

**COMBINED EFFECTS OF TILLAGE, MULCHING AND NITROGEN
FERTILIZER APPLICATION ON MAIZE YIELDS AND SOIL
PROPERTIES IN THARAKA-NITHI COUNTY, KENYA**

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University**

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DECLARATION

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

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DEDICATION

This work is dedicated to the memory of my father, Zeila Dubow, who passed away while I was undertaking this course.

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TABLE OF CONTENTS

DECLARATION.....	ii
DEDICATION	iii
ACKNOWLEDGEMENTS	iv
ABBREVIATIONS AND ACRONYMS	viii
LIST OF TABLES	x
LIST OF FIGURES.....	xii
ABSTRACT	xiv
CHAPTER ONE.....	i
INTRODUCTION.....	1
1.1 Background to the study	1
1.2. Problem statement.....	6
1.3 Research Questions	6
1.4 Objectives.....	7
1.5 Hypotheses.....	7
1.6 Significance of the study.....	8
1.6 Justification of the study	9
1.8 Conceptual framework.....	10
1.9 Definition of key terms	12
CHAPTER TWO.....	14
LITERATURE REVIEW	14
2.1 General overview	14
2.2 Soil tillage and impact on maize crop performance.....	17
2.3 Impact of conventional and minimum tillage systems on soils	23
2.4 Mulch management in soils	26
2.5 Soil organic carbon sequestration	34
2.6 Tillage and soil carbon sequestration.....	36
2.7 Nitrogen fertilization and sustainable agriculture.....	40
2.8 Summary and knowledge gaps	42
CHAPTER THREE.....	44
MATERIALS AND METHODS	44
3.1 Description of the study area	44

3.1.2 Soil characteristics	45
3.2 Experimental design.....	46
3.3 Data collection	48
3.3.1 Rainfall data collection	48
3.3.2 Yield determination.....	48
3.3.3 Mineral N and plant N uptake.....	50
3.3.4 Soil water content.....	52
3.3.5 Soil carbon content.....	53
3.4 Data analyses.....	55
CHAPTER FOUR	56
RESULTS AND DISCUSSION	56
4.1 Rainfall amount and distribution.....	56
4.2 Effects of soil tillage, nitrogen application and mulching practices on grain and stover yields of maize	61
4.2.1 Grain and stover yields	61
4.3 The impact of soil tillage and mulch management on soil mineral N content.....	81
4.3.1 Soil mineral N concentrations during the LR2015 cropping season	81
4.3.2 Soil mineral N concentrations during the SR2015 cropping season.....	92
4.3.3 Nutrient use efficiency and apparent N recovery.....	103
4.4 Effects of soil tillage and mulching practices on soil water content ...	109
4.4.1 Effect of soil tillage and mulching practices on soil water content and crop evapotranspiration.....	109
4.5 Effects of soil tillage and mulch management combination on soil carbon content.....	123
4.5.1 Effects of soil tillage and soil surface treatment on soil carbon in soil aggregates.....	123
CHAPTER FIVE.....	138
CONCLUSIONS AND RECOMMENDATIONS.....	138
5.1 Conclusions.....	138
5.3 Recommendations	143
5.4 Suggestions for further research	144
REFERENCES	145

ABBREVIATIONS AND ACRONYMS

AASR	Africa Agriculture Status Report
ACCF	Africa Climate Change Fund
ACI	Africa Capacity Index
AGRA	Alliance for a Green Revolution in Africa
AR4D	Agricultural research for development
AU	African Union
BCR	Benefit-Cost Ratio
C	Carbon
CAADP	Comprehensive Africa Agriculture Development Programme
CIAT	International Centre for Tropical Agriculture
CIMMYT	International Maize and Wheat Improvement Centre
CSA	Climate Smart Agriculture
CT	Conventional tillage
DM	Dry matter
GNU	Grain nitrogen uptake
GY	Grain yield
LSD	Least significant difference
FAO	Food and Agriculture Organization of the United Nations
IAEA	International Atomic Energy Agency
ICRAF	World Agroforestry Centre
IPCC	Intergovernmental Panel on Climate Change
ISFM	Integrated Soil Fertility Management
KALRO	Kenya Agricultural and Livestock Research Institute (formerly KARI)
KARI	Kenya Agricultural Research Institute (now KALRO)
NUE	Nitrogen use efficiency
NB	Net benefit
Ndff	Nitrogen derived from fertilizer
Ndfs	Nitrogen derived from soil
Nfrs	Nitrogen fertilizer remained in the soil

NAE	Nitrogen agronomic efficiency
NRE	Nitrogen recovery efficiency
NPE	Nitrogen physiological efficiency
SOC	Soil organic carbon
TVC	Total variable cost

LIST OF TABLES

Table 3.1: Initial physical and chemical soil characteristics at Kirege site.....	45
Table 3.2: Experimental treatments and their combinations in Chuka	46
Table 4.1: Rainfall events characteristics during the study period.....	56
Table 4.2: Effects of tillage practices, mulch management and nitrogen fertilization on maize grain yields in Kirege, Meru South	62
Table 4.3: Effects of tillage practices, mulch management and nitrogen fertilization on maize stover yields in Kirege, Meru South	66
Table 4.4: Treatment effects of soil tillage, mulch management and nitrogen fertilization on water use efficiency for maize grain yield production in Kirege	78
Table 4.5: Seasonal treatment effects of soil tillage, mulch management and nitrogen fertilization on water use efficiency for maize biomass production in Kirege	79
Table 4.6: Seasonal distribution of mineral N (kg ha^{-1}) at 0-20 and 20-40 cm soil depths during LR2015 season in Kirege, Meru South District	82
Table 4.7: Seasonal distribution of mineral N (kg ha^{-1}) at 40-60 and 60-80 cm soil depths during LR2015 season in Kirege, Meru South District.....	82
Table 4.8: Seasonal distribution of mineral N (kg ha^{-1}) at 0-20 and 20-40 cm soil depths during SR2015 season in Kirege, Meru South District.....	94
Table 4.9: Seasonal distribution of mineral N (kg ha^{-1}) at 40-60 and 60-80 cm soil depths during SR2015 season in Kirege, Meru South District.....	95
Table 4.10: Relationship between maize grain yields and mineral N concentrations in two cropping seasons in Kirege	99
Table 4.11 Baseline soil carbon content (2012) and soil carbon changes in 2015 in soil micro-aggregates in different soil tillage, mulch management and nitrogen fertilization treatments in Kirege	124

Table 4.12 Baseline soil carbon content (2012) and soil carbon changes in 2015 in soil meso-aggregates in different soil tillage, mulch management and nitrogen fertilization treatments in Kirege	127
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Table 4.13 Baseline soil carbon content (2012) and soil carbon changes in 2015 in soil macro-aggregates in different soil tillage, mulch management and nitrogen fertilization treatments in Kirege	129
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LIST OF FIGURES

Figure 1.1: Conceptual framework for the study	11
Figure 3.1: Map showing the study area, Tharaka-Nithi County and the site, Kirege Primary School	44
Figure 4.1: Daily rainfall amounts for the short rains (SR) seasons in 2013, 2014 and 2015	57
Figure 4.2: Daily rainfall amounts for the long rains (LR) seasons in 2013, 2014 and 2015	58
Figure 4.3: Seasonal effects of soil tillage and mulch management on NO ₃ -N concentrations at (a) 0-20 cm and (b) 20-40 cm depths and at different times in the LR15 cropping season in Kirege	Error! Bookmark not defined.
Figure 4.4: Seasonal effects of soil tillage and mulch management on NO ₃ -N concentrations at (a) 40-60 cm and (b) 60-80 cm depths and at different times in the LR15 cropping season in Kirege	Error! Bookmark not defined.
Figure 4.5: Seasonal effects of soil tillage and mulch management on NO ₃ -N concentrations at (a) 0-20 and (b) 20-40 cm depths and at different times in the SR2015 cropping season in Kirege	Error! Bookmark not defined.
Figure 4.6: Seasonal effects of soil tillage and mulch management on NO ₃ -N concentrations at (a) 40-60 and (b) 60-80 cm depths and at different times in the SR2015 cropping season in Kirege	Error! Bookmark not defined.
Figure 4.7: Seasonal effects of soil tillage, mulch management and nitrogen fertilization on agronomic nitrogen use efficiency (aNUE) in (a) LR2013, SR2013 and LR2014 and (b) SR2014, LR2015 and SR2015 cropping seasons in Kirege	104
Figure 4.8: Effects of tillage and soil surface treatment on apparent N recovery during short rain 2015 season.....	107
Figure 4.9: Soil moisture changes under different tillage and soil surface treatment effects in (a) 0–30 cm (b) 30-50 cm and (c) 0-100 cm soil profile depths during long rains 2014 (LR2014) season in Kirege	111

Figure 4.10: Soil moisture changes under different tillage and soil surface treatment effects in (a) 0–30 cm (b) 30-50 cm and (c) 0-100 cm soil profile depths during short rains 2014 (SR2014) season in Kirege.....	112
Figure 4.11: Crop evapotranspiration under different tillage and soil surface treatment combination during LR2014, SR2014 and LR2015 cropping seasons in Kirege	117
.....	125
Figure 4.12: Effects of soil tillage, mulch management and nitrogen fertilization treatments on soil carbon changes in soil micro-aggregate class size in 0–80 cm soil profile depths between 2012 (baseline) and 2015 (end-term) in Kirege	125
Figure 4.13: Effects of soil tillage, mulch management and nitrogen fertilization treatments on soil carbon changes in soil meso-aggregate class size in 0–80 cm soil profile depths between 2012 (baseline) and 2015 (end-term) in Kirege.	128
.....	130
Figure 4.14: Effects of soil tillage, mulch management and nitrogen fertilization treatments on soil carbon changes in soil macro-aggregate class size in 0–80 cm soil profile depths between 2012 (baseline) and 2015 (end-term) in Kirege	130

ABSTRACT

High dependence on rain-fed agriculture, low and erratic rainfall, inadequate water and soil conservation techniques and declining soil fertility expose resource-poor farmers to low agricultural productivity in tropical regions. A study was conducted in 2012 at Kirege Primary School in Tharaka Nithi County to evaluate the effects of soil tillage, soil surface management and nitrogen fertilisation on rain-fed maize yields and properties of Humic Nitisols. Eight treatment combinations (T1M0N1, T1M0N0, T1M1N1, T1M1N0, T0M0N1, T0M0N0, T0M1N1 and T0M1N0) were laid out in randomised complete block design and replicated thrice. Data on grain and stover yields, mineral N, soil water content and soil organic carbon content were collected over six cropping seasons. Physical fractions of soil organic matter were evaluated down to 0-80 cm depths. T1M1N1 and T1M0N1 treatment combinations significantly had the highest maize yields in three out of six seasons (SR2013, LR2014 and SR2014), ranging from a low of 1.9 Mg ha⁻¹ in SR2013 to a high of 4.9 Mg ha⁻¹ in LR2015. T1M1N1 combination was superior for stover yields in four out of six seasons, ranging from a low of 2.7 Mg ha⁻¹ in SR2013 to a high of 7.9 Mg ha⁻¹ in LR2015. T0M0N1 combination had highest water use efficiency for biomass production (WUEB), with the highest water use efficiencies noted in LR2014 at 13.3 kg ha⁻¹ mm⁻¹ and short rains 2014 at 9.6 kg ha⁻¹ mm⁻¹. Significantly higher WUE_{GY} of 9.6 kg ha⁻¹ mm⁻¹ were recorded in T0M0N1 in short rains 2014 and 3.4 kg ha⁻¹ mm⁻¹ in T1M0N1 in long rains 2015. Generally, the NO₃-N concentrations in all treatments decreased with increase in soil depth from 0-20 and 20-40, after which the concentrations increased from 40-60 and 60-80 cm depths. There were significant differences in the amount and distribution of soil nitrate-N at the depths of 60-80 cm at 10 WAP, with higher net N mineralisation in minimum tillage treatments than in conventional tillage treatments. The highest soil water content in the study conserved in the minimum tillage with mulch retained at 0 kg of N fertiliser while minimum tillage treatments had higher crop evapotranspiration. Overall, soil carbon content decreased with increase in soil depth. In all the three class size aggregates, the highest increases in soil carbon were noted in the 0-20 cm depths, with the highest overall increases in both soil meso-aggregates and macro-aggregates between 2012 and 2015 observed in T1M1N1 combination. There was enhanced soil carbon in the 0-20 cm depth in all the three aggregate fractions in treatments with conventional tillage combinations, with increases of 3.5 t C ha⁻¹ in micro-aggregates, 2.2 t C ha⁻¹ in meso-aggregates and 3.7 t C ha⁻¹ in macro-aggregates. While more rains fall during the SR seasons, the LR seasons were found to be more important, with higher grain and stover yields in SR than LR. Retention of mulch on-farm was found to be crucial for soil water conservation at soil depths below 50 cm and enhancing mineralisation of nitrogen, showing a clear potential for seasonal water buffering. This underscores the possibility of adapting to erratic climate regimes. This research has confirmed the importance of conventional tillage practices in ensuring better maize yields for farmers and promoting soil C content in smallholder maize-based farming systems conducted in Humic Nitisols and that in the long-term the formation of stable micro-aggregates in smallholder farms can be useful carbon sinks.

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Over 80% of the agriculture in sub-Saharan Africa (SSA) is under rain-fed agriculture, of which the bulk is under smallholder farming (Rockstrom, 2003). SSA is the only remaining region in the world where per capita food production has either remained constant over the last four decades or even declined (ICRAF, 2014), with the average maize production of 1 ton per ha representing about 30% of the true potential (AGRA, 2016). Agricultural systems in the region are diverse, vast and are characterized by unreliable rainfall, droughts and dry spells occasioned by climate variability. Low soil fertility is increasingly recognized as a fundamental biophysical cause for declining food security among smallholder farming households in sub-Saharan Africa (SSA) (Sanchez, 2002). In Kenya, maize production has decreased by about 14% over the last decade, with a widening gap between production and consumption (Olwande, 2012).

The high dependence on rain-fed agriculture, combined low water availability caused by low, erratic and unreliable rainfall and inadequate water and soil conservation techniques, and scarcity of knowledge on effectiveness of easily accessible soil and water conservation practices (Jaetzold *et al.*, 2006; Johansen *et al.*, 2012; Ngetich *et al.*, 2014; Nezomba *et al.*, 2015; Sime *et al.*, 2015) forms the basis of the exposure of the resource-poor farmers to low and declining agricultural productivity. Continued soil and water resources degradation, making

them unsuitable for agricultural production, is of great concern hence cropping systems need to be adapted in line with these emerging challenges. To counter such a scenario, Govaerts *et al.* (2005) proposed adoption of cropping systems that can preserve natural resources, have higher and stable yields and at the same time are more robust against drought and more profitable for the farmer. One of the critical components of such a cropping system is appropriate tillage system and suitable use of crop residues as mulch.

Tillage influences soil natural phenomena and ecological processes leading to a remarkable change in soil properties. In practice, tillage has been extensively adopted for its multiple functions, including change of soil properties, such as bulk density, penetration resistance and aggregate stability (Guan *et al.*, 2014). It influences both biotic and abiotic processes, modifying structural properties such as cracks, aggregates, and pore continuity, as well as affecting soil aeration, temperature and moisture levels (Huwe, 2003; Guan *et al.*, 2014). Choice of an appropriate tillage method is critical in agricultural production.

Management of soil through conventional tillage changes soil water storage, evaporation losses and soil susceptibility to runoff generation (Ngetich *et al.*, 2014). Although the critical advantage of weed control in conventional tillage is well noted, it has been established that it deprives soils of adequate water holding capacity, deteriorates soil structure and stability, can cause soil compaction and affect soil microbial life (Lal, 2004; Marcela, 2009; Ketema and Yimer, 2014).

Conventional tillage also leads to low soil carbon because of low levels of plant residue, increased soil erosion and reduced organic matter input to the soil system (Marcela, 2009; Ketema and Yimer, 2014). Low soil organic matter content is associated with low water holding capacity of soil hence low soil water availability for plant uptake.

Minimum tillage minimizes soil disturbance save for the planting spot while crop mulch retention involves leaving at least 30% of residues in situ (Ngoma *et al.*, 2015). Minimum tillage is widely reported to reduce soil erosion, enhance infiltration, improve soil organic stocks and enhance soil quality in various crops and environments, while minimizing risks of soil degradation under rain-fed conditions (Vlek and Tamene, 2010; Prasad *et al.*, 2016). It is also reported to improve the soil's physical properties and water storage, increases infiltration rates, reduces erosion and lead to increased soil organic matter (Dalal, 1989; Bradford and Huang, 1994; Hao *et al.*, 2000). Despite the highly publicized benefits of minimum tillage, in Kenya, there is limited empirical evidence on its effect on maize yields and water use efficiency under typical smallholder farmer conditions.

Mulching the soil surface with a layer of plant residue is an effective method of conserving water and soil because it reduces surface runoff, increases infiltration of water into the soil and retards soil erosion (Adekalu *et al.*, 2007). Mulching is considered highly beneficial in the tropics with high rainfall intensity especially

on the sloping ground because it reduces runoff and soil loss (Adekalu *et al.*, 2007). For instance, Bezborodov *et al.* (2010) observed an increased water use efficiency of 1.55 to 1.84 kg m⁻³ in maize while Deng *et al.* (2006) reported an improved water-use efficiency of 10 to 20%.

Nitrogen (N) is often the most limiting nutrient in agricultural systems; thus, supplying the soil with N for crop production is imperative to achieve maximum yields (Watts *et al.*, 2017). Hence, application of inorganic nitrogen fertilizers is obligatory for efficient and profitable smallholder agricultural production (Campiglia *et al.*, 2014). Different soil management practices, including tillage, have different effects on N dynamics. Nitrogen use efficiency (NUE) is estimated at 30 to 50% in most agricultural soils leaving the excess (50 to 70%) subjected to runoff, leaching, and volatilization (Watts *et al.*, 2017).

Tillage affects N dynamics in the soil through the effect on soil structure, aeration, soil organic matter degradation and crop residue mineralization (Karlen *et al.*, 1998; Wienhold *et al.*, 1999; Keshavarz Afshar *et al.*, 2016). The amount of rhizo-deposited C can influence soil microbial activities, soil N transformation, such as mineralization–immobilization, and plant uptake of soil released N (Jackson *et al.*, 2008; Richardson *et al.*, 2009; Fang *et al.*, 2016). Hence, tillage method can affect crop response to N fertilizer applied in crop production. For instance, Masvaya *et al.* (2017) observed that mineralization, N uptake, and crop yields were stimulated under plow (conventional) tillage compared with the ripper (reduced) tillage.

Generally, the crop's response to N depends significantly on moisture availability, and since tillage affects soil moisture, it is expected to influence crop's response to N as well (Keshavarz Afshar *et al.*, 2016). The potential benefits of the tillage, mulch application and fertility amendment application on crop productivity and soil N dynamics are related to the management intensity (Masvaya *et al.*, 2017). Few studies have examined the combined effects of different tillage systems and N fertilizer (Watts *et al.*, 2017) on crop productivity.

The sustainability of any crop production system is dependent not only on appropriate tillage system but also supplying adequate amounts of N for uptake (Fang *et al.*, 2016). Although several studies have shown that minimum tillage can improve soil physical properties and increase agricultural production (K'Owino, 2010; Allam *et al.*, 2014), there is limited information on the effects of minimum tillage and mulching practices on water use efficiency and crop yields in Humic Nitisols under a rain-fed farming system. Furthermore, the impact of nitrogen integration with tillage on crop production and soil N dynamics under tropical farming systems is not well understood.

To unravel ways of improving crop productivity of rain-fed crops under limited resource endowment conditions, like the ones experienced by smallholder rain-fed dependent farmers, understanding the combined effects of tillage methods and N fertilizer is imperative. Thus, there is a need not only to understand how N fertilizer

under conventional and conservation tillage influence maize performance and selected physicochemical properties of Humic Nitisols.

1.2. Problem statement

Continued degradation of soil resources exposes smallholder farmers in Kenya to low and declining agricultural productivity. To reverse soil degradation and improve farm productivity and resilience there is need to understand the combined effects of tillage methods and mulching and their effects on crop yields, soil water dynamics and soil organic carbon dynamics under the smallholder maize farming system. Smallholder farmers need to adopt cropping systems that can conserve natural resources, withstand climatic shocks and ensure better yields. Although several studies (Bandyopadhyay, 2009; K'Owino, 2010; Alam *et al.*, 2014) have shown that conservation tillage can improve soil physical properties and increase agricultural production, there is limited information on the effects of minimum tillage and mulching practices on crop yields and soil properties in Humic Nitisols of rain-fed farming system of the Central Highlands of Kenya. This research sought to evaluate the impact of soil tillage and mulching practices on overall soil quality and farm yields, and determine the appropriate farmland management practices for smallholder farmers growing maize in the Central Highlands of Kenya.

1.3 Research Questions

The study sought to answer the following research questions:

- i. How do the combined effects of soil tillage, nitrogen fertilizer application, and mulching affect crop yields?
- ii. How does minimum tillage, mulching, and nitrogen fertilizer management affect soil mineral N?
- iii. To what extent do soil tillage and mulch management affect soil water content?
- iv. How do soil tillage and mulch management affect soil carbon content?

1.4 Objectives

The overall objective of the study was to evaluate the effects of soil tillage, mulching and nitrogen fertilizer application on maize yields and selected soil properties in Tharaka-Nithi County. To achieve this, the specific objectives were:

- i. To determine the effects of soil tillage, N application and mulching practices on yields of maize
- ii. To assess the impacts of soil tillage and mulching practices on soil mineral N content
- iii. To investigate the effects of soil tillage and mulching practices on soil water content
- iv. To evaluate the effects of soil tillage and mulching practices on soil carbon content

1.5 Hypotheses

The following hypotheses guided the research:

- i. Soil tillage, N application, and mulching significantly increase crop yields
- ii. Minimum tillage, mulching, and nitrogen fertilizer management increase soil mineral N

- iii. Minimum tillage and mulching significantly increase soil moisture availability
- iv. Minimum tillage and mulching significantly increase soil carbon content

1.6 Significance of the study

The study contributes to scientific knowledge on quantitative evaluation of the influence of minimum tillage and mulching on crop performance and soil water and carbon dynamics in the sub-humid conditions of Central Highlands of Kenya. The findings of the study on maize grain yields and efficient use of water resources can help smallholder farmers who are in need of guidance on best-bet farmland management practices, and who potentially stand to gain from suggestions on doubling their yields and incomes. Extension workers can also use the findings of the study at the Ministry of Agriculture areas similar to where the study was conducted to address the increasing national grain yield gap for the staple maize cropping system.

Farmers too stand to benefit from the possibilities of greater incomes through reducing wastage, mainly through the increased competitive use of soil cover material, such as maize stover, for livestock. The findings contribute to the overall enhancement of agricultural production systems in Kenya through quantitative evaluation of the influence of tillage and mulching on resource use efficiency, crop growth, and yields.

1.6 Justification of the study

The study focused on the maize cropping system and possibilities of enhancing its production in the Central Highlands of Kenya. Since the early 20th century, maize has been the main staple crop of Kenya. It is Kenya's most important crop, with more than 2.1 million ha of Kenya's crop-harvested area occupied by maize (DTMA, 2015). Maize, therefore, accounts for 40% of all crop area in Kenya, and its production is a national priority (DTMA, 2015).

At the household and food markets' levels, maize is Kenya's single most important tradeable food commodity. Kenya's per capita maize consumption is estimated at 103 kg/person/year, compared to 73 kg for Tanzania, 52 kg for Ethiopia, and 31 kg for Uganda (DTMA, 2015): this shows the importance attached to maize production. However, in spite of its vast importance for food security and economic well-being of the country, the productivity and production have not shown significant improvements over the years.

The Central Highlands of Kenya is one of the most crucial breadbasket areas producing maize. However, there is evidence showing that maize production is reducing: for instance, the proportion of cropped land allocated to maize production has fallen from 41% in 1997 to 35% in 2007 (Kibaara *et al.*, 2008). There is a need to incorporate agricultural intensification in smallholder maize farming systems in the region.

1.8 Conceptual framework

The reversing of soil fertility decline should be central to modernizing agriculture in the Central Highlands of Kenya. A holistic approach is needed to improve soil fertility and increase food production. Such an approach would include integrated soil nutrient replenishment strategies that coincide with better soil and water conservation.

Figure 1.1 illustrates the linkages between sustainable agricultural growth, intensification, and development (best expressed in sustained farm productivity, better environmental quality and improved incomes from agriculture by smallholder farming systems) on one hand and adoption of low-cost, yield-enhancing farm-level agricultural practices on the other side. It hinges on the opportunity to learn, in which this study has assessed data from the trial site and answers fundamental biophysical questions on agricultural growth by focusing on mulch management and appropriate soil tillage practices (Figure 1.1).

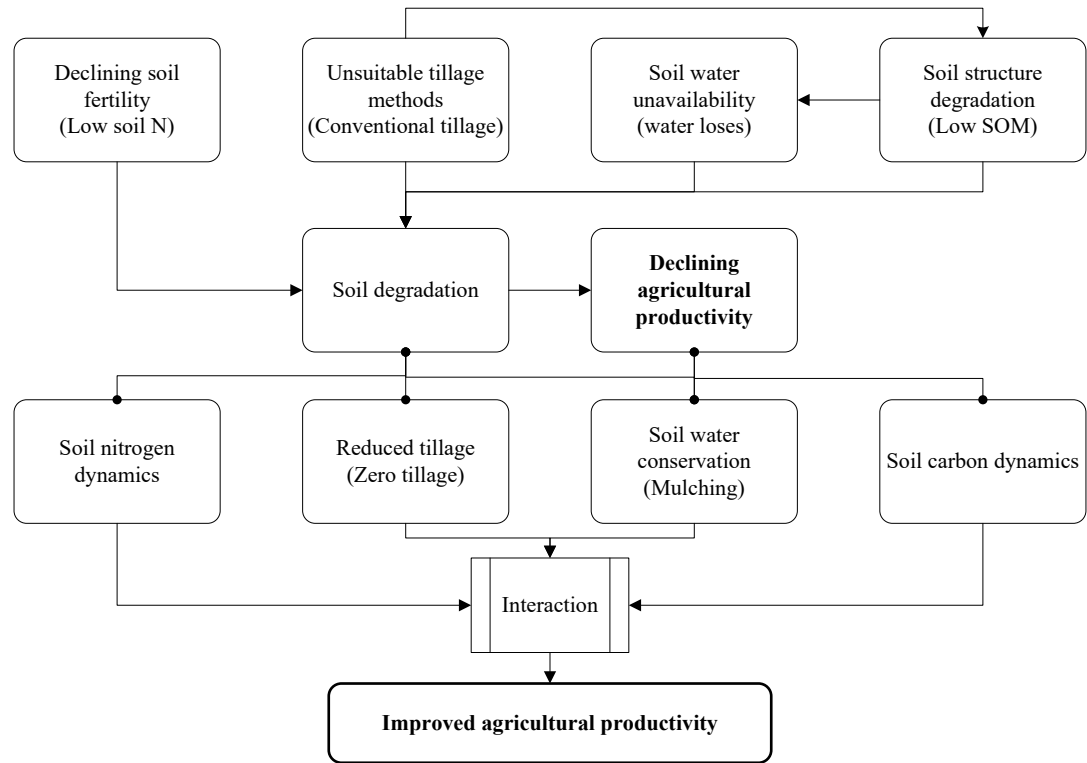


Figure 1.1: Conceptual framework for the study

Tillage practices and mulch management regimes play an essential role in the dynamic processes governing soil fertility. It is possible, with adequately designed tillage and mulch management practices, to alleviate soil-related constraints in achieving potential maize productivity while maintaining and improving soil quality. However, improperly designed tillage and mulch management practices can set in motion a wide range of degradative processes like accelerated erosion, depletion of soil organic matter and fertility, deterioration in soil structure, and disruption in cycles of water, carbon, nitrogen and other major nutrients, thus aggravating agricultural production in Kenya.

