.1. Given that the crop water requirements were met during the first two years

Table 4.1: Effect of Tillage, Herbicide Application, Agroforestry, Mulching and Number of CA Practices on Crop Water Requirement (mm).

	Year 2	Year 3
	Tillage	
CT	340	243
NT	343	239
	Number of CA practices applied	
One	344^a	245^a
Two	342^a	242^a
Three	345^a	239^a
	Intercropping	
Maize/Common beans	345	243
Maize/Dolichos beans	339	242
	Herbicide	
Yes	346	240
No	343	243
	Agroforestry	
Yes	347	243
No	345	242
	Mulch	
Yes	343	241
No	346	243
	Interaction of tillage, agroforestry, herbicide application and mulching	
CTMBL	348^a	242^a
CTMB	348^a	246^a
CTMBMu	338^a	242^a
CTMD	337^a	241^a
NTMBL	348^a	241^a
NTMB	338^a	244^a
NTMBMu	345^a	239^a
NTMD	346^a	248^a
NTHMBL	339^a	240^a
NTHMB	346^a	241^a
NTHMBMu	349^a	239^a
NTHMD	345^a	241^a

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$**;** Key: **CT** conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

of the experiment but not in the third, the latter was facing a meteorological drought. There was no significant effect of tillage, herbicide application, agroforestry, mulching and number of conservation agriculture practices applied on ET_c. This is in agreement with Lotfi and Pessarakli (2023) who found that management practices have no significant effect on ETc during the initial stages of implementation. During the second year which was a wet season CT had lower ET_c that NT by 1% and during the 3rd year which was a dry season NT had lower ET_c by 1.6% compared to CT. The application of three conservation agriculture practices resulted in lower ET_c by 2.3% and 1.3% compared to one and two practices respectively in the 3rd year. The ET_c was lower in 2nd and 3rd year by 1.7% and 0.4% respectively when maize was intercropped with common beans compared to intercropping maize with dolichos.

During the 3rd year, herbicide application resulted into lower ET_c by 1.3% compared to no herbicide application due to improved soil moisture availability when herbicide was applied. The inclusion of agroforestry in conservation agriculture had higher ET_c by 0.6% and 0.4% in the 2nd and 3rd year respectively. Mulching had lower ET_c in 2nd and 3rd year by 0.9% and 0.8% respectively compared to no mulch. The normal farmer practice of conventional tillage combined with intercropping maize with common beans had highest ET_c in 3rd year by 2.9% compared to no till combined with intercropping maize with common beans and mulching.

Maize growth has been classified into mainly four growth stages, establishment stage first 15 days, vegetative growth is usually 15 to 60 days, flowering stage from 60th to 80th day and maturity stage which is normally from 80th to 120th day (Djaman *et al.,* 2022). Effect of moisture stress during different stages has been documented by Cakir (2004). Varying results have been found on effect of moisture stress on maize yield during different stages, but it has generally been concluded that maize is most sensitive to water stress during flowering stage, that is, tasselling and silking stages (Sah *et al.,* 2020). The tasselling and silking stages is the period between 60th and 80th day during maize growths. In a study by Kyei-Mensah *et al.* (2019), the effect of rainfall variability on crop yields was evaluated and results showed that in major seasons the variability of rainfall was lower compared to the minor seasons and crop yield reduced over the period. For instance, Amikuzino and Donkoh (2012) revealed that there was a strong relationship between the total rainfall encountered during planting season and the inter-annual yields of crops. The rainfall patterns affected the soil moisture and is discussed in section 4.2.1 and its effects on maize growth during the various stages.

4.2 Soil Physical Properties

4.2.1 Soil Moisture

Soil moisture storage was monitored in two (2nd and 3rd years) of the three seasons under study. Season one (1st year) was omitted because the data set was incomplete. The soil water profile for different treatments for two selected days, that is, a day during rainy period of the season (wet day) which was 50 day of the year (DOY) and a day during extended dry period of the season (dry day) which was DOY 80 in the in the 3rd year growing season is shown in Figures 4.2 and 4.3 respectively.

Soil water content generally increased with depth up to 60 cm and then started decreasing with depth up to 105 cm after which it remained almost constant. There was no positive water content during the dry and wet days of the year as well as in any of the treatments indicating that there was no drainage below the root zone. Tittonel *et al.* (2012) and Silva *et al.* (2024) highlighted the need to evaluate the effect of conservation agriculture technologies on the seasonal water balance with a goal of identifying those practices that can maximise the soil moisture buffer capacity.

The findings on the effects of tillage, mulch and type of bean used for intercropping is shown in Figure 4.2. Tillage had no significant effect on soil water content though CT had slightly non-significant higher soil water content that NT. Mulching significantly affected soil water content in all the depths during the selected dry and wet days in the 3rd year. Based on soil water content along the soil profile, conservation agriculture-based components such as mulching showed significantly higher soil water content in both dry and wet seasons. This concurs with previous finding of Araya *et al.* (2015) and Mhlanga *et al.* (2021). Soil water content along the soil profile was significantly higher when dolichos was intercropped with maize compared to the scenario in which common bean was intercropped with maize

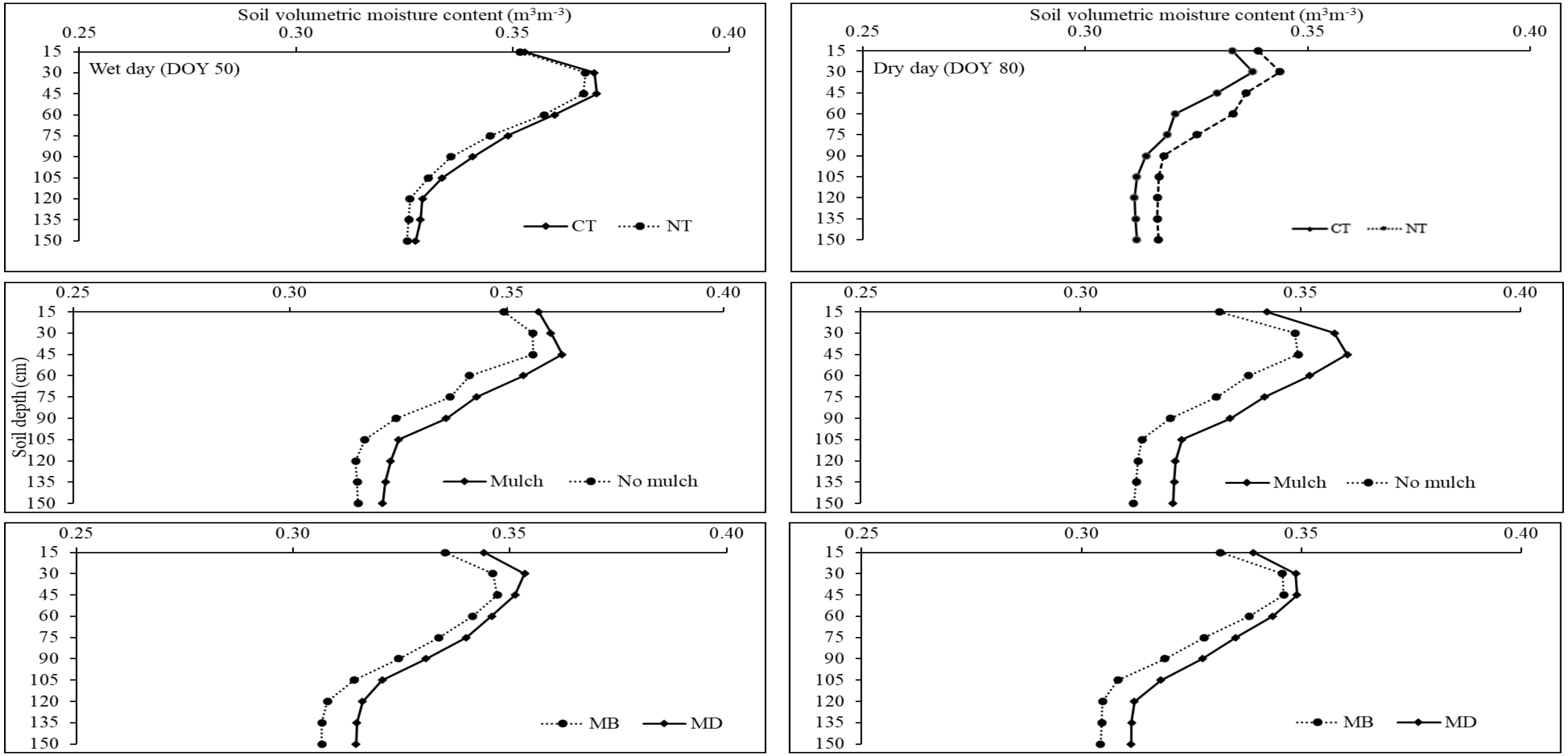

Figure 4.2: Root Zone Volumetric Water Content Comparison on Two Dates, Wet Day (DOY 50) and Dry Day (DOY 80) during the Third Year Growing Season Versus Soil Depth (CM) In Year.

Key: CT, conventional tillage; NT, no till intercropping maize with common beans; MB, intercropping maize with dolichos beans; MD.

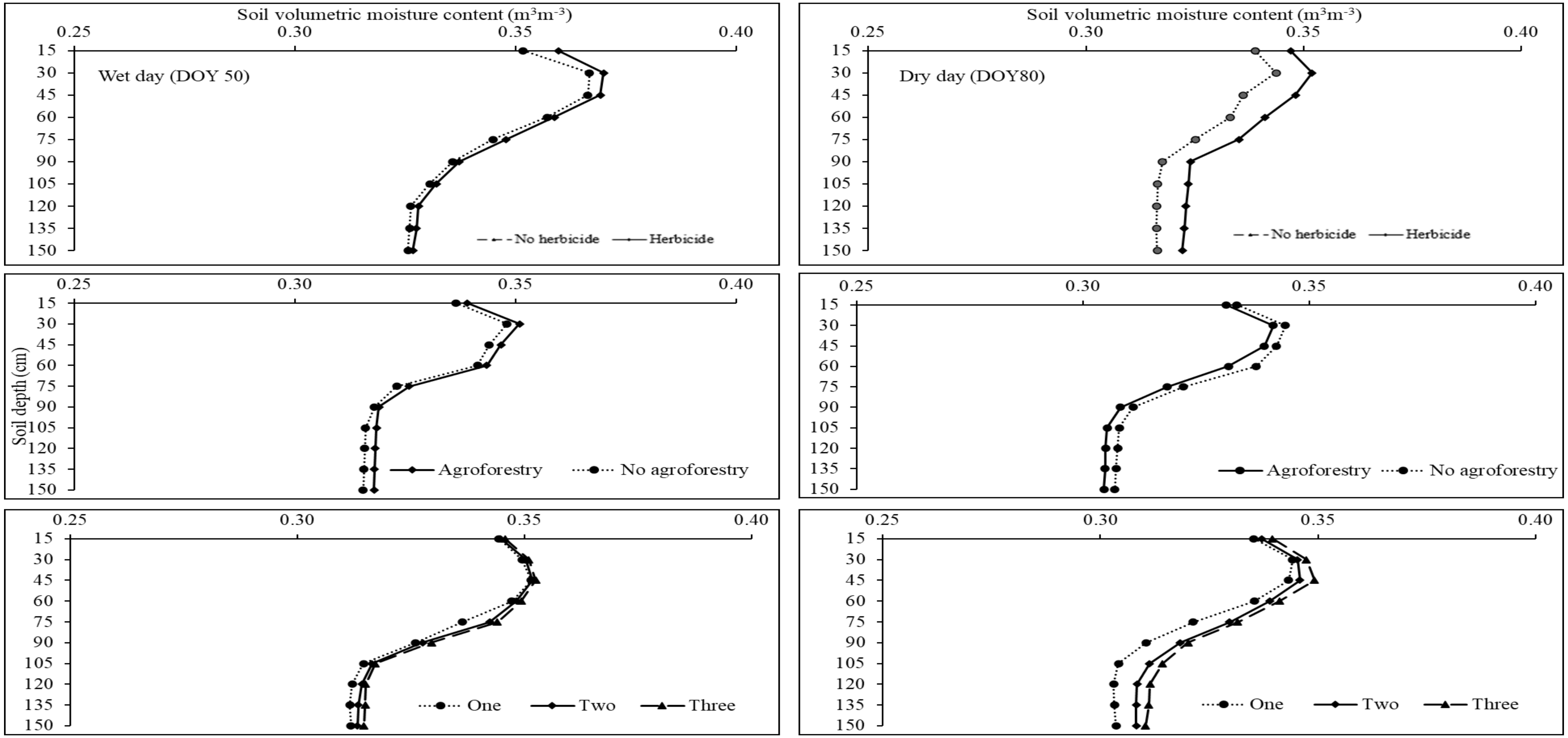

Figure 4.3: Root Zone Volumetric Water Content Comparison on Two Dates, Dry Day (DOY 50) and Wet Day (DOY 80) during the Third Year Growing Season Versus Soil Depth (cm).

Key: One= Application of one CA practice; Two= Application of two CA practices; Three= Application of three CA practices

whether it was during dry or wet days of the year. Though herbicide application had no significant effect on soil water content along the various soil depth profiles during the wet days of the year, it had significant effect during the dry days of the years (Fig. 4.3). Soil water content along the soil profile was not significantly affected in treatments with and without incorporation of agroforestry either during the dry or wet day of the year (See Fig. 4.3). However, soil water content was slightly lower in systems that integrated agroforestry technology and mainly detectable during the dry days of the years. The number of conservation agriculture practices applied had no significant effect on soil water content during the wet season. However, during the dry season, soil water content was lower when only one conservation agriculture practice was applied compared to when two or three practices of conservation agriculture were applied.

Figures 4.4 to 4.9 show the temporal variation in soil moisture storage to 1 m depth as affected by tillage, herbicides, mulch, agroforestry and the number of conservation agriculture practices applied during the 2nd year wet growing season and the dry growing season of 3rd year. The soil moisture storage followed the patterns of rainfall in both seasons. During the 2nd year wet season, soil moisture storage was above the critical drought stress value for vegetative, flowering and yield formation stages for the maize crop, while in the 3rd year season only some treatments had soil moisture that remained readily available.

The effect of tillage alone was not strong enough to cause a significant effect on soil moisture storage in both seasons (Fig. 4.4b and 4.5b). Higher soil moisture storage in CT than in NT as found in the wet season in this study, was previously reported by Obalum *et al.* (2011). They attributed this higher soil moisture storage in CT than NT to temporal improvement of porosity that increases rainfall infiltration and retention in the soil (Li, *et al.*, 2019). In agreement with this study, Jin *et al.* (2007) found that differences in soil moisture storage between conventional and no till practices were most significant in drier years, with relatively higher values in no till systems. Franzluebbers (2002) and Page *et al.* (2019) noted that no till crop production systems led to greater soil organic material stratification and less evaporation thus increasing the surface soil water content. Figures 4.4c and 4.5c shows that

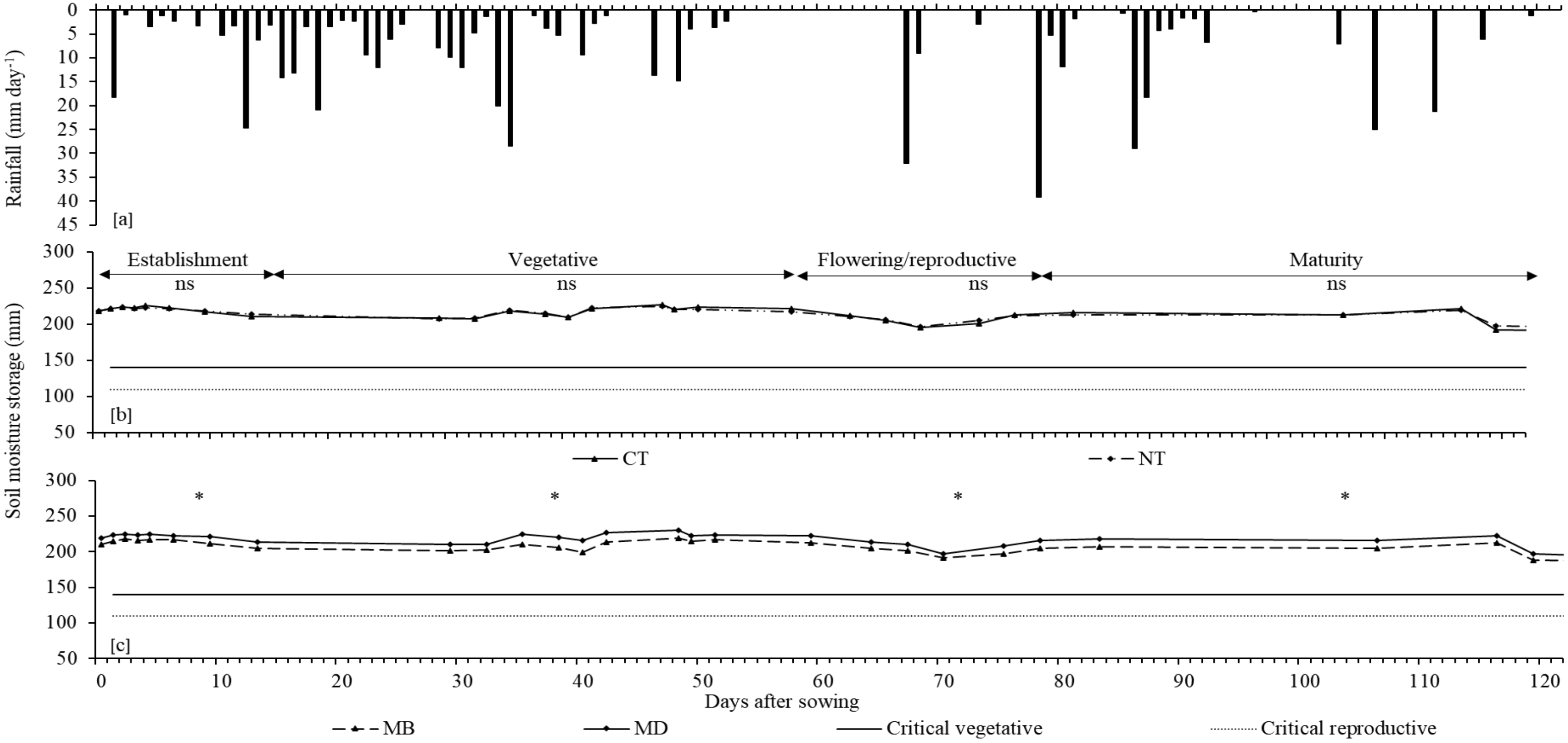

Figure 4.4: Daily Rainfall (a,), and soil moisture storage as affected by tillage (b) and intercropping (c) at various maize growing stages in year 2. Significance levels of differences in soil moisture storage during the growing season are shown by '*' significant difference ($p < 0.05$) and 'ns' no significant difference.

Key: CT, conventional tillage; NT, no till intercropping maize with common beans; MB, intercropping maize with dolichos beans; MD.

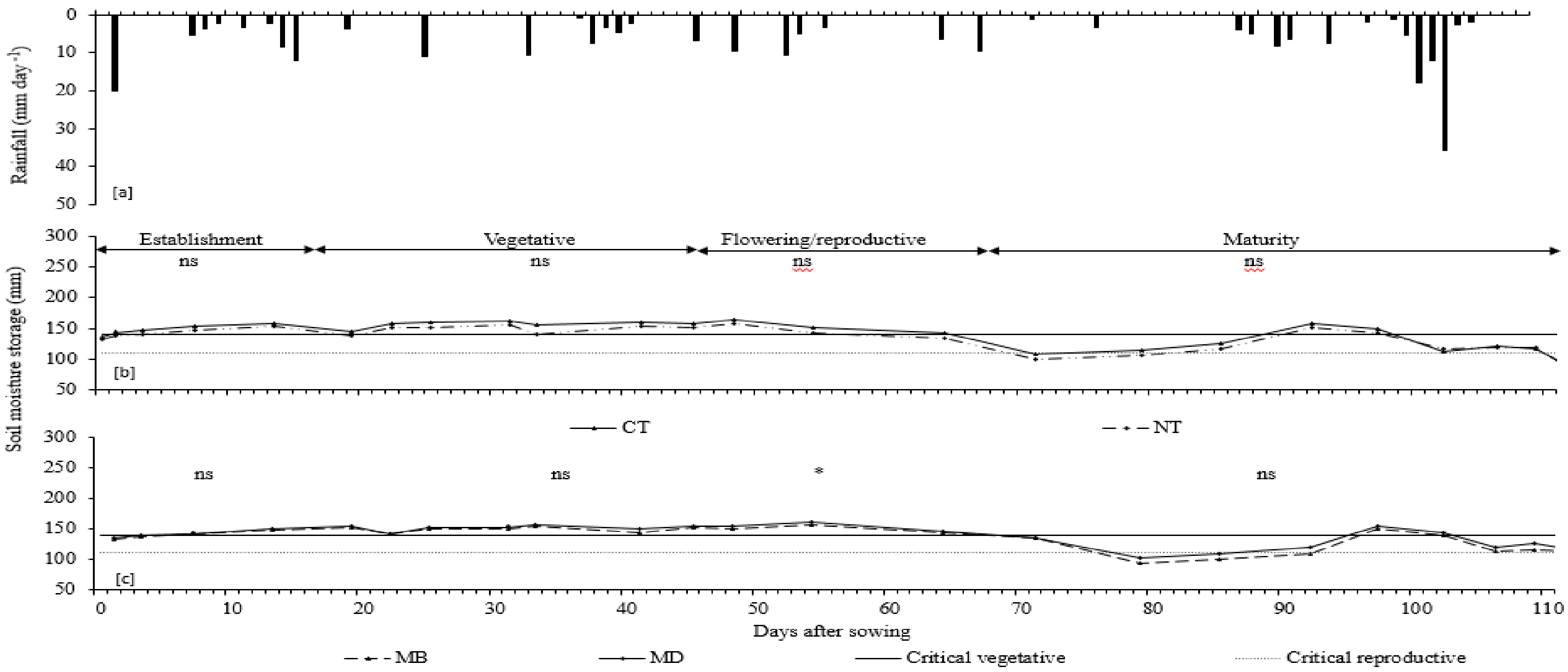

Figure 4.5: Daily Rainfall (a,), and soil moisture storage as affected by tillage (b) and intercropping (c) at various maize growing stages in year 3. Significance levels of differences in soil moisture storage during the growing season are shown by '*' significant difference ($p < 0.05$) and 'ns' no significant difference.

Key: CT, conventional tillage; NT, no till intercropping maize with common beans; MB, intercropping maize with dolichos beans; MD.

intercropping maize with common beans resulted in significantly lower soil moisture storage throughout the growing season during the wet year. The better surface cover by dolichos could be the reason for higher moisture when maize was intercropped with the dolichos. Thus, reducing water loss from the soil. The use of herbicides in NT did not result in a significant difference in soil moisture storage in the wet 2nd year growing season (Fig. 4.6c); the observed higher values from 70 days after sowing in the dry 3rd year of the experiment were not significant (See Fig. 4.7c). The positive effect of herbicides on soil moisture especially during the dry year may be attributed to weed control by the herbicides. The reduction of weeds reduces water use thus contributing to soil moisture conservation (Demo & Bogale, 2024). This is in agreement with Dalley *et al.* (2006) who found that soil moisture where herbicide was applied was similar to the weeds' free treatment.

Mulching resulted in significantly higher soil moisture storage throughout the growing period of the dry season (Fig. 4.7c). Changes in soil moisture storage were more pronounced in the production system using mulch indicating a better response to rain events and more water being taken up by the crop. The higher soil moisture storage in treatments with mulch during the year with lower rainfall may be attributed to the surface cover that may contribute to higher infiltration rates and reduced evaporation (Kader *et al.*, 2017). This is also well illustrated by the soil water along the soil profile.

The effect of mulch on soil moisture follows trends observed by Rockström *et al.* (2009) in savannah agro-ecosystems of East and Southern Africa and in Rwanda by Hitimana *et al.* (2021). Under the rain-fed conditions of the semi-arid and arid ecosystem, conservation of soil moisture by mulching becomes profitable for the crops. In addition to conserving soil moisture, mulching also suppresses the extreme temperature fluctuations and reduces water loss through evaporation resulting to more retention of soil moisture (Shirugure *et al.*, 2003), suppress growth of weeds (Ramakrishna *et al.*, 2006), enhances and maintains soil fertility (Slathia and Paul, 2012) and improves growth and yield of crops (Ban *et al.*, 2009).

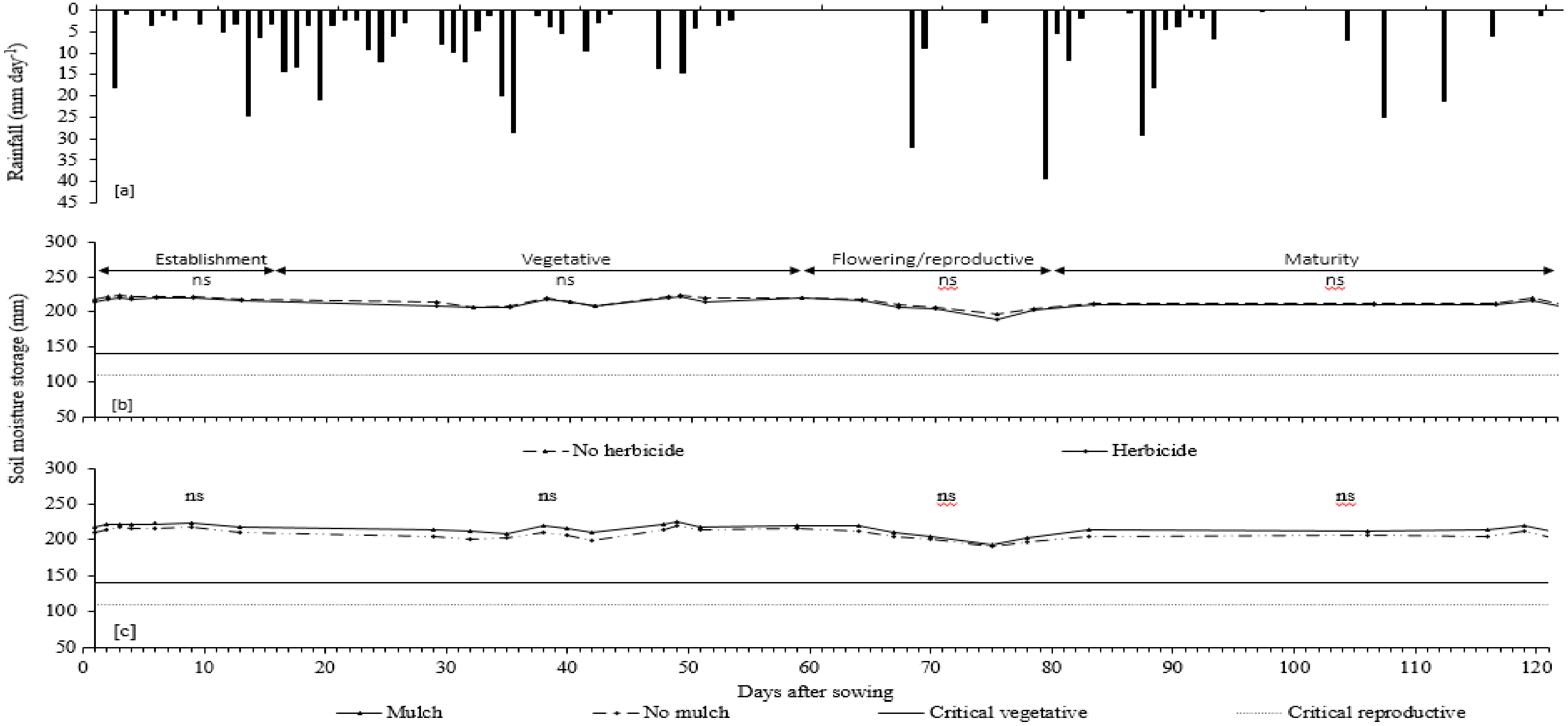

Figure 4.6: Daily Rainfall (a,), and soil moisture storage as affected by herbicide application (b) and mulching (c) at various maize growing stages in year 2. Significance levels of differences in soil moisture storage during the growing season are shown by ‘*’ significant difference ($p < 0.05$) and ‘ns’ no significant difference.

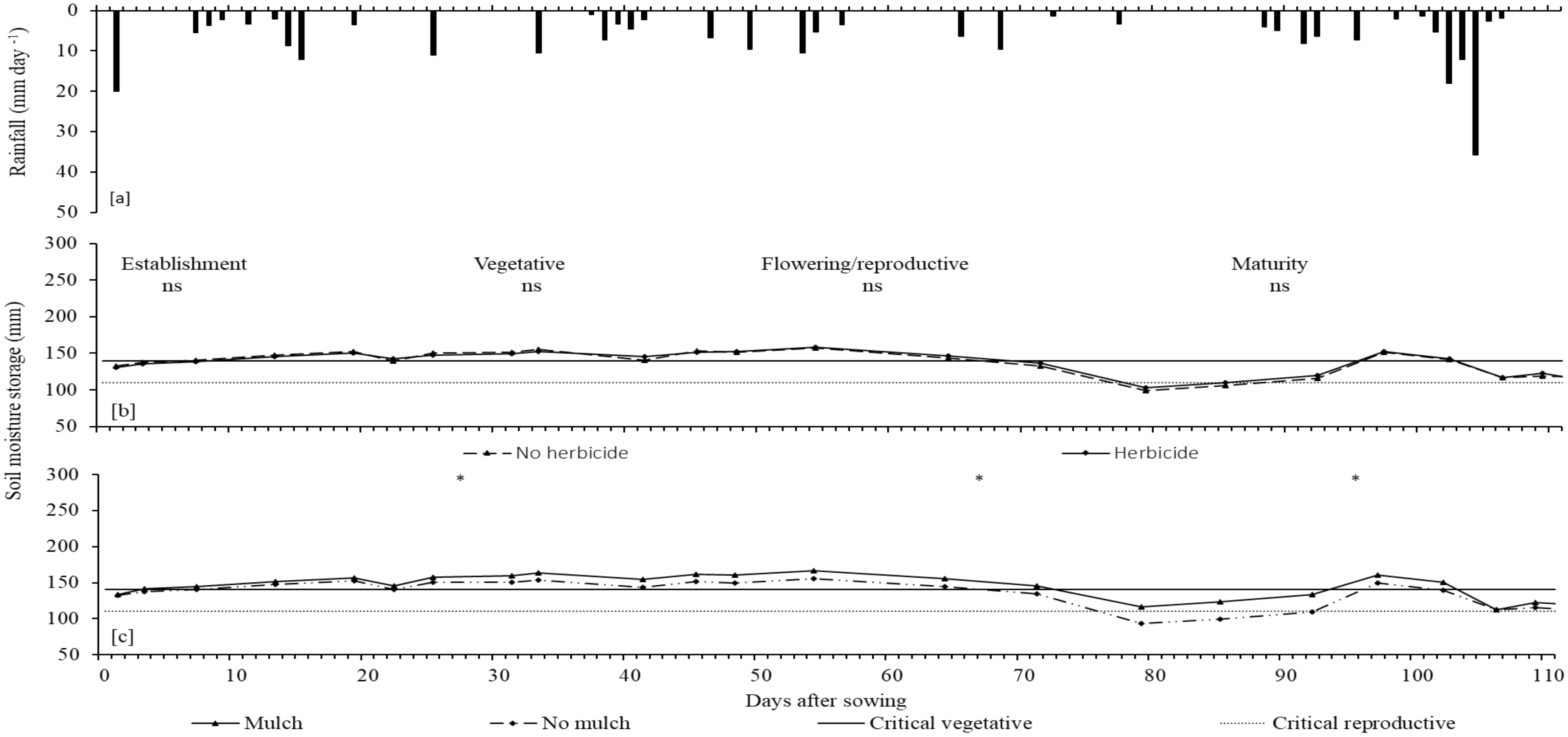

Figure 4.7: Daily Rainfall (a,), and soil moisture storage as affected by herbicide application (b) and mulching (c) at various maize growing stages in year 3. Significance levels of differences in soil moisture storage during the growing season are shown by ‘*’ significant difference ($p < 0.05$) and ‘ns’ no significant difference**.**

Mulching also protects topsoil stability hence improving soil physical conditions (De Silva & Cook, 2003). Mulching results in higher soil moisture storage during silking, tasselling and grain filling which are critical stages during maize growth. However, the competing use of crop residue for livestock feeding hampers the application of mulch hence the need for alternative surface cover.

Practicing agroforestry in CA had no significant effect on soil moisture storage during the wet season, in the 2nd year but it was significantly higher during the flowering stage in the third year of the experimentation. During the 3rd year, the treatment with agroforestry similar to treatments without agroforestry showed drought stress during the flowering stage (Fig. 4.9b). Higher soil moisture storage in soils with leucaena has previously been reported by Kang *et al.* (1990). The higher soil moisture storage under agroforestry is attributed to improvement of soil physical properties which enhances water infiltration and reduces water run-off (Dalzel *et al.,* 2006; Tomar *et al.,* 2021). This may be through leucaena roots that can improve soil structure and create macro-pores, thus increasing water infiltration and reducing surface runoff (Negri, 2018; Sanginga *et al.,* 1992). This study found more soil water content along the profile in treatments with agroforestry system. Agroforestry has previously been found to positively influence microclimate that improves soil moisture and productivity (Baliscei *et al.,* 2013).

An analysis of the data on number of CA practices applied to a farming system is presented in Fig. 4.8c and 4.9c. There was no significant effect on soil moisture was detected during the 2nd year. However, during the third-year, applying one CA practice resulted in significantly lower soil moisture storage compared to application of two or three CA practices (Fig. 4.9c). The latter supported soil moisture storage to remain above the critical value for maize during the growing period, which contrasts the application of only one CA practice, that effected drought stress throughout the year three season. The higher soil moisture in the treatment with mulch and when the three CA practices were used on the farm is important in rain-fed agriculture as it allows moisture buffering (Kodzwa *et al.,* 2020).

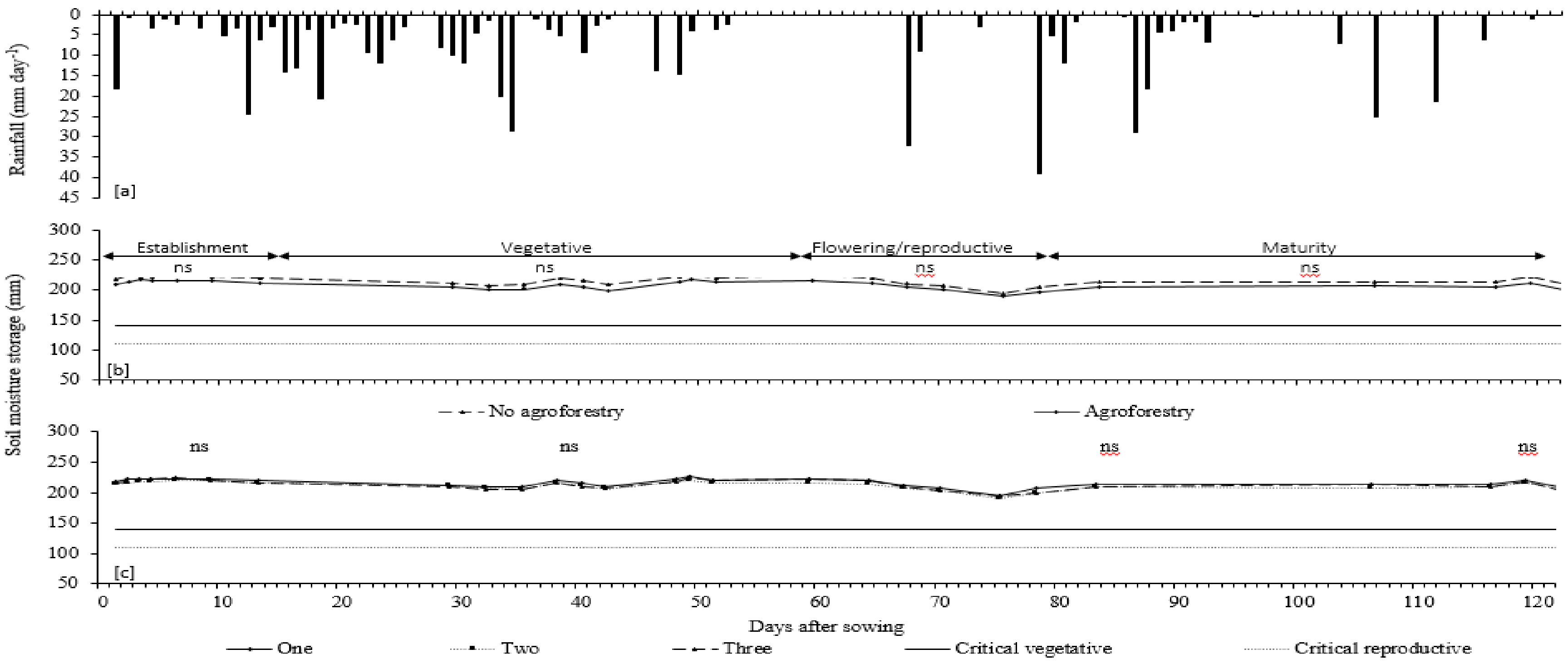

Figure 4.8: Daily Rainfall (a,), and soil moisture storage as affected by agroforestry (b) and number of practices applied (c) at various maize growing stages in year 2. Significance levels of differences in soil moisture storage during the growing season are shown by ‘*’ significant difference ($p < 0.05$) and ‘ns’ no significant difference.