1.9 Definition of key terms

Mulching: This is a layer of maize stover material applied to the surface area of soil to conserve moisture, improve soil health and reduce the growth of weed. In this study, maize stover was applied at the rate of 1 ton per ha.

Agronomic nitrogen use efficiency: This is a measure of crop production per unit of nitrogen fertilizer input and indicates the ratio between the amount of fertilizer N removed from the field by the crop and the amount of fertilizer N applied.

Water use efficiency: This refers to the efficient use of water in plant metabolism: it is a quantitative measurement of how much biomass or yield is produced over a growing season, normalized with the amount of water used in the process.

Minimum tillage: This is the practice of minimizing soil disturbance and allowing crop residue or stubble to remain on the ground instead of being thrown away or incorporated into the soil.

Conventional tillage: A tillage system using cultivation as the major means of seedbed preparation and weed control. Context: Typically includes a sequence of soil tillage, such as plowing and harrowing, to produce a fine seedbed, and also the removal of most of the plant residue from the previous crop.

Diviner 2000: Designed for measuring soil water content over multiple depths at 10 cm intervals, this hand-held tool makes use of capacitance (or dielectric) sensors to measure the dielectric permittivity of soils. The output of the sensor is the frequency response of the soil's capacitance due to its soil moisture level. It is a portable and robust device that consists of a probe and a hand-held data logging display unit, allowing the user to make onsite management decisions.

CHAPTER TWO

LITERATURE REVIEW

2.1 General overview

Soil nutrient mining is a direct result of the continued overexploitation of agricultural land and is traceable to the consumption of critical components of the soil's natural capital (Deryng, 2014). The inclination for nutrient mining of Africa's agricultural land and the severity of its consequences are the highest in the world (Henao and Baanante, 2006). Soil nutrient mining is usually connected with low agricultural land productivity under severe limitations of poverty regarding physical capital (infrastructure) and human capital (especially education) (Beddington *et al.*, 2012).

Continued nutrient mining of soils would mean a future of even higher levels of poverty, food insecurity, environmental damage, and social and political instability (Ehrlich and Ehrlich, 2013). It, therefore, follows that soils must be managed to improve their overall quality and contribute to better returns on agriculture (Giller *et al.*, 2009). It is in this context that smallholder farmers' knowledge of, and acquaintance with, specific crop responses to tillage and surface crop residues as affected by soils quality, climate parameters, and inorganic nitrogen fertilization is necessary for the selection of appropriate tillage and crop mulch management strategies for improved crop production (Rusinamhodzi *et al.*, 2011).

Over the years and centuries in Kenya, as is the case in the broader African continent, soils have been slowly but continuously degraded by removal of nutrients in harvest products, by intensive grazing and by the disruptive effects of unabated soil erosion (AGRA, 2016). Adverse climatic conditions of variable and frequently inadequate rainfall and sometimes long dry seasons characteristic to the Kenyan climate render the country's agricultural soils' landscape vulnerable to over-exploitation and further degradation (Ngetich *et al.*, 2014). Noteworthy also is the limited use of fertilizers because of poor accessibility, lack of availability and lack of affordability. With no significant fertilizer subsidy system, smallholder farmers in Africa typically use less than 10 kg ha⁻¹ of fertilizers per year (Jama *et al.*, 2016).

At the same time as the ongoing deterioration of overall soil quality, it is becoming more and more apparent that there is need to ratchet up global food production in order to feed a growing population that is mostly expanding in cities of the developing world (Beddington *et al.*, 2012). However, increasing continental Africa food production throughout the 21st century is a significant challenge for countries such as Kenya, which is at the precipice of an environmental collapse on account of increasing climate change orchestrated in part by inappropriate agricultural land use practices (Beddington, 2009; Ehrlich and Ehrlich, 2013).

Over the last two decades, agricultural production has intensified in Kenya, especially in as far as the increase with continuous maize cropping (instead of

fallow): this has been accompanied by a slight increase in the application of mineral fertilizers (AGRA, 2016). To mitigate the negative impact of such intensification, various management practices should be considered by smallholder farmers, such as rotations as an alternative to mono-cropping, minimum tillage (MT) instead of conventional tillage (CT), mulch retention on-farm or the adoption of integrated soil fertility management (ISFM) options (Allam *et al.*, 2014; Plaza *et al.*, 2013).

This is in line with ongoing shifts from conventional production systems globally: more farmers in Australia, Canada, the USA, and Latin America are now adopting conservation agriculture (CA) systems, embracing minimum tillage for minimal soil disturbance, surface mulch retention and crop rotation (Vermeulen *et al.*, 2012). This development has been driven by labour savings, control of soil erosion, better soil moisture conservation and the opportunity for better yields and enhanced soil quality (Godfray and Garnett, 2014).

In addition to soil conservation, conservation agriculture systems in the majority of cases have been shown to increase the amount of soil organic matter, which improves soil quality and the environmental sustainability of agro-ecosystems (Wheeler and Braun, 2013). The build-up of SOM involves sequestration of carbon, which may contribute to the mitigation of increasing atmospheric CO₂ levels (Foley *et al.*, 2011).

2.2 Soil tillage and impact on maize crop performance

Soil tillage is thought to be as old as settled agriculture (Badalikova, 2016) and is, by that fact, an integral part of conventional agriculture systems. The precise reasons for tilling a soil include amalgamation of soil amendments, management of weeds, crop residues and agrochemicals such as pesticides, as well as the critical and necessary adjustment and modification of soil physical properties, in the process enhancing soil conditions for crop establishment, growth and yield (Gornal *et al.*, 2010).

Soil tillage operations are executed in order to pulverize and break up the soil and to enable the movement of air and water to promote crop growth and development (Alvarez and Steinbach, 2009). The success or otherwise of crop production systems, amongst other factors, largely depends on tillage and the consequent seedbed setting (*ibid*). Generally, tillage enhances soil bulk density, water retention capacity and resistance to soil penetration (Gustafson *et al.*, 2014).

A comprehensive, exhaustive understanding of tillage effects on soil physical properties is indispensable for successful crop production (Angers and Eriksen-Hamel, 2008). Because of the fact that soil physical properties are essential for plant growth and development, it therefore follows that the effects and influences of tillage practices on yields, soil moisture content, and soil organic carbon sequestration are important soil physical properties that need constant evaluation, especially in the light of changing climates (Gourdji *et al.*, 2013).

Therefore, more intensely than ever before, there is now a renewed focus on understanding and characterising the effects of tillage on soil degradation and thus smallholder agricultural sustainability (AGRA, 2015). There are a variety of tillage systems that can be deployed by smallholder farmers in Africa and beyond, and each of them has advantages and disadvantages that must be considered before decisions are made on their possible use. The two main categories of tillage systems are, as they are generally known, conventional and minimum tillage (Haasnot *et al.*, 2013).

Conventional tillage, which is the more common of the two broad tillage categories, especially in Africa, is often described as mouldboard plowing followed by disking one or more times to obtain a loose, friable seedbed environment (Folberth *et al.*, 2012). The rigorous, intensive operations involved in this tillage system not only kills weeds challenging and competing with crops for water and soil nutrients, but also amends and controls the movement of water and air within the soil, which ends up improving organic matter decomposition and therefore activates the release of essential nutrients like nitrogen for crop growth (Knorr *et al.*, 2005).

Tillage has of late been increasingly tied with the debate of climate change, with the release of nutrients from organic matter overlapping with the emission of greenhouse gases like CO₂ into the atmosphere (Field *et al.*, 2014). It has been

reported in a number of studies that such intensive tillage operations (as characterized by conventional tillage systems, for instance) also adversely affect soil structure and hasten the excessive breakdown of aggregates, in the process leading to loss of soil fertility through erosion (Mahboubi *et al.*, 1993; Rockstrom *et al.*, 2009; Field *et al.*, 2012; Wheeler and von Braun, 2013) and therefore affecting overall productivity.

Minimum tillage is sometimes identified and synonymous with conservation tillage (Six *et al.*, 2000), which implies the storage and retention of more than 30% of the crop residues on the soil surface. These and other attributes of this tillage system has led to researchers (such as Fleisher *et al.*, 2011) averring that minimum tillage was developed to ease and reduce soil-related limitations for crop production and meet the need for the conservation of soil, water, and energy resources.

The conception of minimum tillage, which, in effect, is an amalgamation of primordial and contemporary agricultural practices, was first announced globally as a land use system in farmlands in the late 1940s and early 1950s when tillage was replaced by herbicides in pasture renewal (Haasnot *et al.*, 2013). This land use and evolution is sometimes related with the invention of the herbicide and later herbicides (Derpsch *et al.*, 2008). During the same period, a similar concept was suggested for maize following sod with the accent on mulching to guarantee soil and water conservation (Garnett *et al.*, 2013). Thereafter, maize was planted in a

minimum tillage setting by removing plugs of soil with a sampling tube, dropping in a seed, and substituting the soil removed by the sampler: to the surprise of the research team, the maize thrived and grew well (Folberth *et al.*, 2012).

Subsequently, in the next few decades, there was a rush, especially in the developed world, as farmers swiftly adopted minimum tillage systems for crop production all over the world: today, over 50% of the farmers in the United States of America practice minimum tillage (Deryng *et al.*, 2014). On the other hand, many commercial farmers in Africa have also abandoned conventional tillage in favour of minimum tillage (Gidens, 2009). Despite the aforementioned adoption of minimum tillage in many other parts of the world, however, the adoption of minimum tillage amongst smallholder farmers in sub-Saharan Africa has been very limited (AGRA, 2013), despite the evidence (Godfray and Garnett, 2014) that minimum tillage can be productively and successfully used for tropical agriculture, too.

Minimum tillage-based farming systems have been shown to have several comparative advantages over conventional tillage (Phalan *et al.*, 2014). Some of these advantages and propositions have been discussed by researchers (including Rashidi and Keshavarpur, 2008; Alvarez and Steinbach, 2009) and include the specter of reduced soil erosion by wind and water, as well as the ability to grow crops on sloping land. It has also been pointed out that minimum tillage systems also increase output, efficiency, and productivity of farm workers, while at the

same time improving the timing of planting and harvesting: this is achieved through the more efficient use of soil water and lesser requirements for machinery (Horlings and Marsden, 2011). Other advantages cited also include reduced soil compaction (Badalikova, 2016).

In the tropics, the value proposition and recompenses mentioned for minimum tillage include a progressive and incremental increase in soil organic matter, resulting not only in a higher CEC but also higher P and N levels (Hertel *et al.*, 2010). In addition to this, it has been stated that minimum tillage systems promoted soil structure and significantly improve their soil water holding capacity which contributes in no small way to lessening and reducing soil erosion and dropping the daily maximum temperatures at the soil surface to levels more favorable for plant growth and development (Keys and McConnell, 2005). With regards to crop yields and the all-important issue of productivity, studies have shown that yields minimum tillage have generally been found equal to, or in some instances even higher, than those under conventional tillage systems (Ribaut and Ragot, 2007; Reynolds and Tuberosa, 2008; Rockstrom *et al.*, 2009; Reynolds and Ortiz, 2010).

Despite the aforementioned benefits of adopting minimum tillage farming land use practices, some drawbacks are frequently associated with this system (Beddington *et al.*, 2012). These shortcomings include the need for better management skills among smallholder farmers due to a higher incidence of insects and diseases which

require higher skills on the use of pesticides, which is a put-off for broader scale adoption by smallholder farmers in Africa (Deryng *et al.*, 2014).

Other shortcomings are lower soil temperature in cool months in the highland regions resulting in rescheduling planting in some areas, and higher levels of NO₃ leaching from the root zone (Rockstrom *et al.*, 2009; Deryng *et al.*, 2014). However, the obtaining lower soil temperatures as a result of minimum tillage adoption can be beneficial in the tropics, because the soil temperature is habitually above the optimum required for maximum plant growth (Boucher *et al.*, 2004). Researchers such as Godfray and Garnett (2014) opine that the advantages of the minimum tillage system far outweigh the disadvantages.

In an eight-year research experiment of Sharma *et al.* (2005) found conventional tillage was superior to reduced tillage for crop yields. Ghuman and Sur (2001) found that maize and wheat yield in minimum tillage treatment remained lower than conventional tillage throughout a five year study period. Chen *et al.* (2011) also concluded that maize yields tend to be lower for minimum tillage relative to conventional tillage in cool, humid climate. Low maize grain and stover yields under minimum tillage could have been as a result of poor root development as suggested by Busari and Salako (2013). Better crop growth and yield under conventional tillage as compared to minimum tillage have been reported earlier (Sangakkara, 2007).

2.3 Impact of conventional and minimum tillage systems on soils

The two most conspicuous features of minimum tillage compared with conventional tillage are the retention of crop residues on the soil surface and the reduced mechanical manipulation and mixing of the soil (Sainju *et al.*, 2008). The degree and extent of changes brought about by minimum tillage are mainly determined by the amount of crop residue produced and retained annually, the degree of reduction in tillage, and the length of time that the system is practiced (Six *et al.*, 1999).

Minimum tillage systems, which maintain high surface soil coverage, have occasioned the evolution of significant changes in soil physical properties, especially in the plow layer (Decker *et al.*, 2009). Soil properties that were altered include water holding capacity, bulk density, mechanical strength, structure, porosity, and temperature (Lambin and Geist, 2006). The conservation and more efficient use of soil moisture is one of the chief advantages of minimum tillage crop production systems in maize growing ecosystems (Lambin and Meyfroidt, 2011).

In such ecosystems, the mulch that develops over time is invaluable for its impact on water infiltration and the resulting higher soil water content (Sainju and Singh, 2008). The additional water conserved could carry crops through short drought periods without severe water stresses developing in the plants (Omonode *et al.*, 2006). Nevertheless, the extra water conserved can occasionally be detrimental

under conditions in which excessive amounts contribute to denitrification losses (Lambin and Meyfroidt, 2011).

Leakey *et al.* (2009) and Mahboub *et al.* (2010) found higher rates of water infiltration in soils under minimum tillage than in soils tilled under conventional tillage systems. Besides, Leakey *et al.* (2009) also reported noting higher soil water contents under minimum tilled maize than under conventionally tilled maize throughout the growing season. However, Lal (1999) indicated that minimum tilled plots in comparison with conventionally tilled plots had higher soil water contents to 10 cm depth especially during drought stress periods. During these periods the plants on the conventionally tilled plots showed more severe leaf curling than those on the minimum-tilled plots. On the other hand, Li *et al.* (2009) stated that conventional tillage reduces heat conduction and breaks capillary connections in the soil. As a result, the tilled layer dries quickly, but the subsoil water can be conserved better as with minimum tillage.

Water evaporation at the surface was residue as a result of crop mulch retained at the soil surface with minimum tillage, impacting positively on the greater ability of the soil to store water and therefore increases the water available for plant use. Thus, Licker *et al.* (2010) observed on their part a scenario of lower evaporation and transpiration losses from minimum tilled plots than from conventionally tilled plots. Basing their work on African geographies, Lobell *et al.* (2011) reported that minimum tillage in comparison with conventional tillage resulted in higher

volumetric soil water contents to 60 cm depth during most of the maize growing season. The greatest differences occurred in the upper 20 cm of the low layer (Lobell *et al.*, 2011). Beyond a depth of 30 cm, most researchers reported that tillage systems had little influence on soil water contents during the growing season (Decker *et al.*, 2009).

In the tropics, during the seedling stage of crop growth, often high soil temperatures are encountered, especially when the soil surface is unprotected by mulch retention (Liu and Young, 2010). It is therefore essential to note that the use and adoption of crop residues as mulch on the soil surface will act to minimize these critical problems (Blanco-Canqui and Lal, 2007; Guzman, 2013). It is therefore generally agreed that crop residues retained on the soil surface as a result of minimum tillage reflect sunlight and give insulation to the soil, reducing heat movement into and from the soil and thereby limiting soil temperatures and associated evaporation losses of water (Blanco-Canqui and Lal, 2007). On their part, Johnson and Lowery (2005) showed that the surface mulch associated with minimum tillage not only lowers soil temperature but also results in less fluctuation of soil temperature during the growing season when conventional tillage serves as a reference.

In a tropical setting, very high temperatures often negatively impact on biological activity in the soil. Crop residues on the soil surface can effectively counteract and neutralize this phenomenon. For example, Guzman and Al-Kaisi (2011) reported

that as little as 2 t ha⁻¹ of residues on the surface reduced soil temperature at 5 cm depth by as much as 8°C. However, in temperate environments when soils are warming, the soil temperature at 10 cm depth decreased with 0.15 to 0.30° C for each 1 t ha⁻¹ application of crop residues to the soil surface (Giller *et al.*, 2009). Therefore, in a tropical climate, surface mulching may reduce soil temperature to a level more optimal for growth and activity of plants and micro-organisms, while when soils are warming in temperate climates, the lower temperatures associated with mulching often reduce biological activity.

2.4 Mulch management in soils

Minimum tillage typically coincides with another critical farming land use and surface treatment practice: the retention of crop residues on the soil surface (Hertel *et al.*, 2010). These residues, of especially cereal grain crops, are often viewed as a lower quality farm resource (Giddens, 2009). However, in the tropics where farm residues are some of the most abundant resources, this farming system can play a significant role in improving the sustainability of cropping (Verhulst *et al.*, 2009).

Crop residues have many functions. When left in the farms after harvesting of grain is complete, crop residues play a substantial role in nutrient cycling, soil and water conservation, maintenance of favorable soil properties, and enhance subsequent crop yields (Chen *et al.*, 2011; Dos Reis *et al.*, 2014). In addition to the foregoing, benefits of retaining crop residues on the soil surface in the farm include an emphatic increase in the levels of organic matter and nutrients, as well as moderation of soil and subsoil temperature and enhanced levels of biological

activity in the soil, all of which are important for sustaining crop production (Licker *et al.*, 2010).

Mulch retention and the crop residues so retained are also used for other purposes, including the provision of important livestock feeds during prolonged dry seasons, fuel and even construction material (Derpsch, 2004). Crop residues are also an essential component of the soil organic carbon (SOC) budget and are critical to the development of soil quality indices in various parts of the world (Guzman, 2013).

Mulching is a traditional practice in African smallholder cultivation systems and aimed at controlling soil temperature and heat scorching (FAO, 2013). Besides, mulching maintains a good soil physical condition by conserving soil moisture and enhancing water infiltration and stabilizing soil structure (Joos and Spahni, 2008). Mulching improves biotic activity and adds nutrients to soil thereby improving soil fertility. Mulching was found to increase the yield of crops such as yam, maize (Falade and Ojeniyi, 1997), and tomato (Agele *et al.*, 1999). The type of residue mulching determines its impact on soil physical and chemical properties and crop yields, and this is due to a difference in the biochemical quality of plant mulch material (Hertel *et al.*, 2010).

Use of crop residues as a soil amendment practice is often limited due to the impediment that mulch retention has on essential activities. Such impediment includes mechanical and hand tillage, as well as the adverse effects on crop

productivity associated with incidences and carryover of pests (Rasool *et al.*, 2008), diseases (Tewabeche *et al.*, 2002), and allelopathy and short-term nutrient deficiency (Vleck *et al.*, 2011). On account of these and other reasons cited by smallholder farmers, much of the crop residues are either fed to livestock or burnt on the farm (AGRA, 2016).

When all crop residues are used as livestock feed or removed for other reasons, the above-mentioned soil related benefits are therefore lost (Verhulst *et al.*, 2009). As a result, sustaining soil productivity becomes more problematic and challenging. It is worth noting that the extent and magnitude of the useful effects associated with retaining crop residues on farms depend on the quantity and quality of the residue retained. It also depends on the subsequent crop to be grown on the same field, obtaining edaphic factors at that given time, the topography of the land, the associated climate and soil management regimes in place (Guzman, 2013). Generally speaking, the mulch retention benefits usually increase with increasing amounts of residues available, although it is worth pointing out that even seemingly small amounts of crop mulch retained can provide some benefits for the smallholder farmer (Lambin and Geist, 2006).

Crop residues can act both as a source and sink for essential crop nutrients (Bremer *et al.*, 2001; Ambus and Jensen, 2001). The capacity and ability of crop residues to serve as source and sink of plant nutrients for crop production depend to a large degree on climatic circumstances, soil properties, crop characteristics and the kind

of tillage practices deployed (Lankoski *et al.*, 2004). A deep and proper understanding of the decomposition of crop residues and the fate of the released nutrients is, therefore, essential (Deryng *et al.*, 2014).

Crop residues contain reasonable quantities of plant nutrients and can if appropriately managed and returned to the soil from which it was grown, serve and aid as an efficient and effective means of maintaining the soil organic matter and nutrient levels in soil (Guzman, 2013). It has been noted that recycling of crop residues in the fields is especially important and critical in developing countries, including Kenya because the amount of the nutrients in crop residues are seven to eight times higher than the quantity of nutrients applied as fertilizers (AGRA, 2013).

Also, crop residues are a source of trace elements which are typically absent in many commercial NPK fertilizers (Morris *et al.*, 2007). Finally, it is well known that both organic and inorganic materials each have complementary roles, and their simultaneous deployment, adaptation, and use by farmers will ensure better crop yields (Graham *et al.*, 2007). Proper usage of crop residues by smallholder farmers can, therefore, result in less importation of the typical chemical fertilizers, which results in considerable savings with regards to the scarce foreign exchange for countries such as Kenya (AGRA, 2016).

In most African countries the nutrient balances of most cropping systems are negative, with the off-take of soil nutrients being nearly always higher than the input, indicating that farmers are mining the soils on a continuing basis (Jama *et al.*, 2016). As has been reported before (by institutions including the World Bank in 2013), as a direct result of the nutrient mining, it is now apparent that soils of sub-Saharan Africa are being depleted annually of 22 kg of N, 2.5 kg of P, and 15 kg of K per hectare (AGRA, 2016). This will have direct implications for yields and the continued sustainability, as a livelihood, of smallholder African agriculture (AGRA, 2016).

Therefore, increased, sustained and unremitting crop production requires appropriate soil management and conservation practices, involving the integrated use of organic and inorganic resources (Deryng *et al.*, 2014). Improved crop mulch management should be an essential and integral part of the overarching strategy to reduce the nutrient mining (Porter *et al.*, 2014). As demonstrated by Larson *et al.* (1972), crop residues from the nine principal crops contain on average 40%, 10%, and 80% of the N, P, and K currently applied as fertilizer to those crops, respectively. For instance, a ton of maize residue will typically contain up to 8 kg of N, 1.8 kg of P, 16 kg of K, 6.6 kg of Ca, and 3.4 kg of Mg (Nandwa *et al.*, 1995).

Cereal crops' residues comprise up to 75% of the total biomass production and have lower nutrient concentrations than the grain (Smith *et al.*, 2007). However,

these residues contain about half of the nutrients extracted from the soil through crop production (Unger, 1990). Therefore, returning the cereal crop residues and their associated nutrients to the soil in particularly smallholder farmer systems, where no or very low inputs are used, is essential in slowing down the pace of nutrient losses from the soils (Lobell and Gourdj, 2012). However, crop residues by themselves are not enough to offset the significant problem of nutrient mining in sub-Saharan Africa (AGRA, 2013).

Crop mulch management influences the availability and accessibility of soil-plant nutrients, especially N, and play a significant role in improving soil physical and chemical properties that are essential in controlling wind and water erosion, which ultimately reduce sediment and other contaminant transport to water bodies (Karlen *et al.*, 1994). When crop residues with a wide C: N ratio are incorporated into the soil, the residual inorganic N that had remained in the soil after harvesting is immobilized. Mineralization of the previously immobilized N occurs after maximum immobilization, resulting in a net release of N (Al-Kaisi and Yin, 2005). Under such circumstances, even a portion of fertilizer N added to soil is immobilized, but the mineralization rate of the recently immobilized fertilizer N is higher than that of indigenous organic N for the same period (Fleisher *et al.*, 2011).

The frequently-observed initial yield suppression that follows the application of crop residues in soils is ascribed to N immobilization (Ocio *et al.*, 1991; Reynolds

and Tuberosa, 2008). Generally, it has been reported that crop residues with a C:N ratio of greater than 35 or N content of less than 1.6%, tend to decompose slowly, and will, therefore, cause immobilization (Nandwa, 1995). Apart from the quality of residues, decomposition and the subsequent release of nutrients are a function of the physical environment, and the activity of soil organisms (Licker *et al.*, 2010). Factors that affect the rate of decomposition include the water content, temperature, and pH of the soil, the C, N and lignin content of the residue, and particle size and degree of residue burial in the soil (Sanjiu *et al.*, 2008).

Retention and maintenance of crop residues on the soil surface with minimum tillage decreases the rate of breakdown and decomposition (Dolan *et al.*, 2006). Whereas with conventional tillage where crop residues are incorporated in the soil there is greater mechanical disruption: subsequently, more intimate contact with decomposer organisms increases the rate of decomposition (Ambus and Jensen, 2001). Besides, the secondary tillage operations commonly employed during conventional tillage land use systems are likely to further accelerate the rate of residue decomposition (Deryng *et al.*, 2011).

Organic matter also has a tremendous effect on soil water management particularly in semiarid regions, because it increases infiltration and water holding capacity (Bongaarts and Casterline, 2013). Enhanced soil water-holding capacity resulted from organic matter more readily absorbs water and releases it slowly over the season to minimize the impacts of short-term drought (Osborne *et al.*, 2007). Field

et al. (2014) showed that for a 1% increase in organic matter, the available water holding capacity in the soil increased by 3.7% on a volume basis. Similarly, Mossadeghi *et al.* (2009) concluded that organic matter could absorb up to 90% of its weight as water which substantially increases the water holding capacity of mineral soils. All these factors contribute to improved soil-plant-water relationships which will enhance crop productivity on a sustainable basis.