Key: One= Application of one CA practice; Two= Application of two CA practices; Three= Application of three CA practices

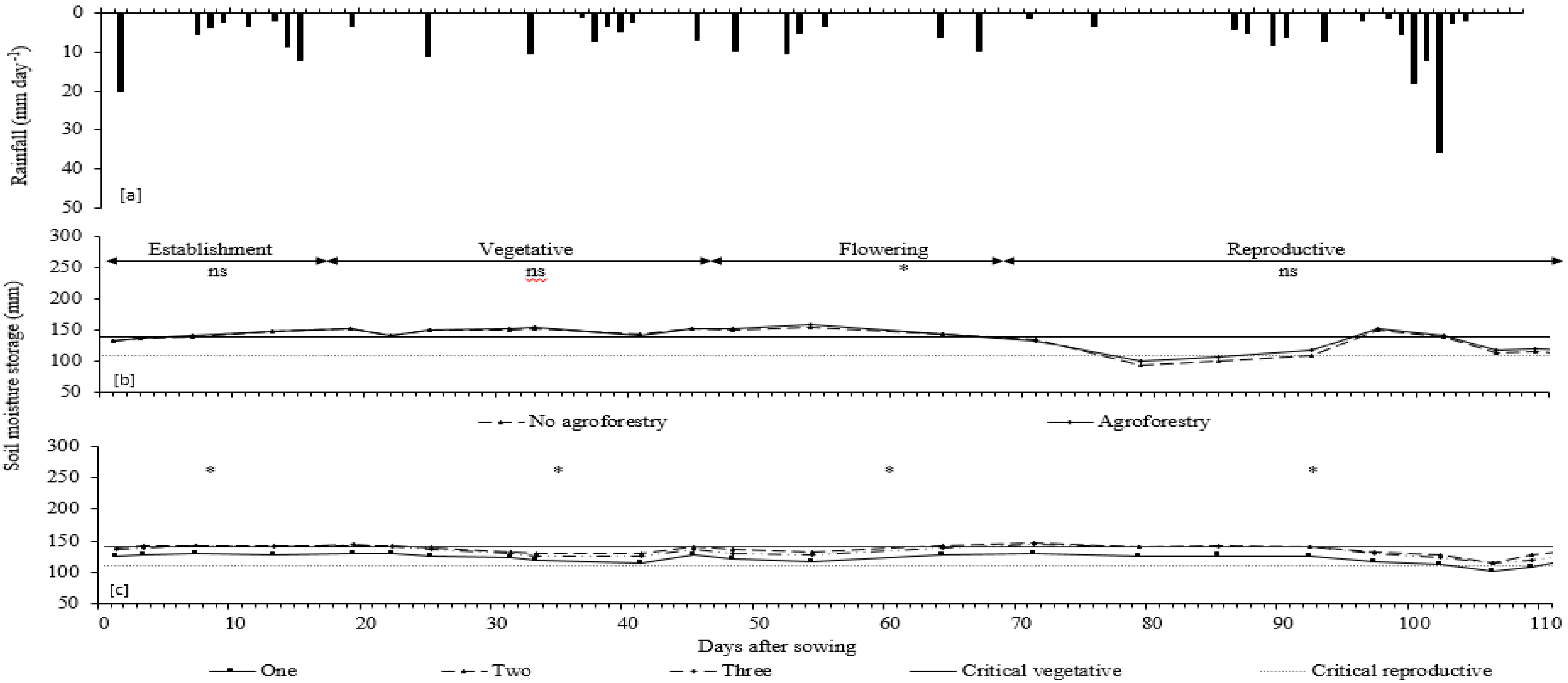

Figure 4.9: Daily Rainfall (a,), and soil moisture storage as affected by agroforestry (b) and number of practices applied (c) at various maize growing stages in year 3. Significance levels of differences in soil moisture storage during the growing season are shown by '*' significant difference ($p < 0.05$) and 'ns' no significant difference.

Key: One= Application of one CA practice; Two= Application of two CA practices; Three= Application of three CA practices

This in turn leads to better and stable yields which make maize farming resilient to climate change in semiarid areas as illustrated in section 4.5. Soil moisture did not drop below critical values for maize during the year two season but did so during dry spells in the year three season for several of treatments. In the dry year season, there were two major dry spells in the first 120 days after sowing. Mulching kept soil moisture above the critical values during both periods of the growing seasons. A simultaneous adoption of two or three conservation agriculture practices also maintained optimal soil moisture conditions during the two dry spells. Noteworthy, is the fact that under those treatments, soil moisture storage was already significantly higher at the onset of the growing season, indicating that they could conserve more rain from the previous wet year season and from the rain showers preceding sowing in 3rd year of the experiment. Higher soil moisture storage determined when all the three practices of conservation agriculture were applied, namely minimal soil disturbance (NT), surface cover (mulching with maize residues) and crop diversification/rotation (intercropping maize, beans and leucaena), concurs with previous findings of Araya *et al.,* (2024) and Obalum *et al.* (2011).

The higher soil moisture storage especially during dry spells is crucial as it will protect the plant against agricultural drought (Barron *et al.*, 2004; Zeri *et al.*, 2020), which affect plant growth and yield. The surface cover conserves soil water which is provided to the crop during the dry spells resulting in higher and stable crop yield. The higher soil moisture storage in the treatment with mulch as cover crop throughout the growing season during the year three may be a clear manifestation of the critical role of crop residue cover is in successful implementation of conservation agriculture. This may indicate that mulching (surface cover) is a key practice in conservation agriculture. The study found that conservation agriculture associated practices considered in this work resulted to higher soil moisture at the beginning of dry reason when the preceding season was wet. This subsequently reduces/eradicates drought stress during a meteorologically dry growing season at least when the preceding season is wet as in this study, resulting into improved yield.

4.2.2 Soil Quality Indicators

4.2.2.1 Bulk Density and Stability Index

The effects of tillage, herbicide, agroforestry, mulching and number of conservation agriculture practices on bulk density and stability index are shown in Table 4.2. Bulk density was significantly affected by tillage with CT showing significantly lower bulk density than NT by 4.2%. The bulk density followed the trend of Abdollahi *et al.* (2017) who found lower bulk density in CT compared to NT. In a review of effect of NT on bulk density, Blanco-Canqui and Ruis (2018) found that NT had different effect on bulk density, depending on duration under management. They concluded that generally on short term it had higher bulk density than CT, the tillage in CT loosens the soil and creates macro-pores thus reducing bulk density. There was no significant effect of intercropping maize with bean compared to dolichos beans on soil bulk density. However, intercropping maize with beans had higher bulk density by as much as 1.7%. The lower bulk density when maize was intercropped with dolichos compared to when intercropped with common bean may be due to the higher rooting system in dolichos that increases porosity.

Mulching resulted into 2.5% lower bulk density though it was not significantly different. Lower bulk density in mulching is in agreement with Jamir and Dutta (2020) and Shaver (2010). The low bulk density is due to higher soil organic matter (Jagadeeswaran & Kumaraperumal, 2019; Ghuman & Sur, 2001) and secondary residue decomposition products that promote more aggregation (Shaver, 2010). The inclusion of agroforestry had a slightly lower bulk density of 1% though not significantly different. Previously lower bulk density in agroforestry have been found by Dori *et al.* (2022) which they attributed to increased porosity through the fine plants' roots and soil organic matter addition through its decayed litter. The study found non-significant effect of herbicide application on soil bulk density and concurs with the findings by Uddin *et al.* (2020).

Table 4.2: Effect of Tillage, Herbicide Application, Agroforestry, Mulching and Number of CA Practices Soil Bulk Density (BD) and Stability Index (SI).

	BD (g cm^{-3})	SI
Tillage		
CT	1.16*	3.4
NT	1.21*	3.5
Number of CA practices applied		
One	1.23^{b}	3.3^{a}
Two	1.19^{ab}	3.4^{a}
Three	1.16^{a}	4.2^{b}
Intercropping		
Maize/Common beans	1.20	3.3
Maize/Dolichos beans	1.18	3.2
Herbicide		
Yes	1.20	3.7
No	1.18	3.4
Agroforestry		
Yes	1.19	3.5
No	1.20	3.4
Mulch		
Yes	1.18	4.0*
No	1.21	3.3*
Interaction of tillage, agroforestry, herbicide application and mulching		
CTMBL	1.18^{a}	3.4^{ab}
CTMB	1.14^{a}	3.2^{a}
CTMBMu	1.15^{a}	3.5^{ab}
CTMD	1.18^{a}	3.4^{ab}
NTMBL	1.24^{a}	3.4^{ab}
NTMB	1.17^{a}	3.3^{a}
NTMBMu	1.22^{a}	3.9^{ab}
NTMD	1.18^{a}	3.4^{ab}
NTHMBL	1.18^{a}	3.6^{ab}
NTHMB	1.21^{a}	3.3^{a}
NTHMBMu	1.26^{a}	4.6^{b}
NTHMD	1.17^{a}	3.2^{a}

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$ * Show significant difference from t-Test

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

The number of conservation agriculture practices applied significantly affected soil bulk density with the application of at least three practices having significantly lower bulk density by 5.1% and 2.6% than in treatments where one or two practices were tested respectively. The significantly lower bulk density when three conservation agriculture practices were applied was caused by positive effect of surface cover that add soil organic matter and the diversified cropping which increased soil pores by the plant roots. Furthermore, application of the three practices is expected to improve soil biological activities that affect macro-pores thus reducing bulk density (Indoria et al., 2017; Karlen *et al.,* 1994). The lowest bulk density in treatment combining conventional tillage, intercropping maize with common beans and mulching could be explained by mechanical manipulation of soil and filling of the open spaces caused by tillage by the less dense organic matter from crop residue (Zuber *et al.,* 2015). The bulk density values were in the optimal range (0.9-1.2 Mg m^{-3}) for field crop production on fine-textured soils as suggested by Olness *et al.* (1998) and Reynolds *et al.* (2003).

Stability index (SI) was not significantly affected by tillage, herbicide application intercropping, agroforestry and the number of conservation agriculture practices applied on a farm system. However, CT had lower SI compared to NT by 2.9% due to the maintenance of soil structure associated with no till. Herbicide application resulted to higher SI by 8.4%. However, it had no significant effect. The SI was not significantly affected by agroforestry though it was 2.9% higher in agroforestry treatment. Mulching had significantly higher SI at 19%. Positive effect of mulch on SI may be due to secondary residue decomposition products that promote soil aggregation (Fu *et al.,* 2021; Shaver, 2010). There was a positive correlation between SI and SOC of all the combined data (Fig. 4.10) indicating the crucial role played by SOC on soil stability index. The treatment with three conservation agriculture practices had significantly higher SI, at 24%, than the treatment testing use of two practices which could be because of higher SOC in the application of the three conservation agriculture practices. The high stability index in treatment with higher SOC is in agreement with Reynolds *et al.* (2009).

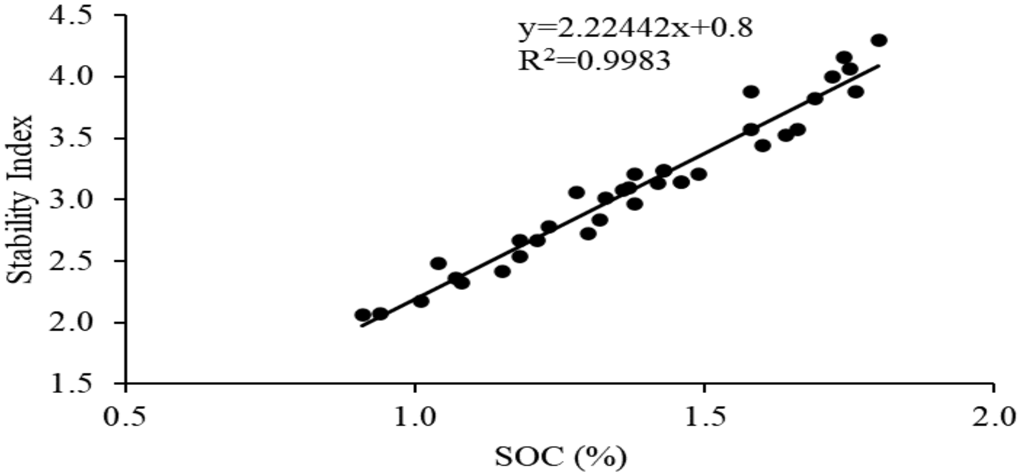

Figure 4.10: Relationship between Soil Organic Carbon (SOC) and Stability Index of all the Combined Data

Combining no till with herbicide, intercropping maize with beans and mulching had the highest SI while CT combined with intercropping maize with common beans had the lowest SI. The highest value of SI was at 4.6% indicating high risk to soil structure degradation. The low SI could result from the high clay content of 60% (clay textural class) in the study area. Despite conservation agriculture practices such as NT, mulching and intercropping improving SI compared to conventional tillage (CT) they did not attain the critical values suggested in literature (7.2%≤stability index≤11.9%) (Reynolds *et al.*, 2007).

4.2.2.2 Soil Air-Water Properties

Tables 4.3 and 4.4 show the effects of by tillage, herbicide application, agroforestry, mulching and number of conservation agriculture practices applied on soil air-water properties. Matric-porosity was not significantly affected by tillage, herbicide application, agroforestry, mulching and number of conservation agriculture practices applied. The low and non-significant differences of matric-porosity may be explained by the fact that the study area has 60% clay. Most of the soil matrixes pores are a result of textural (or plasma) porosity, which is not easily changed by management practices (Reynolds *et al.*, 2007).

Table 4.3: Effect of Tillage, Herbicide Application, Agroforestry, Mulching and the Number of CA Practices on Matric-Porosity (Matpor), Macro-Porosity (Macpor) and Aeration Capacity (AC).

	MatPOR ($m^3 m^{-3}$)	MacPOR ($m^3 m^{-3}$)	AC ($m^3 m^{-3}$)
	Tillage		
CT	0.323	0.055	0.080
NT	0.333	0.048	0.073
	Number of CA practices applied		
One	0.324^a	0.053^a	0.080^a
Two	0.334^a	0.049^a	0.073^a
Three	0.334^a	0.043^a	0.069^a
	Intercropping		
Maize/Common beans	0.338	0.048	0.068
Maize/Dolichos beans	0.329	0.046	0.075
	Herbicide		
Yes	0.339	0.044	0.070
No	0.328	0.051	0.076
	Agroforestry		
Yes	0.345	0.050	0.074
No	0.327	0.047	0.074
	Mulch		
Yes	0.333	0.049	0.073
No	0.329	0.049	0.074
	Interaction of tillage, agroforestry, herbicide application and mulching		
CTMBL	0.336^a	0.052^a	0.083^a
CTMB	0.318^a	0.047^a	0.074^a
CTMBMu	0.319^a	0.061^a	0.082^a
CTMD	0.319^a	0.061^a	0.081^a
NTMBL	0.353^a	0.039^a	0.070^a
NTMB	0.344^a	0.049^a	0.075^a
NTMBMu	0.319^a	0.050^a	0.077^a
NTMD	0.314^a	0.055^a	0.071^a
NTHMBL	0.346^a	0.052^a	0.077^a
NTHMB	0.329^a	0.049^a	0.071^a
NTHMBMu	0.350^a	0.037^a	0.062^a
NTHMD	0.333^a	0.040^a	0.069^a

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$.

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

Higher matric-porosity of 3.0% was found in NT compared to CT. The higher matric-porosity in NT is attributable to maintenance of soil structure in absence of soil disturbance and high soil aggregation due to improved SOC. Herbicide application resulted to 2.9% higher matric-porosity and which could be explained by maintenance of soil structure. Agroforestry and mulching had higher matric-porosity of 5.4% and 1.2% respectively. The many different root sizes of the tree crops that may contribute to soil pores (<30 μm) (Bodner *et al.,* 2014) is plausible explanation of the high matric-porosity found in intercropping maize with beans and leucaena. The number of conservation agriculture practices applied had no significant effect of matric-porosity. However, applying one CA practice resulted to 3.0% lower matric-porosity compared to two and three conservation agriculture practices. There is no minimum or optimum matric-porosity suggested in the literature (Reynolds *et al.,* 2007), thus there are no values to compare.

The tillage, conservation agriculture practices applied, herbicide application, agroforestry, mulching and the number of conservation agriculture practices applied had no significant effect on macro-porosity. CT had higher macro-porosity than NT by 13.6%. The higher macro-porosity found in CT than in NT concur with results of Jabro and Stevens (2022). This may be explained by the loosening of the soil by tillage which may results in higher proportion of larger pores resulting in higher macro-porosity in CT than NT (Verhulst *et al.,* 2010). The non-significant effect of tillage on macro-porosity may be explained by duration under management. Blanco-Canqui and Ruis, (2018) found that duration of less than 5 years resulted to little or no effects of tillage on pore-size distribution, but longer studies of 20 years and more resulted to an increase in the macro-pores. The effect of duration is also reported by Skaalsveen *et al.* (2019) who found that macro-porosity was low in NT for duration of four years. There was no significant effect of mulching on macro-porosity. The slightly higher macro-porosity could be explained by the improvement of organic material on the soil surface (Frøseth *et al.,* 2014). This concurs with Pelosi *et al.* (2017) who found that mulching has positive effect on macro-porosity.

Applying herbicide reduced macro-porosity by 14.7% while agroforestry increased it by 6.2%. The higher macro-porosity in agroforestry is attributable to the root of various crops in this treatment especially the leucaena and concurs with (Zaibon *et al.,* 2016). The interaction between conventional tillage, intercropping maize with dolichos had the highest macro-porosity indicating positive effect of tilling and intercropping maize with dolichos beans on macro-porosity. According to the suggested optimal values of 0.05-0.10 $m^3 m^{-3}$ by Drewry and Paton (2005) only CT attained the suggested optimal values. The low macro-porosity values concur with Taboada *et al.* (2004) who observed that soils with high silt and clay content have typically low macro-porosity like in the study area soil that had 60% clay, 17% silt, and 23% sand.

There was no significant effect of tillage, mulching, herbicide application, agroforestry, and number of conservation agriculture practices applied to a treatment on aeration capacity (AC) as shown in Table 4.3. After three years CT showed higher AC than NT by 10%. This is in agreement with Musukwa, (2018) who found CT had higher air aeration capacity than NT due to temporary increased porosity caused by tillage. Mulching had higher non-significant AC of 4%. The slightly higher AC in mulching is due to the positive effect of mulching on porosity (Brown and Cotton, 2011) that improves the degree of aeration in the soil. Though intercropping had no significant effect on AC, dolichos had 9% higher AC. This could be attributed to extensive dolichos rooting system that positively impacted on the porosity.

The application of herbicide resulted into lower AC of 14 % which could be due to the effect of herbicide on soil biological activity as was found in this study indicated by low soil microbial biomass carbon. There was no significant effect of agroforestry on AC. The higher aeration capacity in agroforestry may be due to the number of crops resulting in more roots that translate to more root pores of varying diameter which upon decay could contribute to high AC. Though there was no significant effect of number of conservation agriculture practices applied on AC, applying one conservation agriculture practice had higher AC compared to the application of two or three conservation agriculture practices by 9.2% and 14.8% respectively. The interaction between conventional tillage and intercropping maize with beans and leucaena resulted into higher AC than the other combinations. The AC values found

Table 4.4: Effect of Tillage, Herbicide Application, Agroforestry, Mulching and the Number of CA Practices on Relative Water Capacity (RWC), Plant Available Water Content (PAWC) and S-Index (S).