There is a direct correlation between mulching and water use efficiency: in a study conducted on the influence of mulch on agronomic characteristics and soil properties in Swaziland, it was noted that grass mulch conserved the highest amount of soil moisture as compared to, for instance, newspaper mulch and black polythene mulch (Ossom and Matsenjwa, 2007). This was attributed to the ability of mulches in protecting crops from intense sunlight thus keeping the micro-climate of the soil cool (Challinor *et al.*, 2009). Also, the mulch was able to increase the infiltration rate of rain or irrigation water, thus improving the moisture regime of the soil (Lobell *et al.*, 2011). The same study also showed the positive effects of mulching in controlling soil temperatures, where the highest mean surface temperatures were recorded in un-mulched soil (Vermeulen *et al.*, 2012). Also, it was noted that with regards to soil chemical properties, other than pH, organic matter and carbon, there were significant effects of mulches (Erenstein *et al.*, 2008).

2.5 Soil organic carbon sequestration

Agricultural ecosystems are estimated to cover a significantly impressive 11% of the earth's total land surface area, including some of the most productive and carbon-rich soils (Adam *et al.*, 2011; Bastia *et al.*, 2013). It is widely acknowledged that organic matter in these soils plays an essential role in a range of soil physical, chemical and biological processes and that soil organic carbon (SOC) is one of the most important indicators of soil quality and health (Antle *et al.*, 2013). Maintaining or increasing soil organic matter is critical to achieving optimum soil functions and therefore fertility and crop production (Fischer *et al.*, 2005).

SOC is the largest terrestrial carbon pool globally, containing more C than the atmosphere and biosphere (Pelton, 2013). It is both a source and, importantly, a sink of CO₂ emissions to and from the atmosphere, thus influencing future climate change (Schmitz *et al.*, 2012). Understanding SOC dynamics is also essential for maintaining C stocks to sustain and improve crop yields (Liu *et al.*, 2007). As a component of the terrestrial carbon cycle, soil can be either a source or sink of atmospheric carbon dioxide (Lal, 2007). Though carbon emissions from agricultural activities contribute to the enrichment of atmospheric CO₂ (Kimble *et al.*, 2002), yet carbon sequestration in agricultural soils, through the adoption of improved management practices, can mitigate this trend (Antle *et al.*, 2013). Conventional agriculture typically results in soil carbon depletion and reduced productivity (Osborne *et al.*, 2013).

SOC is a central component of soil as it checks soil degradation and augments soil chemical, biological, and physical properties (Berdanier and Conant, 2011). The nature and reactivity of SOC depend upon changes in management practices and land use (Cerli *et al.*, 2012). Surface soil contains more SOC than the other underlying soil horizons (Falloon *et al.*, 2014). Management practices and land use changes can significantly influence the concentration of SOC through vegetation cover dynamics, use of mineral fertilizer, and organic matter inputs, such as crop residues (Srinivasan *et al.*, 2012).

The magnitude of organic matter and soil carbon stock result from an equilibrium between the inputs (mostly from farming biomass detritus) and outputs to the system (mainly decomposition and transport), which are driven by various parameters of natural or human origins (Amundson, 2001). Organic matter amendments, for example, crop straw return, have been widely recommended as practices enhancing crop yield while increasing soil quality (Song *et al.*, 2015).

The influence of conservation tillage and cover crops on soil organic carbon appropriation has been the emphasis of many studies because of the potential of these management techniques to contribute to atmospheric C loss and its subsequent sequestration (Long *et al.*, 2006; Rosenthal *et al.*, 2012; Leakey *et al.*, 2012; Lobell, 2013). The SOC sequestration has been shown to retain more SOC with decreasing soil disturbance or enhanced crop rotation diversity, as demonstrated by studies such as by West and Post (2002).

The decrease of organic matter in topsoil can have dramatic adverse effects on water holding capacity of the soil, on structure stability and compactness, nutrient storage and supply and on soil biological life such as mycorrhizas and nitrogen-fixing bacteria (Sombroek *et al.*, 1993), contributing to the obtaining scenarios of low yields and continuing nutrient mining in Kenyan and African soils. Studies conducted in, among other regions, Latin America and Africa shows that there can be as much as 300 kilograms of extra maize harvest per ha, with every increase of 1 mg of SOC in the root zone of the same 1 ha (Carter, 2010; Pelton, 2013; Porter *et al.*, 2014). It is, therefore, essential to study the impact of soil surface treatment on SOC levels and the attendant effects on yields of maize in smallholder farmer settings.

2.6 Tillage and soil carbon sequestration

Concerns about rising atmospheric CO₂ levels have prompted considerable interest in recent years regarding the sink potential of soil organic carbon (Kimball, 2011). The world's soils are estimated to contain 1500 Gt of SOC, roughly double the amount of C in the atmosphere (Schlesinger, 2000). And while that total pales in comparison to the 38,000 Gt of C contained in the world's oceans (Smith *et al.*, 2007), it attracts attention because it is potentially responsive to modification (Asseng *et al.*, 2013). Indeed, though fossil fuel combustion has been the primary cause of increasing CO₂ in the atmosphere, land modifications have been a significant contributor (Deryng *et al.*, 2014).

The impact of tillage practices on SOC build-up has been the focus of many studies because these management techniques contribute to atmospheric C loss or sequestration in soils (Olson *et al.*, 2010; Deryng *et al.*, 2014). Studies on SOC build-up have invariably shown that SOC is retained (or sequestered) with decreasing soil disturbance (Fronning *et al.*, 2008). In 67 long-term agricultural experiments from around the world, West and Post (2002) summarized that SOC stock could be increased by adopting either rotational farming or improving mulch retention. On the other hand, Pikul *et al.* (2008) showed in a ground-breaking study that the potential to sequester C was not possible under continuous maize grain farming systems.

Change in frequency and intensity of tillage practices alters the bulk density and soil organic matter in the soil profile (Six *et al.*, 2001). It has been reported that the reduction in SOC content (by volume) of soils having an initial content of between 20 and 50 g kg⁻¹ was 20% less after cultivation, which was most pronounced during the first 20 years of cultivation (Mando *et al.*, 2005). In addition, changes in SOC storage were more variable in the upper 15 cm of soil than in the top 30 cm (Juo *et al.*, 1996). Also, it is worth noting that Kitur *et al.* (1994) and Hussain *et al.* (1999) assessed the effects of minimum tillage and conventional tillage on SOC content (by weight) and found that the content was lowest for conventional and highest for minimum tillage.

The treatment differences in the SOC as mentioned earlier were attributed to the effects of amalgamation of crop residues below the 0- to 5-cm layer in the conventional and minimum tillage treatments (Olson *et al.*, 2010; Deryng *et al.*, 2014). Effects of tillage on SOC content were not significant in the 5-15 cm layer (Fronning *et al.*, 2008). On their part, Ismail *et al.* (1994) noted that there was a decrease in SOC (by volume) in the 0-30 cm silt loam layer of soil during the first five years of farming. It was also noted that, while there was no noticeable change in the following five years, there was an increase in SOC in the last ten years in both minimum tillage and conventional tillage treatments in comparison with sod plots. The SOC was higher in minimum tillage than in conventional tillage.

On their part, other ground-breaking researchers including Hunt *et al.* (1996) and Angers and Giroux (1996) reported in their findings that minimum tillage systems increased SOC content (by weight) compared with conventional tillage systems in the plow layer (or the top 5 cm layer) of soils with a range of soil textures, including loamy sand, silt loam, and silty clay loam.

In a yet another study carried out in Nigeria on the effect of tillage and mulching on soil properties and crop growth and yields, where the cropping system soybean, it was noted that the stability of soil macro-aggregates (>2.0 mm) and the large micro-aggregates (<0.05 mm diameter) was significantly affected by conventional tillage and mulch retention practices (Ogban *et al.*, 2008). The mechanism of aggregates formation and breakdown in the soil are relatively well understood.

Mulches generate the organic matter that binds soil particles and stabilizes aggregates, reduces the kinetic energy of the impacting raindrops, and soil compaction and aggregate disintegration (Sanchez, 2010).

The recent world-wide focus and attention regarding the nearly cataclysmic global warming phenomenon have motivated the scientific community to search for efficient soil management and cropping systems to convert CO₂ from the air into SOC (Lal, 2007). Agricultural practices can either render a soil either a sink or a source of atmospheric carbon dioxide (CO₂), with direct influence on the greenhouse effect (Deryng *et al.*, 2014). Some studies conducted in a wide array of geographies in the tropics have demonstrated that C sequestration in minimum tillage soils is associated with soil carbon sequestration in tropical ecoregions (Bayer *et al.*, 2006; Bernoux *et al.*, 2006; Cerri *et al.*, 2007).

Showing the nexus of adaptability, some researchers have suggested that the most important factors to increase CO₂ mitigation and the SOC stock of tropical soils are the amount and quality of the crop residues added, regardless of both the climate effect on the decomposition rates and the physiognomies of soil mineralogy and soil type (Paustian *et al.*, 1997; Sá *et al.*, 2001; Six *et al.*, 2002; Kong *et al.*, 2005; Bayer *et al.*, 2006; Tristram and Six, 2007). Moreover, intensive investigations have reported that C storage is proportionately linked with C from crop residue input (Paustian *et al.*, 1997; Sá *et al.*, 2001; Kong *et al.*, 2005; Séguy *et al.*, 2006; Bernoux *et al.*, 2006; Bayer *et al.*, 2009).

Other studies have reported on the way in which tillage practices and mulch retention significantly increase hydraulic conductivity, K_s , with higher values in the land that was tilled in conventional tillage than in soils that were under minimum tillage (Zhang *et al.*, 2005). The observed pattern of differences points out to the relative effects of conventional tillage and minimum tillage techniques on pore-size distribution (Knox *et al.*, 2012). The hydraulic conductivity was reportedly higher in conventionally tilled soils with a preponderance of macropores than in minimum tillage soils with the pore-size distribution skewed toward the micro-pores (Zhang *et al.*, 2005): this effect may have been enhanced in the tilled plots by the mulching techniques. The significantly high values of K_s in tilled soils could still be attributed to soil loosening, and that soil settling lagged behind the compacting effect of rainfall (Zhang *et al.*, 2005).

2.7 Nitrogen fertilization and sustainable agriculture

The doubling of agricultural food production worldwide over the past four decades has been associated with a 7-fold increase in the use of nitrogen (N) fertilizers (Hirel *et al.*, 2007). Nitrogen fertilizers enable farmers to achieve the high yields that drive modern agriculture (Deryng, 2014). The use of nitrogen fertilizer will continue to increase substantially as the global population and food requirements grow (AGRA, 2013). International Fertilizer Industry Association (IFA) forecasts suggest that nitrogen fertilizer applications totalled nearly 100 million in the year 2011 alone (AGRA, 2011).

The availability of residual and supplemental N to maize crop plants can be significantly affected by management practices such as soil tillage (Hong *et al.*, 2007). For example, soil tillage modifies the soil environment that influences microbial activity and hence N transformation (Fox and Bandel, 1986). Some of the N can undergo many changes before taken up by crops. The primary forms in which N is taken up are NO_3^- and NH_4^+ (Tisdale *et al.*, 1985; Mengel and Kirkby, 1987). The two ions are dissimilar in the charge they carry, and their reactions in soil and plants differ. Maize prefers NH_4^+ -N during early growth stages and NO_3^- -N in later growth stages (Dibb and Welch, 1976).

Modification of the soil environment by tillage systems can significantly influence N mineralization (Smith and Sharpley, 1990). Moreover, mineralization rate is affected by the wetting and drying of soils. Degens and Sparling (1995) have reported that when soils are rewetted after a period of drying there was an increase in the rate of mineralization in comparison with soils which had been maintained in a moist condition. As a result, organic matter is mineralized more slowly in minimum tilled than in conventionally tilled soils.

There is need great need to improve the nitrogen use efficiency of crops, especially in the agrarian zones of developing countries like Kenya which primarily depend on agriculture for their economic growth and food security (Jama *et al.*, 2016). This can be achieved through the adoption of practices that improve efficient mineral uptake, and which can be deployed to produce plants with yields that are

equivalent to conventional varieties but which require significantly less nitrogen fertilizer because they use it more efficiently (DTMA, 2015).

2.8 Summary and knowledge gaps

This literature review sought to show how sustainable agricultural intensification can be delivered to build the resilience of the agricultural systems among smallholder farmers in Kenya. Agriculture has been characterized as a socio-ecological system that is usually managed to produce, distribute, process, and consume food, fuel, and fiber for the benefit of humankind. Consequently, in the light of changing climates and the attendant variability, agricultural resilience should be structured to go beyond the farm. The chapter sought to show how the physical space of production (the farmland) can be the center of resilience through the adoption of land use systems that enhance this attribute.

From the literature reviewed the following knowledge gaps have been identified which this study seeks to address. This includes the awareness that the feasibility of climate-resilient tillage and mulch management practices in as far as sustainable maize grain yields, soil water conservation and the build-up of soil carbon is concerned, has not been adequately investigated in the context of smallholder farming systems in Humic Nitisols of the Central Highlands of Kenya. This needs further research to improve the adaptability of the maize farming system in this region to changing climates. This is critical in that the continued sustainability of the farming systems in the region is hinged on continued and sustained growth in maize yields.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study area

The study was carried out at Kirege Primary school, located in Tharaka Nithi County, Kenya (Figure 3.1). Kirege lies in the Upper Midland Agro-ecological Zone 3 (UM3) on the eastern slopes of Mount Kenya, at an altitude of about 1400 m above the sea level. The annual mean temperature is about 20°C, and total annual rainfall ranging from 1200 mm to 1400 mm received in two seasons, the long rains (LR), occurring between mid-March and June, and the short rains (SR), occurring between mid-October and December.

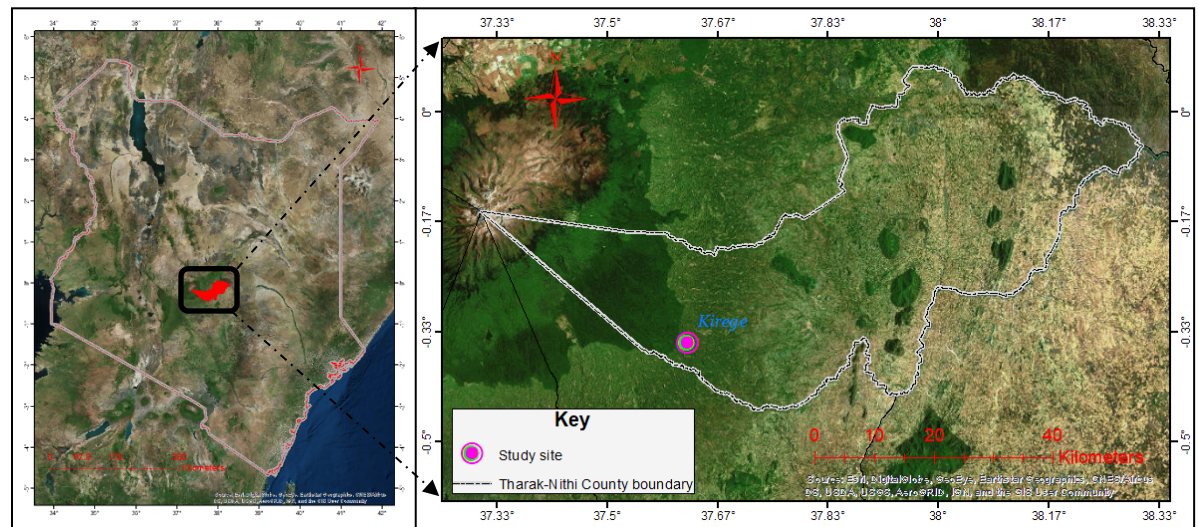


Figure 3.1: Map showing the study area, Tharaka-Nithi County and the site, Kirege Primary School (source: author)

The soil types in the experimental field are predominantly Humic Nitisols (FAO and UNESCO, 1988). Major crops grown are beans (*Phaseolus vulgaris*), potatoes

(*Solanaceae Solanum*), sweet potatoes (*Ipomoea batatas*), cabbages (*Brassica oleracea*), kales (*Brassica carinata*), tomatoes (*Lycopersicon esculentum*), onions (*Allium cepa* L.) and maize (*Zea mays* L.). The farmers in the region primarily rely on small-scale rain-fed farming, which is mostly non-mechanized and involves little use of external inputs. It is a predominantly maize growing intercropped with common beans zone with smallholdings ranging from 0.1 to 2 ha with an average of 1.2 ha per household.

3.1.2 Soil characteristics

The initial soil characteristics of the research site are presented in Table 3.1. These initial characteristics show the soil in the study area was acidic (pH 4.7), had low organic carbon, very low nitrogen content and low total phosphorus. The textural class is clay soil (Table 3.1).

Table 3.1: Initial soil physical and chemical characteristics at Kirege site

Parameter	Status
Soil texture	Clay
pH	4.7
Exchangeable acidity (me %)	0.4
Total N (%)	0.002
Available P (g/kg)	0.2
Total Organic Carbon (%)	0.017
Exchangeable K ⁺ (cmol+/kg)	0.4
Exchangeable Ca ²⁺ (cmol+/kg)	0.4
Exchangeable Mg ²⁺ (cmol+/kg)	0.5

The soil types in Meru South are predominantly Humic Nitisols (FAO and UNESCO, 1988; Jaetzold *et al.*, 2007). The soils are typically deep, well-drained and weathered with moderate to high inherent fertility.

3.2 Experimental design

The field experiment was implemented following a randomized complete block design replicated three times, over a period of six growing seasons (LR2013, SR2013, LR2014, SR2014, LR2015 and SR2015). The plots measured 7 m by 7 m. The treatments were two types of tillage methods (conventional tillage and minimum tillage), two types of soil surface management, mulching (crop residue retention) and bare surface (crop residue removed) and two levels of nitrogen fertilizer application (120 kg N ha^{-1} applied and 0 kg N ha^{-1}) leading to eight (8) treatments. The treatments combination structure is as shown in Table 3.2.

Table 3.2: Experimental treatments and their combinations in Chuka

Tillage	Residue	Nitrogen level	Combination
Conventional Tillage	Without mulch	120 Kg/ha N	T1M0N1
Conventional Tillage	Without mulch	0 Kg/ha N	T1M0N0
Conventional Tillage	Mulch applied	120 Kg/ha N	T1M1N1
Conventional Tillage	Mulch applied	0 Kg/ha N	T1M1N0
Minimum Tillage	Without mulch	120 Kg/ha N	T0M0N1
Minimum Tillage	Without mulch	0 Kg/ha N	T0M0N0
Minimum Tillage	Mulch applied	120 Kg/ha N	T0M1N1
Minimum Tillage	Mulch applied	0 Kg/ha N	T0M1N0

Between the plots, a 1 m wide alley was left, while between the blocks, a 2 m wide alleys were left. Land preparation was done using hand hoeing, and all

aboveground fallow biomass was removed from the site before trial establishment. Hybrid maize, H516, a medium maturing hybrid maize seed variety, sown at a depth of 5 cm was the test crop throughout the trial period. Maize spacing was 0.75 m by 0.50 m (plant population of about 53,333). An extra seed per hill was sowed to ensure max plant population but was thinned out to two, fourteen days after emergence.

For the mulch-receiving plots, mulch was applied at the rate of 1 ton per ha while for fertilizer-receiving plots to achieve 30% cover crop, while nitrogen was applied at a rate of 120 kg ha⁻¹ in a split, because of the low nitrogen in the soil and the relative acidity of the soil. The rates as applied were also chosen to understand the effect of agricultural intensification. Maize stover was used as the mulch for all treatments, with the residues chopped into 10 cm sizes and applied two weeks after planting. The starter fertilizer was NPK 23:23:0 calculated at a rate of 60 kg ha⁻¹ while the remaining half (60 kg ha⁻¹) was applied by top dressing with urea 30 days after planting.

Phosphorus was blanket applied to supply 90 kg ha⁻¹ of P inclusive of the amount provided by the starter fertilizer. The source of the extra phosphorus was triple superphosphate (TSP) fertilizer, applied at planting. All fertilizer application was through banding. Maize stover from the preceding season's harvest was used. All other standard agronomic practices were followed for optimal productivity.

3.3 Data collection

3.3.1 Rainfall data collection

Daily rainfall amounts were determined using tipping-bucket, data logging rain gauge, Hobo, model; RG3-M (manufactured by Onset Computer Corporation Company) with a 0.2 mm resolution installed within the field trial site. The data logger was launched at the beginning of the season and read out at the end of each season, although frequent checks were done to monitor its functionality.

Besides the data logging rain gauge, a backup manual rain gauge was mounted nearby. Once read out, the data were exported using HOBOWare Pro Version 3.2.2 as CSV files and further processed in MS Excel. Daily rainfall was calculated by multiplying the number of tips per day (09:00 h) by 0.2 mm tipping bucket resolution of the rain gauge.

3.3.2 Yield determination

Six plants were tagged per plot for the determination of growth, dry matter yield and yield components. After harvest, grain and stover (above-ground biomass minus grain) yields were determined from a net plot of 21 m² and extrapolated to per hectare basis. To achieve this, the following parameters were determined during and after harvesting at the end of each season: Net-plot stand count per plot; Number of cobs per net plot; Fresh weight of all cobs with grains (kg) from the net plot; Dry weight of all the cobs with grains (kg) from the net plot; Dry weight of the grains (kg) after shelling; weight of dry cobs after shelling; Fresh weight of

stover from the net plot; Fresh weight of randomly sampled stover from the net plot; Dry weight of the sampled stover after oven drying at 65°C until constant weight.

Based on this information, per unit area, grain and biomass yield weight were calculated. The grain mass was converted to a per hectare basis after standardizing at 13% moisture content while the stover was calculated based on the stover fresh weight and weight difference of the fresh and dry stover samples and converted to per hectare basis.

Water use efficiency (WUE) was calculated based on total biomass or grain yield per unit of crop water used. Actual evapotranspiration (synonym to consumptive use of water), was estimated by multiplying reference evapotranspiration (in effect, potential evapotranspiration) with an appropriate value of a crop coefficient, which usually corresponds closely with the green crop cover.

The total evapotranspiration over the whole growing season (ET_c in mm), the amount of infiltration (D_w), and WUE efficiency were calculated using equation 1 (Tao *et al.*, 2015), equation 2 (Sun *et al.*, 2010) and equation 3 (Fan *et al.*, 2013).

$$ET_c = P_e + S - D_w \quad \text{Equation 1}$$

$$D_w = 0.1 \times P_e \quad \text{Equation 1}$$

$$WUE = \frac{Y}{ET_c} \quad \text{Equation 1}$$

where P_e is the effective precipitation (mm) measured using the automatic rain gauge, ΔS is the change in soil water stored in the 0 to 100 cm soil layer (mm) before sowing and at harvest, and Y is biomass or grain yield (kg ha^{-1}).

3.3.3 Mineral N and plant N uptake

To determine the nitrogen assimilated by the maize crop, all of the crops were harvested including roots (0 - 20 cm). Crop samples were separated to grain and stem. Subsequently, all of the samples were heated and dried at 45°C until constant weight was achieved, and then crushed to powder until they were able to pass a 0.15 mm sieve, awaiting total nitrogen concentration analysis.

Soil samples for analysis of mineral N ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) soil samples were collected two days after N fertilization and approximately every three weeks afterward until harvest in both LR15 and SR15 seasons. The soil samples were taken to the depth of 80 cm, which was divided into four layers: 0-20 cm; 20-40 cm; 40-60 cm, and 60-80 cm each season in two seasons (LR2015 and SR2015). Approximately 10 g of air-dried soil was placed in a 125 mL Nalgene bottle along with 50 mL of $2 \text{ M L}^{-1}\text{KCl}$.

The Nalgene bottles were shaken for 30 min, and after that, the extraction solution was filtered through Whatman No. 42 filter paper into 20 mL scintillation vials.

The filtered solution was stored in a -4°C refrigerator until analyses for NO₃-N and NH₄-N. The NO₃-N and NH₄-N were determined colourimetrically using a Segmented Flow Analyzer after extraction with 1% K₂SO₄. A more detailed description of the method can be found in Dresler (2009).

Representative grain and stover samples from the harvest area of all plots at the Kirege research site were collected to determine their N contents. The stover was chopped into smaller pieces before the grain and stover were dried, crushed and stored for analysis. A standard steam distillation procedure was used for the determination of N after the samples were digested in sulphuric acid. Soil nitrate-N content (unit, kg N ha⁻¹) was calculated by an average bulk density of 1.25, 1.12, 1.34 and 1.18 g cm⁻³ for 0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm soil layers, respectively.

Apparent recovery efficiency of nitrogen (ARE_N), i.e., plant N uptake (kg ha⁻¹) per kg N applied, was calculated as suggested by Dilz (1988). Agronomic efficiency of nitrogen (AEN), i.e., the yield (kg ha⁻¹) increase for each kg N applied, was calculated according to (Novoa and Loomis, 1981), where N_{app} = nitrogen applied.

Determination of the total nitrogen concentration in the maize was done using the micro-Kjeldahl method by digesting the sample in H₂SO₄-H₂O₂ solution. By adding an excess of sodium hydroxide solution, the ion ammonium was released in ammonia form, distilled and received on a boric acid solution or a volumetric

sulphuric acid solution. The ammonia was determined with a volumetric acid solution or by back-titration with sodium hydroxide solution of known concentration.

3.3.4 Soil water content

Soil moisture content was determined continuously at the onset of the season, week 2, 4, 6, 8, 10, 12 and 14 after planting using Diviner 2000, a capacitance approach. Diviner 2000 is a portable and robust device measuring soil water over multiple depths (at 10 cm intervals) in the profile. Diviner 2000 consists of a probe and hand-held data logging display unit allowing the researcher to make onsite management decisions for all the treatments.

Aluminium access tubes with a diameter of 50 mm and a length of 130 cm were installed vertically at a depth of 110 cm at the beginning of the experiment, with three replicates for each treatment. The first measurements were taken at 0.1 m then at 0.1 increments after that to 1 m depth. Monitoring of soil moisture was started after the start of each of the rainy seasons, from mid-March to June for the long rains, and mid-October to December for the short rains. Six access tubes located close to the field experiments were used for calibration; samples were taken at a distance of 0.3 m from each tube and the same depth as the readings.

The soil moisture sensor gave output in volumetric water content (mm of water per 100 mm of soil measured). This was converted from a scaled frequency reading using a default calibration equation, which is based on data obtained from numerous scientific studies in a range of soil textures.

3.3.5 Soil carbon content

To determine changes in soil organic carbon status as affected by the application of tillage and mulch management practices, the study undertook soil sampling up to a depth of 80 cm before land preparation and residue application, for each of the 24 plots. Soil samples were collected in October 2012 (the baseline year) and in December 2015 at depths of 0-20, 20-40, 40-60 and 60-80 cm. Four soil cores, one from near each of the four corners of the plot (1.5 m from adjacent, above or below plot, and 1.5 m from guard rows), were obtained for each depth and composited by crumbling and mixing.

The samples were air-dried, pulverized and shaken by using a high-speed mixer for one hour to ensure adequate dispersion. The suspension was mechanically stirred for one hour and sieved through 2mm, 75 μ m, and 50 μ m sieves to separate the particulate organic matter (POM). Particle size fractionation was applied to isolate three different soil fractions. Density fractionation intended to achieve active, intermediate and passive OM pools. Density fractionation of the SOC was performed using the method of Meijboom *et al.* (1995). Air-dried soil samples

(400 g) were wet sieved over two sieves with tap water (top sieve mesh size 250 μ m, bottom sieve mesh size 150 μ m) until the passing water became clear.