	RWC	PAWC (m^3 m^{-3})	S
Tillage			
CT	0.786	0.119	0.026
NT	0.807	0.118	0.024
Number of CA practices applied			
One	0.787^a	0.117^a	0.023^a
Two	0.808^a	0.118^a	0.024^a
Three	0.815^a	0.121^a	0.026^a
Intercropping			
Maize/Common beans	0.806	0.125	0.025
Maize/Dolichos beans	0.817	0.206	0.022
Herbicide			
Yes	0.817	0.119	0.023
No	0.797	0.117	0.025
Agroforestry			
Yes	0.808	0.116	0.025
No	0.802	0.124	0.024
Mulch			
Yes	0.805	0.118	0.024
No	0.803	0.117	0.024
Interaction of tillage, agroforestry, herbicide application and mulching			
CTMBL	0.787^a	0.127^a	0.025^a
CTMB	0.795^a	0.125^a	0.027^a
CTMBMu	0.784^a	0.115^a	0.028^a
CTMD	0.779^a	0.110^a	0.025^a
NTMBL	0.820^a	0.126^a	0.026^a
NTMB	0.808^a	0.140^a	0.030^a
NTMBMu	0.791^a	0.108^a	0.019^a
NTMD	0.807^a	0.102^a	0.023^a
NTHMBL	0.805^a	0.120^a	0.025^a
NTHMB	0.812^a	0.115^a	0.022^a
NTHMBMu	0.839^a	0.157^a	0.026^a
NTHMD	0.814^a	0.105^a	0.019^a

Means followed by the same superscript within a column are not significantly different at $p\leq0.1$.

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

in the study were lower than the optimal values (>0.12-0.17 m^3 m^{-3}) suggested by Drewry (2006) signifying aeration problems in the soil at the experimental site.

There was no significant effect of tillage on relative water content (RWC) though it was higher in NT than CT by 12.7%. The higher RWC in CT could be attributed to the high macro-porosity caused by tillage as explained Verhulst *et al.* (2010). Though agroforestry, mulching and herbicide application had no significant effect on RWC, the application of herbicide, agroforestry and mulching had higher RWC by 2.5%, 0.8% and 0.2% respectively. The higher RWC when agroforestry and mulching were applied could be explained by the positive effect of agroforestry and mulching on soil porosity as documented by De Vleeschauwer Ngaba *et al.* (2024). Application of one conservation agriculture practice resulted to lower RWC compared to the application of two and three conservation agriculture practices by 2.6 % and 3.6 % respectively. The interaction between NTH with intercropping maize with beans and mulching had highest RWC. However, majority of RWC values in this study were greater than optimal RWC values ($0.6 \leq RWC \leq 0.7$) proposed by Olness *et al.* (1998) for maximum microbial activity. This implies that the soil may experience limited microbial activity due to limited aeration (Skopp *et al.*, 1990).

The plant available water content (PAWC) was not significantly affected by tillage, agroforestry, herbicide, mulching and the number of conservation agriculture practices applied. The PAWC was higher in CT than NT. The lower PAWC in NT relative to CT is in agreement with Blanco-Canqui *et al.* (2018) who found no effect of NT on plant available water content. Mulching and herbicide application resulted into higher PAWC by 1.7% and 0.9% respectively. Bondì *et al.*, (2024) and Gicheru (1994) found similar results, where crop residues had higher PAWC which the author attributed to higher SOC that improves soil water retention capacity. Though number of conservation agriculture practices applied had no significant effect on PAWC, the application of three practices had higher PAWC by 2.5% and 3.4% compared to application of two and one conservation agriculture practice respectively. The higher PAWC when applying three conservation agriculture practices is attributable to the positive effect on SOC which has been related to enhanced PAWC (Blanco-Canqui *et al.*, 2013; Page *et al.*, 2019). The positive effect of combining NT with residue cover on PAWC is demonstrated by having the highest PAWC when NT is carried out together with herbicide application, intercropping maize with common beans and mulching. Optimal PAWC values (0.15 m^3 $m^{-3}\leq$ PAWC$\leq$0.2 m^3 m^{-3}) have been suggested by Cockcroft and Olsson (1997) for fine-textured soils below which the soil is considered droughty. The combination of NTH with intercropping maize with common beans and mulching was the only treatment that achieved optimal PAWC of 0.15 m^3m^{-3}.

After the three years of the study S-index (S) was not affected by tillage, intercropping, agroforestry, herbicide, mulching and the number of conservation agriculture practices applied. However, CT had higher S than NT by 8%. Applying three conservation agriculture practices had higher S by 12% than compared to when one conservation agriculture practice was applied, and by 8% when two conservation agriculture practices were applied. Such low values of S have been found by Cunha *et al.* (2011) in Brazil, while evaluating effect of tillage and cover crops on soil physical quality. Application of herbicide resulted into 8% lower S though the difference was not significant.

Mulching resulted in a 1% higher S while agroforestry had 4.1% higher S. The combination of conventional tillage with intercropping maize with beans and mulching resulted to the highest S. The values of S in this study were lower than the suggested optimal value of 0.035 (Dexter, 2004) thus classifying the soils as physically degraded. The low S may summarise the low physical quality of the soil in the area indicated by previously discussed soil physical quality parameters in section 4.2.3. However, this critical value has been considered by various authors as not applicable to all types of soils or different management practices and should be applied with caution (Moncada *et al.*, 2014). This is supported by Cunha *et al.* (2011) who found good correlation between S and other soil physical properties using critical values suggested by Andrade and Stone (2009). Therefore, there is need to establish S values for different soil types (Moncada *et al.*, 2014).

4.2.3 Saturated Hydraulic Conductivity (Ks)

Tillage had positive effect on K_s as shown (Table 4.5) by the significantly higher K_s in CT than NT by 44%. The higher K_s in CT compared to NT concurs with Jabro and

Table 4.5 Effect of Tillage, Herbicide Application, Agroforestry, Mulching and Number of CA Practices Applied on Soil Saturated Hydraulic Conductivity (K_s) and Aggregate Stability.

	K_s (cmday^{-1})	Mean Weight Diameter (mm)
Tillage		
CT	17.6^{*}	0.59
NT	11.2^{*}	0.66
Number of CA practices applied		
One	12.2^{b}	0.52^{a}
Two	9.4^{a}	0.56^{ab}
Three	8.9^{a}	0.62^{b}
Intercropping		
Maize/Common beans	6.9^{*}	0.58
Maize/Dolichos beans	9.3^{*}	0.63
Herbicide		
Yes	9.7	0.50
No	10.2	0.58
Agroforestry		
Yes	14.3^{*}	0.61
No	8.6^{*}	0.57
Mulch		
Yes	10.3	0.59
No	9.1	0.56
Interaction of tillage, agroforestry, herbicide application and mulching		
CTMBL	29.9^{b}	0.52^{a}
CTMB	11.3^{a}	0.54^{a}
CTMBMu	14.9^{a}	0.56^{a}
CTMD	14.3^{a}	0.50^{a}
NTMBL	15.0^{a}	0.66^{a}
NTMB	10.8^{a}	0.56^{a}
NTMBMu	9.3^{a}	0.64^{a}
NTMD	8.2^{a}	0.65^{a}
NTHMBL	15.4^{a}	0.65^{a}
NTHMB	13.7^{a}	0.58^{a}
NTHMBMu	12.4^{a}	0.48^{a}
NTHMD	8.5^{a}	0.60^{a}

Means followed by the same superscript within a column are not significantly different at $p \leq 0.05$; ns. not significant; *Show significant difference from t-Test

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

Stevens (2022) who found CT had higher K_s due to greater number of voids, soil macro-pores and increased pore volume caused by tillage. There was higher and significant effect on hydraulic conductivity when maize was intercropped with dolichos compared to intercropping with common beans. The higher K_s in dolichos is attributable to higher rooting system in dolichos that increases porosity that enhances

K_s as hypothesised by da Silva *et al.* (2021). Agroforestry had significantly 49.8% higher K_s. The extensive rooting system of maize and leucaena that enhances porosity in agroforestry treatment explains the higher K_s.

The higher K_s found in agroforestry is in agreement with Dahiya *et al.* (2022). Mulching had 12.4% higher K_s though it was not significantly different. The slightly higher K_s under mulching is associated with higher SOC in the treatment that has positive effect on bulk density and porosity which positively affected K_s.

Hydraulic conductivity was significantly affected by the number of conservation agriculture practices applied. Applying one conservation agriculture practice had significantly higher K_s than applying two by 27.5% or three conservation agriculture practices by 32.9%. The tilling practice resulted in higher K_s. Intercropping maize with bean and leucaena when combined with any of the two-tillage management resulted into higher $K_{s,}$ while the interaction between CT with intercropping maize with leucaena had the highest K_s. The K_s values were very low which is not surprising given the high 60% clay content of soil at the experimental site. Karuku *et al.* (2012) showed that clay soils are expected to have lower K_s values. Similar low K_s values have been found in other semi-arid areas in Kenya (Karuma *et al.,* 2014).

4.2.4 Aggregate Stability (AS)

Results presented in Table 4.5 shows that tillage, herbicide application, mulching and agroforestry had no significant effect on aggregate stability. Aggregate stability was not significantly affected by tillage but was higher by 10.6% in NT than in CT. The lower aggregate stability in CT compared to NT could be explained by the mechanical disruption of macro-aggregates from tillage operation as suggested by Six *et al.* (1998). The results from the study are consistent with others that found higher aggregate stability in NT compared to CT (Govaerts *et al.,* 2009). There was no significant effect on aggregate stability on intercropping maize with common beans compared to dolichos though it was higher by 8% in the experiment where dolichos was used as an intercrop. This is in agreement with Hu *et al.* (2022) who found that intercropping had no significant effect on soil aggregate stability.

Treatment that incorporated mulching as a practice realized higher (5.7%) aggregate stability though this did not significantly differ from other treatments.

This trend of higher aggregate stability in crop residue retention found in this study is consistent with findings of Castioni *et al.* (2018). This could be attributed to the increased SOC that increases the source of carbon for microbial activity that forms nucleation centres for aggregation (Novelli *et al.*, 2020) and long-term soil aggregate stabilization (Xiao *et al.,* 2020). The application of herbicide lowered aggregate stability by 14.8% while agroforestry increased the stability by 6.8% though the increases were not significantly different. The lower aggregate stability when herbicide was applied is attributable to the effect of herbicide on soil biological activity as evidenced by lower soil microbial biomass carbon in this study. This is because soil microorganisms are the primary agents of aggregate stabilization through deposition of extracellular polysaccharides (Novelli *et al.,* 2020).

The higher aggregate stability in treatments adopting agroforestry (leucaena) could be explained by the good rooting system of the maize, beans and leucaena resulting in increased binding of the soil hence high stability. This concurs with the findings by Choudhury *et al.* (2014), who observed effects of crops on soil aggregation through their root systems and their effect on soil microbial biomass. The number of conservation agriculture practices applied significantly affected aggregate stability. Practicing three conservation agriculture practices had significantly higher aggregate stability compared to one conservation agriculture practice and two conservation agriculture practices by 17.5% and 10.2% respectively. The interaction between no tillage and intercropping maize with beans resulted to highest aggregate stability though not significantly different from the other treatments. This is in line with Abdollahi *et al.* (2017) who demonstrated that diversified cropping when combined with NT improved soil physical properties such as structure compared to NT alone.

4.3 Soil Chemical Properties

4.3.1 Soil Organic Carbon, pH, and Cation Exchange Capacity

Table 4.6 shows the effects of tillage, mulching, herbicide application and number of conservation agriculture practices applied on soil organic carbon (SOC), pH and cation exchange capacity (CEC). There was a gradual increase in SOC in NT. After three years, CT had significantly lower SOC by 17% compared to the NT. The higher SOC in NT concurs with the findings reported by Kumar (2018) and Song *et al.* (2019) which could be attributed to the higher oxidation rate of soil organic matter (SOM) in CT compared to NT (Balota & Auler, 2011). The application of herbicides resulted in 24% higher SOC in the 3rd year of the study. The significant effect of herbicide on SOC concurs with what is reported by Ayansina and Oso (2006) and Sebiomo *et al.* (2011).

Intercropping had significant effect on SOC in the 3rd year of the research, with the intercrop of maize and dolichos having significantly higher SOC than the intercrop of maize with common beans. Dolichos is a perennial crop and has more biomass when compared to common bean which is an annual crop. This implies that treatments with dolichos as intercrop would have higher SOM input in the soil leading to higher SOC values. The SOC was not significantly affected by the incorporation of agroforestry as a conservation agriculture technology, though the treatment with agroforestry had 6% more SOC and increased over the three years. Similar results of higher SOC under agroforestry have previously been found by Wang *et al.* (2015). They attributed the higher SOC to likely inputs of carbon from leaf-drop in the agroforestry-based treatment. The non-significant effect of agroforestry can be attributed to the relatively young age of the systems (Osei *et al.*, 2018).

Mulching resulted in significantly higher SOC over the entire period of the study. It had more SOC by 10%, 18% and 21% in the 1st, 2nd and 3rd years respectively. The higher SOC in mulching is because the crop residues are precursors of SOC (Verhulst *et al.,* 2010). Current findings concur with what Bu et al. (2020) and Chalise *et al.* (2018) reported. Applying three conservation agriculture practices resulted in significantly higher SOC compared to one or two conservation agriculture practices and it was lowest when one conservation agriculture practice was applied. Combining no till with herbicide, intercropping maize with common beans and mulching resulted in the highest SOC. The higher SOC when NT and mulching are combined concurs with the findings of Ye *et al.* (2019) who found higher SOC when straw mulching was combined with no till.

Soil pH was significantly affected by tillage with CT having significantly lower pH in the entire study period compared to NT. There was an increase of soil pH with time in NT to values near neutral which is ideal for crop growth. A higher pH in NT as compared with CT in the study area which has Phaeozem soils, has previously been found in Oxisol soils in Brazil by Sidiras and Pavan (1985) and in Plinthsol soils in South Africa by Loke *et al.* (2013). Intercropping had no significant effect on pH but intercropping maize with common beans had slightly higher pH. Herbicide application resulted to significantly higher pH by 6% and 4% in the 2nd and 3rd year of the study respectively. The higher pH may be due to higher soil organic matter which is expected to buffer soil pH.

Practicing agroforestry in conservation agriculture, had no significant effect on pH. Previous studies such as that of Jesus *et al.* (2006) found higher pH in agroforestry treatment which differs from this study. The higher pH in agroforestry can be attributed to its effect on soil organic matter which in turn has an effect on soil pH. Though mulching had no significant effect on pH, it resulted to higher mean pH by 3%. The higher pH in mulching may be attributed to the buffering resulting from the higher SOC (Duiker and Beegle, 2006). This is in agreement with Govaerts *et al.* (2007) who found higher pH in permanent raised beds with residue compared to conventional beds without residue.

The number of conservation agriculture practices applied had a significant effect on pH. When one conservation agriculture practice was applied the pH was significantly lower compared to two or three practices. Application of one conservation agriculture practice had almost consistent low soil pH. The higher soil pH found when three conservation agriculture practices is in agreement with Ligowe *et al.* (2017) and Ngwira *et al.* (2012). Soil pH is an important soil fertility indicator due to its influence on soil processes including nutrient dynamics (Loke *et al.,* 2013). From this perspective, NT and crop residues thus play a crucial role in buffering soil pH in the study area. This would go a long way in ameliorating soil acidity which remove

Table 4.6: The Effect of Tillage, Herbicide Application, Agroforestry Mulching and Number of CA Practices on Soil Organic Carbon (SOC), (pH) and Cation Exchange Capacity (CEC).

	SOC (%)			pH			CEC (cmol^{+} kg^{-1} soil)		
Tillage									
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
CT	1.49	1.6^{*}	1.49^{*}	5.9^{*}	5.8^{*}	5.9^{*}	11.2	10.7	10.2
NT	1.36	1.31^{*}	1.75^{*}	6.6^{*}	6.7^{*}	6.8^{*}	12.5	13.1	12.6
Number of CA practices applied									
One	1.51^{a}	1.25^{a}	1.42^{a}	5.9^{a}	5.8^{a}	5.8^{a}	10.9^{a}	10.2^{a}	9.4^{a}
Two	1.34^{a}	1.49^{a}	1.70^{b}	6.4^{b}	6.5^{b}	6.6^{b}	12.0^{a}	12.6^{ab}	12.5^{ab}
Three	1.61^{a}	1.85^{b}	2.90^{c}	6.6^{b}	6.8^{b}	6.9^{b}	15.0^{b}	14.7^{b}	14.8^{b}
Intercropping									
Maize/Common beans	1.33	1.32	1.48^{*}	6.3	6.3	6.5	11.2	11	11.2
Maize/Dolichos beans	1.49	1.52	1.61^{*}	6.2	6.2	6.4	12.6	13	12.9
Herbicide									
Yes	1.43	1.6	1.89^{*}	6.4	6.6^{*}	6.7^{*}	13	13.2	13.6
No	1.43	1.43	1.62^{*}	6.2	6.2^{*}	6.4^{*}	11.9	11.9	11.4
Agroforestry									
Yes	1.35	1.48	1.78	6.2	6.4	6.5	11.8	13	12.7
No	1.45	1.49	1.68	6.3	6.3	6.5	12.4	12.1	12
Mulch									
Yes	1.55^{*}	1.73^{*}	2.03^{*}	6.4	6.4	6.7	14.0^{*}	13.8^{*}	14.1^{*}
No	1.39^{*}	1.41^{*}	1.60^{*}	6.3	6.3	6.4	11.7^{*}	11.9^{*}	11.5^{*}
Interaction of tillage, agroforestry, herbicide application and mulching									
CTMBL	1.4^{a}	1.4^{ab}	1.5^{ab}	5.9^{a}	5.9^{ab}	6.1^{ab}	10.4^{a}	11.3^{a}	10.9^{a}
CTMB	1.5^{a}	1.2^{a}	1.3^{a}	5.9^{a}	5.8^{ab}	5.7^{a}	11.8^{ab}c	11.9^{a}	8.7^{a}
CTMBMu	1.4^{a}	1.5^{ab}	1.7^{ab}	6.0^{a}	5.7^{ab}	6.2^{abc}	12.0^{abc}	12.1^{a}	12.5^{a}
CTMD	1.6^{a}	1.1^{a}	1.4^{ab}	6.0^{a}	5.7^{a}	5.8^{a}	10.6^{ab}	10.1^{a}	8.8^{a}
NTMBL	1.3^{a}	1.5^{ab}	1.8^{abc}	6.5^{a}	6.7^{bc}	6.9^{bc}	13.1^{abc}	14.9^{a}	14.0^{a}
NTMB	1.2^{a}	1.4^{ab}	1.6^{ab}	6.6^{a}	6.7^{bc}	6.9^{c}	11.1^{abc}	9.3^{a}	12.0^{a}
NTMBMu	1.5^{a}	1.8^{ab}	1.9^{abc}	6.5^{a}	6.7^{c}	6.8^{c}	15.1^{c}	14.5^{a}	14.1^{a}
NTMD	1.4^{a}	1.5^{ab}	1.6^{ab}	6.4^{a}	6.5^{abc}	6.6^{bc}	10.6^{ab}	10.9^{a}	10.4^{a}
NTHMBL	1.3^{a}	1.5^{ab}	2.0^{bc}	6.3^{a}	6.6^{abc}	6.6^{bc}	11.9^{abc}	12.9^{a}	13.3^{a}
NTHMB	1.4^{a}	1.5^{ab}	1.6^{ab}	6.3^{a}	6.5^{abc}	6.7^{bc}	12.1^{abc}	11.5^{a}	12.5^{a}
NTHMBMu	1.7^{a}	1.9^{b}	2.5^{c}	6.7^{a}	6.9^{bc}	7.0^{bc}	14.9^{bc}	14.8^{a}	15.6^{a}
NTHMD	1.3^{a}	$1.5a^{b}$	$1. 5^{ab}$	6.4^{a}	6.5^{abc}	6.7^{bc}	13.2^{abc}	13.8^{a}	13.1^{a}

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$, *Show significant difference from t-Test

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

the burden of buying liming materials for the resource poor farmers (Wang *et al.*, 2010).