The soils from these determinations were dried for the analysis of organic carbon. In this procedure, potassium dichromate ($K_2Cr_2O_2$) and concentrated H_2SO_4 were added to between 0.5 g and 1.0 g of soil or sediment. The solution was swirled and allowed to cool before adding water to halt the reaction. The addition of H_3PO_4 to the digestive mix after the sample cooled helped eliminate interferences from the ferric (Fe^{3+}) iron that may be present in the sample.

The soil was spread on top of a nest of sieves with an opening of 2,000 μ m, 75 μ m, and 50 μ m. Sieve sizes were chosen based on the assumption that the > 0.05 mm fraction was the most susceptible to changes in land use or management. The sieves were placed in a wet-sieving apparatus, similar to that described by Kemper and Rosenau (1986). Aggregates were physically separated into three water-soluble aggregate-size fractions (WSA). The obtained micro- and macro-organic matter, the three soil aggregate fractions; 2,000 μ m, 75 μ m, and 50 μ m, was categorized as microaggregates (labelled as "MIC" in the equation below), mesoaggregates ("MSA") and macroaggregates ("MAC") fractions respectively.

The SOC from each fraction was determined, after removal of undecomposed plant residue, using the standard Walkley-Black procedure (1934).

$$MAC = \sum \text{proportion of WSA} > 2\text{mm (2 mm sieves)}$$

$$MSA = \sum \text{proportion of WSA } 75 \mu\text{m to } 2\text{mm i.e } 75 \mu\text{m sieve}$$

$$MIC = \sum \text{proportion WSA} < 50 \mu\text{m; i.e } 50 \mu\text{m sieve.}$$

Where MAC refers to macroaggregates, MSA refers to mesoaggregates and MIC refers to microaggregates.

3.4 Data analyses

All data was captured and managed in MS Excel and analysed using SAS software. Yield, harvest index, crop evapotranspiration, and water use efficiency for grain and biomass production (WUE_{GY} and WUE_B , respectively), maize grain and stover yield data, soil nitrate-N, soil ammonium-N and agronomic efficiency use data were subjected to analysis of variance using the General Linear Model (GLM) using SAS version 9.2 software (SAS Institute, 2004) to obtain an F value of the model effect.

Pair-wise comparison of soil organic carbon content differences between the start and the end of the experiments was analysed using student t-test. Differences between treatment means were examined using the least significance difference (LSD) at $p = 0.05$.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Rainfall amount and distribution

Total rainfall amounts received in individual seasons varied throughout the entire experimental period (Table 4.1). A total amount of 223 mm, 502 mm and 842 mm was received during the LR2013, LR2014, and LR2015, respectively (Table 4.1).

Table 4.1: Rainfall events characteristics during the study period

Rainfall amount range (mm)	LR2013	SR2013	LR2014	SR2014	LR2015	SR2015
>80	1	0	0	2	0	0
>60 and < 80	1	0	0	3	1	1
>40 and < 60	1	2	2	2	6	4
>20 and < 40	3	6	4	5	7	17
>10 and <20	6	10	11	11	9	14
<10 and >5	6	6	8	7	10	8
<5	45	13	17	16	52	30
Total Events	63	37	42	46	85	74
Total rainfall received (mm)	222.6	447.8	501.55	855	842	1,065.8

On average, higher amounts of rainfall were received during the short rain seasons than in the long rain seasons. During SR2013, SR2014 and SR2015 total amounts of rainfall received were 448 mm, 855 mm, and 1,066 mm, respectively (Table 4.1). The high rainfall received during the short rains seasons is indicative of its reliability as far as crop performance is concerned.

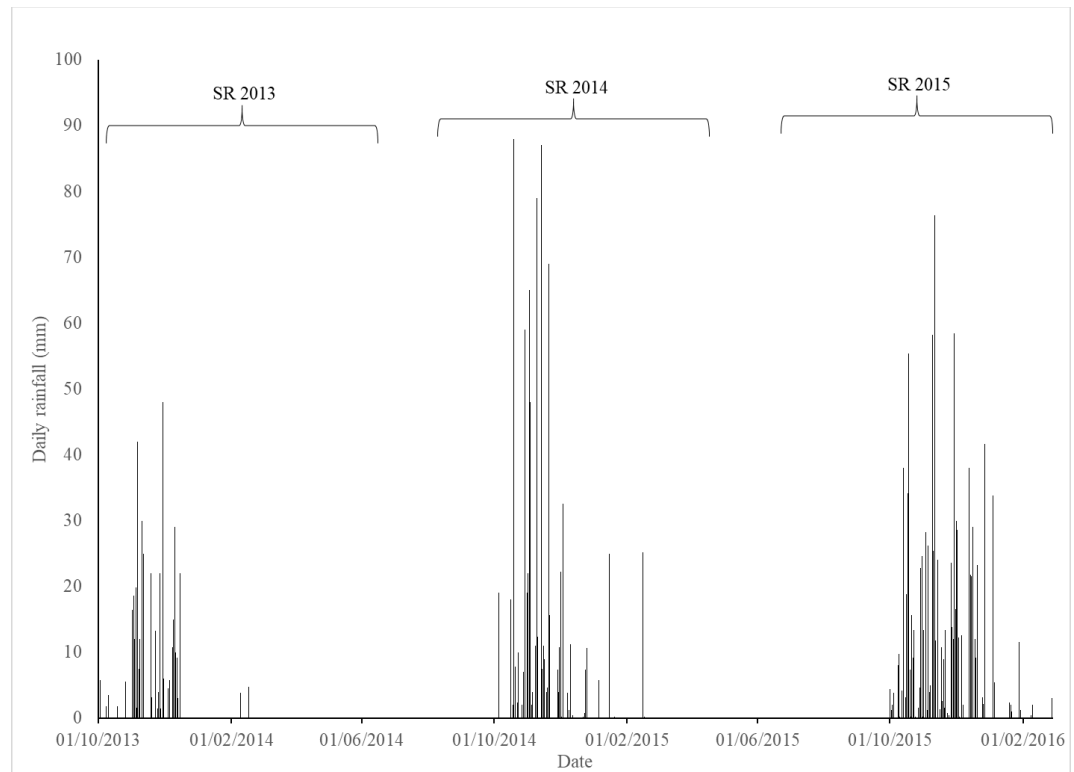


Figure 4.1: Daily rainfall amounts for the short rains (SR) seasons in 2013, 2014 and 2015

There were significant variations in total seasonal rainfall amounts received: for example; there was a difference of 843 mm between SR2015 seasons (highest) and LR2013 season (lowest) rainfall amounts (Table 4.1, Figures 4.1 and 4.2).

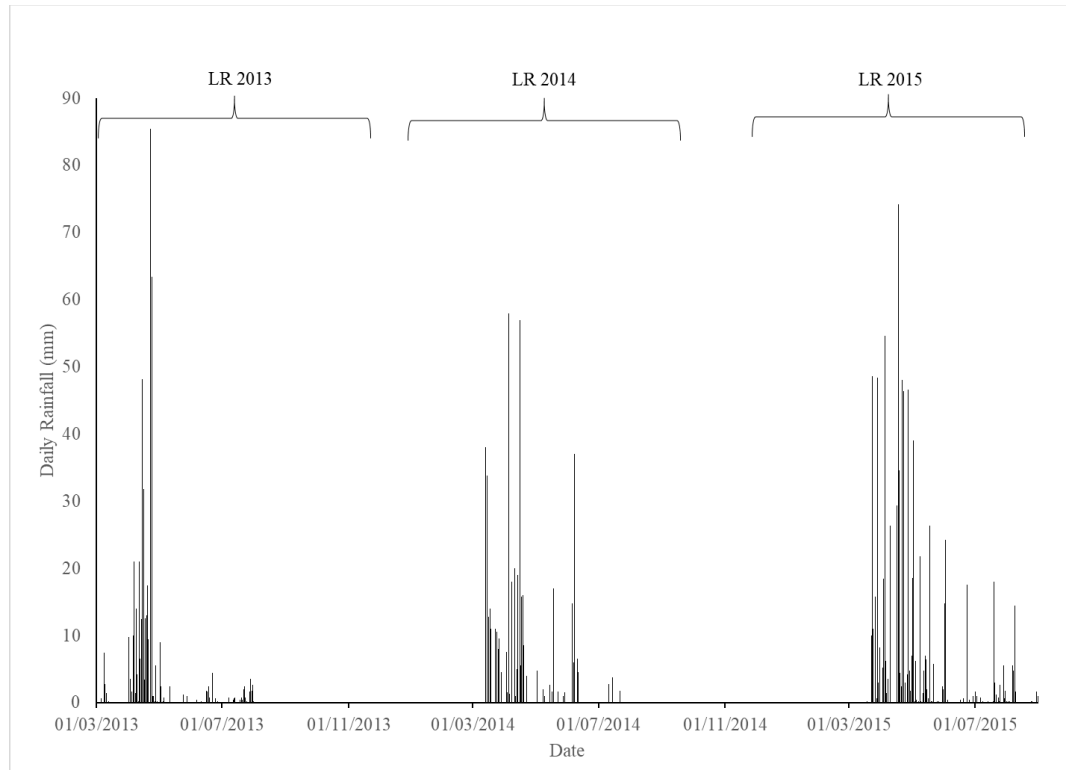


Figure 4.2: Daily rainfall amounts for the long rains (LR) seasons in 2013, 2014 and 2015

The LR2014 season was generally dry at the beginning of the season, with the season onset occurring around mid-March and cessation in early June, with frequent dry spells of different lengths in-between (Figure 4.2). The SR2014 season was generally wet throughout. The LR2015 was generally a wet season with late-onset (late March) and cessation dates (late June) (Figure 4.2).

The number and description of all rainfall events (rainfall amount ranges observed at a single point at the Kirege site) that occurred in the six seasons of research in Kirege are presented in Table 4.1. A total of 347 rainfall events were recorded in

the three years of research in Kirege (Table 4.1). Generally, during all the seasons, much of the rainfall received was usually below 5 mm and accounted for about 50% of all the rainfall events in the six seasons. During the extended warm and dry periods, especially the few weeks preceding the long rains, rainfall of less than 5 mm may not add any moisture to the soil reservoir as most of it is evaporated before entering the soil and the soil profile is water efficient after the off-season dry spell.

The lowest rainfall recorded was in LR2013 (222.6 mm, Table 4.1): this season was also noted for the fact that 71% of all rainfall events recorded were less than 5 mm (Table 4.1), which was the highest proportion of rainfall events of less than 5 mm in all the seasons. In only three episodes (1 event in LR2013 and two events in SR2014) did the rainfall amount recorded exceeded 80 mm. A meteorological drought of 49 days was experienced at the beginning of the LR2013 season (Figure 4.2).

Of the six seasons, SR2013 had the lowest number of rainfall events (37), which is also consistent with the fact that this season had the second lowest rainfall amount recorded in all the seasons (Figure 4.1). The rainfall event with the maximum rainfall amounts in this season was between 40 and 60 mm, with only 49% of the rainfall occurring being greater than 10 mm. Thirty-five percent of the total rainfall events were below 5 mm.

The SR2014 season had two events of more than 80 mm, three events of between 80 mm and 60 mm and two events of between 40 mm and 60 mm. It had 16 rainfall events of not more than 5 mm per day. During SR2013 season, a dry spell of nineteen days was experienced towards the end of the season (Figure 4.1). Although regarding the total rainfall amounts LR2015 season was second least, it had comparatively better distribution than the other five seasons (Figure 4.1).

There were no extreme events recorded. It was noted that most rainfall events were concentrated between 5 mm and 60 mm per day. It had the second highest proportion of rainfall events with less than 5 mm per day, at 61% of all events recorded. There was also a dry spell of twenty-one days at the beginning of the LR2015 season (Figure 4.2).

These results, showing more rains during short rains seasons, correspond with the findings of Mucheru-Muna *et al.* (2014) in a study carried out in Meru South sub-county in Tharaka-Nithi County. The sub-humid regions suffer from the high frequency of droughts and dry spells (Rockström *et al.*, 2010; Mucheru-Muna *et al.*, 2014). Dry spells period can strongly affect crop growth and productivity (Ngetich *et al.*, 2014).

The rainfall pattern and amounts observed agree with findings by Mucheru-Muna *et al.* (2010) and Ngetich *et al.* (2014) who conducted their research within the same region. The intra-seasonal variations noted in this research are in agreement

with findings in other regions in sub-Saharan Africa, such as Ethiopia and Sudano-Sahelian belt. Sivakumar (1991), Seleshi and Zanke (2004) and Tilahun (2006) have all reported high variations in annual and seasonal rainfall totals and rainy days.

Understanding of daily rainfall behaviour is essential for drought mitigation planning in rain-fed agriculture (Mzezewa *et al.*, 2010). Rainfall amounts and patterns affect the soil water content in cropping fields, affect crop biomass production and have direct consequences in terms of yields and livelihoods for smallholder farmers.

Dry spell analysis is of help in estimating the probability of occurrence of intra-season drought, meaning that appropriate management practices can be adopted early on in the season. Because the majority of farmers in the Central Highlands of Kenya depend on rain-fed agriculture, the understanding of rainfall dynamics are also important in the development of strategies for improving the socioeconomic well-being of smallholder farmers.

4.2 Effects of soil tillage, nitrogen application and mulching practices on grain and stover yields of maize

4.2.1 Grain and stover yields

The treatment effects of tillage practices, mulch management and nitrogen fertilization on maize grain are presented in Tables 4.2. During LR2013, T1M1N1

treatment had significantly ($p=0.002$) the highest grain yields which were about 244% compared to the control (T1M0N0) (Table 4.2). It was followed by T0M0N1 and T1M0N1 with 122% and 89%, respectively, significantly ($p=0.002$) higher yield difference compared to the control (Table 4.2).

Table 4.2: Effects of tillage practices, mulch management and nitrogen fertilization on maize grain yields in Kirege, Meru South

Treatment	Maize grain yields (Mg ha ⁻¹)					
	LR2013	SR2013	LR2014	SR2014	LR2015	SR2015
T1 M1 N1	3.1 ^a	1.6 ^a	4.2 ^a	3.0 ^{ab}	4.3 ^{ab}	3.7 ^a
T0 M0 N1	2.0 ^b	1.9 ^a	4.6 ^a	3.2 ^a	3.1 ^{bc}	2.4 ^{ab}
T1 M0 N1	1.7 ^{bc}	0.4 ^c	4.4 ^a	3.0 ^{ab}	4.9 ^a	2.9 ^a
T0 M1 N1	1.4 ^{bcd}	1.5 ^{ab}	4.6 ^a	2.0 ^{bc}	3.5 ^{abc}	2.6 ^{ab}
T1 M1 N0	1.1 ^{bcd}	0.7 ^{bc}	3.7 ^a	1.4 ^{bc}	2.9 ^{bc}	2.0 ^b
T1 M0 N0	0.9 ^{cd}	0.7 ^c	3.5 ^a	1.8 ^{bc}	2.8 ^c	1.9 ^b
T0 M1 N0	0.9 ^{cd}	0.6 ^c	4.5 ^a	1.4 ^c	2.3 ^c	2.4 ^b
T0 M0 N0	0.5 ^d	0.4 ^c	3.0 ^a	0.7 ^c	3.1 ^{bc}	2.4 ^b
SED	0.2859	0.2372	0.804	0.46	0.648	0.568
<i>p</i> -value	0.002	0.002	0.234	0.029	0.028	0.0414

Where: T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹. Means with different letters in the same column indicate statistically significant differences (LSD test, $p<0.05$)

In the SR2013 season, T1M1N1 and T1M0N1 were the only treatments which were significantly ($p=0.002$) higher (129% and 171%, respectively) compared to the control (Table 4.2). In LR2014 season, there was no significant ($p=0.234$) difference between all the treatments, control included, although it is worth noting that the overall performance of the season regarding grain yields was second highest after LR2015 (Table 4.2).

The grain yield performance of T1M1N1, T0M0N1, T1M0N1, was high by 67%, 78%, and 67%, respectively compared to the control (Table 4.2). The rest of the treatments were not statistically different from the control. During LR2015 season, only two treatments, T1M1N1 and T1M0N1, were significantly ($p=0.028$) different, with 57% and 77% higher grain yield compared to the control (Table 4.2). The SR2015 season followed the same trend as that of the preceding LR2015 season. The yield difference between the T1M1N1 and T1M0N1 compared to the control were 90% and 52%, respectively (Table 4.2). The T0M0N0 treatment performance was consistently poor throughout the experimental period with the first four seasons' average yields registering below the control amounts (Table 4.2).

Maize grain yields were significantly higher in conventional tillage treatments as compared to minimum tillage treatments in the four out of the six research cropping seasons. Conventional tillage treatments aggregated together, had generally higher grain yields than minimum tillage treatments during LR2013, SR2013, SR2014 and LR2015, respectively, while minimum tillage had on aggregate higher grain yields in SR2013 and LR2014, respectively (Table 4.2).

Retention of mulch on-farm improved maize grain yields in this study. In the LR2013 and SR2013 seasons, maize grain yields were observed to be higher under mulch retained treatments, with 20% and 25% more grain yields, respectively, compared to mulch removed treatments (Table 4.2). Except for one season

(SR2014), maize grain yields under mulch retained treatments were higher than mulch removed treatments. The yields under mulch retained treatments ranged from a low of 1.1 Mg ha⁻¹ (in SR2013) to a high of 6.0 Mg ha⁻¹ (in LR2015). On the other hand, the yields for mulch removed treatments ranged from a low of 0.84 Mg ha⁻¹ (SR2013) to a high of 4.8 Mg ha⁻¹ (LR2015) (Table 4.2).

Application of fertilizer improved maize grain yields throughout the study period, with grain yields ranging from a low of 1.4 Mg ha⁻¹ (in SR2013) to a peak of 6.3 Mg ha⁻¹ (in LR2015) (Table 4.2). Treatments that had no nitrogen fertilizer applied had noticeably lower maize grain yields, ranging from 0.6 Mg ha⁻¹ (in SR2013) to a high of 4.4 Mg ha⁻¹ during LR2015.

During the LR2013 season, T1M1N1 treatment had significantly ($p=0.002$) the highest stover yields, which was about 63% higher compared to the control (T1M0N0) (Table 4.3). It was followed by T1M0N1 and T0M0N1 with 41% and 34%, respectively, significantly ($p=0.002$) higher stover yields as compared to the control (Table 4.3). In the SR2013 season, except for T0M0N0 which had significantly lower (-43%) stover yields than the control, the other treatments had no significant effects compared to the control. In the LR2014 season, only T1M1N1 and T0M0N1 had significantly ($p<0.001$) higher stover yields (74% and 60%) compared to the control (Table 4.3). Just like the first season of the experiment (LR2013), T1M1N1, T1M0N1, and T0M0N1 were the only treatments

that had significant ($p=0.032$) effects on biomass yields compared to the control in the SR2014 season (Table 4.3).

Table 4.3: Effects of tillage practices, mulch management and nitrogen fertilization on maize stover yields in Kirege, Meru South

Maize stover yields (Mg ha ⁻¹)						
Treatments	LR2013	SR2013	LR2014	SR2014	LR2015	SR2015
T1 M1 N1	5.6 ^a	2.7 ^a	6.3 ^a	4.6 ^b	7.9 ^a	6.0 ^a
T1 M0 N1	4.8 ^{ab}	2.6 ^a	5.4 ^{abc}	5.7 ^a	7.5 ^{ab}	5.3 ^{ab}
T0 M0 N1	4.6 ^b	2.9 ^a	5.8 ^{ab}	4.6 ^b	6.3 ^{bc}	4.3 ^{bc}
T0 M1 N1	4.2 ^{bc}	2.7 ^a	5.1 ^{abc}	4.2 ^{bc}	5.2 ^{cd}	4.6 ^{abc}
T1 M1 N0	3.6 ^c	2.3 ^{ab}	4.2 ^{cd}	2.8 ^{de}	4.7 ^{de}	3.6 ^c
T0 M1 N0	3.3 ^c	2.3 ^a	4.6 ^d	2.1 ^{cd}	3.7 ^{cd}	3.5 ^{abc}
T1 M0 N0	3.4 ^c	2.3 ^{ab}	3.6 ^{bcd}	3.6 ^e	5.2 ^e	4.7 ^c
T0 M0 N0	1.0 ^d	1.2 ^b	2.1 ^e	2.6 ^e	3.5 ^e	3.4 ^c
SED	0.26	0.34	0.38	0.23	0.54	0.39
<i>p</i> -value	<.001	0.018	<.001	0.032	0.014	0.051

Note:

T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹,
 T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1=
 conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0=
 conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum
 tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage +
 mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch
 removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed +
 0 kg N ha⁻¹

Means with different letters in the same column indicate statistically
 significant differences (LSD test, $p < 0.05$)

Within the same season, T0M1N0 and T0M0N0 affected the biomass yields negatively by a margin of -41% and -28%, respectively (Table 4.3). In LR 2015 season, T1M1N1 and T1M0N1 were the only treatments which had significantly ($p=0.014$) higher biomass yields (54% and 43%, respectively) compared to the control. Just like in SR 2014 season, the T0M1N0 and T0M0N0 significantly affected the biomass yields negatively (-29% and -32%, respectively) compared to the control (Table 4.3).

There was also significantly higher stover yields noted under conventional tillage treatments in five of the six cropping seasons – LR2013 (25% higher stover yields), LR2014 (10% higher stover yields), SR2014 (19% higher stover yields), LR2015 (26% higher stover yields) and SR2015 (19% higher stover yields) (Table 4.3). Generally, like grain yields, residue levels influenced maize stover yields in three out of the six cropping seasons.

There were higher stover yields in mulch-retained treatments in LR2013 and LR2014 than in mulch-removed treatments. Mulch removed treatments had higher yields only in SR2014 (Table 4.3). On the whole, the stover yields were generally higher under mulch retained treatment, ranging from a low of 4.4 Mg ha⁻¹ (SR2015) to a high of 10.1 Mg ha⁻¹ (LR2014) than treatments with mulch removed (Table 4.3).

There were no significant differences between the control and all the treatments except T0M1N0 and T0M0N0, which negatively affected the stover yields compared to the control in SR 2015 season (Table 4.3). It is noteworthy that stover yield under T0M0N0 treatment was consistently low throughout the study period followed by T0M1N0 (Table 4.3).

It was noted, too, that nitrogen fertilizer effect was also equally as pronounced in stover yields (Table 4.3), where yields in treatments with nitrogen fertilizer had much higher stover yields in all the six cropping seasons. The stover yields under

nitrogen fertilizer applied treatments ranged from a low of 4.3 Mg ha⁻¹ (during SR2015) to a high of 11.2 Mg ha⁻¹ in the season of LR2015 (Table 4.3).

Nitrogen fertilization, therefore, noticeably influenced stover yields in all the cropping seasons without exception. Significantly higher maize stover yields were noted, showing yield increases of between 25% (SR2015) and 58% (LR2013) in the N fertilizers plots as compared to the yields in the non-fertilized plots (Table 4.3).

Variation in yields during the cropping season could be attributed to the amount and distribution of rainfall (Figures 4.1 and 4.2). For instance, maize yields were highest during the SR2015 season, which received high rainfall amounts and good rainfall distribution during the season (Figure 4.1). The reduction in maize grain yield in SR2013 (Table 4.2) in all the treatments was due to the late onset of rain which delayed sowing and early cessation of rain which decreased grain filling.

Much less rainfall than normal occurred in April and May 2013 (Figure 4.2), with only 37 rainfall events recorded during this season (Table 4.1), the lowest number of events in all of the six seasons. The paucity of rain during this season caused late sowing of maize. This late sowing predisposed the maize crop to adverse environmental conditions such as early onset of water stress and desiccating winds in July during the anthesis and grain filling stages, severely retarding vegetative

growth. These factors caused premature termination of growth which is reflected in the low maize grain yields for this season (SR2013).

In contrast, in the two following seasons of SR2014 and SR2015, the rainfall received during the April-May period, which was much higher than the SR2013 season (Figure 4.1). This rainfall also had better temporal distribution, as characterized by the 46 and 74 rainfall events, respectively (Table 4.1), which had the effect of adequately wetted the soil and promoted early planting (Figure 4.1). As the rainfall extended to June and part of July, this subsequently resulted in favourable conditions for grain filling.

The delayed onset of rains and poor rainfall amounts notwithstanding, in the SR2013 season, when the maize crop faced terminal drought in May and June, the combination of minimum tillage and nitrogen fertilization of 120 kg per ha resulted in higher grain yield than any other combination. This is attributed to the fact that in drier weeks of this season the minimum tillage land use provided a better soil environment by reducing the temperature and conserving water, resulting in better grain filling and hence better maize grain yields.

The maize grain yields in treatments with nitrogen fertilizer and mulch retention can be considered high when compared to maize yields usually obtained by smallholders in Kenya, which is typically around 1.1 Mg ha⁻¹ (FAOSTAT, 2015).

This relatively high yield may be explained by the presence of nitrogen fertilization and maize residue stover.

Previous research carried out in the tropics suggested that minimum tillage with mulch retention and with nitrogen fertilizer applied maintains, and in some instances increases, maize yields in comparison with conventional tillage (Thierfelder and Wall, 2012; Ngwira *et al.*, 2013). These suggestions are generally in agreement with the results obtained from this study.

High maize grain yields were observed under T0M0N1 combination in three seasons (SR2013, LR2014, and SR2014), with the highest grain yields in the other three seasons occurring in conventional tillage treatments. Higher yields under minimum tillage, mulch retention, and fertilizer application could have been as a result of enhanced nutrient mobilization. Meena *et al.* (2015) found that mulch retention under conventional tillage was the most effective approach for smallholder farmers in improving seed yield of green grams.

In this study, the lowest maize grain yields were generally observed in T0M0N0 treatments. This is in agreement with research findings from studies done elsewhere; for instance, Govaerts *et al.* (2005) reported that minimum tillage (with no input from residue and nitrogen fertilizer) posted the lowest maize grain yields in the subtropical highlands of Central Mexico: the same finding was also reported by Guto *et al.* (2011) in the sub-humid highlands of Kenya.

On the other hand, Govaerts *et al.* (2005) reported that mulch retention is of importance in minimum tillage systems; but the benefits are evident after about five years for maize and wheat growing. Nitrogen fertilizer is an essential practice for incorporation with minimum tillage systems, and its role is likely more pronounced when water is not the most limiting factor to crop growth (Vanlauwe *et al.*, 2014; Sommer *et al.*, 2014). This was observed during LR2014 and SR2014 seasons. Yield decrease for maize under minimum tillage has been ascribed to poor crop establishment (Halvorson *et al.*, 2006), restricted root growth due to compaction (Cid *et al.*, 2014) and nutrient deficiencies (Rusinamhodzi *et al.*, 2011; Ogle *et al.*, 2012).

Pittelkow *et al.* (2015) performed a global meta-analysis that showed minimum tillage systems negatively impact maize. Nitrogen fertilizer is an essential practice for incorporation with no-till systems, and its role is likely more pronounced when water is not the most limiting factor to crop growth (Vanlauwe *et al.*, 2014; Sommer *et al.*, 2014). Stover yields resulted in significant combined effects throughout the experimental period except during LR2015 (Table 4.3). Conventional tillage, mulch retention, and nitrogen (CRF) treatment combination was superior in all the cropping seasons.

Jat *et al.* (2014) found that no-till plus mulch retention initially resulted in lower yields compared to conventional tillage with mulch removed in a rice-wheat

rotation in India and higher after six years. Additionally, He *et al.* (2011) in an eleven-year experiment found that mean yield advantage of no-tillage was slight in the first five years of the experiment, but the improvement to a mean value of 6.2% in the subsequent six years. This could be used for partial explanation of the results of this study and suggest additional experiment period. Improved yield under conventional tillage systems could have resulted from reduced compaction, greater mineralization or improved early season growth due to the higher soil temperatures that occur with tillage.

Under both conventional tillage and nitrogen fertilizer application and minimum tillage and nitrogen fertilizer application, grain yields were higher compared with no nitrogen fertilizer application treatments. This could be probably due to low soil N availability hence high response to nitrogen fertilization. Use of nitrogen fertilizer increased maize yields in different tillage systems (Patil and Sheelavantar, 2006).

More grain yields were also observed in mulch-retained and nitrogen fertilizer applied and no residue retained treatment combination. The results of increased stover under conventional tillage and fertilizer effects correspond with Jantalia and Halvorson (2011) who found an increase in stover yields with use of nitrogen fertilizer in the conventional tillage system. Without N fertilizer, these authors also found lowered quality in maize stover.

The influence of soil tillage on crop yields is related to its effects on nutrient and water use efficiency and root growth. The performance of minimum tillage technique is reported to be highly affected by weather conditions during the growing season (Wang *et al.*, 2006). The results of this study correspond with a study by Mehmood *et al.* (2014) who found significantly higher grain yields under conventional tillage compared to minimum tillage. Additionally, Sommer *et al.* (2012) reported that there were no significant differences in yields or yield components between minimum tillage and conventional tillage.

These findings are also in agreement with the results of previous research conducted under similar conditions, such as by Halvorson *et al.* (2006). The lower grain yield recorded under minimum tillage plots may have resulted from the slow early maize crop growth compared to the conventional tillage system (Halvorson *et al.*, 2006). Some researchers who have reported continuously lower maize yields by minimum tillage treatments as compared to conventional tillage (such as Sims *et al.*, 1998) have recommended that strategies such as pre-plant tillage may be necessary to optimize maize grain yield under minimum tillage.

Other researchers, including Kitur *et al.* (1984), have contended that lower grain yield of maize posted by minimum tillage treatments might be due to greater N immobilization and NO₃ leaching in minimum tillage as compared to conventional tillage. On the other hand, others such as Meijer *et al.* (2013) and Maltas *et al.*

(2013) have both postulated that increased soil water in the root zone is the primary factor causing plant growth and yield increase with conventional tillage.

Other researchers who have also reported lower minimum tillage yields as compared to conventional tillage yields (such as Izumi *et al.*, 2004) argue that continuous minimum tillage practice gradually improved the soil condition for the root system development. Izumi *et al.* (2004) additionally postulate that root growth was improved after consecutive years of minimum tillage practice due to the improvement of the physical properties of the soil; the penetration resistance became much favourable to the root growth in the minimum tillage treatments.

Therefore, in maize, the reduction in productivity resulting from the minimum tillage practice can be mitigated by alleviating the restraint of root growth (Khurshid *et al.*, 2006). It may well, therefore, be the case that the yield potential for maize cropping system is more strongly influenced by continuous minimum tillage system in the long run.

The results for stover yields as recorded in this study agree with findings of other researchers, including Mupangwa *et al.* (2007), who researched the effect of tillage and mulching on maize yields and water content of clayey and sandy soils. The authors in the aforementioned study, which took place in Zimbabwe, concluded that tillage methods significantly influenced stover production, with conventional

tillage systems returning the highest maize stover yields on clay soil in similar agro-ecologies in southern Africa.

These results are also in agreement with research conducted in an area with similar soils conditions in West Bengal, India, where De and Bandyopadhyay (2013) investigated the influence of soil conservation techniques on growth parameters and yield of maize. Their research conducted under smallholder farming systems in India, the authors also concluded that, despite their assumptions, conventional tillage plots returned better maize stover yields.

Save for the two seasons (LR2013 and SR2013), maize grain yields were not much different under mulch retention and no mulch retention. There could have been slow nutrient mineralization under treatments covered with mulch. Maize stover is known to have high C/N ratio (>60 to 1), and its microbial decomposition can easily lead to nitrogen immobilization (Nicolardot *et al.*, 2001; Bengtsson *et al.*, 2003; Ngetich, 2012) caused by decomposing microorganisms using existing soil nitrogen thus depleting it in soils.

Nitrogen (N) is an important nutrient that plays a vital role in plant growth and crop yield (Andrews *et al.*, 2013). Therefore, nitrogen application is essential. Soil fertility in Kirege experimental field was characterized by nitrogen deficiency and low phosphorous (Table 3.1). Therefore, strong response to N fertilizer was expected. Application of fertilizer significantly influenced maize grain yields and

stover yields (Tables 4.2 and 4.3) throughout the study period. This corroborated with the results of Mtambanengwe *et al.* (2006). The grain yields were higher in fertilizer applied level throughout the six cropping seasons. Application of nitrogen fertilizer led to increased grain and stover yields in this study.

These results are also in agreement with similar studies carried out in similar agro-ecologies, including Stanger and Lauer (2008), who reported dramatic increases in yields in response to applications of N fertilizer and concluded that nitrogen fertilization at 12 g N m⁻² input was the key to high maize grain yields and optimum economic return on smallholder farming. The study agrees with observations made by Deryng (2014) that the N₂O emission rates for maize production globally has dropped, showing that maize as a crop is mostly positively responsible to the application of N fertilizers.

The results are also in agreement with studies by Conijn *et al.* (2011), who concluded that application of 100 kg mineral N ha⁻¹ results in average rain-fed maize yields of between 2.5 and 3.5 tonnes of grain dry matter per ha across most croplands in Africa: typically, this yield will be one to three times the actual maize yields that are registered by smallholder farmers themselves when they are not using nitrogen fertilizers.

4.2.2. Maize grain and stover water use efficiency

The treatment effects of soil tillage, residue practices and nitrogen fertilization on water use efficiency (WUE) for grain yield and biomass production (WUE_{GY} and WUE_B , respectively) are presented in Tables 4.4 and 4.5. During the two cropping seasons of SR2014 and LR2015, there were significant differences in WUE_{GY} , with significantly higher WUE_{GY} of $9.6 \text{ kg ha}^{-1} \text{ mm}^{-1}$ noted in T0M0N1 in SR2014 ($p=0.018$) and $3.4 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in T1M0N1 in LR2015 ($p=0.05$) than the control (T0M0N0) (Table 4.4).

Table 4.4: Treatment effects of soil tillage, mulch management and nitrogen fertilization on water use efficiency for maize grain yield production in Kirege

Treatments	Water use efficiency in grain yield production (WUE _{GY})		
	LR2014	SR2014	LR2015
T1 M1 N1	4.4 ^a	9.1 ^a	3.0 ^{ab}
T1 M0 N1	5.5 ^a	8.5 ^a	3.4 ^a
T0 M0 N1	4.7 ^a	9.6 ^a	2.2 ^{bc}
T0 M1 N1	4.6 ^a	9.0 ^a	2.5 ^{abc}
T1 M1 N0	4.0 ^a	7.7 ^{ab}	2.1 ^{bc}
T1 M0 N0	3.5 ^a	9.2 ^a	2.0 ^{bc}
T0 M1 N0	4.3 ^a	7.6 ^{ab}	1.7 ^c
T0 M0 N0	3.1 ^a	4.1 ^b	2.1 ^{bc}
SED	0.904	1.142	0.3071
<i>p</i> -value	0.458	0.018	0.05

Note: Means with different letters in the same column indicate statistically significant differences (LSD test, $p < 0.05$)

T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

Generally, T0M0N1 (minimum tillage with mulch removed and no nitrogen fertilizer applied) had higher WUE for biomass production (WUE_B), with the highest water use efficiencies as noted in LR2014 at 13.3 kg ha⁻¹ mm⁻¹ and SR2014 at 9.6 kg ha⁻¹ mm⁻¹ ($p < 0.001$, Table 4.5). Generally, the lowest WUE_B were recorded in T0M0N0 treatments (6.3 kg ha⁻¹ mm⁻¹ and 4.1 kg ha⁻¹ mm⁻¹, in LR2014 and SR2014, respectively) (Table 4.5).

Table 4.5: Seasonal treatment effects of soil tillage, mulch management and nitrogen fertilization on water use efficiency for maize biomass production in Kirege

Treatments	Water use efficiency for biomass production (WUE_B) in maize		
	LR2014	SR2014	LR2015
T1 M1 N1	12.0 ^a	9.1 ^a	7.8 ^{ab}
T1 M0 N1	12.2 ^{ab}	8.5 ^a	8.3 ^a
T0 M0 N1	13.3 ^a	9.6 ^a	6.4 ^{bc}
T0 M1 N1	11.8 ^{ab}	9.0 ^a	6.3 ^{bc}
T1 M1 N0	10.2 ^{abc}	7.7 ^{ab}	5.2 ^{cd}
T1 M0 N0	8.6 ^{bc}	9.2 ^a	5.6 ^{cd}
T0 M1 N0	9.7 ^{abc}	7.6 ^{ab}	4.1 ^d
T0 M0 N0	6.3 ^c	4.1 ^b	4.7 ^d
SED	1.132	1.142	0.443
<i>p</i> -value	0.101	<.001	0.457

Note: Means with different letters in the same column indicate statistically significant differences (LSD test, $p < 0.05$)

T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

The type of tillage system practiced had an effect on the WUE for both grain yield and biomass production, with higher WUE_B noted in conventional tillage treatments in SR2014 and LR2015 (Table 4.5). In the two cropping seasons, WUE_{GY} was also higher under conventional tillage treatments (Table 4.4).

Generally, the residue practices implemented in the study did not significantly affect the water use efficiencies, except for a lone growth season (SR2014), when there was pointedly higher WUE_B under mulch removed treatments. Generally,

there were higher water use efficiencies in mulch removed treatments as compared to mulch retained (Tables 4.4 and 4.5).

The findings of the study show that the grain and biomass WUE of maize under conventional tillage was higher as compared to minimum tillage, suggestive of the fact that tillage played a significant role in improvement in water use efficiency. The findings in this study are in agreement with observations made by previous researchers, including Machado *et al.* (2008), who, in their study of the effects of soil tillage on water use and grain yields of wheat in Oregon, United States, determined that minimum tillage suppress water use efficiency. Similar results were also reported by Mohammad *et al.* (2006) who assessed water use efficiency as influenced by tillage under rain-fed conditions for wheat production in Peshawar, Pakistan.

Soil water use efficiency is an essential crop index used to assess how soil water is used efficiently for total biomass and grain yield production. These results are essential for identifying soil tillage and surface treatment practices that are efficient in the use of limited soil water for maize biomass and grain yield production. The appropriate farming land use practices, when adopted by smallholder farmers, can be of vital importance in enhancing sustainable maize production in the Central Highlands of Kenya, where rain-fed agriculture is mostly practiced.

Additionally, with the increasing prospects of climate change and its attendant impacts on smallholder agriculture as a result of reduced and erratic rainfall, it is important to ensure smallholder farming systems are attuned to the reality of lower precipitation. It is, therefore, imperative to adopt best-fit tillage and soil surface management regimes that could utilize, effectively and efficiently, the scarce soil water without drastically constraining crop production in the Central Highlands. These regimes have the potential of thereby sustaining maize crop production and alleviating poverty among resource-poor farmers.

4.3 The impact of soil tillage and mulch management on soil mineral N content

4.3.1 Soil mineral N concentrations during the LR2015 cropping season

The seasonal treatment effects of soil tillage practices and mulch management regimes on nitrate-nitrogen ($\text{NO}_3\text{-N}$) concentrations in the soil profile in Kirege in the long rains of 2015 (LR2015) at depths of between 0 and 80 cm are presented in Tables 4.6 and 4.7 and Figures 4.3 and 4.4. In this season, the amount of exchangeable $\text{NH}_4\text{-N}$ was low: most of inorganic N found in the soil in the depths of 0-80 cm during this season (LR2015) was in the form of $\text{NO}_3\text{-N}$. Consequently, all changes in mineral N in this season are therefore presented in terms of $\text{NO}_3\text{-N}$ concentrations (Table 4.6 and 4.7).

Table 4.6: Seasonal distribution of mineral N (kg ha^{-1}) at 0-20 and 20-40 cm soil depths during the LR2015 season in Kirege, Meru South District

Treatment	LR2015 season											
	Weeks After Planting (0-20 cm soil depth)						Weeks After Planting (20-40 cm soil depth)					
	0	4	7	10	14	20	0	4	7	10	14	20
T1 M0 N1	20.4 ^a	34.4 ^a	6.5 ^{ab}	4.4 ^a	11.6 ^a	26.3 ^a	21.6 ^a	36.1 ^a	7.5 ^a	4.4 ^a	16.5 ^a	27.1 ^a
T0 M1 N0	16.7 ^a	32.9 ^a	4.2 ^{ab}	3.5 ^a	4.2 ^a	8 ^b	10.7 ^a	26.1 ^a	10.6 ^a	3.4 ^a	16.8 ^a	27.6 ^a
T0 M0 N0	18.5 ^a	32.6 ^a	3.1 ^b	0.5 ^a	8.1 ^a	14.3 ^{ab}	14.2 ^a	25.4 ^a	7.6 ^a	3.0 ^a	16.5 ^a	21.9 ^a
T0 M0 N1	21.1 ^a	31.9 ^a	7.2 ^{ab}	2.7 ^a	11.2 ^a	18.5 ^{ab}	7.5 ^a	25.0 ^a	4.5 ^a	2.7 ^a	6.4 ^b	15.4 ^{ab}
T0 M1 N1	18.6 ^a	29.3 ^a	6.9 ^{ab}	4.4 ^a	14.5 ^a	31.0 ^a	11.4 ^a	24.7 ^a	5.3 ^a	2.0 ^a	5.0 ^b	8.1 ^c
T1 M1 N1	16.6 ^a	27.7 ^a	10.0 ^a	3.6 ^a	14.2 ^a	28.5 ^a	13.7 ^a	22.9 ^a	5.3 ^a	2.5 ^a	7.4 ^b	12.2 ^{ab}
T1 M1 N0	15.2 ^a	24.2 ^a	5.84 ^{ab}	1.5 ^a	9.7 ^a	15.5 ^{ab}	12.9 ^a	21.5 ^a	7.8 ^a	3.0 ^a	7.6 ^b	12.5 ^{ab}
T1 M0 N0	13.1 ^a	18.6 ^a	4.1 ^{ab}	2.4 ^a	6.3 ^a	12.6 ^{ab}	9.3 ^a	15.6 ^a	4.7 ^a	2.4 ^a	3.5 ^b	5.8 ^c
LSD	1.825	1.619	0.354	0.25	0.47	1.33	0.67	1.911	0.53	0.30	1.98	1.465
<i>p</i> value	0.622	0.542	0.036	0.621	0.73	0.05	0.77	0.366	0.552	0.736	0.05	0.049

Note: Means with different letters in the same column indicate statistically significant differences (LSD test, $p < 0.05$)

T1M1N1= conventional tillage + mulch retained + 120 kg N ha^{-1} , T1M1N0= conventional tillage + mulch retained + 0 kg N ha^{-1} , T1M0N1= conventional tillage + mulch removed + 120 kg N ha^{-1} , T1M0N0= conventional tillage + mulch removed + 0 kg N ha^{-1} , T0M1N1= minimum tillage + mulch retained + 120 kg N ha^{-1} , T0M1N0= minimum tillage + mulch retained + 0 kg N ha^{-1} , T0M0N1= minimum tillage + mulch removed + 120 kg N ha^{-1} , T0M0N0= minimum tillage + mulch removed + 0 kg N ha^{-1}

Table 4.7: Seasonal distribution of mineral N (kg ha^{-1}) at 40-60 and 60-80 cm soil depths during LR2015 season in Kirege, Meru South District

Note: Means with different letters in the same column indicate statistically significant differences (LSD test, $p < 0.05$)

T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹

Treatment	LR2015 season											
	Weeks After Planting (40-60 cm soil depth)						Weeks After Planting (60-80 cm soil depth)					
	0	4	7	10	14	20	0	4	7	10	14	20
T1 M0 N1	23.7 ^a	37.0 ^a	14.1 ^a	4.4 ^a	29.5 ^a	46.1 ^a	30.6 ^a	43.7 ^a	14.2 ^a	5.0 ^a	34.0 ^a	53.0 ^a
T0 M1 N0	18.4 ^a	34.7 ^a	9.5 ^{ab}	4.1 ^a	28.3 ^a	44.2 ^a	25.2 ^a	35.5 ^{ab}	13.8 ^a	4.4 ^a	30.9 ^a	48.4 ^{ab}
T0 M0 N0	18.8 ^a	30.0 ^a	6.0 ^b	3.6 ^a	13.4 ^a	21.0 ^a	24.2 ^a	28.4 ^{ab}	11.2 ^{ab}	3.8 ^a	21.0 ^{ab}	31.8 ^{ab}
T0 M0 N1	17.3 ^a	27.3 ^a	10.0 ^{ab}	4.0 ^a	13.8 ^a	21.5 ^a	18 ^a	24.4 ^{ab}	8.5 ^{ab}	3.6 ^a	16.3 ^{ab}	22.1 ^{ab}
T0 M1 N1	13.7 ^a	21.0 ^a	6.5 ^{ab}	2.4 ^a	15.4 ^a	24.1 ^a	17.2 ^a	24.3 ^{ab}	8.3 ^{ab}	2.9 ^a	13.8 ^{ab}	20.9 ^{ab}
T1 M1 N1	15.0 ^a	17.9 ^a	6.4 ^{ab}	3.2 ^a	7.2 ^a	11.3 ^a	16.0 ^a	21.1 ^{ab}	6.7 ^{ab}	2.6 ^a	13.7 ^{ab}	20.8 ^{ab}
T1 M1 N0	3.9 ^a	16.7 ^a	3.5 ^b	2.2 ^a	2.7 ^a	4.2 ^a	9.4 ^a	13.2 ^{ab}	6.7 ^{ab}	2.2 ^a	3.3 ^b	5.0 ^{ab}
T1 M0 N0	6.6 ^a	15.4 ^a	3.2 ^b	1.7 ^a	3.3 ^a	5.2 ^a	5.7 ^a	8.1 ^b	4.8 ^b	1.8 ^a	1.8 ^{ab}	2.8 ^b
LSD	2.619	1.79	0.47	0.18	1.91	3.28	3.79	1.97	0.51	0.27	1.43	2.98
<i>p</i> value	0.54	0.81	0.03	0.765	0.86	0.65	0.87	0.04	0.018	0.83	0.04	0.02

¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹
¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

During this cropping season, there was significantly high soil moisture from seeding to the tillering stages of growth (Figure 4.1). This was followed by about three weeks of meteorological drought, which lasted until just before anthesis, after which subsequently there were weeks of continuous rain until physiological maturity of the crop.

In this season, the $\text{NO}_3\text{-N}$ concentrations in all treatments decreased with increase in soil depth from 0-20 and 20-40 cm, after which the concentrations increased from 40-60 and 60-80 cm depths (Tables 4.6 and 4.7, and Figures 4.3 and 4.4). In the LR2015 season, the highest $\text{NO}_3\text{-N}$ concentrations were noted at 4 WAP across all the treatments in the 0-20 and 20-40 cm depths. Conversely, in the 40-60 and 60-80 cm depths, the highest $\text{NO}_3\text{-N}$ concentrations were recorded at 20 WAP across all the treatments.

There were significant differences in $\text{NO}_3\text{-N}$ concentrations at the 0-20, 20-40, 40-60 and 60-80 cm depths throughout the season. The highest overall increase in $\text{NO}_3\text{-N}$ concentration in the entire season between the start of the season and the end of the season was observed at the 20-40 cm depth in T0M1N0 treatment, which had higher nitrate-nitrogen accumulation of 158% at the end of the season (20 WAP) as compared to the start of the season (0 WAP) (Table 4.6). On the other hand, the highest overall decline in $\text{NO}_3\text{-N}$ concentration in the season, of -52%,

was also noted in the same treatment (T0M1N0), occurring at the 0-20 cm depth (Table 4.6).

The highest increases in $\text{NO}_3\text{-N}$ concentration between the start and end of the season in 0-20 cm depth occurred in T1M1N1 treatment, where the mineral N content increased by 77% by 20 WAP (Table 4.6). At this depth, the highest decline in mineral N content was recorded in T0M1N0 treatments, where a decline of 72% occurred. Generally, there were higher levels of residual nitrate-nitrogen accumulations in the lower 40-60 and 60-80 cm depths at 20 WAP (Table 4.7), while the upper 0-20 and 20-40 cm depths generally had declined by the end of the season (Table 4.6).

In the initial 0-20 cm depth, there were significant differences at 7 WAP ($p=0.036$) and 20 WAP ($p=0.05$) (Table 4.6), with the highest mineralization noted in the T1M1N1 treatments in both weeks (respectively, 10 kg N ha^{-1} and $29.3 \text{ kg N ha}^{-1}$), and the lowest in T0M0N0 and T0M1N0, respectively. At the 20-40 cm depth, there were significant differences at 14 WAP ($p=0.05$) and 20 WAP ($p=0.049$), with the T0M1N1 treatments accounting for the highest net mineralization ($16.8 \text{ kg N ha}^{-1}$ and $27.6 \text{ kg N ha}^{-1}$), and T1M0N0 with the lowest mineral N content, during both instances (Table 4.6).

In the 40-60 cm depth, there were only significant differences in mineral N concentrations during the 7 WAP ($p=0.03$), T1M0N1 treatment accounting for the

highest $\text{NO}_3\text{-N}$ concentrations of $14.1 \text{ kg N ha}^{-1}$ (Table 4.7). In the 60-80 cm depth, there were significant differences in mineralization noted in 4 WAP ($p=0.04$), 7 WAP ($p=0.018$), 14 WAP ($p=0.04$) and 20 WAP ($p=0.02$). The highest mineralization in all these weeks noted in T1M0N1 treatment (respectively, $43.7 \text{ kg N ha}^{-1}$, $14.2 \text{ kg N ha}^{-1}$, 34 kg N ha^{-1} and 53 kg N ha^{-1}) (Table 4.7). At this depth (60-80 cm), the lowest mineralization in all the growing season was noted in the T1M0N0 treatment (Table 4.7).

In the 0-20 cm soil depth, the $\text{NO}_3\text{-N}$ concentrations ranged from a high of $34.5 \text{ kg N ha}^{-1}$ (T1M0N1 treatments at 4 WAP) to a low of 0.5 kg N ha^{-1} (T0M0N0 treatments at 10 WAP) (Table 4.6). In the next 20-40 cm soil depth, the $\text{NO}_3\text{-N}$ concentrations ranged from a high of $36.1 \text{ kg N ha}^{-1}$ (T1M0N1 treatments at 4 WAP) to a low of 2.0 kg N ha^{-1} (T0M1N1 treatments at 10 WAP) (Table 4.6). In the deepest profile examined, 0-80 cm, the $\text{NO}_3\text{-N}$ concentrations ranged from a low of 1.8 kg N ha^{-1} (T1M0N0 treatments at 10 WAP) to a high of 53 kg N ha^{-1} (T1M0N1 treatments at 20 WAP) (Table 4.7).

During the LR2015 season, there was also a noticeable overall increase of $\text{NO}_3\text{-N}$ from the start of the planting season (0 WAP) all the way to 4 WAP, with soil N mineralization reaching a peak at 4 WAP ($34.5 \text{ kg NO}_3\text{-N ha}^{-1}$ in the T1M0N1 treatments) at the depth 0-20 cm (Figure 4.3). This peak in nitrate-N concentrations at this time was attributed to the adequate moisture and greater microbial activity in the T1M0N1 treatments that may have encouraged higher

levels of mineralization in these treatments (in the absence of crop mulch). The enhanced mineralization could have occurred in the LR2015 season in the context of permissive temperatures and moist soil obtaining at this time in the planting season, which was immediately after the onset of the rain.

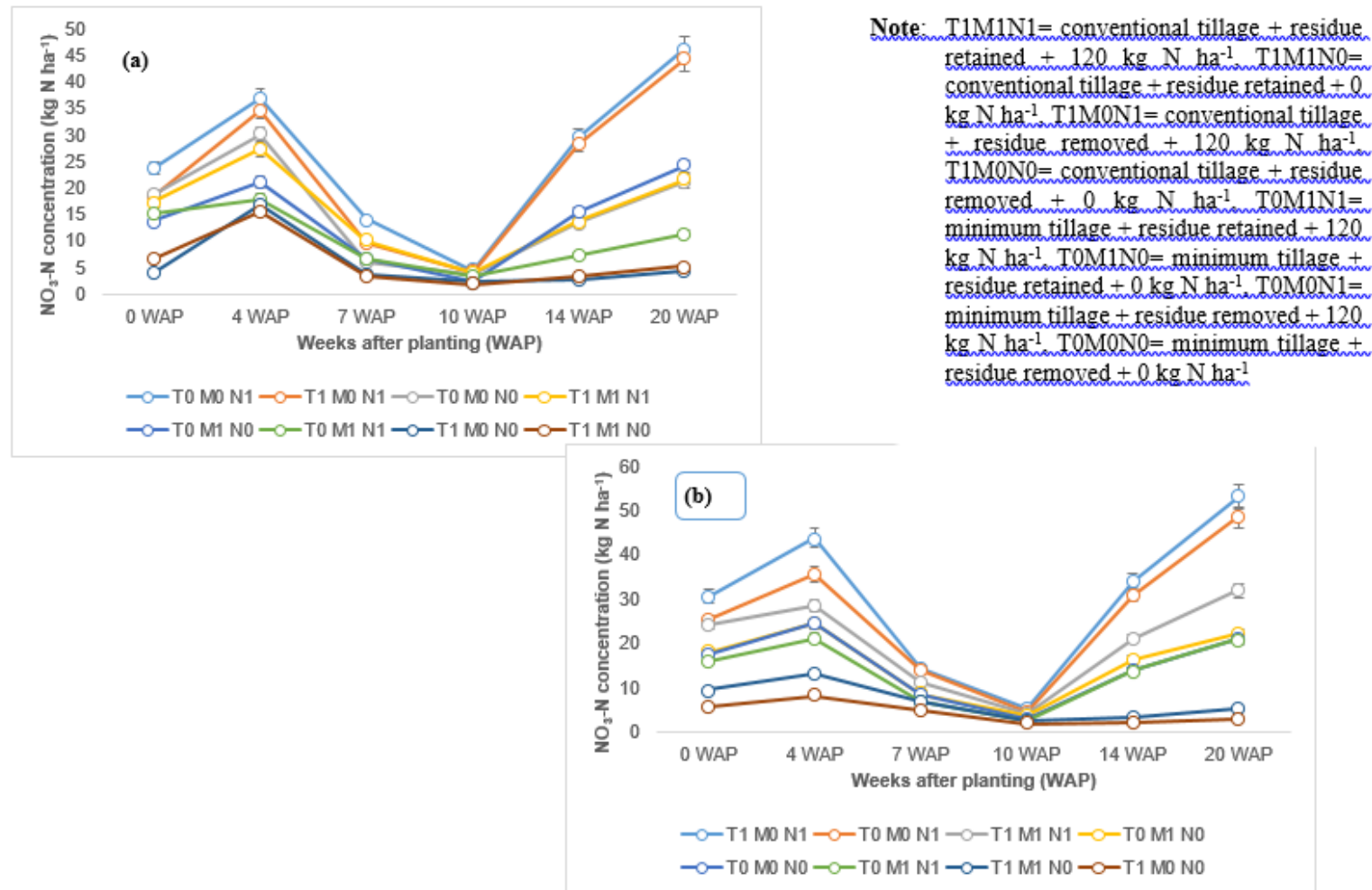


Figure 4.3: Seasonal effects of soil tillage and mulch management on NO₃-N concentrations at (a) 0-20 cm and (b) 20-40 cm depths and at different times in the LR15 cropping season in Kirege

The N mineralization peak at 4 WAP in the surface 0-20 cm depth was subsequently followed by a decrease that started at 7 WAP till 14 WAP (Figure 4.3). From 14 WAP onwards, there was again an increase in NO₃-N, that lasted until 20 WAP (Figure 4.3). In contrast, the lowest NO₃-N concentrations were noted in the 10 WAP, with the significant decrease in NO₃-N concentrations observed in this period attributed to the cooler soil temperatures obtaining at that time and the moister soils, which may have encouraged denitrification.