Soil cation exchange capacity (CEC) decreased in CT with time and was lower than in NT. The high CEC in NT and treatments with crop residue concurs with the observations of Duiker and Beegle (2006) and of Govaerts *et al.* (2007). This higher CEC is due to higher amount of soil organic matter which increases CEC of soil. There was no significant effect of intercropping on CEC over the entire study period. However, when maize was intercropped with dolichos the CEC was slightly higher compared to when maize was intercropped with common beans. This may be explained by slightly higher SOC in dolichos treatment.

Mulching had significantly higher CEC during the entire study period. Previous study by Mohanty *et al.* (2015) had similar findings of higher CEC when mulching was done using crop residues and when all the three conservation agriculture practices were applied. They related the higher CEC to residue incorporation. The protection of SOM under NT and intercropping positively affected CEC.

Soil CEC was not significantly affected by herbicide application and practicing agroforestry in conservation agriculture. The CEC remained almost constant in treatment with no herbicide. In a study in Nigeria Aherobo and Ataikuru (2020) found higher but non-significant effect of herbicide application on CEC which concurs with this study. Higher CEC under agroforestry has previously been found by Tsegaye *et al.* (2023), which again concurs with this study. Ngaba *et al.* (2024) notes that effect of agroforestry on CEC may be due to the effect on soil organic matter which has an impact on CEC. The number of conservation agriculture practices applied had a significant effect on CEC during the entire study duration. Appling one conservation agriculture practice resulted in significantly lower CEC. Combining no tillage, herbicide application, intercropping maize with common beans and mulching resulted in significantly the highest CEC. The higher CEC in the conservation agriculture practices improves retention of plant nutrients, thus efficient utilization of applied fertilizers which contribute to conservation of the environment due to the expected reduced nutrient leaching (Ahuja *et al.*, 2006).

4.3.2 Primary Macronutrients N, P, K and C: N Ratio

Type of tillage, mulching, herbicide application, incorporation of agroforestry and the number of conservation agriculture practices applied had a significant effect on N (Table 4.7). Conventional tillage had lower and constant N during the entire period of the study and it was significantly lower than NT by 29% in the 3rd year. Similar results of higher N in NT have previously been reported Govaerts *et al.* (2007) and Khorami *et al.* (2018). This was attributed to improved biological processes that enhance N fixation (Torabian *et al.,* 2019). Though intercropping maize with dolichos had slightly more N than intercropping maize with common beans, the difference was not significant. There was a significant increase in N in mulch treatment in this study which concurs with the findings reported by Graham *et al.* (2002) and Khorami *et al.* (2018). The higher N mulching is attributable to the higher SOC that release N during decomposition (Salinas-Garcıa *et al.,* 2002).

Table 4.7: The Effect of Tillage, Herbicide Application, Agroforestry, Mulching and Number of CA Practices on Nitrogen (N), and Phosphorous (P).

	N (%)			**P (ppm)**		
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Tillage						
CT	0.14	0.14	0.14^{*}	30^{*}	39^{*}	39^{*}
NT	0.15	0.16	0.18^{*}	37^{*}	54^{*}	59^{*}
Number of CA practices applied						
One	0.14^{a}	0.14^{a}	0.13^{a}	34^{a}	39^{a}	37^{a}
Two	0.14^{a}	0.15^{ab}	0.16^{b}	36^{a}	51^{a}	58^{a}
Three	0.16^{a}	0.16^{b}	0.20^{c}	40^{a}	68^{b}	73^{b}
Intercropping						
Maize/Common beans	0.14	0.14	0.15	36	52	54
Maize/Dolichos beans	0.15	0.16	0.17	33	49	52
Herbicide						
Yes	0.15	0.16	0.18^{*}	39	60	63^{*}
No	0.14	0.15	0.16^{*}	33	46	49^{*}
Agroforestry						
Yes	0.14	0.15	0.19^{*}	38	51	59^{*}
No	0.15	0.15	0.15^{*}	34	51	52^{*}
Mulch						
Yes	0.16	0.16	0.20^{*}	36	58^{*}	63^{*}
No	0.14	0.15	0.13^{*}	35	48^{*}	50^{*}
Interaction of tillage, agroforestry, herbicide application and mulching						
CTMBL	0.14^{a}	0.14^{a}	0.16^{b}	36^{a}	52^{ab}	52^{abc}
CTMB	0.13^{a}	0.12^{a}	0.10^{a}	26^{a}	31^{a}	31^{ab}
CTMBMu	0.14^{a}	0.15^{a}	0.17^{b}	29^{a}	39^{ab}	45^{abc}
CTMD	0.16^{a}	0.15^{a}	0.12^{a}	28^{a}	34^{ab}	28^{a}
NTMBL	0.14^{a}	0.15^{a}	0.19^{bc}	42^{a}	50^{ab}	$62ab^{c}$
NTMB	0.15^{a}	0.16^{a}	0.17^{b}	41^{a}	54^{ab}	$58ab^{c}$
NTMBMu	0.15^{a}	0.15^{a}	0.18^{bc}	37^{a}	66^{ab}	72^{c}
NTMD	0.15^{a}	0.16^{a}	0.17^{b}	28^{a}	44^{ab}	45^{abc}
NTHMBL	0.14^{a}	0.15^{a}	0.21^{c}	35^{a}	53^{ab}	65^{abc}
NTHMB	0.15^{a}	0.16^{a}	0.17^{b}	43^{a}	66^{ab}	69^{bc}
NTHMBMu	0.17^{a}	0.17^{a}	0.21^{c}	43^{a}	70^{b}	73^{c}
NTHMD	0.14^{a}	0.16^{a}	0.17^{b}	33^{a}	$51a^{b}$	45^{abc}

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$, *Show significant difference from t-Test

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

There was a significant effect of herbicide application and agroforestry on N in the 3rd year. Nitrogen was significantly higher by 11% and 21% respectively in treatments with herbicide application and agroforestry. Aherobo and Ataikaru (2020) found that herbicide application had effect on N. Previous studies have shown that leucaena which was used in this study has high N fixation potential (Imogie *et al.,* 2008). This N fixation ability may explain the high N content in treatments with leucaena. This treatment with Leucaena attained the optimal required level in soil as suggested by Bruce and Rayment (1982) in medium category of N in soil of 0.15 to 0.17%.

The number of conservation agriculture practices applied significantly affected N in the 3rd year. Treatments where one conservation agriculture practice was applied had the least N and where three conservation agriculture practices were applied had the highest N. The combination of conservation agriculture practices NT, intercropping maize with common beans, mulching and herbicide application had the highest N compared to the other treatments. Higher N when all the three conservation agriculture practices were applied as found in this study has also been previously reported by Govaerts *et al.* (2006). They attribute this to a higher soil organic matter content under conservation agriculture where mineralisation results into higher N.

The available P content was significantly affected by tillage with CT showing significantly lower P than NT (Table 4.7). The order of tillage effect on P was CT<NT over the three years of the study. The high P in NT is attributable to reduced P fixation (Duiker and Beegle, 2006). Phosphorous was slightly lower in the 2nd and 3rd year of the study in treatments using dolichos as an intercrop compared to when maize was intercropped with common beans. Mulching resulted in significantly higher P in the 2nd and 3rd year by 17% and 21% respectively. Results of higher P in treatments with mulching are in agreement with those of Loke *et al.* (2013) and Yang *et al.* (2019). They suggested that the P mineralization of mulching material was promoted by the release of organic acid during decomposition (Bahl *et al.,* 1998). Furthermore, the SOC from crop residues may interact with P fixation sites in the soil, thus increasing P availability (Ohno & Erich, 1997).

The available P content was significantly affected by herbicide and agroforestry in the 3rd year. Herbicide application and agroforestry had higher significant P by 22%

and 12% than treatments with no herbicide application and no agroforestry respectively. The higher P in the herbicide treatment may be due to the higher soil organic matter which during its mineralization may increase P in soil. Higher P found in agroforestry concurs with the findings presented by Cardoso *et al.* (2003) which is attributed to nutrient cycling as argued by Belsky *et al.* (1993).

Application of the three conservation agriculture practices resulted in significantly higher P in the 2nd and 3rd year, while P was lowest when only one conservation agriculture practice was applied. Application of the three conservation agriculture practices had significantly higher mean P compared to application of one or two conservation agriculture practices. The interaction of tillage, herbicide application, agroforestry and mulching significantly affected P after two years, i.e., in the second and third year. Combining no tillage with herbicide use, intercropping maize with common beans and mulching had the highest P during the entire study period.

Tillage had a significant effect on K with CT having significantly lower K than NT (Table 4.8). This is in line with Alharbi (2017) who indicated that no till had a positive effect on K. The higher amounts of K have been associated with higher soil organic matter (Edwards *et al.,* 1992). Potassium was not significantly affected by mulching though mulching treatments had higher K. Ranaivoson *et al.* (2017) reported increased amounts of available K under mulching which is agreement with the findings of this study. During decomposition of organic matter, there is release of K (Govaerts *et al.,* 2007). The application of herbicide resulted into significantly higher K. Sebiomo et al. (2012) found higher K in treatments with herbicide application which concurs with this study. The higher amount is attributed to the chelation of K by the herbicide that allows its accumulation in the soil (Sebiomo *et al.,* 2012). It is also related to the effect of herbicides on the release of fixed K from the mineral lattice or solubilisation effects caused by certain fungi and bacteria, which decompose the alumino-silicate minerals thus releasing K (Singh, 2014).

The inclusion of agroforestry in conservation agriculture in form Leucaena shrub had significantly higher K. This concurs with Sarvade *et al.* (2019) who in their review

Table 4.8: The Effect of Tillage, Herbicide Application, Agroforestry Mulching and Number of CA Practices on Potassium (K), and Carbon Nitrogen Ratio (C:N).

	K (ppm)			C: N		
Tillage						
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
CT	282^{*}	312^{*}	320^{*}	10.4	9.3	10.8
NT	341^{*}	374^{*}	402^{*}	9.5	10	9.9
Number of CA practices applied						
One	280^{a}	307^{a}	310^{a}	10.6^{a}	9.3^{a}	11.1^{b}
Two	337^{b}	372^{b}	392^{b}	9.4^{a}	9.7^{a}	9.6^{a}
Three	354^{b}	393^{b}	437^{c}	10.0^{a}	10.0^{a}	11.0^{ab}
Intercropping						
Maize/Common beans	322	356	375	10	9.2	10.1
Maize/Dolichos beans	327	353	383	10.1	9.6	10.8
Herbicide						
Yes	353^{*}	392^{*}	415^{*}	9.4	10.1	9.8
No	312^{*}	343^{*}	361^{*}	10	9.7	10.4
Agroforestry						
Yes	350^{*}	381^{*}	412^{*}	9.7	10	9.6
No	317^{*}	352^{*}	368^{*}	9.8	9.7	10.4
Mulch						
Yes	332	371	406	10	10.8^{*}	10.7
No	323	356	370	9.7	9.5^{*}	10
Interaction of tillage, agroforestry, herbicide application and mulching						
CTMBL	340^{bcd}	377^{c}	399^{cd}	10.0^{a}	10.0^{ab}	9.3^{ab}
CTMB	274^{ab}	292^{ab}	295^{ab}	11.3^{a}	10.0^{ab}	12.7^{b}
CTMBMu	288^{abc}	328^{abc}	346^{bc}	10.0^{a}	10.0^{ab}	10.0^{ab}
CTMD	226^{a}	253^{a}	239^{a}	10.3^{a}	7.3^{a}	11.3^{ab}
NTMBL	338^{bcd}	371^{bc}	404^{cd}	9.7^{a}	10.0^{ab}	9.7^{ab}
NTMB	295^{abcd}	362^{bc}	400^{cd}	8.7^{a}	8.7^{ab}	9.7^{ab}
NTMBMu	367^{d}	385^{c}	421^{cd}	10.3^{a}	11.3^{b}	10.3^{ab}
NTMD	364^{cd}	376^{c}	385^{bcd}	9.3^{a}	10.0^{ab}	10.0^{ab}
NTHMBL	371^{d}	396^{c}	434^{cd}	9.3^{a}	10.0^{ab}	9.7^{ab}
NTHMB	338^{bcd}	$366b^{c}$	399^{cd}	9.3^{a}	9.7^{ab}	9.3^{ab}
NTHMBMu	340^{bcd}	400^{c}	452^{d}	9.7^{a}	11.0^{b}	11.7^{ab}
NTHMD	363^{cd}	407^{c}	375^{bcd}	9.3^{a}	9.7^{ab}	8.7^{a}

Means followed by the same letter within a column are not significantly different at $p \leq 0.1$, *Show significant difference from t-Test

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

reported agroforestry systems showed higher K values. This was attributed to break down of litter from the plants in agroforestry. The treatment with no tillage with herbicide, intercropping maize with common beans and mulching had significantly the highest K means. When one conservation agriculture practice was applied it had lower K than when two or three conservation agriculture practices were applied. Similar results, of higher K, when all conservation agriculture practices are applied were found by Rani *et al.* (2023). They attributed this to the return of residues to the soil surface thus contributing to surface accumulation of K under no tillage and mulching.

Table 4.8 shows that C:N ratio was not significantly affected by tillage practices, though CT had higher C: N ratio than NT in the 3rd year. The non-significant effect of tillage on C:N ratio is similar to observations made by Terefe and Lemma (2016). And Sahoo *et al*., (2022). The number of conservation agriculture practices applied significantly affected the C:N ratio in the 3rd year, with application of one conservation agriculture practice having significantly lower C:N ratio than two and three conservation agriculture practices. However, there was no difference in C: N ratio between application of two or three conservation agriculture practices in the third year. There was no significant effect of herbicide application and agroforestry on C:N ratio though herbicide application and agroforestry resulted into lower C:N ratio.

Mulching had significant effect on C:N ratio in the 2nd year with mulching having higher C:N ratio. The C:N ratio is affected by the type of organic material added to the soil (Lynch, 2014) and the higher C:N ratio in mulching, is attributable to the quality of organic matter. Maize residue used for mulching contains relatively much carbon (C) in the form of lignin thus resulting in a relatively high C:N ratio and low decomposition rate (Bengtsson *et al.,* 2003; Lynch, 2014). Therefore, organic matter with low C:N ratio is expected to decompose more rapidly than litter with a higher C:N ratio. Thus, the quality of the crop residues should be considered as it affects soil quality. If the added organic material contains more nitrogen (N) in proportion to C, then N is released into the soil from the decomposing organic material. Conversely, if the organic material has a low N content in relation to C, then the microorganisms will utilize the soil N for further decomposition and the soil N will be immobilized and will not be available (Tittarelli *et al.,* 2018). When the C:N ratio is greater than 30:1, N is immobilized by soil microbes while if C:N ratio is less than 20:1, there is a release of mineral N in to the soil environment (Terefe and Lemma, 2016). The N released to the soil when C: N < 20:1 is available for plant uptake (Jones, 2003). Therefore, the C: N of < 20 in this study may indicate availability of N for plants use.

4.3.3 Secondary Macronutrients Ca and Mg

There was neither significant effect by tillage, herbicide application, agroforestry, mulching and number of conservation agriculture practices nor a trend on both Ca and Mg as shown in Table 4.9. However, CT had higher mean Ca than NT by 10%. The mean Mg was lower in CT compared to NT by 6%. The non-significant effect of tillage on Ca and Mg found in this study concurs with that of Duiker and Beegle (2006), Govaerts *et al.* (2007), and Rhoton (2000). In contrast, Edwards *et al.* (1992) found higher Ca in NT than in CT systems though it was not significantly different. Other studies have found an effect of tillage on exchangeable Mg and Ca, but after four or more years of research (Lv *et al.,* 2023).

Though the number of conservation agriculture practices applied had no significant effect on Ca applying one conservation agriculture practice resulted to higher mean of Ca by 7% and 9% compared to two and three conservation agriculture practices respectively. Applying one conservation agriculture practice had lower mean of Mg by 9% and 6% compared to two and three conservation agriculture practices respectively. The application of herbicide resulted into 2% and 4% higher mean of Ca and Mg respectively. The higher Ca in herbicide application contradicts with what is reported by Sebiomo et al. (2011) who found lower Ca where herbicide was applied. Practicing agroforestry had no significant effect on Ca and Mg, the mean Ca was lower by 3% and mean Mg higher by 1%. Ojeda et al. (2016) found higher Ca and Mg in farming systems using in agroforestry systems and attributed it to higher

Table 4.9: The Effect fo Tillage, Herbicide Application, Agroforestry Mulching and Number of CA Practices on Calcium (Ca) and Magnesium (Mg).

	Ca (ppm)				**Mg (ppm)**			
	Tillage							
	Year 1	Year 2	Year 3	Mean	Year 1	Year 2	Year 3	Mean
CT	1147	1347	1292	1262	703	464	440	536
NT	947	1357	1100	1134	711	497	489	566
	Number of CA practices applied							
One	1175^{a}	1348^{a}	1306^{a}	1277^{a}	691^{a}	468^{a}	419^{a}	526^{a}
Two	974^{a}	1378^{a}	1223^{a}	1192^{a}	731^{a}	501^{a}	482^{a}	572^{a}
Three	1080^{a}	1213^{a}	1180^{a}	1158^{a}	669^{a}	492^{a}	517^{a}	560^{a}
	Intercropping							
Maize/Common beans	1042	1224	1242	1169	743	480	490	571
Maize/Dolichos beans	922	1235	1235	1131	658	486	441	528
	Herbicide							
Yes	1033	1327	1320	1227	719	513	489	574
No	1047	1352	1196	1198	707	481	464	551
	Agroforestry							
Yes	873	1473	1198	1181	673	513	472	552
No	1099	1300	1250	1216	724	485	473	560
	Mulch							
Yes	1073	1256	1202	1177	692	479	512	557
No	1032	1373	1249	1218	717	496	459	561
	Interaction of tillage, agroforestry, herbicide application and mulching							
CTMBL	927^{a}	1353^{a}	1073^{a}	1118^{ab}	633^{a}	482^{a}	412^{a}	509^{a}
CTMB	1287^{a}	993^{a}	1233^{a}	1171^{ab}	703^{a}	486^{a}	448^{a}	546^{a}
CTMBMu	1060^{a}	1340^{a}	1247^{a}	1216^{ab}	738^{a}	452^{a}	502^{a}	564^{a}
CTMD	1313^{a}	1700^{a}	1613^{a}	1542^{b}	739^{a}	438^{a}	398^{a}	525^{a}
NTMBL	860^{a}	1647^{a}	1247^{a}	1251^{ab}	621^{a}	512^{a}	477^{a}	537^{a}
NTMB	780^{a}	1207^{a}	980^{a}	989^{a}	774^{a}	508^{a}	521^{a}	601^{a}
NTMBMu	1060^{a}	1180^{a}	1047^{a}	1096^{ab}	682^{a}	473^{a}	506^{a}	553^{a}
NTMD	1087^{a}	1393^{a}	1127^{a}	1202^{ab}	767^{a}	497^{a}	451^{a}	572^{a}
NTHMBL	833^{a}	1420^{a}	1273^{a}	1176^{ab}	764^{a}	545^{a}	526^{a}	612^{a}
NTHMB	1113^{a}	1193^{a}	1500^{a}	1269^{ab}	753^{a}	459^{a}	473^{a}	562^{a}
NTHMBMu	1100^{a}	1247^{a}	1313^{a}	1220^{ab}	657^{a}	512^{a}	529^{a}	566^{a}
NTHMD	1087^{a}	1447^{a}	1193^{a}	1242^{ab}	703^{a}	537^{a}	428^{a}	556^{a}

Means followed by the same letter within a column are not significantly different at $p \leq 0.1$;

Key: CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

rates of release of these elements from the leaves litter. The mean Ca and Mg were lower by 3% and 1% respectively in mulch treatments. The interaction between conventional tillage and intercropping maize with dolichos had significantly the highest mean Ca, while the interaction between no till, herbicide application and intercropping maize with common beans and leucaena had the highest Mg. The lack of a significant effect between and among different treatments in this study may be due to the time factor as this study was carried out for three years only. The extent of changes in these properties increases with time as noted by Rhoton (2000). This is in agreement with Dick *et al.* (1991) indicating that it is difficult to detect changes due to NT after only two or three years of such research.