The fact that generally, much more nitrate-nitrogen accumulated at the end of the LR2015 season in 40-60 cm and 60-80 cm depths than was recorded at the beginning of the season has great importance in terms of nitrogen fertilizer application (Figure 4.4). It was noted during this season that tillage influenced nitrogen mineralization, as can be noted in the generally higher levels of nitrogen mineralization in minimum tillage treatments in all depths throughout the season from 4 WAP (Tables 4.6 and 4.7).

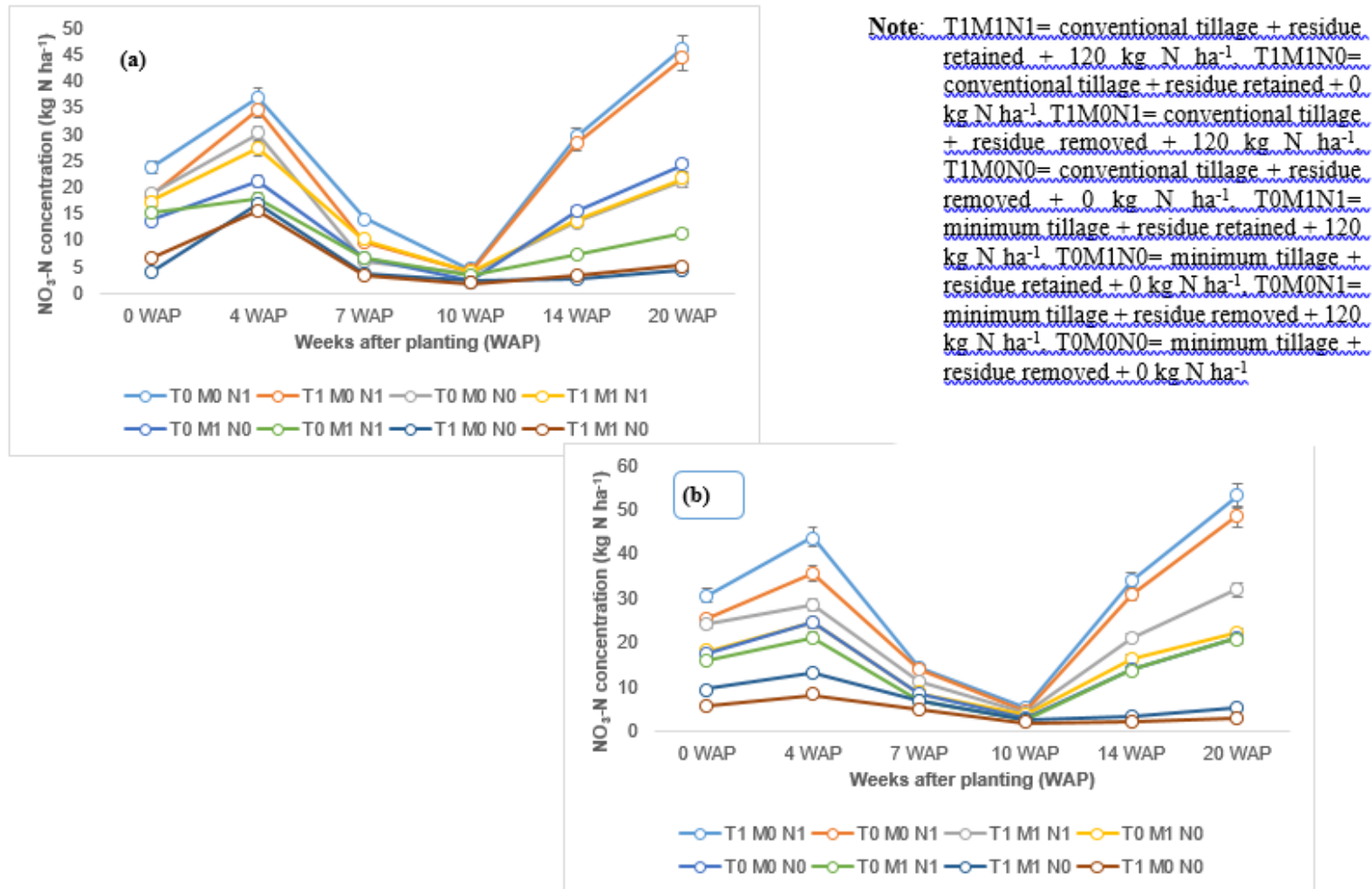


Figure 4.4: Seasonal effects of soil tillage and mulch management on NO₃-N concentrations at (a) 40-60 cm and (b) 60-80 cm depths and at different times in the LR15 cropping season in Kirege

The significant increase in $\text{NO}_3\text{-N}$ deeper in the soil profile noted at 14 and 20 WAP in the minimum tillage treatments in the subsoil (depths of 60-80 cm) could be attributed to the effects of leaching, as the cold conditions obtaining at this time were not favourable for immobilization (or mineralization) to occur, with a concurrent decline in microbial activity. Furthermore, when the maize crop was harvested in early August, any subsequent accumulation in N would have moved through the soil profile, reaching deeper depths, unhindered by crop uptake.

The type of mulch management practices implemented in the research (mulch retained and mulch removed) had much more influence than tillage systems on the soil mineral N concentrations, especially at 0, 4 and 7 WAP. There was higher mineralization of soil nitrogen in treatments with no mulch retained. There were higher levels of net N mineralization in mulch-removed treatments at 0 WAP, 4 WAP, and 7 WAP. In the 0-20 cm depths, there was higher nitrogen mineralization in mulch retained treatments, while in all the other three depths (20-40, 40-60 and 60-80 cm), the reverse was true, with more net mineralization under mulch removed treatments (Tables 4.6 and 4.7).

The variations in $\text{NO}_3\text{-N}$ concentrations across the profile might have been due to the high demand for N in the study area's predominating Humic Nitisols (which have been characterized earlier in this study (Table 3.1) as having low organic matter and poor aeration status because of the high clay content), which may have led to significant denitrification.

The results indicate that considerable N mineralization occurred between the seeding and tillering stages of the maize crop (which occurred in this season approximately 4 WAP), as well as between anthesis and maturity stages of the crop under somewhat drier conditions (as the long rains tapered off). This pattern of NO₃-N concentration variations across the maize planting timeline agrees with the findings of Mugwe *et al.* (2011), who assessed soil inorganic N and N uptake by maize in the same geography.

These results are in agreement with the findings of Mucheru-Muna (2008) and Chirwa *et al.* (2006), who both reported declining mineral N concentrations, especially in the top 0-20 cm and in seasons with adequately distributed rainfall, such as was the case during the LR2015 cropping season in this study. These results also correspond with findings reported by Devkota *et al.* (2013), who investigated tillage and nitrogen fertilization effects on yield and nitrogen use efficiency of irrigated cotton, and by Mehdi and Madramootoo (1999), who studied soil nitrate distribution under grain and silage maize using three tillage practices on a loamy sand in south-western Quebec, Canada.

4.3.2 Soil mineral N concentrations during the SR2015 cropping season

The treatment effects of soil tillage practices and mulch management regimes on nitrate-N concentration in the soils in Kirege in the short rains of 2015 (SR2015) cropping season are presented in Tables 4.8 and 4.9. In this season, the NO₃-N

concentrations in all treatments generally increased with increase in soil depth from 0-20 and 20-40 cm, after which the concentrations reduced from 40-60 but again increased in the 60-80 cm depths (Tables 4.8 and 4.9). As in the preceding season (LR2015), in this cropping season, the highest $\text{NO}_3\text{-N}$ concentrations in the depths were noted at 4 WAP across all the treatments. However, unlike the preceding season, the lowest $\text{NO}_3\text{-N}$ concentrations were noted at 14 WAP in all the treatments (Tables 4.8 and 4.9).

In the 0-20 cm soil depth, the $\text{NO}_3\text{-N}$ concentrations ranged from a high of 87.8 kg N ha^{-1} (T1M0N1 treatments at 4 WAP) to a low of 2.9 kg N ha^{-1} (T1M0N0 treatments at 14 WAP) (Table 4.8). In the subsequent depth of 20-40 cm, the $\text{NO}_3\text{-N}$ concentrations ranged from a high of 119 kg N ha^{-1} (T1M0N1 treatments at 4 WAP) to a low of 2.4 kg N ha^{-1} (T0M0N1 treatments at 14 WAP) (Table 4.8). In the deepest profile examined, 60-80 cm, the $\text{NO}_3\text{-N}$ concentrations ranged from a low of 4 kg N ha^{-1} (T1M1N1 treatments at 14 WAP) to a high of 104 kg N ha^{-1} (T1M0N1 treatments at 4 WAP) (Table 4.9).

Table 4.8: Seasonal distribution of mineral N (kg ha^{-1}) at 0-20 and 20-40 cm soil depths during the SR2015 season in Kirege, Meru South District

Treatment	SR2015 season											
	Weeks After Planting (0-20 cm soil depth)						Weeks After Planting (20-40 cm soil depth)					
	0	4	7	10	14	20	0	4	7	10	14	20
T1 M0 N1	45.6 ^a	87.7 ^a	16.1 ^a	15.35 ^a	5.33 ^a	11.58 ^a	46.5 ^a	119 ^a	18.9 ^a	27.0 ^a	8.0 ^a	11.6 ^a
T0 M1 N0	43.2 ^a	83.8 ^a	17.5 ^a	21.75 ^a	3.15 ^a	6.41 ^a	38.0 ^a	97 ^a	29.5 ^a	13.9 ^a	4.0 ^a	8.0 ^a
T0 M0 N0	41.1 ^a	79.2 ^a	18.1 ^a	19.86 ^a	4.78 ^a	10.41 ^a	36.0 ^a	92 ^a	17.9 ^a	17.4 ^a	6.6 ^a	10.8 ^a
T0 M0 N1	38.5 ^a	73.2 ^a	10.1 ^a	23.22 ^a	4.12 ^a	8.96 ^a	34.3 ^a	88 ^a	12.8 ^a	20.6 ^a	4.0 ^a	7.0 ^a
T0 M1 N1	36.9 ^a	71.1 ^a	17.2 ^a	15.09 ^a	4.10 ^a	8.91 ^a	33.0 ^a	84 ^a	21.5 ^a	33.3 ^a	18.7 ^a	30.7 ^a
T1 M1 N1	36.6 ^a	69.9 ^a	11.3 ^a	33.44 ^a	4.89 ^a	10.17 ^a	31.2 ^a	80 ^a	45.1 ^a	23.3 ^a	5.4 ^a	9 ^a
T1 M1 N0	32.9 ^a	63.3 ^a	17.5 ^a	22.87 ^a	5.73 ^a	14.64 ^a	28.7 ^a	73 ^a	27.0 ^a	13.0 ^a	14.2 ^a	23.3 ^a
T1 M0 N0	31.4 ^a	58.6 ^a	24.6 ^a	12.98 ^a	2.89 ^a	6.28 ^a	26.7 ^a	68 ^a	18.5 ^a	24.3 ^a	5.1 ^a	8.4 ^a
LSD	26.81	30.44	25.77	16.81	18.54	10.48	16.81	50.14	40.34	17.54	23.18	28.29
<i>p</i> value	0.755	0.315	0.359	0.855	0.532	0.633	0.785	0.733	0.803	0.502	0.351	0.288

Note: Means with different letters in the same column indicate statistically significant differences (LSD test, $p < 0.05$)

T1M1N1= conventional tillage + mulch retained + 120 kg N ha^{-1} , T1M1N0= conventional tillage + mulch retained + 0 kg N ha^{-1} , T1M0N1= conventional tillage + mulch removed + 120 kg N ha^{-1} , T1M0N0= conventional tillage + mulch removed + 0 kg N ha^{-1} , T0M1N1= minimum tillage + mulch retained + 120 kg N ha^{-1} , T0M1N0= minimum tillage + mulch retained + 0 kg N ha^{-1} , T0M0N1= minimum tillage + mulch removed + 120 kg N ha^{-1} , T0M0N0= minimum tillage + mulch removed + 0 kg N ha^{-1}

Table 4.9: Seasonal distribution of mineral N (kg ha^{-1}) at 40-60 and 60-80 cm soil depths during the SR2015 season in Kirege, Meru South District

Treatment	SR2015 season											
	Weeks After Planting (40-60 cm soil depth)						Weeks After Planting (60-80 cm soil depth)					
	0	4	7	10	14	20	0	4	7	10	14	20
T1 M0 N1	63.0 ^a	94.0 ^a	43.6 ^a	18.5 ^a	8.8 ^a	13.4 ^a	46.4 ^a	104.4 ^a	52.8 ^a	44.5 ^a	21.3 ^a	39.8 ^a
T0 M1 N0	60.5 ^a	88.8 ^a	56.4 ^a	16.8 ^a	4.0 ^a	6.1 ^a	40.6 ^a	88.9 ^a	28.1 ^a	17.4 ^a	12.1 ^a	18.9 ^a
T0 M0 N0	59.0 ^a	88.1 ^a	47.2 ^a	12.7 ^a	8.0 ^a	15.1 ^a	39.0 ^a	87.7 ^a	28.3 ^a	26.1 ^a	5.4 ^a	10.2 ^a
T0 M0 N1	55.7 ^a	83.2 ^a	19.8 ^a	16.8 ^a	6.4 ^a	9.8 ^a	38.9 ^a	87.6 ^a	61.6 ^a	16.6 ^a	15.0 ^a	28.0 ^a
T0 M1 N1	54.0 ^a	82.2 ^a	20.1 ^a	22.7 ^a	7.2 ^a	9.4 ^a	35.9 ^a	78.5 ^a	71.3 ^a	13.1 ^a	3.7 ^a	6.9 ^a
T1 M1 N1	54.5 ^a	81.4 ^a	37.3 ^a	20.1 ^a	6.1 ^a	9.2 ^a	33.1 ^a	74.4 ^a	43.9 ^a	18.4 ^a	2.4 ^a	4.4 ^a
T1 M1 N0	46.1 ^a	71.8 ^a	44.7 ^a	37.9 ^a	14.2 ^a	21.5 ^a	31.0 ^a	72.0 ^a	49.8 ^a	28.9 ^a	12.5 ^a	27.0 ^a
T1 M0 N0	39.4 ^a	58.1 ^a	22 ^a	19.2 ^a	5.8 ^a	8.8 ^a	30.4 ^a	68.5 ^a	25.2 ^a	26.5 ^a	7.5 ^a	14.0 ^a
LSD	15.19	62.01	36.11	17.59	11.24	17.89	14.12	64.5	45.2	21.24	13.89	33.2
<i>p</i> value	0.868	0.44	0.889	0.104	0.397	0.918	0.56	0.358	0.999	0.597	0.418	0.945

Note: Means with different letters in the same column indicate statistically significant differences (LSD test, $p < 0.05$)

T1M1N1= conventional tillage + mulch retained + 120 kg N ha^{-1} , T1M1N0= conventional tillage + mulch retained + 0 kg N ha^{-1} , T1M0N1= conventional tillage + mulch removed + 120 kg N ha^{-1} , T1M0N0= conventional tillage + mulch removed + 0 kg N ha^{-1} , T0M1N1= minimum tillage + mulch retained + 120 kg N ha^{-1} , T0M1N0= minimum tillage + mulch retained + 0 kg N ha^{-1} , T0M0N1= minimum tillage + mulch removed + 120 kg N ha^{-1} , T0M0N0= minimum tillage + mulch removed + 0 kg N ha^{-1}

The pattern of soil nitrate-N distributions in the short rains season of 2015 (SR2015) followed a similar configuration as that of the preceding season (LR2015), except for the noticeably much higher $\text{NO}_3\text{-N}$ levels in this season (Figure 4.5 and 4.6). The increased levels of nitrate-N leaching could be attributed to the much higher levels of precipitation that fell at the start of the season (Figures 4.1 and 4.2, and Table 4.1), which was also well distributed throughout the season, and which exponentially increased plant growth rate and N uptake.

There were no significant of between soil tillage and mulch management treatments on $\text{NO}_3\text{-N}$ concentrations during the entire growing period in the SR2015 season. However, the results generally showed that $\text{NO}_3\text{-N}$ concentration was highest under minimum tillage and no mulch retention effects in all the sampled depths during the first 4 and 7 weeks after planting in LR2015. The least mineralization in these weeks (4 and 7) in this season was noted in conventional tillage and mulch retained combination treatment (0-20 cm and 60-80 cm depths) and minimum tillage and mulch retained treatment (20-40 cm and 40-60 cm depths) (Figure 4.5 and 4.6). Additionally, it was noted that nitrate-N concentration in this season (LR2015) was the highest in the top depth (0-20 cm) compared to the last sampled depth (60-80 cm) at the beginning of the season (Figure 4.5 and 4.6).

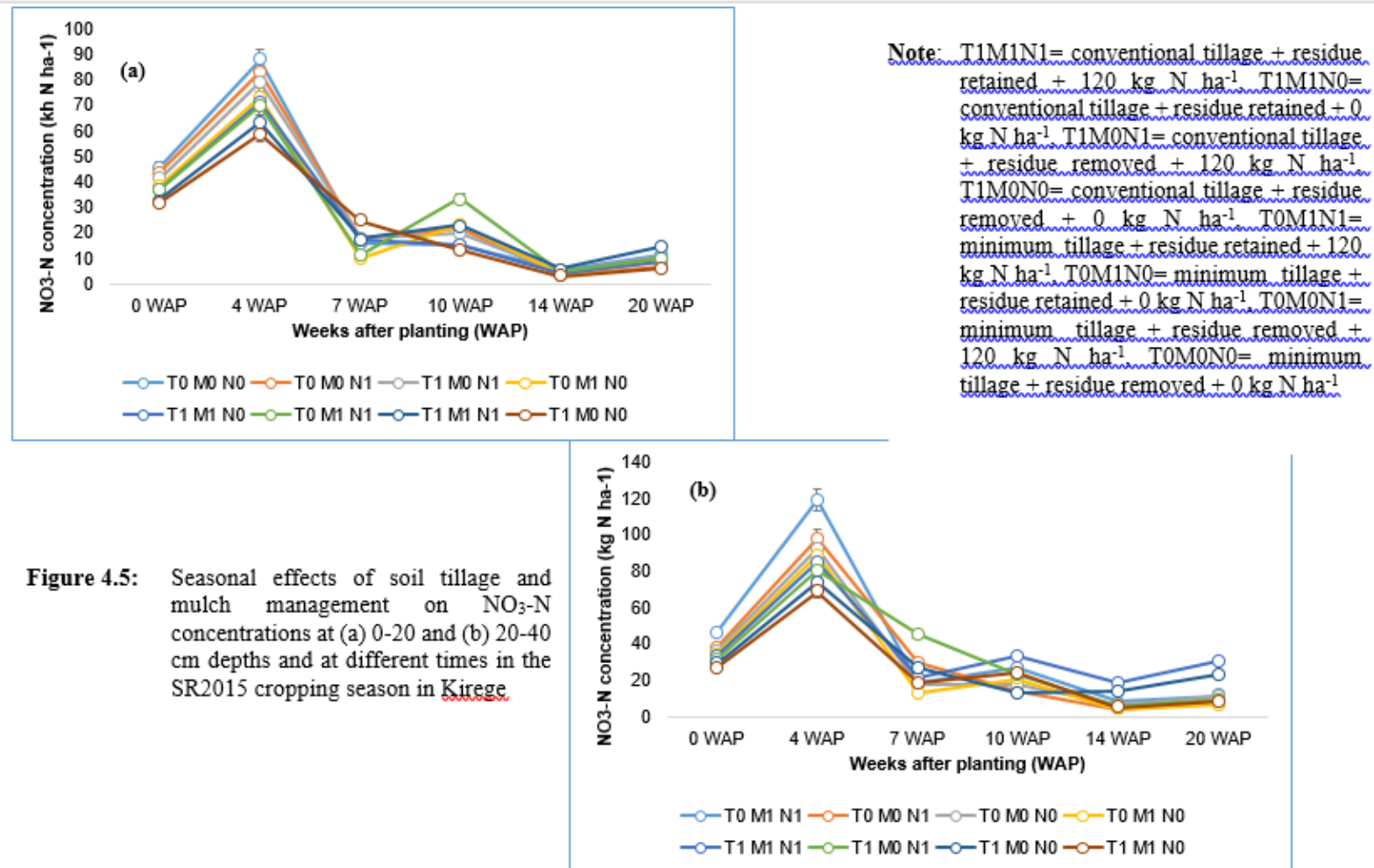


Figure 4.5: Seasonal effects of soil tillage and mulch management on NO₃-N concentrations at (a) 0-20 and (b) 20-40 cm depths and at different times in the SR2015 cropping season in Kirege.

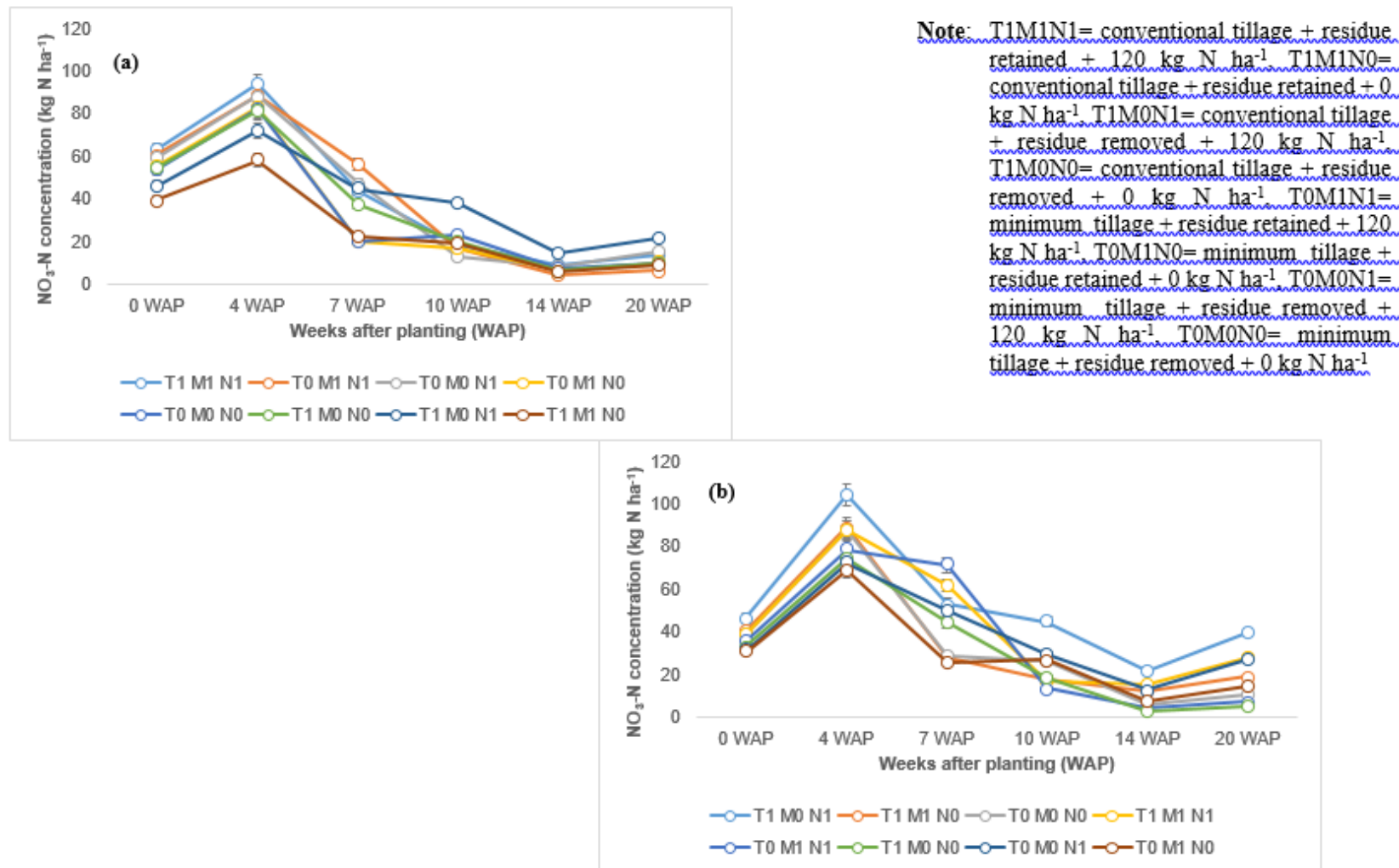


Figure 4.6: Seasonal effects of soil tillage and mulch management on NO₃-N concentrations at (a) 40-60 and (b) 60-80 cm depths and at different times in the SR2015 cropping season in Kirege

In August (20 WAP), NO₃-N concentration increased in all the depths; however, there were no significant effects. On the other hand, nitrate concentration was high in 60-80 cm depth without residue application at the end of the season, which could be ascribed to NO₃-N leaching (Table 4.9). The effects of mulch retention had a high concentration on NO₃-N in the top depth at the end of the season, which could be as a result of reduced N leaching.

In the short rains of 2015 (SR2015), mulch retained under conventional tillage systems had a high nitrate-N concentration in the last sampling depth (60-80 cm) (Table 4.9). The continuous decrease in NO₃-N concentration was observed in all the depths throughout the short rains 2015 season. On the other hand, nitrate concentration was high in the last sampled depth during the SR2015 season, which could be as a result of NO₃-N leaching (Table 4.9) since the SR2015 season recorded the highest amount of rainfall (Figure 4.1), which could have facilitated nutrient leaching.

There was a strong correlation between maize grain yields and soil mineral N concentrations in the long rains of 2015 (LR2015), but a weaker correlation during the short rains season, SR2015 (Table 4.10). The correlation in the long rains was especially strong at 20 WAP in LR2015, $r^2=0.65$.

Table 4.10: Relationship between maize grain yields and mineral N concentrations in two cropping seasons in Kirege

The correlation coefficient (r)

	0-20 cm		20-40 cm		40-60 cm		60-80 cm	
WAP	LR2015	SR2015	LR2015	SR2015	LR2015	SR2015	LR2015	SR2015
4	0.1755	-0.3139	0.4098	0.0133	0.3754	0.0672	0.5333	-0.0872
7	0.5105	0.2187	0.3054	0.0043	0.416	0.0946	0.4917	0.2123
10	0.3895	0.3497	0.3716	0.3998	0.3873	0.2056	0.2183	0.1578
20	0.6502	0.2896	0.5426	0.0574	0.3341	0.2265	0.5072	0.3208

Nitrogen (N) is one of the essential nutrients for maize plant growth. Conversely, its often the most limiting nutrient for crop production (Lobell, 2007) in most agricultural systems due to the large amounts harvested with the crops and because it can easily be lost through leaching, gaseous losses, runoff or erosion (Rufino *et al.*, 2006). Available N (nitrate-N) concentrations in soil varied during the two cropping periods. Generally, mineral nitrogen concentrations in all depths were observed to be higher during SR2015 compared to LR2015. This could be attributed to the high amount of rainfall experienced during the SR2015 season (Figures 4.1) hence more water in the soil. According to Anga *et al.* (2006), more water in the soil provides better conditions for N mineralization.

Towards the end of the cropping seasons, $\text{NO}_3\text{-N}$ concentrations were observed to be higher under mulch retention treatments. This could have been because of surface application of the residue which tends to decompose slowly. The higher amounts of mineral nitrogen under mulch retention treatments in the top depth as both seasons progressed could be attributed to reduced ammonia volatilization and N leaching and favourable soil water and temperature conditions. Su *et al.* (2014)

reported an increase in N uptake in the mulched treatment than in the un-mulched treatment.

On their part, Schomberg *et al.* (1994) reported that surface residues tend to decompose more slowly than soil-incorporated residues, as a result of more significant fluctuations in surface temperature, moisture and reduced availability of nutrients to microbes colonizing the surface residue. Besides, Huang *et al.* (2008) also reported that minimum tillage systems with stubble retained resulted in the highest plant N uptake due to higher soil available water.

High mineral N concentration was observed at the beginning of the two seasons (LR2015 and SR2015) in the two tillage systems which could be ascribed to 'N flush'. The N flush phenomenon is a result of topsoil rewetting (Oikeh *et al.*, 2003). However, $\text{NO}_3\text{-N}$ content was higher at the beginning of the two seasons under MT compared to conventional tillage. Excluding tillage reduces nitrogen mineralization (Lindn, 1994; Davies *et al.*, 1996), thus higher nitrogen values under minimum tillage as compared to conventional tillage during the two seasons.

Wright *et al.* (2005) also found mineralizable nitrogen was highest under no-tillage and minimum tillage in surface soils for corn. A decline in available N was observed in this study during the active growth period in the two seasons which could be as a result of crop uptake as also reported by (Kushwaha *et al.*, 2000).

In a long-term experiment, Plaza-Bonilla *et al.* (2014) found that soil NO₃-N content was higher under conventional tillage compared to no-tillage in the topsoil in the last months of a season as also observed during the LR2015 and SR2015 seasons. High concentration of NO₃-N towards the end of the season was also observed by Shisanya *et al.* (2009) in a study conducted in the Central Highlands of Kenya. Wyngaard *et al.* (2012) found that tillage systems affected nitrogen in the top layer, where minimum tillage had higher values relative to conventional tillage as observed at the beginning in the two seasons in this study.

Continuous soil tillage could also have enhanced downward movement of mineral N under conventional tillage system. Using stable isotopes, Busari *et al.* (2016) noted a general depletion in nitrogen under minimum tillage compared with conventional tillage and reported this to be an indication of high nitrogen mineralization and subsequent volatilization that occurred under conventional tillage as against carbon sequestration taking place under minimum tillage. This implies a possibility of minimum tillage reducing soil nitrogen leaching (Yagioka *et al.*, 2015) and volatilization to the atmosphere.

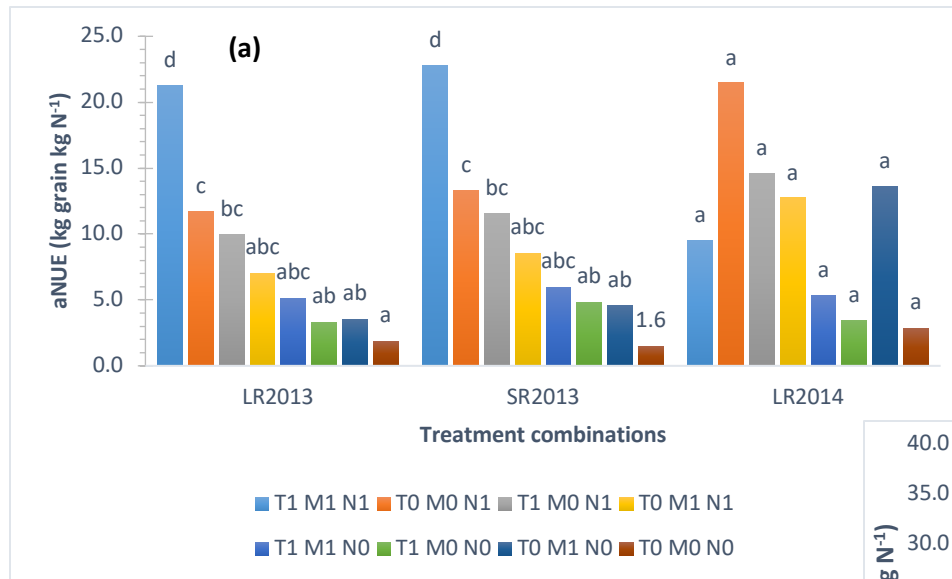
Generally, mineral NO₃-N was higher under conventional tillage compared to minimum tillage during crop maturity period. Higher concentration of NO₃-N to NH₄-N under conventional tillage compared to minimum tillage could have been a result of nitrification inhibition in minimum tillage soils. Nitrification results in increased yield and increased N-use efficiency (Bhatia *et al.*, 2010).

The strong coefficient of correlation between maize grain yields and mineral N concentration in the soil noted in this study is in agreement with previous research, such as Ikerra *et al.* (1999), who reported a strong correlation of $r^2 = 0.92$ in her study of the relationship between topsoil inorganic N and maize yields in Gliricidia intercropping.

4.3.3 Nutrient use efficiency and apparent N recovery

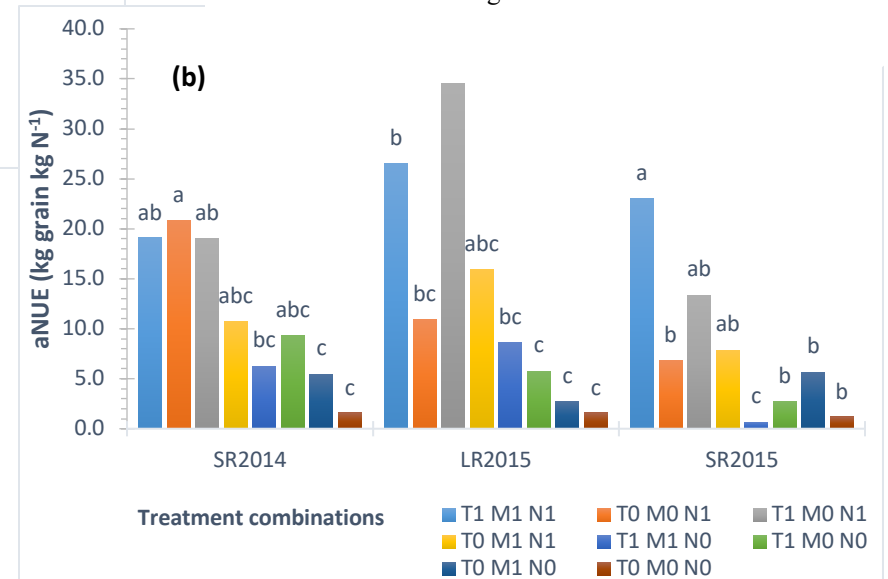
The effects of soil tillage, mulch management and nitrogen fertilization on agronomic nitrogen use efficiency (aNUE) for six consecutive cropping seasons in Kirege are presented in Figure 4.7 “a” and “b”. Neither tillage nor mulch management practices had any significant impact on aNUE in any of the seasons during the experimental period. The aNUE in the research area ranged from a low of 0.7 kg grain kg N⁻¹ under T1M1N0 in LR2014, to a high of 35 kg grain kg N⁻¹ in LR2015 in T1M0N1 treatments (Figure 4.7).

Generally, the lowest aNUE rates were noted in T0M0N0 treatments. On average, the season with the highest aNUE rates was LR2015 (Figure 4.2), which was an exceptionally wet season, while the season with the lowest rainfall totals, SR2013 (Figure 4.1), was also the season with the lowest aNUE rates, showing the correlation between the amount of rainfall recorded and the aNUE performance (Figure 4.7).



Note: T1M1N1= conventional tillage + residue retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + residue retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + residue removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + residue removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + residue retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + residue retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + residue removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + residue removed + 0 kg N ha⁻¹

Figure 4.7: Seasonal effects of soil tillage, mulch management and nitrogen fertilization on agronomic nitrogen use efficiency (aNUE) in (a) LR2013, SR2013 and LR2014 and (b) SR2014, LR2015 and SR2015 cropping seasons in Kirege



Relative to the other treatments, the results of this study show that both T0M0N1 and T1M1N1 and to a lesser extent, T1M0N1, appear to have improved nitrogen use efficiency through reducing nitrogen loss to leaching and denitrification. This is very crucial as it is worth noting that in the intensive smallholder agriculture practiced in the arable Central Highlands of Kenya, N supply is often much less than the crop requirements. The results show that there was a significant effect for the types of tillage practices and mulch management options implemented. In the LR2013, SR2013 and LR2015 seasons, there was notably higher aNUE for conventional tillage treatments (Figure 4.7).

Generally, there were higher levels of aNUE under conventional tillage treatments (long-term mean of 12.2 kg grain kg N⁻¹), as compared to minimum tillage treatments (long-term mean of 8.8 kg grain kg N⁻¹) (Figure 4.7). Retention of residue on soil surface improved aNUE, with mulch retained treatments significantly enhancing aNUE in LR2013 and SR2013 (Figure 4.7). However, the long-term means for mulch retained and mulch removed treatments were much closer.

The effects of soil tillage, mulch management regimes and nitrogen fertilization on mineral N recovery during the short rains of 2015 (SR2015) are presented in Figure 4.8. Apparent recovery efficiency of nitrogen (ARE_N) was observed at both 10 and 20 WAP in all treatments, except for T1M1N0 and T0M0N0, treatments, which had no nitrogen fertilizer applied (Figure 4.8).

Generally, T1M1N1 (conventional tillage, nitrogen fertilizer applied and mulch retained) treatments had the more superior ARE_N in the season, with the highest nitrogen recovery of 34 kg N ha^{-1} observed at 26 WAP (in December 2015 and January 2016, Figure 4.8). There was much less nitrogen recovery at 26 WAP under all treatments, especially under the treatments with no nitrogen fertilizer applied (including T0M0N0). In minimum tillage treatments with mulch retained, nitrogen recovery was only observed at 20 WAP. Nitrogen recovery was highest under nitrogen application level at 20 WAP compared to all other levels.

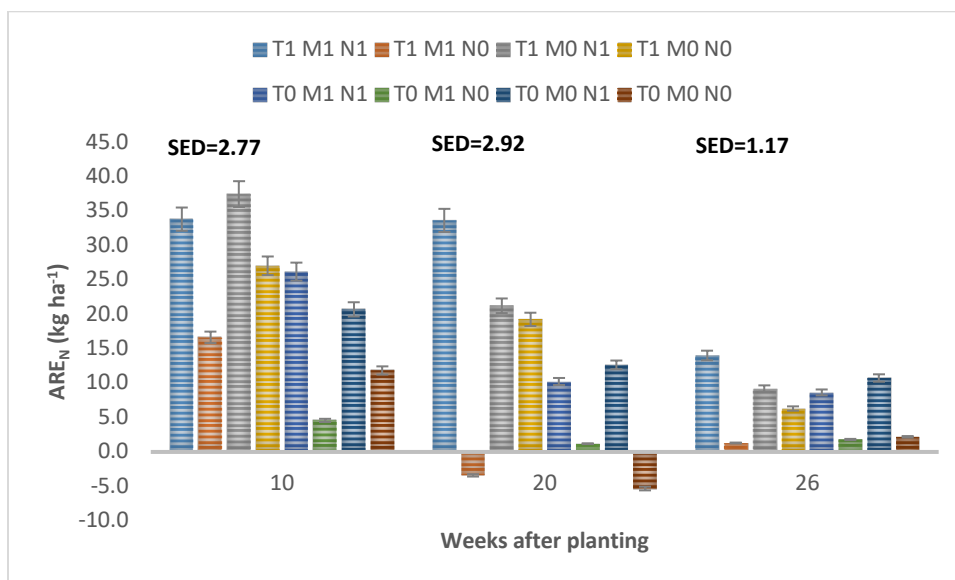


Figure 4.8: Effects of tillage and soil surface treatment on apparent N recovery during short rain 2015 season.

Note: T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

Significant nitrogen recovery under fertilized levels was also reported by Sepaskhah and Barzegar (2010) who found higher rice grain protein contents and nitrogen recovery efficiency in nitrogen applied treatments. However, these results are in contrast with Qiao (2012) who reported nitrogen use efficiency to be highest in control treatments compared to treatments with increased N application rate.

Higher grain yields were also observed in this study during SR2015 (Table 4.2) which could be attributed to high rainfall amount (Figure 4.1) and N recovery (Figure 4.8) at 20 WAP. This is usually the time in the growing season when maize crop is at flowering (production of a photosynthetically active canopy) and physiological maturity phenological stages (remobilization of canopy-N to the developing grain during crop maturation) (Okeyo *et al.*, 2014), whose functionality strongly influences yield. Low ARE_N in no nitrogen treatments could be due to continuous soil N mining. Sheldrick and Lingard (2004) argued that in most countries soils are mined of N where adequate N fertilizers are not applied.

Reduced nitrogen loss under mulch retention treatments (Figures 4.5 and 4.6) could have been a result of high rainfall amount during the SR2015 season (Figure 4.1) which may have favoured N mineralization. This corroborates with the results of Fischler *et al.* (1999) in a study conducted in Uganda. In a study by Limon-Ortega *et al.* (2000), results showed that treatments with crop mulch retention showed a tendency for more nitrogen uptake. Su (2014) reported significant plant N uptake in the treatments with nitrogen fertilizer compared with the treatments with no nitrogen.

There were no significant effects on nitrogen use efficiency between tillage and fertilization. This was also observed by Angas and Lampurlane (2003) under tillage and fertilization combination in a study conducted in the Mediterranean semiarid rain-fed conditions of Spain. Ghuman and Sur (2001) reported a higher

mean N uptake in the minimum tillage with mulch retention treatment, though the effect of tillage and residue was not significant compared with conventional tillage treatments.

4.4 Effects of soil tillage and mulching practices on soil water content

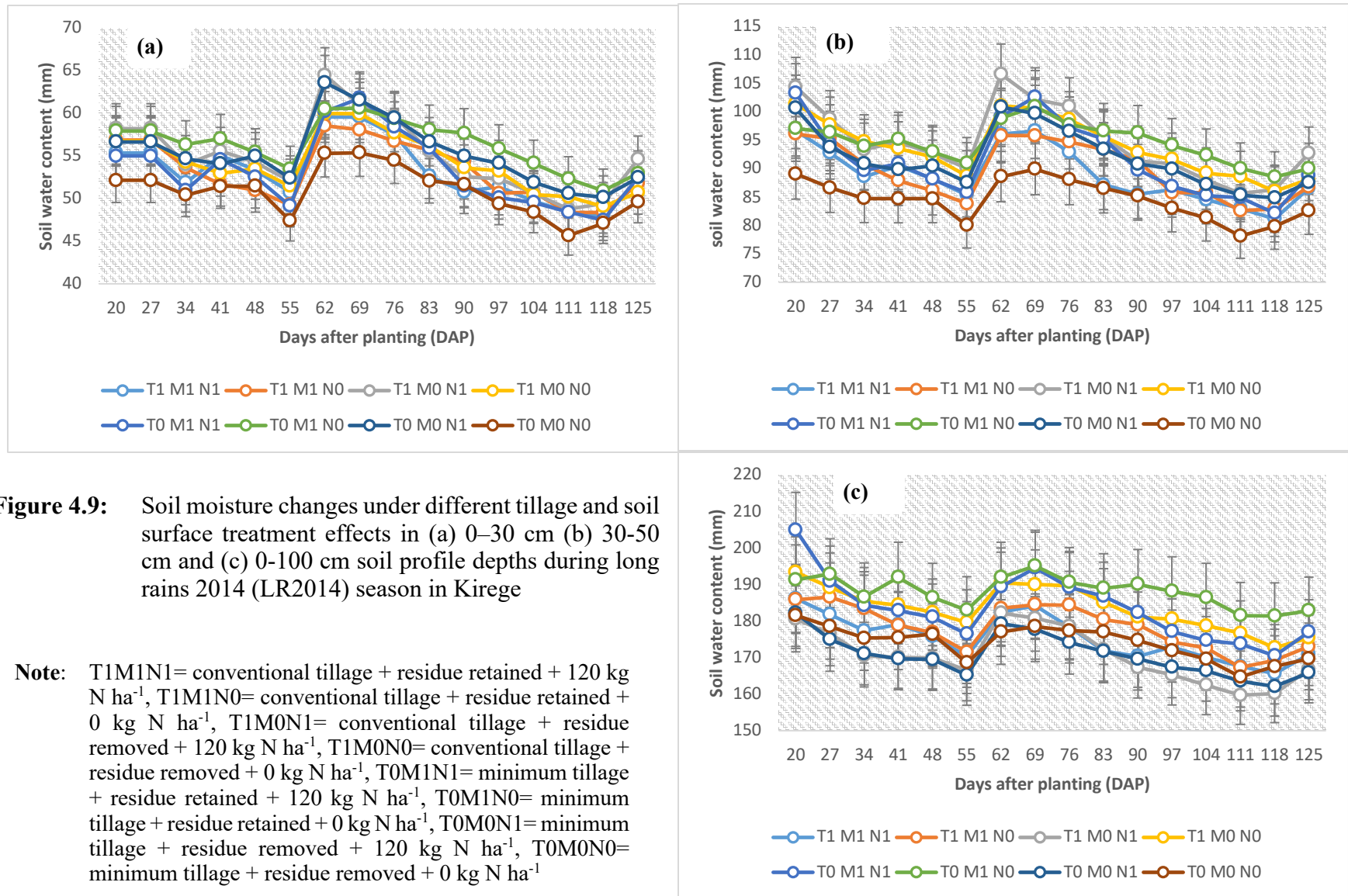
4.4.1 Effect of soil tillage and mulching practices on soil water content and crop evapotranspiration

The seasonal treatment effects of soil tillage, mulch management and nitrogen fertilization on soil water content in the soil profile (up to the depth of 100 cm) in Kirege are presented in Figures 4.9 and 4.10. During the research period, there was an essential variation with regards to annual precipitation at Kirege (Table 4.1 and Figures 4.1 and 4.2), and it was, therefore, necessary to evaluate both the effect of soil surface treatments (soil tillage, mulch management, and nitrogen fertilization) and annual precipitation on soil water content.

While there were no significant effects at all the assessed depths (0-30, 0-50 and 0-100 cm) between tillage practices, nitrogen application and mulch retention on soil water content during LR2014 and SR2014 cropping seasons, generally the highest soil water in both seasons was conserved in T0M1N0 (minimum tillage with mulch retained and 0 kg of N fertilizer applied) in the 0-30 and 0-100 cm depths. T0M1N0 treatments consistently had higher soil water throughout the two growing seasons in the depths to 100 cm, with a mean seasonal soil water content of 188 and 175 mm in LR2014 and SR2014, respectively. In the 0-30 cm growth zone, the T0M1N0 treatments also had the highest soil water content in both

seasons, with a seasonal mean of 56 and 58 mm in LR2014 and SR2014, respectively (Figures 4.9 and 4.10).

Conversely, T1M0N1 treatments (conventional tillage with mulch removed and nitrogen fertilizer applied) consistently had the lowest soil water content in the depths to 100 cm in the two growing seasons, with a mean seasonal water content of 171 and 160 mm in LR2014 and SR2014, respectively (Figures 4.9 and 4.10).



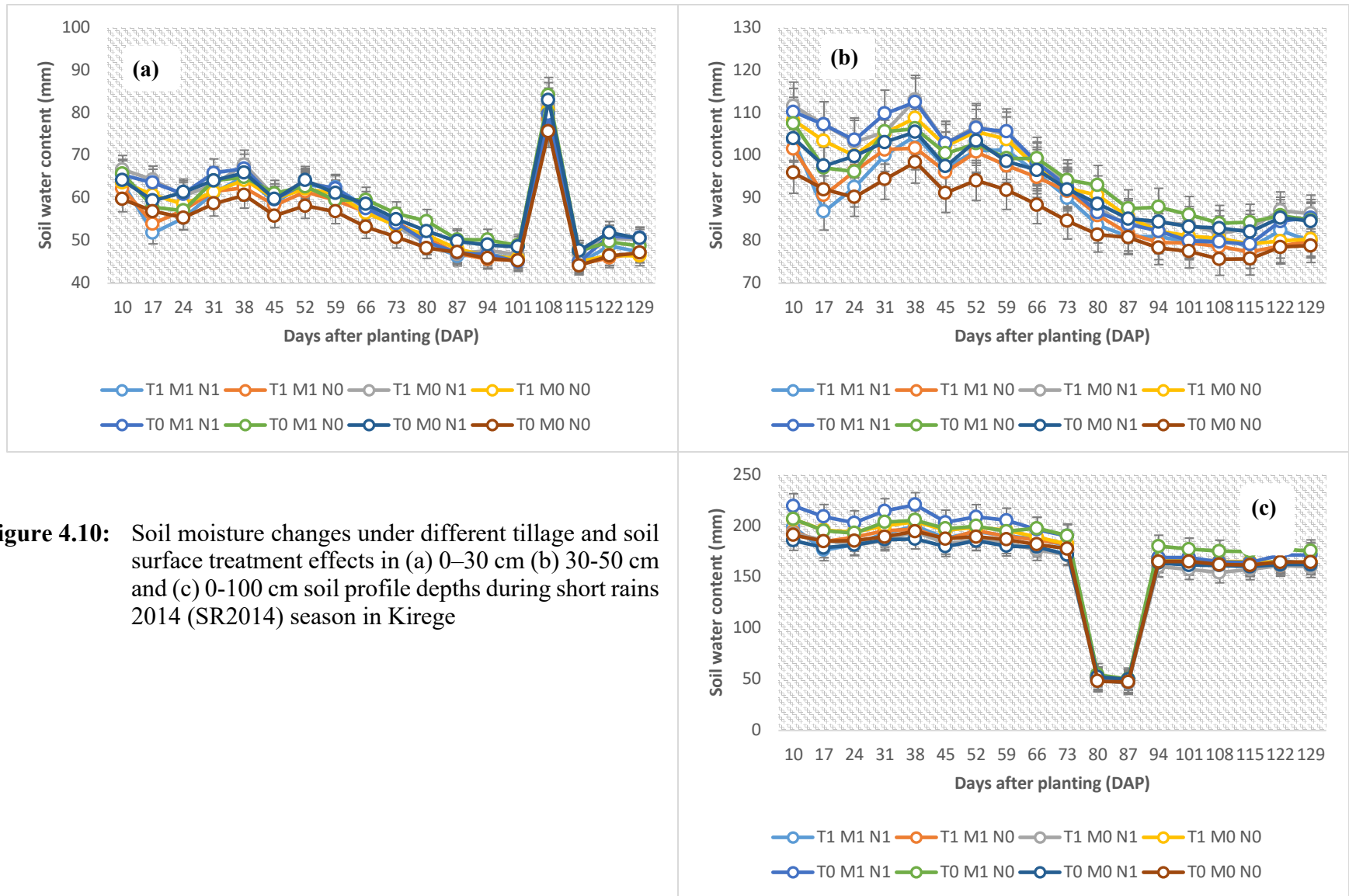


Figure 4.10: Soil moisture changes under different tillage and soil surface treatment effects in (a) 0–30 cm (b) 30–50 cm and (c) 0–100 cm soil profile depths during short rains 2014 (SR2014) season in Kirege

In all the treatment combinations, the highest soil water content, of 188 mm, was noted in T0M1N0 treatments in LR2014, during which season the Kirege site had above-normal seasonal precipitation (502 mm, Figure 4.2). Volumetric soil water content for all treatment combinations tended to decrease from planting to harvesting during all the two cropping seasons, possibly as a result of a higher transpiration demand by the mature maize plant population.

In the first season (LR2014), soil water decreased gradually during the maize growing season in all treatments and at all depths. The highest soil water content was recorded 62 days after planting while the lowest level was recorded 111 days after planting (Figure 4.9). In the second season (SR2014), soil water also decreased gradually during the maize growing season in all treatments and at all depths. The highest soil water content was recorded, however, at 108 days after planting and the lowest level at 115 days after planting (Figure 4.10).

Volumetric soil water content for all treatment combinations tended to decrease from planting to harvesting during all the three cropping seasons. There were significant differences in mulch management treatments, by volumetric soil moisture in the depths of 0–100 cm, during the all three growing seasons of LR2014, SR2014 and LR2015, which occurred at all measurement periods.

The two most significant soil moisture differences in the mulch management plots in the 0-100 cm depth were noted in the residue-retained plots in the long and short

rains of 2014 (LR2014 and SR2014). Mulch retained treatments significantly conserved more soil moisture, in the process resulting in more plant-available soil water and ensuring higher buffering in the event of water stress during the maize growing season. This is especially crucial in the light of erratic rainfall and periods of meteorological drought throughout the length of growing season.