No till and leaving crop residues in the field had a positive effect on exchangeable bases (Ca and Mg) as they resulted in higher contents of these elements compared to CT and treatments without crop residues. The higher amounts of these elements have been associated with higher soil organic matter (Edwards *et al.,* 1992). During decomposition of the organic matter there is release of these nutrients. Similar results have been observed by Duiker and Beegle (2006) and Govaerts *et al.* (2007).

4.3.4 Micronutrients Mn, Fe, Zn and Cu

Table 4.10 shows that Fe and Zn were not significantly affected ($p>0.05$) by tillage, herbicide application, agroforestry, mulching and the number of CA practices applied. There was no clear trend of tillage effect on Fe and Zn. The mean Fe was higher in CT than NT by 6%. While the mean Zn was 5% lower in CT compared to NT. The micronutrients Zn, Fe, Cu and Mn have previously been found to be higher in NT and with crop residue retention (Loke *et al.,* 2013). This is in agreement with findings of this study. The non-significant effect of tillage on Fe, Mn and Cu is similar to findings of Govaerts *et al.* (2007) and Rhoton, (2000) after three years of applying NT. The mean Fe was lower in herbicide and mulching treatment by 3% and 7% respectively. Herbicide application had no effect on mean Zn. However, agroforestry had higher mean Zn by 16% while mulching resulted into lower mean Zn by 15%. The lower micronutrient contents when herbicides were applied compared to no herbicide application may be due to their chelation by the herbicides (Huber, 2010). This has further been corroborated by Paul *et al.* (2013) who found reduced micronutrients when herbicide was applied, due to their immobilization. The non-significant effect of

Table 4.10: The Effect of Tillage, Herbicide Application, Agroforestry Mulching and Number of CA Practices on Iron (Fe) and Zinc (Zn).

	Fe (ppm)				**Zn (ppm)**			
Tillage								
	Year 1	Year 2	Year 3	Mean	Year 1	Year 2	Year 3	Mean
CT	80	66	89	78	2.3	1.7	2.6	2.1
NT	79	67	73	73	2.3	1.9	2.3	2.2
Number of CA practices applied								
One	78^{a}	64^{a}	89^{b}	77^{a}	2.5^{a}	1.6^{a}	2.8^{a}	2.3^{a}
Two	83^{a}	68^{a}	80^{ab}	77^{a}	2.3^{a}	1.9^{a}	2.3^{a}	2.2^{a}
Three	70^{a}	63^{a}	65^{a}	66^{a}	2.4^{a}	1.9^{a}	2.1^{a}	2.1^{a}
Intercropping								
Maize/Common beans	74	67	81	74	2.6	1.8	2.3	2.2
Maize/Dolichos beans	79	64	82	75	2.4	1.7	2.1	2.1
Herbicide								
Yes	80	64	78	74	2.5	2.0	2.2	2.2
No	79	66	81	76	2.3	1.8	2.5	2.2
Agroforestry								
Yes	82	62	87	77	2.4	1.8	3.2	2.5
No	79	67	78	74	2.4	1.9	2.1	2.1
Mulch								
Yes	75	65	73	71	2.2	1.8	2.1	2.0
No	81	66	82	76	2.4	1.9	2.5	2.3
Interaction of tillage, agroforestry, herbicide application and mulching								
CTMBL	74^{a}	65^{a}	89^{a}	76^{a}	2.3^{a}	1.9^{a}	2.5^{a}	2.7^{a}
CTMB	78^{a}	65^{a}	89^{a}	77^{a}	2.8^{a}	1.7^{a}	2.2^{a}	2.2^{a}
CTMBMu	86^{a}	71^{a}	88^{a}	82^{a}	1.8^{a}	1.7^{a}	2.2^{a}	1.9^{a}
CTMD	82^{a}	62^{a}	89^{a}	78^{a}	2.5^{a}	1.4^{a}	2.2^{a}	2.0^{a}
NTMBL	76^{a}	63^{a}	92^{a}	77^{a}	2.1^{a}	1.6^{a}	2.7^{a}	2.1^{a}
NTMB	71^{a}	68^{a}	80^{a}	73^{a}	2.5^{a}	2.0^{a}	2.2^{a}	2.2^{a}
NTMBMu	81^{a}	67^{a}	65^{a}	71^{a}	2.5^{a}	1.8^{a}	2.2^{a}	2.2^{a}
NTMD	87^{a}	72^{a}	57^{a}	72^{a}	2.3^{a}	2.2^{a}	2.2^{a}	2.2^{a}
NTHMBL	97^{a}	59^{a}	79^{a}	78^{a}	2.7^{a}	2.0^{a}	2.9^{a}	2.5^{a}
NTHMB	77^{a}	67^{a}	78^{a}	74^{a}	2.6^{a}	2.0^{a}	2.2^{a}	2.3^{a}
NTHMBMu	58^{a}	58^{a}	88^{a}	61^{a}	2.3^{a}	1.9^{a}	1.9^{a}	2.1^{a}
NTHMD	85^{a}	74^{a}	65^{a}	82^{a}	2.3^{a}	2.0^{a}	1.9^{a}	2.1^{a}

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$; CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

agroforestry on micronutrients deviates from finding of Singh *et al.* (2007) and Yadav and Bisht (2014) who found a significant effect of agroforestry on micronutrients.

Table 4.11 shows that Mn and Cu were not significantly affected by tillage, herbicide application, agroforestry, mulching and number of conservation agriculture practices applied. As was the case for Fe and Zn there was no clear trend of tillage effect on Mn and Cu. The CT resulted into lower mean Mn by 7% compared with NT. The mean Mn was not affected by herbicide application.

However, the mean Mn was lower in agroforestry and mulching treatments by 1% and 9% respectively. Application of one conservation agriculture practice had lower mean Mn by 4% compared to two and three conservation agriculture practices. The choice of intercropping crop had no significant effect on both Cu and Mn, but intercropping maize with common beans had slightly lower Mn compared to dolichos. Herbicide application and agroforestry resulted into higher mean of Cu by 15% and 8% respectively, while mean Cu was lower by 4% in mulching treatment. Mean Cu was higher in in two conservation agriculture practices by 12% and 15% compared to one and three conservation agriculture practices respectively. There was no clear trend of the effect of various treatments on the micronutrients.

Table 4.11: The Effect of Tillage, Herbicide Application, Agroforestry Mulching and Number of CA Practices on Manganese (Mn) and Copper (Cu).

	Mn (ppm)				Cu (ppm)			
Tillage								
	Year 1	Year 2	Year 3	Mean	Year 1	Year 2	Year 3	Mean
CT	85	126	99	103	2.2	1.7	3.1	2.3
NT	121	131	84	110	2.3	1.6	3.1	2.3
Number of CA practices applied								
One	99^a	114^a	103^a	104^a	2.3^a	1.8^a	2.7^a	2.3^a
Two	114^a	120^a	89^a	108^a	2.3^a	1.7^a	3.8^a	2.6^a
Three	99^a	137^a	87^a	108^a	2.3^a	1.7^a	2.7^a	2.2^a
Intercropping								
Maize/Common beans	119	127	90	112	2.4	1.7	3.3	2.5
Maize/Dolichos beans	145	116	102	121	2.3	1.8	3.1	2.5
Herbicide								
Yes	114	115	93	107	2.5	1.8	3.9	2.7
No	103	126	92	107	2.2	1.7	3.1	2.3
Agroforestry								
Yes	98	103	99	100	2.3	1.7	3.7	2.6
No	110	129	90	109	2.3	1.7	3.2	2.4
Mulch								
Yes	87	144	87	106	2.1	1.7	3.2	2.4
No	113	115	94	107	2.4	1.7	3.4	2.5
Interaction of tillage, agroforestry, herbicide application and mulching								
CTMBL	81^a	121^a	117^a	106^a	2.1^a	1.8^a	2.7^a	2.2^a
CTMB	77^a	123^a	117^a	106^a	2.7^a	1.8^a	2.7^a	2.4^a
CTMBMu	61^a	158^a	87^a	102^a	1.8^a	1.7^a	3.2^a	2.6^a
CTMD	121^a	101^a	76^a	99^a	2.1^a	1.7^a	2.7^a	2.2^a
NTMBL	150^a	88^a	84^a	107^a	2.4^a	1.7^a	3.0^a	2.4^a
NTMB	113^a	123^a	68^a	102^a	2.2^a	1.6^a	3.8^a	2.2^a
NTMBMu	104^a	137^a	84^a	108^a	2.4^a	1.7^a	2.5^a	2.2^a
NTMD	115^a	154^a	101^a	123^a	2.1^a	1.5^a	3.0^a	2.5^a
NTHMBL	63^a	100^a	95^a	86^a	2.5^a	1.6^a	3.5^a	3.2^a
NTHMB	147^a	125^a	79^a	117^a	2.6^a	1.8^a	3.1^a	2.5^a
NTHMBMu	95^a	139^a	90^a	108^a	2.2^a	1.8^a	2.9^a	2.3^a
NTHMD	152^a	97^a	106^a	119^a	2.6^a	1.9^a	2.9^a	2.8^a

Means followed by the same superscript within a column are not significantly different at $p \leq 0.1$; CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

4.4 Soil Microbial Biomass

Table 4.12 shows that tillage, herbicide application, agroforestry, mulching and number of conservation agriculture practices applied had a significant effect on soil microbial biomass as indicated by soil microbial biomass carbon (SMBC). The SMBC under NT was significantly higher by 68% than under CT. Kraut-Cohen *et al.* (2020) and Wang *et al.* (2012) found conservation tillage resulted in improving soil biological activity in comparison to CT and concurs with this study. The higher soil microbial biomass in no till may be associated with favourable conditions under no till such as increasing aeration, lower temperatures and moisture fluctuations, and higher total soil carbon (Alvear *et al.,* 2005; Nyamwange *et al.,* 2021).

Intercropping maize with common beans and covering the soil surface with mulch at 1.5 Mg ha-1 had significantly higher SMBC of 35% and 44% than just intercropping maize with dolichos or with common beans respectively. The soil microbial biomass increased in mulching and as the number of crops intercropped with maize increased. This aligns the findings with others showing that soil microbial biomass is sensitive to aboveground plant diversity and that it increases with increase in the number of plants (McDaniel et al., 2014). This can be explained by the fact that diverse plants are likely to alter soil microbes due to their differences in biochemical composition (Nilsson et al., 2008), effect on micro climate which drive soil biological processes (Lorentzen *et al.,* 2008), and labile carbon compounds exuded by roots that are quickly incorporated into microbial biomass and help promote higher soil biological activities (Kong *et al.,* 2011).

Herbicide application had no significant effect on SMBC. However, SMBC was lower when herbicide was applied by 16%. The lower SMBC is in agreement with Pertile *et al.* (2020). Mulching had significantly higher SMBC. This is explained by Böhme and Böhme (2006) and Prommer *et al.* (2020) that carbon additions of virtually any form to arable soils often increase the amount of soil microbial biomass, hence the increase of soil biological activity with addition of crop residues. Combining no till with covering the soil with residue mulch had a positive effect on SMBC with combining no till intercropping maize with beans and covering soil

Table 4.12: Soil Microbial Biomass Carbon (SMBC) as Affected by Tillage, Herbicide Application, Agroforestry, Mulching, Number of CA Practices Applied in Year Three

	SMBC (ppm)
Tillage	
CT	530^{*}
NT	710^{*}
Number of CA practices applied	
One	500^{a}
Two	570^{a}
Three	780^{c}
Intercropping	
Maize/Common beans	507
Maize/Dolichos beans	510
Herbicide	
Yes	520
No	620
Agroforestry	
Yes	610
No	580
Mulch	
Yes	720
No	540
Interaction of tillage, agroforestry, herbicide application and mulching	
CTMBL	580^{ab}
CTMB	460^{a}
CTMBMu	600^{ab}
CTMD	450^{b}
NTMBL	780^{bc}
NTMB	510^{ab}
NTMBMu	920^{c}
NTMD	650^{ab}
NTHMBL	460^{a}
NTHMB	550^{ab}
NTHMBMu	630^{ab}
NTHMD	430^{a}

Means followed by the same superscript within a column are not significantly different at $p \leq 0.05$, *Show significant difference from t-Test

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

surface with mulch having the significantly highest value (130%) compared to combining conventional tillage with intercropping maize and common beans.

The total soil carbon and soil pH affect soil microbial biomass. Therefore, this study sought the relationship between total soil carbon and soil pH with CO_2 burst. The study found a positive relationship between CO_2 burst with total soil carbon and soil pH as shown in Figure 4.11a and b respectively.

Soil microbial biomass is expected to increase with total soil carbon (Sebiomo *et al.*, 2011), resulting in a positive correlation as was also found in this study (Fig. 4.11a). Build-up of total soil carbon provides food for soil microorganisms hence high soil biological activity (Murphy *et al.,* 2011), though this relationship can be affected by

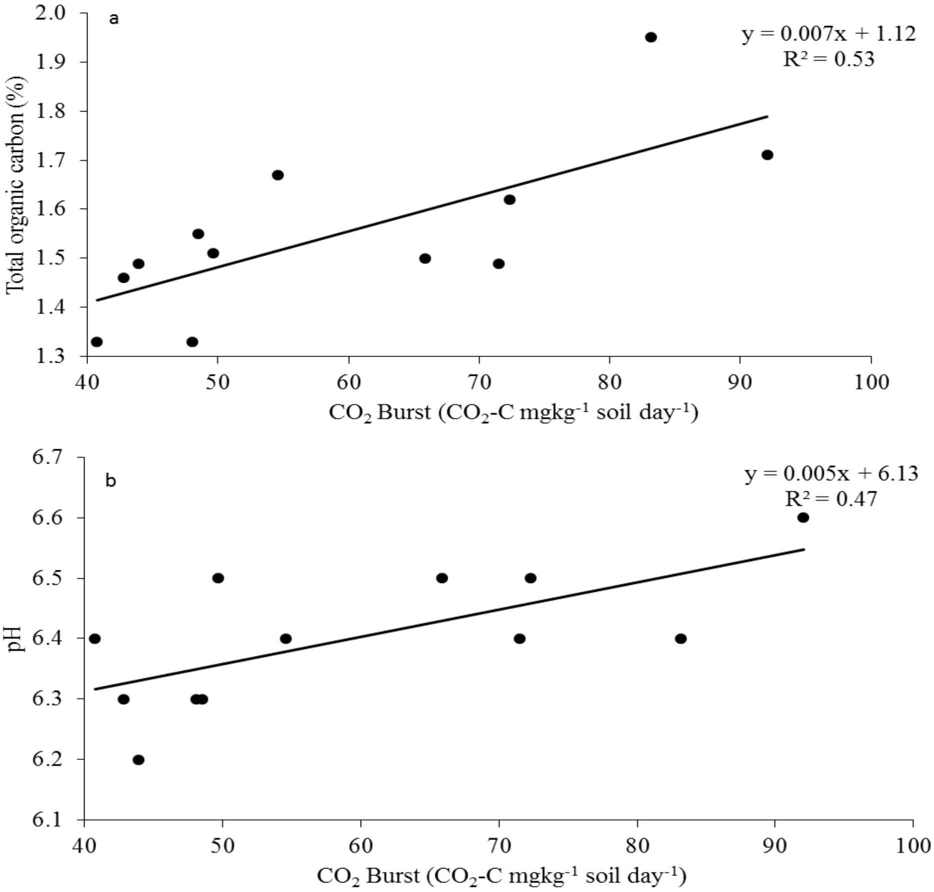

Figure 4.11: Soil CO_2 Burst as a Function of b) Total Soil Organic Carbon, and b) pH

other factors like soil moisture, soil temperature regime and microclimate. Good correlation of soil microbial biomass with pH was also observed (Fig. 4.11b). The current study findings agree with those by Catania *et al.* (2022). Soil pH affects soil microbial biomass, with positive correlations, which was also found by Cookson et al. (2007). Increasing pH increases the amount of negatively charged groups on humus colloids and thus increases the solubility of soil organic matter (Andersson *et al.,* 2000). This increases the availability of organic carbon that support microbial activity hence high soil microbial biomass with increasing pH (Murphy *et al.,* 2011).

4.5 Crop Yield

Tables 4.13 and 4.14 present maize yield and maize yield stability index for the 1st and 2nd year wet seasons, and the dry 3rd year of the study, for the different treatments. Tillage significantly affected maize grain yield only in the dry year season in year three, with CT showing significantly lower yield than NT by 33.9%. Over the years NT had more stable yield with CV of 62.16% compared to CT with 93.87%. This is in line with previous findings that showed that during wet years CT performs better than conservation agriculture (Lenssen *et al.,* 2014; Yemadje *et al.,* 2022). This is affirmed by Dong *et al.* (2022) and Thierfelder *et al.* (2015) whose study findings found out that NT significantly affected maize yield during seasons with low rainfall. In another study where similar conditions were tested, findings indicated that yield from field that were not tilled and with plant residues retained on the farm were more productive in nutrient and water use when compared with those from tilled fields and with crop residue removed (Baumhardt *et al.,* 2013). Therefore, the improvement of crop yields from 20% to 120% has been realized through sustainable agriculture (Kassam *et al.,* 2009). Most of the conservation agriculture benefits, in terms of yield when compared to CT, have been realized in regions with moisture deficiency or during dry years (Mupangwa *et al.,* 2012; Su *et al.,* 2021). This is in agreement with this study where the NT treatments had higher yield during the dry year season compared to the CT treatment. Higher yield in systems utilizing NT compared to those using CT during dry years have also been demonstrated in findings by Ngwira *et al.* (2012) and Sun *et al.* (2018).

Table 4.13: Effect of Tillage, Agroforestry, Herbicide Application, Mulching and Number of CA Practices Applied on Maize Grain Yield (kg ha^{-1})

	Year 1	Year 2	Year 3
Tillage			
CT	2950	2939	1688^{*}
NT	2345	2803	2261^{*}
Number of CA practices applied			
One	2896^{a}	2803^{a}	1640^{a}
Two	2607^{a}	2876^{a}	2173^{b}
Three	2228^{a}	2657^{a}	2592^{b}
Intercropping			
Maize/Common beans	2767	2920	1838
Maize/Dolichos beans	2562	3007	2026
Herbicide			
Yes	2552	2723	2381^{*}
No	2649	2871	1974^{*}
Agroforestry			
Yes	2632	2464	2217^{*}
No	2821	2762	1860^{*}
Mulch			
Yes	2526	2887	2338^{*}
No	2821	2762	2033^{*}
Interaction of tillage, agroforestry, herbicide application and mulching			
CTMBL	2716^{a}	2504^{a}	1883^{ab}
CTMB	3292^{a}	2438^{a}	1523^{a}
CTMBMu	3123^{a}	3346^{a}	1829^{ab}
CTMD	2682^{a}	3468^{a}	1517^{a}
NTMBL	2408^{a}	1859^{a}	2317^{ab}
NTMB	2080^{a}	3270^{a}	1787^{ab}
NTMBMu	2242^{a}	3042^{a}	2633^{b}
NTMD	2648^{a}	3042^{a}	2305^{ab}
NTHMBL	2775^{a}	3030^{a}	2453^{ab}
NTHMB	3093^{a}	2577^{a}	2270^{ab}
NTHMBMu	2214^{a}	2273^{a}	2551^{ab}
NTHMD	2127^{a}	3013^{a}	2249^{ab}

Means followed by lower case superscript in the column were not significantly different at $P \leq 0.05$. *Show significant difference from t-Test; CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

Similar conclusions were made by Rusinamhodzi *et al.* (2011) in a meta-analysis of conservation agriculture on maize yield under raid-fed conditions. The higher yield in NT based systems compared to CT in the dry year are attributable to better capture and storage of plant available water (Bekele *et al.,* 2022; Lenssen *et al.,* 2014; Rusinamhodzi *et al.,* 2011), particularly when water is limiting. This may be due to improved soil properties which increases soil water retention in rain-fed farming (Bekele *et al.,* 2022). Thus, better rain water capture and retention in the soil associated with NT would be expected to result to higher yields compared to CT based systems especially in dry seasons. The benefits of conservation tillage include plant water availability, soil aggregation, improved soil organic matter and transmission capacity of soil water thus outweighing conventional tillage and this enhances the infiltration features of the soil (Bhattacharyya *et al.,* 2008). Minimum tillage activities raise soil organic carbon (Nyamadzawo *et al.,* 2008) which promote efficient utilization of nutrients (Tittonell *et al.,* 2012) resulting to higher crop yields (Ngigi *et al.,* 2006). A negative effect of tillage during dry years has also been found by Abdullah (2014) and Liu *et al.* (2017). Furthermore, no till is expected to have a positive effect on yield stability as documented by Macholdt and Honermeier (2017). This is important in regard to climate change with rainfall becoming more erratic, with more and longer dry spells and less rainy days.

Findings from this study indicated that there was no significant difference between intercropping maize with common beans and intercropping maize with dolichos beans during the three years of the study. However, intercropping maize with dolichos beans resulted to 3% and 10% higher maize yield in the 2nd and 3rd years respectively compared to intercropping maize with common beans. Intercropping maize with dolichos beans resulted to stable yield compared to intercropping maize with common beans with CV values of 15.57% and 49.98% respectively. This may be explained by the better soil moisture storage determined through this study and previous studies (Ngenga *et al.,* 2022) when dolichos was intercropped with maize compared to the maize and common beans intercrop. This is due to effect of better surface cover by the dolichos that continue growing in the field even after maize is harvested compared to beans that is a short season growing crop that is harvested even before maize is harvested.

Mulching played an important role, especially during the drier than average year as evidenced by a significant 13% higher maize yield. The positive effect of surface cover during the drier than average year is in agreement with Biamah *et al.* (1993). They associated higher yield to the presence of mulch that improves rainwater partitioning. Liu *et al.* (2017) argue that as water is most limiting in dry years and since a crop is more sensitive to changes in soil moisture below critical water stress, any soil management practice that improves soil moisture retention will have a positive impact on yield. It has been reported that permanent soil cover reduces soil water loss through evaporation (Dahiya *et al.,* 2007), modifies soil temperature (Cook *et al.,* 2006), decreases soil erosion leading to high rainfall infiltration (Rockström *et al.,* 2009) as well as suppressing weeds and improving soil microbial activity (Chilimba, 2002). Other benefits of mulch include surface cover that reduces evaporation, which improve water use efficiency (Snyder *et al.,* 2015). Furthermore, mulching with organic material has been associated with improved soil fertility that leads to better plant nutrients supply that has a positive effect on the crop yield (Adekiya *et al.,* 2019).

Mulching in the present study had soil moisture above critical moisture of 150 mm for maize especially during critical stages of maize growth, and thus a positive impact of mulch on maize yield. Similar observations were made by Cakir (2004) who concluded that the short-term positive effect of mulching on maize yield is critical in that farmers will be attracted to adopting this practice as one of conservation agriculture component. Besides, Abdullah (2014) also found higher crop yields due to soil surface covering with crop residues. In Japan, Kader *et al.* (2017) found similar results of higher crop yield in treatments with mulch compared to no mulching. The higher yield as a result of mulching has been attributed to higher soil moisture that enhance plant nutrient availability and root growth (Sarkar and Singh, 2007). The role played by such conservation agriculture practices in managing soil productivity, retaining and conserving soil water and decreasing the production costs has aided in achieving higher crop yields (Hossain *et al.,* 2015).

Table 4.14: Effect of Tillage, Agroforestry, Herbicide Application, Mulching and Number of CA Practices Applied on Maize Grain Yield Stability

	R^2
	Tillage
CT	0.939
NT	0.622
	Number of CA practices applied
One	0.864
Two	0.994
Three	0.005
	Intercropping
Maize/Common beans	0.500
Maize/Dolichos beans	0.156
	Herbicide
Yes	0.944
No	0.981
	Agroforestry
Yes	0.606
No	0.934
	Mulch
Yes	0.766
No	0.898
	Interaction of tillage, agroforestry, herbicide application and mulching
CTMBL	0.744
CTMB	0.498
CTMBMu	0.979
CTMD	0.984
NTMBL	0.368
NTMB	0.704
NTMBMu	0.086
NTMD	0.924
NTHMBL	0.971
NTHMB	0.336
NTHMBMu	0.811
NTHMD	0.395

CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

Considering the competing uses of the crop residues, the current study incorporated agroforestry in conservation agriculture in the form of establishment of leucaena in the farming system. This technology resulted in significantly higher maize yield during the drier than average year by 16%, but no significant effect during the 1st and 2nd years (wet seasons). The yield was more stable in treatments incorporating agroforestry as conservation agriculture component with CV of 60.61% compared to those which did not (CV of 93.39%). The study found that leucaena species if used in conservation agriculture is beneficial as evidenced by the higher maize yield during the dry season. Tree-based intercropping helps in climate regulation and enhances agriculture through improved soil quality, nutrient mineralization, biological control and pollination (Alam *et al.* 2014). This is in agreement with the finding of this study where intercropping maize with leucaena had higher maize yield especially during the dry season. Considering that drier than average seasons are likely to occur in the study area, practicing agroforestry in conservation agriculture will enhance more stable yield contributing to food and nutrition security. Furthermore, leucaena is a nitrogen fixing plant that may improve soil fertility thus resulting into better yields. The higher and stable maize yield as a result of cropping maize together with leucaena is explained by Chintu *et al.* (2004) and Chirwa *et al.* (2003). They attribute the positive effect of leucaena to improving the soil structure, rainfall storage and enhancement of nutrients recycling. Mugendi *et al.* (1999) found higher N uptake of 105 to 110 kg ha^{-1} in maize/leucaena systems compared to 96 to 105 kg ha^{-1} in maize monocultures.

Herbicide use is common in farming systems practicing conservation agriculture (Colbach and Cordeau, 2022). This underlines the importance of testing it in this study. Results from the data analysis indicated that there was significant effect of use of herbicide in control of weeds from the 3rd year of the experiment with herbicide application having higher maize yield by 17%. Previous studies that agree with this study findings of higher maize yield with application of herbicide include those by Bibi *et al.* (2020) and Ibade and Mohammed, (2020). The positive effect of herbicide on maize yield especially during the dry season is associated with reduced weed population which results in reduced competition for water and nutrients between the maize and weeds. This results in better nutrients and water use efficiency translating into higher yields (Hassan *et al.,* 2010).

Applying all the three practices of conservation agriculture considered in this study resulted in significantly higher yield compared to applying one or two conservation agriculture practices during the drier than average year, with applying one conservation agriculture practice showing 33.0% and 58.0% lower maize yield compared to systems using two and three conservation agriculture practices, respectively. When considering total maize yield of the wet seasons in 1st and 2nd years of the experiment as well as the 3rd year which was drier than the average growing seasons, applying two or three conservation agriculture practices resulted in higher and more stable values than applying only one practice (6.9% and 8.6% higher, respectively).

The stability is shown by the lower CV of 48% in treatments using three conservation agriculture practices compared to 86.37% and 99.41% in one and two conservation agriculture practices respectively. The yield stability agrees with what was reported by Govaerts *et al.* (2005) and Su *et al.* (2021). Yield stability is an important aspect of crop production under rain-fed and more adverse conditions. A stable system shows a small change in response to changes in the environment (Hollósy *et al.*, 2023).

During the 3rd year which was a dry year, the two conventional practices of conventional tillage with maize and common beans or dolichos had the lowest maize yield, compared to no till with maize, beans and mulch. However, in the 2nd year wet season, no till combined with maize, common beans and mulch had 12.3% lower yield than the conventional practices with dolichos, but still 24.8% higher than the conventional practice with common beans. Further, no till method with maize, common beans and mulch in the form of maize residue had more stable yield compared to the other treatments as evidenced by the lowest CV of 8.6% during the dry year season. Practicing no till combined with intercropping maize with common beans and leucaena or applying mulch at a rate of 1.5 Mg ha^{-1} resulted to the highest yield during the dry year season. These practices showed an increase in maize yield of up to 63.0% and 73.0%, respectively, as compared to the most conventional system of CT with maize and common beans. This may be attributed to the higher soil moisture in farming systems using the conservation agriculture, especially during the critical dry period of flowering (tasselling) and grain filling. Another reason could be the improved nutrient uptake especially nitrogen when maize is intercropped with leucaena which is likely to result in higher maize yield than when maize is grown alone (Sileshi *et al.,* 2011; Mugendi *et al.,* 1999). The positive effect of no till combined with intercropping maize with common bean and leucaena and covering the soil surface with maize residue is in agreement with the findings of Pittelkow *et al.* (2015).

4.6 Rain Water Use Efficiency

The effect of tillage on rain water use efficiency (RWUE) is presented in Table 4.15. The RWUE was significantly affected by tillage during the 3rd year (dry season). The CT had 33% significantly lower RWUE than NT. Better RWUE in NT compared to CT has been previously demonstrated by Oduor *et al.* (2023). They attributed the higher RWUE in NT (compared to CT) to decreased evaporation, thus optimizing rainfall use.

There was no significant effect of intercropping maize with either common bean or dolichos beans during the three years of study. During the wet season intercropping maize with common beans had higher RWUE by 7.5% compared to intercropping maize with dolichos beans. Additionally, intercropping maize with dolichos beans had 10% higher RWUE in comparison with common beans during the dry year. Higher RWUE found when dolichos beans was intercropped with maize compared to common beans intercrop with maize could be due to more coverage of ground area thus reducing water loss through evaporation (Maitra *et al.,* 2021). The incorporation of agroforestry in conservation agriculture using leucaena trees had a higher RWUE by 16%, while covering soil surface with maize residues mulch significantly increased RWUE during the dry season by 19.8%. Higher water use efficiency in combining NT with crop residue has been reported by Zhang *et al.* (2014). Cantero-Martinez *et al.* (2003) also found better water use efficiency of no-tillage in the driest years in Spain.

Table 4.15: Rainfall Water Use Efficiency (kg ha^{-1} mm^{-1}) as Affected by Tillage, Mulching Agroforestry, Herbicide Application and Number of CA Practices

	Year 1	Year 2	Year 3
	Tillage		
CT	4.3	5.5	6.3*
NT	3.4	5.3	8.4*
	Number of CA practices applied		
One	4.2^{a}	5.2^{a}	6.1^{a}
Two	3.8^{a}	5.3^{a}	8.0^{b}
Three	3.3^{a}	5.0^{a}	9.6^{b}
	Intercropping		
Maize/Common beans	4	5.4	6.8
Maize/Dolichos beans	3.7	5.6	7.5
	Herbicide		
Yes	3.7	5.1	8.8*
No	3.9	5.3	7.3*
	Agroforestry		
Yes	3.8	4.6	8.2*
No	4.1	5.1	6.9*
	Mulch		
Yes	3.7	5.3	8.6*
No	4.1	5.1	6.9*
	Interaction of tillage, agroforestry, herbicide application and mulching		
CTMBL	3.9^{a}	4.6^{a}	7.0^{ab}
CTMB	4.8^{a}	4.5^{a}	5.6^{a}
CTMBMu	4.5^{a}	6.2^{a}	6.8^{ab}
CTMD	3.9^{a}	6.4^{a}	8.5^{ab}
NTMBL	3.5^{a}	3.4^{a}	8.6^{ab}
NTMB	3.0^{a}	6.1^{a}	6.6^{ab}
NTMBMu	3.3^{a}	5.7^{a}	9.7^{b}
NTMD	3.9^{a}	5.7^{a}	5.3^{ab}
NTHMBL	4.0^{a}	5.9^{a}	9.1^{ab}
NTHMB	4.5^{a}	4.8^{a}	8.4^{ab}
NTHMBMu	3.2^{a}	4.2^{a}	9.4^{ab}
NTHMD	3.1^{a}	5.6^{a}	8.3^{ab}

Means followed by lower case letter in the column were not significantly different at $P \leq 0.05$. *Show significant difference from t-Test; CT conventional tillage, NT no till, NTH no till herbicide, NTMB no till maize & beans, NTMD no till maize & dolichos, NTMBL no till maize, beans & leucaena, NTMBMu no till maize, beans & mulch, NTHMB no till herbicide maize & beans, NTHMD no till herbicide maize & dolichos, NTHMBL no till herbicide maize, beans & leucaena, NTHMBMu no till herbicide maize, beans & mulch, CTMB conventional till maize beans, CTMD conventional till maize & dolichos, CTMBL conventional till maize, beans & leucaena , CTMBMu conventional till maize, beans & mulch.

Better water use efficiency under mulching is congruent to the findings of Kader *et al.* (2017) in Japan and Qin *et al.* (2015) in China. The authors attributed higher water use efficiency to better soil structure due to build-up of biological microflora and fauna as this led to increased infiltration and reduction of water losses by evaporation and runoff. Plausible explanation to the higher RWUE determined in this study would be due to the effect of agroforestry on microclimate. This microclimate reduces water loss through reduced evaporation making the water available to the plant. The different roots depths of the agroforestry on microclimate. This microclimate reduces water loss through reduced evaporation making the water available to the plant. The different root depths of the trees and shrubs in agroforestry and annual crops ensure they exploit water and nutrient resources at different depths. The trees and shrubs exploit deeper soil layers than the annual crops, thus avoiding competition and resulting to better RWUE (Hatfield and Dold, 2019). Sileshi *et al.* (2011) found higher RWUE when maize was intercropped with leucaena compared to maize monoculture which the authors attributed to the role that leucaena plays in mitigating soil degradation and agricultural drought. The finding of higher RWUE in agroforestry is in agreement with Droppelmann *et al.* (2000) who found monocrop annuals having lower water use efficiency compared to alley cropping system in semi-arid Kenya.

Applying all the three practices of conservation agriculture resulted in significantly higher RWUE compared to applying one or two conservation agriculture practices during the dry season in the 3rd year by 36.5% and 16.7% respectively. The RWUE was significantly increased by 17% by herbicide application in the 3rd year. The higher RWUE in treatments with herbicide is due to the reduced weeds hence reduced competition for water, nutrient and light between the maize crop and weeds and therefore better water use by the maize crop (Thimmegowda, *et al.*, 2016). The positive effect of herbicide on RWUE has previously been reported by Singh *et al.* (2015).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Overview of the Research Study

The study hypothesised that conservation agriculture practices namely tillage, mulching, herbicide application and agroforestry had effect on soil physicochemical properties, soil microbial biomass, maize yield and water productivity under rain-fed agriculture. The tillage, mulching and herbicide application only significantly affected a selected physical property; namely saturated hydraulic conductivity and bulk density and had no significant effect on Ca, Mg, Fe, Cu, Mn and Zn. Tillage had also significant effect on soil microbial biomass, maize yield, and SOC, N, P and K. Mulching had significant effect on soil microbial biomass, maize yield, soil macro nutrients (N and P) and SOC. Herbicide application had significant effect on soil pH, SOC, N, P, K, maize yield and RWUE. However, herbicides application had no significant effect on soil microbial biomass. The agroforestry had significant effect on N, P, K, SMBC, maize yield and RWUE. The application of three conservation agriculture practices had significant positive effect on maize yield, soil microbial biomass, major soil chemical properties (pH, SOC, N, P, K and CEC) compared to application of one conservation agriculture practice.

5.2 Conclusion

Tillage, mulching, herbicide application and inclusions of agroforestry in conservation agriculture had no significant effects on soil physical properties within a period of three years except the soil saturated hydraulic conductivity and bulk density. However, these practices had positive and significant effect on macronutrients, soil organic carbon and cation exchange capacity but had no significant effect to secondary macronutrients (calcium and magnesium) and micronutrient (iron, zinc, copper and manganese).

Tillage, mulching, herbicide application and inclusions of agroforestry in conservation agriculture had significant effect soil microbial biomass as indicated by higher soil microbial biomass carbon.

Tillage, mulching, herbicide application and inclusions of agroforestry in conservation agriculture had a positive and significant effect on maize yield and rain water use efficiency during the season with rainfall below normal. The conservation agriculture practices have the capacity to improve and stabilize maize yield in rain-fed agriculture among small-scale farmers

5.3 Recommendations

(1) From the research results it was found that conservation agriculture practices had no significant effects on soil secondary macronutrients, micronutrients and majority of soil physical properties. This was attributed to the short study period of three years. It is therfore, recommended that long term research of at least more than four years be undertaken to evaluate long term effect of conservation agriculture on these parameters.

(2) Conservation agricultures practices namely no till, and mulching had siginificant effect on soil microbial biomass. Thus, conservation agriculture is recommended in order to improve soil microbial properties.

(3) Due to the negative effect of herbicide on soil microbial biomass it is recommended to reduce herbicide application in conservation agriculture and explore sustainable weed control methods.

(4) The application of conservation agriculture practices such as no till and mulching resulted to more and stable maize yield during the dry year. Therefore, it is recomemnded to apply conservation agricultre in semi arid zone to achieve better crop yield.

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APPENDICES

Appendix I: Analysis of Variance on the Effect of Number of Conservation Practice on Soil Physical Properties

	Sum of Squares	df	Mean Square	F	Sig.
Bulk density	0.040	2	0.020	2.682	0.076
Stability index	7.562	2	3.781	8.217	0.001
Matric porosity	0.001	2	0.001	0.475	0.624
Macro porosity	0.001	2	0.000	0.497	0.611
Aeration capacity	0.001	2	0.000	0.501	0.608
Plant available water content	0.000	2	0.000	0.109	0.897
Relative water content	0.007	2	0.004	0.584	0.561
S-index	0.000	2	0.000	0.623	0.539
Soil hydraulic conductivity	118.666	2	59.333	5.881	0.004
Aggregate stability	0.118	2	0.059	5.843	0.005

Appendix II: Analysis of Variance on the Effect of Number of Conservation Practice on Soil Chemical Properties in Year One

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	pH	2.728	11	0.248	3.036	0.011
	N	0.004	11	0	1.199	0.339
	OC	0.551	11	0.05	0.956	0.508
	P	1314.889	11	119.535	3.323	0.007
	K	66592.556	11	6053.869	8.855	0
	CEC	81.33	11	7.394	3.133	0.009
	CN	15.556	11	1.414	1.184	0.348
	Ca	915555.556	11	83232.323	0.732	0.699
	Mg	93384.667	11	8489.515	0.986	0.485
	Mn	34576.47	11	3143.315	1.058	0.432
	Cu	2.423	11	0.22	0.315	0.975
	Fe	3057.63	11	277.966	0.763	0.671
	Zn	2.203	11	0.2	0.796	0.643

Appendix III: Analysis of Variance on the Effect of Number of Conservation Practice on Soil Chemical Properties in Year Two

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	pH	6.223	11	0.566	5.304	0.000
	N	0.004	11	0.000	0.996	0.477
	OC	1.582	11	0.144	2.875	0.015
	P	5065.639	11	460.513	3.110	0.010
	K	70697.889	11	6427.081	8.727	0.000
	CEC	114.290	11	10.390	1.863	0.098
	CN	34.306	11	3.119	3.509	0.005
	Ca	1314266.667	11	119478.788	1.590	0.165
	Mg	35931.840	11	3266.531	1.403	0.234
	Mn	16447.860	11	1495.260	2.152	0.057
	Cu	0.401	11	.036	.766	0.669
	Fe	818.633	11	74.421	1.400	0.236
	Zn	1.782	11	.162	.956	0.508

Appendix IV: Analysis of Variance the Effect of Number of Conservation Practice on Soil Chemical Properties in Year Three

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	pH	6.481	11	0.589	8.285	0.000
	N	0.031	11	0.003	23.033	0.000
	OC	3.195	11	0.290	6.314	0.000
	P	7642.000	11	694.727	4.022	0.002
	K	119790.306	11	10890.028	10.901	0.000
	CEC	151.321	11	13.756	1.574	0.170
	CN	42.972	11	3.907	2.197	0.052
	Ca	1083855.556	11	98532.323	.495	0.888
	Mg	68226.680	11	6202.425	.591	0.818
	Mn	8082.788	11	734.799	.902	0.552
	Cu	25.613	11	2.328	1.202	0.337
	Fe	4486.143	11	407.831	1.175	0.354
	Zn	10.708	11	.973	1.155	0.366

Appendix V: Analysis of Variance on the Effect of Number of Conservation Practice on Soil Microbial Biomass

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	0.000	2	134.595	2.176	0.001

Appendix VI: Analysis of Variance on the Effect of Number of Conservation Practice on Maize Yield and Rain Water Use Efficiency in Year One

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	Yield	1612388.595	2	806194.298	1.467	0.25
	RWUE	2.656	2	1.328	1.471	0.24

Appendix VII: Analysis of Variance on the Effect of Number of Conservation Practice on Maize Yield and Rain Water Use Efficiency in Year Two

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	Yield	227666.451	2	113833.226	0.219	0.804
	RWUE	0.438	2	0.219	0.218	0.805

Appendix VIII: Analysis of Variance on the Effect of Number of Conservation Practice on Maize Yield and Rain Water Use Efficiency in Year Three

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Number of CA practices	Yield	3456003.417	2	1728001.708	11.779	0.000
	RWUE	19.905	2	9.952	11.804	0.000

Appendix IX: Abstract of Fifth Publication

Journal of Agriculture, Science and Technology (JAGST) 2024 Vol. (23) No. (1): Pp (28-64)

Effect of tillage, mulching, herbicide application, intercropping and agroforestry on soil moisture maize yield and rainwater use efficiency in semi-arid Kenya: A case study of Laikipia East

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ABSTRACT

Conservation agriculture (CA) is promoted in Sub-Saharan Africa to address land degradation and low productivity among small-scale farmers. However, contrasting results have been reported from studies testing the impact of CA on land degradation and productivity. This study was conducted to investigate the effect of tillage, mulching, herbicide application, intercropping, and agroforestry on soil moisture storage, crop yield, and rainwater use efficiency (RWUE). Three main treatments consisting of conventional tillage (CT), no tillage (NT), and no tillage with herbicides (NTH) were tested. In each of the treatments, four sub-treatments, which included (a) maize and beans, (b) maize and dolichos, (c) maize, beans, and leucaena, and (d) maize, beans, and mulch (1.5 metric tonnes Ha^{-1}) replicated three times, were investigated. This implies that a split-plot design with 3 main plots and 4 subplots was used. The experiments ran for a period of three years and were characterised by two years of wetter than average. Tillage significantly affected crop yield, soil moisture, and RWUE during the dry year, with CT showing a significantly lower 33.9% and 33% maize yield and RWUE, respectively, than NT. Similarly, mulching significantly increased maize yield and RWUE by 13% and 19.8%, respectively, in the same year. Maize yield and RWUE were significantly increased in treatments that had agroforestry by 16% and 15.8%, respectively. By extension, it means that agroforestry has a positive impact on maize yield, soil moisture, and RWUE. The study showed that NT and mulch are critical aspects of CA in that they avoid drought stress on maize during dry seasons while enhancing maize yield. Agroforestry showed potential to further improve CA in semi-arid zones, resulting in higher yields in dry years. Even though the dry growing season under study corresponded with a meteorological drought, practicing two or three CA practices could avoid agricultural droughts due to the conservation of soil moisture that becomes available to crops during dry periods. The ‘best’ practice (no till with maize, beans, and mulch) resulted in up to 74% higher yield in the dry year and still up to 24% higher yield in the wet growing season under study, compared to the conventional practice. The study concludes that NT, mulching, and incorporating agroforestry in California had a significant effect on soil moisture, maize yield, and RWUE, especially in seasons with rainfall below normal.

Keywords: conservation agriculture, tillage, mulching, herbicide application, agroforestry, soil moisture

Appendix X: Abstract of Fourth Publication

Sustainable Agriculture Reviews Volume 29

Chapter 6

Building Resilience against Drought and Floods: The Soil-Water Management Perspective

Wim Cornelis, Geofrey Waweru and Tesfay Araya

Abstract

Many regions in the world are suffering from agricultural droughts and floods, two sides of the same coin. They result in shortage of available water for plant growth or accumulation of water on farm land that is normally not submerged, respectively. The incidence of droughts and floods is not only caused by extreme weather events, but also by an imbalanced partitioning of rainfall, with higher blue water flows at the expense of green water, i.e. soil moisture generated from infiltrating rain. This chapter suggests that poor partitioning of rainwater and an unbalanced water regime is associated with soil structural degradation, lack of physical structures or evapotranspiration controlling measures, among others. Appropriate soil-water management practices could be a first step in building resilience against agricultural droughts and floods. Such practices refer to the management of soil (in whatever way) with the purpose of enhancing the quantity and flow of soil water. They range from improving physical soil quality, i.e., increasing rainwater infiltration capacity and plant-available water capacity through the use of soil amendments, conservation agricultural practices and other field water conservation practices, over farming practices such as use of mulches and cover crops, to soil conservation practices, and runoff and flood water harvesting techniques. In this chapter, two examples from semi-arid zones in Kenya and Ethiopia are given that demonstrate that soil-water management practices lead to more water being conserved and thus reduce drought and flood risk, resulting in at least 40% higher maize and wheat yields when rainfall was lower than normal. On a Vertic Phaeozems in Kenya, best results were obtained when applying three conservation agriculture practices (minimal disturbance, soil cover, diversified cropping). On a Vertisol in Ethiopia, conservation agriculture-based soil-water management practices with narrow raised beds and furrows outperformed other tested practices. Though not demonstrated with data, this chapter also suggests that soil-water management practices can affect the incidence of hydrological and meteorological droughts and floods as well.

Keywords Drought · Flood · Soil-water management · Soil quality · Crop production · Maize · Wheat · Semi-arid

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Appendix XI: Abstract of Third Publication

Geophysical Research Abstracts Vol. 18, EGU2016-12421, 2016

Conservation agriculture among small scale farmers in semi-arid region of Kenya does improve soil biological quality and soil organic carbon

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Abstract

The low food production in Sub-Saharan Africa (SSA) has been attributed to declining soil quality. This is due to soil degradation and fertility depletion resulting from unsustainable conventional farming practices such as continuous tillage, crop residue burning and mono cropping. To overcome these challenges, conservation agriculture (CA) is actively promoted. However, little has been done in evaluating the effect of each of the three principles of CA namely: minimum soil disturbance, maximum surface cover and diversified/crop rotation on soil quality in SSA. A study was conducted for three years from 2012 to 2015 in Laikipia East sub-county in Kenya to evaluate the effect of tillage, surface cover and intercropping on a wide variety of physical, chemical and biological soil quality indicators, crop parameters and the field-water balance. This abstract reports on soil microbial biomass carbon (SMBC) and soil organic carbon (SOC). The experimental set up was a split plot

design with tillage as main treatment (conventional till (CT), no-till (NT) and no-till with herbicide (NTH)), and intercropping and surface cover as sub treatment (intercropping maize with: beans, MB; beans and leucaena, MBL; beans and maize residues at 1.5 Mg ha-1 MBMu, and dolichos, MD). NT had significantly higher SMBC by 66 and 31% compared with CT and NTH respectively. SOC was significantly higher in NTH than CT and NT by 15 and 4%, respectively. Intercropping and mulching had significant effect on SMBC and SOC. MBMu resulted in higher SMBC by 31, 38 and 43%, and SOC by 9, 20 and 22% as compared with MBL, MD and MB, respectively. SMBC and SOC were significantly affected by the interaction between tillage, intercropping and soil cover with NTMBMu and NTHMBMu having the highest SMBC and SOC, respectively. We conclude that indeed tillage, intercropping and mulching substantially affect SMBC and SOC. On the individual components of CA, tillage and surface cover had the highest effect on SMBC and SOC, respectively, but the highest positive effect was realized when all the three principles were applied consecutively. Therefore, CA has the potential to improve biological soil quality among small scale rainfed farmers and thus promote sustainable production.

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Appendix XII: Abstract of Second Publication

Conference on Desertification and Land Degradation. University 16th- 17th June 2015
Gent, Belgium

Effect of conservation agriculture on maize yield under rainfed agriculture in semi-arid region of Kenya.

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Effect of conservation agriculture on maize yield under rainfed agriculture in semi-arid region of Kenya

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Background and objective

- Declining food production in SSA- cereal yield remains low at 1.2 Mg ha^{-1}
- Cause: poor soil fertility, land degradation and low rainfall with high intraseasonal variability and high potential evaporation
- Conservation agriculture (CA): minimum soil disturbance, permanent soil cover and diversified crop rotation
- Promoted to overcome these challenges and contribute to sustainable crop production.
- Small-scale farmers in SSA hardly apply all the principles for various reasons
- Need to evaluate effect of each principle and their interaction under rainfed small scale farming in semi-arid area
- Objective: Determine effects of no tillage, intercropping, and soil cover on SWC and crop yields under rain-fed small scale farming in semi-arid area.

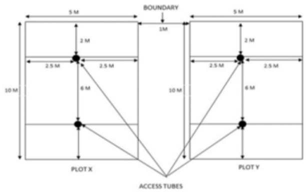

Fig. 1 Plots and neutron access tubes set up

Fig. 2 Surface cover after harvesting (a) dolichos, (b) leucaena(c) maize residues

Material and methods

Study site

- Laikipia East Sub County, Kenya(0°02'52.8"N, 37°06'57.9" 1962 m) between 2012 and 2014
- Rainfall 750 mm bimodal pattern (long rains between March-June, and short rains October-January), temperature between 16°C and 20°C
- Soils Vertic Phaoezems

Treatments

- Split plot design - 3 tillage treatments: (1) conventional tillage (CT), (2) no tillage (NT), (3) no tillage with herbicides (NTH)
- 4 sub-plots: intercropping and surface cover: (a) intercropping with beans (MB), (b) intercropping with dolichos (*Lablab purpureus* L.) (MD), (c) intercropping with beans (*Phaseolus vulgaris* L.) and leucena ((*Leucaena leucocephala* (Lam.) de Wit)) (MBL), (d) intercropping with beans and application of mulch (1.5 Mg ha^{-1} of maize residues) (MBMu), in three replicates
- 12 treatments: NTMB, NTMD, NTMBL, NTMBMu, NTHMB, NTHMD, NTHMBL, NTHMBMu, CTMB, CTMD, CTMBL, CTMBMu

Fertilization: Basal application 50 kg ha^{-1} NPK fertilizer (17-17-17) and top dressing when maize at knee height with 50 kg ha^{-1} calcium ammonium nitrate
Soil water measurement: at depths 15, 30, 45, 60, 75, 90, 105, 120, 135, 150 cm with neutron probe (Hydroprobe® model 503, CPN Corporation, Martinez CA USA)
Maize Yield: harvested at physiological maturity. Two grids of 2 m by 2 m next to the access tubes (Fig. 1) were sampled. Whole dry mature maize plants were cut, weighed and total biomass recorded. Then threshing was done and grain weight taken
Data analysis: Testing normality and ANOVA using General Linear Model, multiple mean comparison performed by Tukey post hoc test (0.05 probability level).

Results

- pH was ideal for crop growth but N and OC are low (Table 1)
- Season 1 and 2 wetter and 3 drier compared to long term average rainfall average (Fig. 3)
- CTMBMu had significantly higher soil water content (SWC) (Fig. 4)
- CT had high yield in wet season and CA in dry season (Fig. 5)
- Tillage significantly affected yield in season 3 (Fig. 5)
- Crop residues improved yield in dry season (Fig. 6 & 7)

Table 1 Basic soil properties at the research site

	Depth	
	0-15cm	15-30cm
pH	6.4	6.3
N (%)	0.14	0.10
OC (%)	1.4	1.3
P (ppm)	74.7	62.9
K (ppm)	322	281
EC (dS m^{-1})	0.15	0.16
CEC (cmol$^{(+)}$ kg^{-1})	21.2	23.3
BD (Mg m^{-3})	1.24	1.29

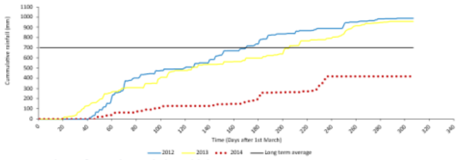

Fig 3 Comparison of annual cumulative with long term mean

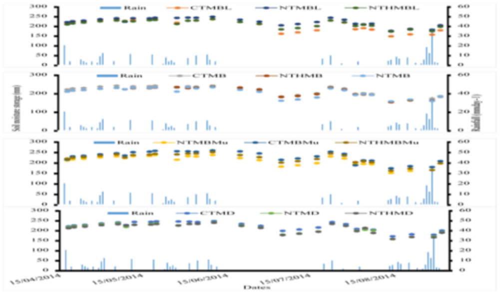

Fig. 4 Treatment effect on soil moisture storage

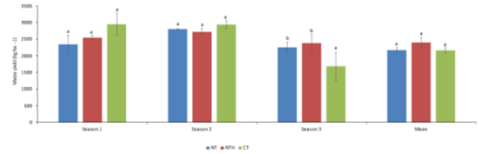

Fig. 5 Comparison of tillage effect on maize grain yield between the seasons. Columns represent averages and error bars standard deviations. Treatments labeled with the same letter are not significantly different at p<0.05

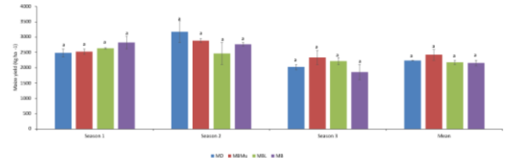

Fig. 6 Comparison of intercropping and surface cover effect on maize grain yield between the seasons. Columns represent averages and error bars standard deviations.Treatments labeled with the same letter are not significantly different at p<0.05.

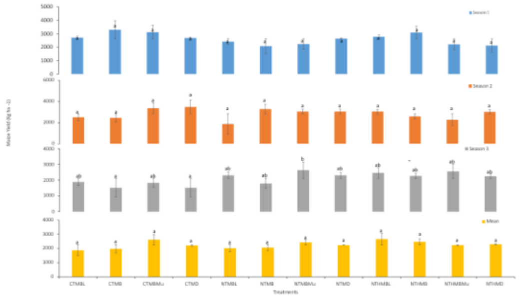

Fig. 7 Comparing the effect of interaction between tillage, intercropping and surface cover on maize grain yield. Columns represent averages and error bars standard deviations.Treatments labeled with the same letter are not significantly different at p<0.05.

Conclusion

Soil cover positively affect SWC
CA has a positive effect on yield during dry year
Incorporating agroforestry (leuacaena shrub) may improve CA systems
CA can promote sustainable crop production among small scale rainfed farmers in semi-arid areas of SSA

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Flemish Interuniversity Council-University Development Cooperation (VLIR UOS) Belgium, Jomo Kenyatta University of Agriculture and Technology and Kenya Agricultural Research Institute (KARI)

Appendix XIII: Abstract of First Publication

Joint proceedings of the 27th Soil Science Society of East Africa and the 6th African Soil Science Society

Transforming rural livelihoods in Africa: How can land and water management contribute to enhanced food security and address climate change adaptation and mitigation? 20-25 October 2013. Nakuru, Kenya.

Farmers’ perception of conservation agriculture in Laikipia East District in Kenya

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Abstract

Agriculture sector contributes about 24% of Kenya’s, GDP. Small scale farmers provide 75% of the labour force and 75% of the market output produce. Both land degradation and adverse climatic conditions threatens sustainable food production by small scale farmers. However, land degradation has decreased land resilience thereby exacerbating the effects of droughts. Conservation agriculture (CA) has the potential to contribute in addressing the challenge of adapting agriculture to land degradation and adverse climate. Adoption of a technology depends on several paradigms among them the perception paradigm Perceptions are influenced by factors such as culture, education, gender, age, resource endowments and institutional factors. Laikipia East district is arid semi-arid area with the average yearly rainfall is 750 mm, but the distribution is very unequal, and rain-fed agriculture is the predominant activity. Soil degradation is common due to unsustainable agricultural practices such as intensive tillage. The data was collected using 130 questionnaires in seven locations. The data was analyzed using SPSS version 16. Most of the farmer derive their livelihood on farm 75%. The level of education and gender influence farmers perception to CA with female and higher education lever with higher perception towards CA. Land ownership influence farmers perception to CA with higher positive perception in farmers with own land compared to the ones leasing land. There is competition for crop residue between surface cover and livestock feed which negative affect farmers' perception to CA. Farmers associate CA with herbicides that portrays CA as expensive. Socio-economic factors have influence on farmers' perception to CA.

Key words: conservation agriculture, perception, tillage, herbicides, surface cover, livestock.