The volumetric soil moisture content in the mulch retained treatments was 9 to 10% greater in mulch retained treatments when averaged over the three seasons compared to mulch removed treatments, showing that the crop residue on the soil surface reduced evaporation and consequent moisture loss. Except for the LR2014 season, the other two seasons posted average seasonal rainfall amounts (Figure 4.2): therefore, since most evaporation occurs when the soil is wet, the residue insulated the wet Nitisols from solar energy and reduced evaporation.

In two (LR14 and SR14) of the three cropping seasons, there was noticeably higher soil water content available in the soil profile up to the depth of 100 cm under the no-nitrogen applied treatments. However, in the upper soil profile, in the SR2014 and LR2015 seasons, there was significantly more soil water available in the 120kg/ha nitrogen treatments at a depth of 10-30cm and 30-50cm. The higher soil water content in the no-N treatments at the depth to 100 cm in this study might be related to the poor plant stand and subsequently lower yields (Tables 4.2 and 4.3).

The results also show that much of the difference in the soil water retention and conservation between the two mulch management regimes occurred below the depth of 50 cm, with the mulch retained treatments significantly conserving water below this depth, away from potential evaporation. This means that the water so conserved will be available for buffering the maize crop in case of seasonal water stress, which is increasingly becoming a reality for smallholder farmers in the Central Highlands of Kenya.

Significant differences between tillage treatments were noted in LR2014 and SR2015, with significantly higher soil water content under minimum tillage treatments in the depths to 100 cm. In the topsoil, however, it was difficult to identify any trends, although there was marginal better soil water conserved under minimum tillage in SR2014 and LR2015. However, during the SR2014 cropping season, soil water content was significantly ($p=0.01$) conserved under minimum tillage farming practices compared to conventional tillage at the depths of 0-100 cm.

The results show that reduction of primary soil tillage intensity (through the minimum tillage practices) increased the amount of moisture and level of soil moisture conservation in the deeper soil layers, although the increase was only marginal and not significant for two of the three cropping seasons. These results also show that conventional tillage and minimum tillage had conserved nearly the same levels of soil water content in the first 0-50 cm in all the three seasons, showing little variation between the two tillage practices in the study.

The results are indicative of the fact that the implemented minimum tillage practice improved soil water-holding capacity and water use efficiency through decreasing soil bulk density, increasing soil porosity, and promoting the formation of soil water-stable aggregates, although this had no significant impact on the subsequent maize crop yields (Tables 4.2 and 4.3).

The influence of soil tillage practices, mulch management and nitrogen fertilization on consumptive use of water (crop evapotranspiration) for the three growing seasons, LR2014, SR2014, and LR2015, are presented in Figure 4.11. Generally, T0M1N1 treatments (minimum tillage with mulch retained and nitrogen fertilizer applied) had the highest crop evapotranspiration in two of the three seasons (LR2015 and SR2014), while the lowest crop evapotranspiration was noted in T1M0N1 treatments (conventional tillage with mulch removed and nitrogen fertilizer applied) (Figure 4.11).

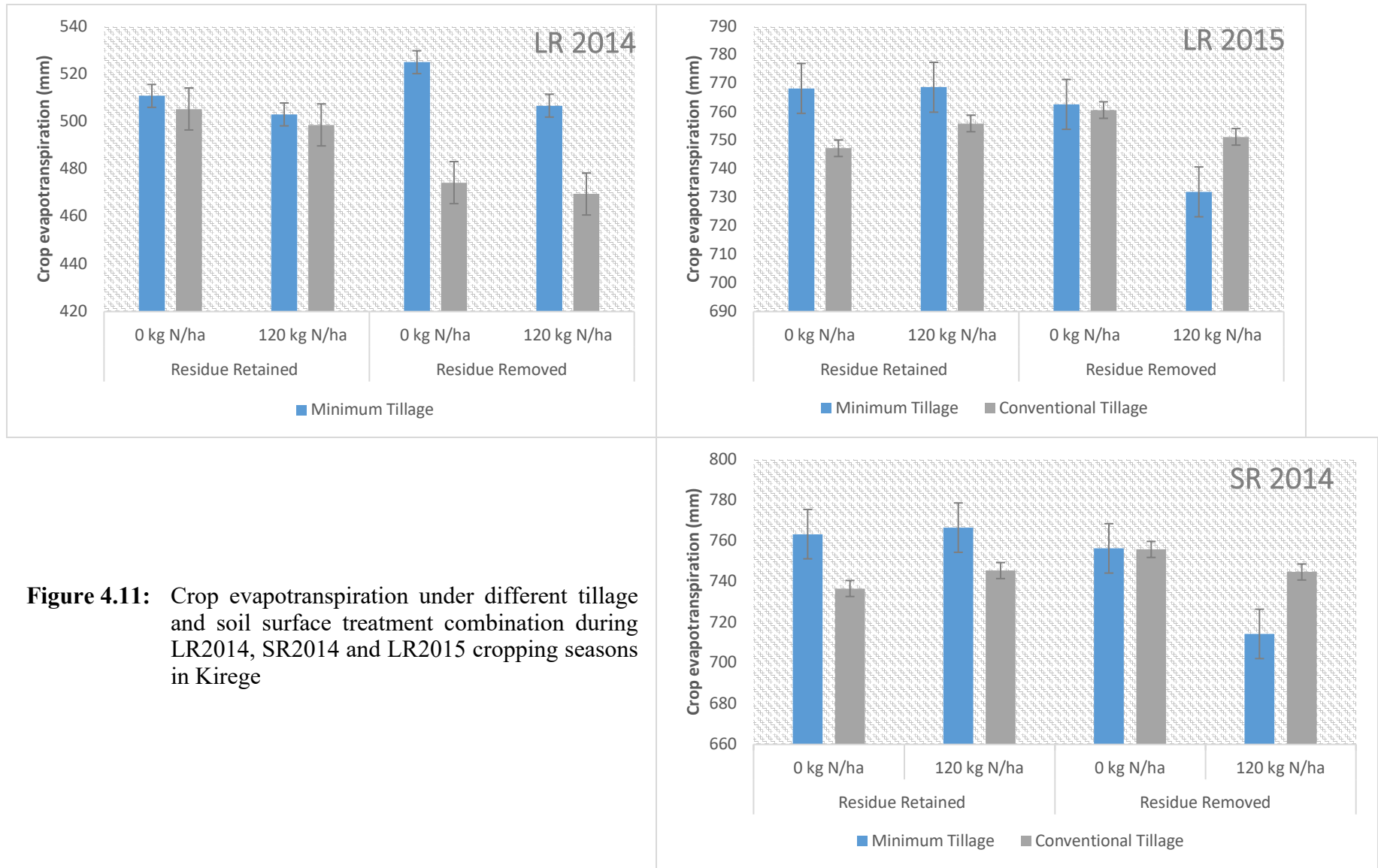


Figure 4.11: Crop evapotranspiration under different tillage and soil surface treatment combination during LR2014, SR2014 and LR2015 cropping seasons in Kirege

Relative to the others, the highest overall crop evapotranspiration in LR2015 occurred in T0M1N1 treatments: it is also noteworthy that this treatment also had one of the highest maize grain and stover yields in this season (Tables 4.2 and 4.3). The results also show a distinct pattern in which there was higher crop evapotranspiration under minimum tillage treatments in all the three seasons, as compared to conventional tillage ones: in LR2014, ET_c was higher in the minimum tillage treatments by about 5% compared to conventional tillage treatments, which was attributed to increased soil water availability. Removal of residue on the soil surface and no application of N fertilizer also resulted in higher water loss through crop evapotranspiration (Table 4.11).

The improved water conservation efficiency with mulch retention in minimum tillage systems was reflected in the soil moisture content throughout each of the two growing seasons as well as in the maize stover yields (Table 4.3), where T0M1N1 treatments had some of the highest maize stover yields in the six growing seasons. In the trial, soil moisture content in the top 100 cm of the minimum tillage treatments was lower when residue was retained compared to when residue was removed, which was linked to lower soil temperatures.

Efficient maize crop production is highly influenced by soil water availability during the growing season, which is why it is imperative to apply a tillage and soil management combination system that helps maintain a favourable soil water regime for optimal maize crop growth and development. The T0M1N1 treatments

appeared to have disturbed the soil as little as possible, reduced evaporation losses and ensured that crop residues that were maintained on the surface conserved the soil's natural structure and allowed for more efficient soil water conservation.

Similar results showing higher crop evapotranspiration under minimum tillage systems have been reported by researchers including Busari *et al.* (2016), who studied the impacts of conservation tillage on soil, crop and the environment in different eco-regions of the world. On their part, Dalmago *et al.* (2004) studied evapotranspiration in maize crops as a function of soil tillage systems in Eldorado do Sul, Brazil, and came to similar conclusions, reporting higher crop evapotranspiration in plots under minimum tillage system.

These results are in agreement with similar studies carried out to determine the relationship between tillage practices and mulch management regimes on soil water conservation, including the results by Verhulst *et al.* (2009), who conducted research on the importance of crop mulch management in maintaining soil quality in minimum tillage systems in rain-fed farming systems in Mexico. In their long-term comparison trials, conducted under both in rain-fed and irrigated wheat systems, Verhulst *et al.* (2009) concluded that it was vital to incorporate crop residue management in maintaining soil quality in minimum tillage systems.

Other researchers, including Moreno *et al.* (1997) and Lamm *et al.* (2009) also reported higher soil water content under treatment combinations primarily

featuring minimum tillage than under conventional tillage. On the other hand, Hussain *et al.* (1999) found non-significant differences between the soil water content on silty loam between the conventional tillage, conservation tillage, and no-till systems.

It was, therefore, surmised that the crop residues retained on the soil surface in this research, therefore, reflected sunlight and insulated the soil, reducing heat movement into and from the soil and thereby reducing soil temperatures and limiting by that fact the evaporation losses of water from the soil. These results are in agreement with previously conducted research, including the seminal work by Verhulst *et al.* (2011) that investigated soil water content, maize yield and associated stability as affected by tillage and crop mulch management in rain-fed highlands in Mexico, and who reported that mulch retention had higher soil water content than management practices involving mulch removal.

The results also tally with the findings of Curtis (2013), who assessed the influence of cover crop mulch management on soil moisture, vine growth, and productivity in a pre-production vineyard in the Willamette Valley: he reported higher levels of soil moisture were maintained in mulch retained treatments through the summer of 2011 in the research zone. The results in this study are also in consonance with the findings of a study commissioned by CIMMYT (International Maize and Wheat Improvement Centre) in Mexico, which reported that increased soil moisture conservation by mulch retention in minimum tillage systems was

reflected in higher soil moisture content throughout the growing season (Verhulst, 2009). In this study on rain-fed soils by CIMMYT, soil moisture content in the top 60 cm of the minimum till plots was lower when residue was removed, compared to when residue was retained.

These findings agree with the observations of Blevins *et al.* (1971), who reported that minimum tillage (in comparison with conventional tillage) resulted in higher volumetric soil water contents to 60 cm depth during most of the maize-growing season. The higher soil water content in minimum tillage treatments in the deeper soil layers could be attributed to reduced evaporation and better water infiltration due to the stubble retained in the treatments subjected to reduced tillage activities (Triplett *et al.*, 1968).

Similar results were also reported by Sheng and Bao (2011), whose research on the effects of minimum tillage on soil water content and physical properties in maize farming systems in the semiarid region of northern China also showed more soil water content in minimum tillage system. These findings also agree with those of Reijntjes *et al.* (1992), who reported that conventional tillage systems tend to reduce heat conduction and break capillary connections in the soil. As a result, the tilled layer dries quickly, and the subsoil water can be conserved at about the same levels of soil moisture conservation as in minimum tillage treatments.

These research findings confirm observations and findings by previous scientists (including Otengi *et al.*, 2007) that conventional tillage practices can conserve deeper soil moisture by providing diffusion resistance to water vapour and obstruction to liquid water flow by breaking the capillary connection to the surface. In this manner, conventional tillage reduces evaporation from deeper layers, thus acting much like a layer of mulch.

Regarding the finding that minimum tillage practices generally conserve more soil moisture than conventional tillage, the findings in this research also is in consonance with previous research carried out by, for instance, Kovac *et al.* (2005) who, in their study of the effects of soil conservation tillage on soil moisture dynamics under single cropping and crop rotation, reported that soils under minimum tillage had significantly higher moisture content than tested conventional tillage plots. The research findings are indicative of the fact that minimum tillage can increase water use efficiency by minimizing direct evaporation from the soil in an environment characterized by erratic and increasingly unreliable rainfall.

The results in this research are in agreement with results by other previous researchers, including Song *et al.* (2010), who, in their study on the impact of long-term fertilization on soil water content in Haploborolls, reported that after three years of trials in north-east China that the no fertilizer treatments had total soil water content higher by 1.2% and 3.1% as compared to fertilized treatments.

4.5 Effects of soil tillage and mulch management combination on soil carbon content

4.5.1 Effects of soil tillage and soil surface treatment on soil carbon in soil aggregates

The seasonal effects of application of soil tillage practices, nitrogen fertilization and mulch management treatments on changes in soil carbon content in different soil fractions at different depths in Kirege between the years 2012 (baseline) and 2015 (end-term) are presented in Tables 4.11, 4.12 and 4.13 and in Figures 4.12, 4.13, and 4.14.

Overall, soil carbon concentrations decreased with increase in soil depth. In all the three fractions, the highest increases in the soil C were noted in the 0-20 cm depths, with higher increments observed in soil macro-aggregates. In soil micro-aggregates, all treatments had positive increases in their soil carbon by the end of the LR2015 season as compared to the LR2012 season. In this fraction, there were significant ($p=0.04$) increases in soil carbon at the 0-20 cm depths, with T1M1N0 treatments recording 463% increases between 2012 and 2015 (Table 4.11). T1M1N0 treatments had the highest incremental changes in the soil C content in 40-60 cm depth, with significantly ($p<0.001$) higher increases of 209% in LR2015 as compared to the soil C content in LR2012 (Table 4.11 and Figure 4.12).

Table 4.11 Baseline soil carbon content (2012) and soil carbon changes in 2015 in soil micro-aggregates in different soil tillage, mulch management and nitrogen fertilization treatments in Kirege

Soil carbon content at baseline (LR2012) and end-term (LR2015) at different depths in t C ha ⁻¹												
Treatments	0-20 cm			20-40 cm			40-60 cm			60-80 cm		
	LR2012	LR2015	% change	LR2012	LR2015	% change	LR2012	LR2015	% change	LR2012	LR2015	% change
T1 M1 N1	3.15	6.58 ^a	109	2.72	4.23 ^a	55	1.75	2.76 ^{ab}	58	3.42	2.68 ^a	(22)
T1 M1 N0	1.17	6.56 ^a	463	1.65	5.24 ^a	218	1.02	3.14 ^{bcd}	209	2.63	2.95 ^a	12
T1 M0 N1	2.84	6.06 ^a	113	2.29	4.74 ^a	107	1.13	1.80 ^d	60	2.23	2.39 ^a	7
T1 M0 N0	3.17	5.28 ^{ab}	67	3.11	3.04 ^a	(3)	2.91	4.24 ^{ab}	46	2.73	4.00 ^a	47
T0 M1 N1	4.04	5.88 ^{ab}	46	3.14	5.73 ^a	83	4.33	2.75 ^{cd}	(37)	4.36	2.97 ^a	(32)
T0 M1 N0	2.37	3.99 ^b	68	2.30	5.51 ^a	140	3.46	4.94 ^a	43	1.94	3.32 ^a	71
T0 M0 N1	3.30	5.06 ^{ab}	53	3.29	5.57 ^a	69	0.91	3.95 ^{abc}	334	2.57	4.05 ^a	57
T0 M0 N0	2.97	4.95 ^{ab}	67	3.06	4.40 ^a	44	3.78	3.08 ^{bcd}	(19)	4.50	2.79 ^a	(38)
LSD		1.20			1.58			0.889			2.507	
<i>p</i> -value		0.04			0.248			<.001			0.226	

Note: T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

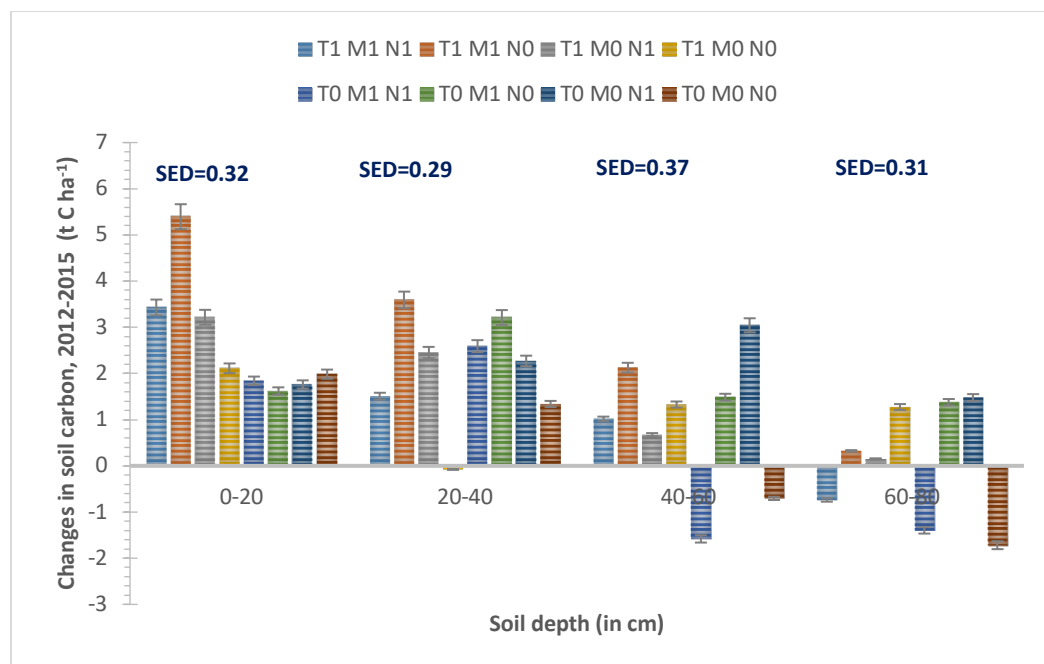


Figure 4.12: Effects of soil tillage, mulch management and nitrogen fertilization treatments on soil carbon changes in soil micro-aggregate class size in 0–80 cm soil profile depths between 2012 (baseline) and 2015 (end-term) in Kirege

Key: T1M1N1= conventional tillage + residue retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + residue retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + residue removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + residue removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + residue retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + residue retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + residue removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + residue removed + 0 kg N ha⁻¹

The soil C content in soil microaggregates in the 0-20, 20-40 and 40-60 cm depths increased in all the treatments, to varying degrees, between the years 2012 and 2015, while the 60-80 cm depth saw little increases and in some cases reductions in overall soil C. The soil C content significantly increased under conventional tillage system at all depths, except at 60-80 cm depth (Figure 4.12). In soil micro-

aggregates fraction, the soil C at the end of the research increased by as much as 463% (in T1M1N0 treatment combination at 0-20 cm depth).

In soil meso-aggregates, T1M0N1 treatments significantly ($p=0.03$) accounted for the highest soil C increases at a depth of 20-40 cm in the research period, with the soil C content rising by 256% from 1.2 t C ha⁻¹ in LR2012 to 4.3 t C ha⁻¹ in LR2015 (Table 4.12). Generally, in the 60-80 cm depths, there were reductions in soil C content in soil meso-aggregate fractions (Table 4.13).

The highest increases in soil C content in soil meso-aggregates were observed in T1M1N1 combined treatment (conventional tillage with mulch retained and nitrogen fertilizer applied), where the soil C content as LR2015 increased by 644% (Table 4.12 and Figure 4.13).

Table 4.12 Baseline soil carbon content (2012) and soil carbon changes in 2015 in soil meso-aggregates in different soil tillage, mulch management and nitrogen fertilization treatments in Kirege

Soil carbon content at baseline (LR2012) and end-term (LR2015) at different depths in t C ha ⁻¹												
Treatments	0-20 cm			20-40 cm			40-60 cm			60-80 cm		
	LR2012	LR2015	% change	LR2012	LR2015	% change	LR2012	LR2015	% change	LR2012	LR2015	% increase
T1 M1 N1	3.43	6.60 ^a	92	2.78	3.79 ^{abc}	37	1.18	3.33 ^a	182	3.80	2.82 ^a	-26
T1 M1 N0	2.42	4.50 ^a	86	2.20	4.51 ^{ab}	105	1.71	4.11 ^a	140	1.78	3.57 ^a	101
T1 M0 N1	2.96	5.36 ^a	81	1.22	4.35 ^{ab}	256	2.53	2.42 ^a	-4	1.81	2.39 ^a	32
T1 M0 N0	3.53	4.54 ^a	29	2.44	2.36 ^c	-3	3.18	4.07 ^a	28	4.64	2.53 ^a	-45
T0 M1 N1	3.29	3.58 ^a	9	2.62	3.98 ^{abc}	52	2.91	3.78 ^a	30	3.75	2.57 ^a	-32
T0 M1 N0	4.14	4.09 ^a	-1	2.83	2.83 ^{bc}	0	4.81	3.72 ^a	-23	2.12	3.39 ^a	60
T0 M0 N1	2.66	4.28 ^a	61	2.72	4.73 ^a	74	2.13	4.06 ^a	91	2.56	4.44 ^a	73
T0 M0 N0	3.141	4.26 ^a	36	3.18	3.39 ^{abc}	7	3.074	4.17 ^a	36	3.67	2.46 ^a	-33
LSD		1.573			1.12			1.31			2.30	
<i>p</i> -value		0.24			0.03			0.581			0.321	

Note: T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

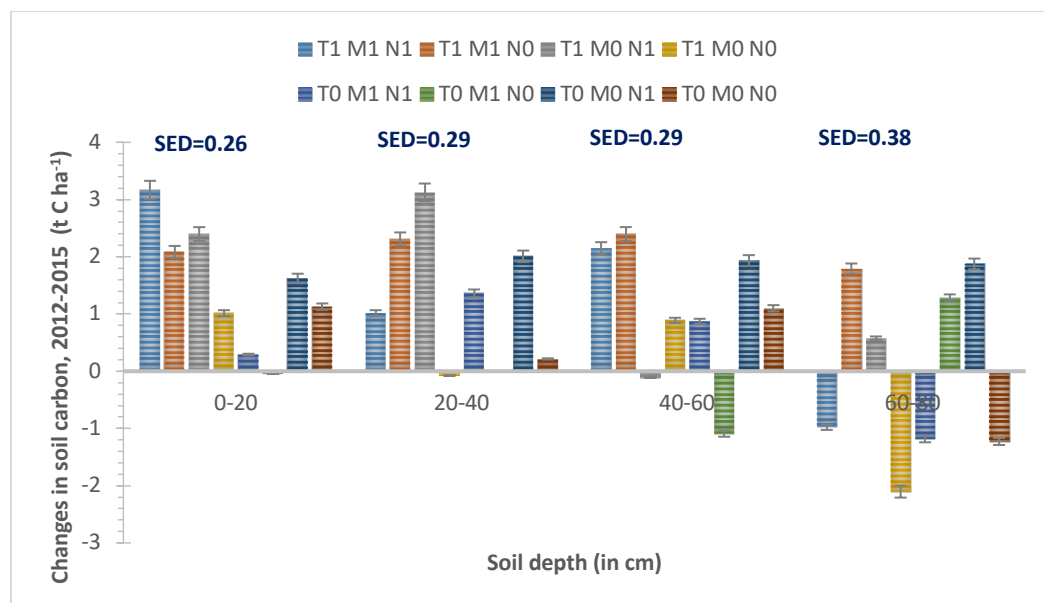


Figure 4.13: Effects of soil tillage, mulch management and nitrogen fertilization treatments on soil carbon changes in soil meso-aggregate class size in 0–80 cm soil profile depths between 2012 (baseline) and 2015 (end-term) in Kirege.

Key: T1M1N1= conventional tillage + residue retained + 120 kg N ha⁻¹,
T1M1N0= conventional tillage + residue retained + 0 kg N ha⁻¹,
T1M0N1= conventional tillage + residue removed + 120 kg N ha⁻¹,
T1M0N0= conventional tillage + residue removed + 0 kg N ha⁻¹,
T0M1N1= minimum tillage + residue retained + 120 kg N ha⁻¹,
T0M1N0= minimum tillage + residue retained + 0 kg N ha⁻¹, T0M0N1=
minimum tillage + residue removed + 120 kg N ha⁻¹, T0M0N0=
minimum tillage + residue removed + 0 kg N ha⁻¹

On the other hand, at the lowest profile depth of 60–80 cm, generally there was either much less increments or, in some cases, reductions in overall soil C content, with more intense reductions in soil C content noted in the soil macro-aggregates (Table 4.13 and Figure 4.14).

Table 4.13 Baseline soil carbon content (2012) and soil carbon changes in 2015 in soil macro-aggregates in different soil tillage, mulch management and nitrogen fertilization treatments in Kirege

Soil carbon content at baseline (LR2012) and end-term (LR2015) at different depths in t C ha ⁻¹												
Treatments	0-20 cm			20-40 cm			40-60 cm			60-80 cm		
	LR2012	LR2015	% change	LR2012	LR2015	% change	LR2012	LR2015	% change	LR2012	LR2015	% increase
T1 M1 N1	0.7	5.20 ^a	644	2.97	1.65 ^c	-44	2.33	2.57 ^{ab}	10	3.48	1.46 ^a	-58
T1 M1 N0	1.56	4.26 ^a	173	1.55	4.99 ^a	222	1.89	2.25 ^{ab}	20	2.20	2.69 ^a	22
T1 M0 N1	2.97	6.81 ^a	129	4.16	2.88 ^{bc}	-31	2.80	2.19 ^b	-22	1.22	1.20 ^a	-2
T1 M0 N0	3.07	6.64 ^a	116	1.90	2.69 ^{bc}	41	1.90	2.76 ^{ab}	45	2.34	2.31 ^a	-1
T0 M1 N1	1.82	2.34 ^a	29	2.61	3.51 ^{ab}	34	2.06	2.89 ^{ab}	40	2.31	3.1 ^a	34
T0 M1 N0	1.94	2.71 ^a	40	2.21	1.4 ^c	-37	3.53	2.52 ^{ab}	-28	2.52	2.20 ^a	-13
T0 M0 N1	2.51	2.38 ^a	-5	1.28	2.60 ^{bc}	102	1.72	3.16 ^a	84	1.77	2.22 ^a	25
T0 M0 N0	1.58	3.03 ^a	92	3.05	2.87 ^{bc}	-6	2.82	2.52 ^{ab}	-11	5.00	2.20 ^a	-56
LSD		1.58			1.011			0.57			0.65	
<i>p</i> -value		0.746			<.001			0.046			0.12	

Note: T1M1N1= conventional tillage + mulch retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + mulch retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + mulch removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + mulch removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + mulch retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + mulch retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + mulch removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + mulch removed + 0 kg N ha⁻¹

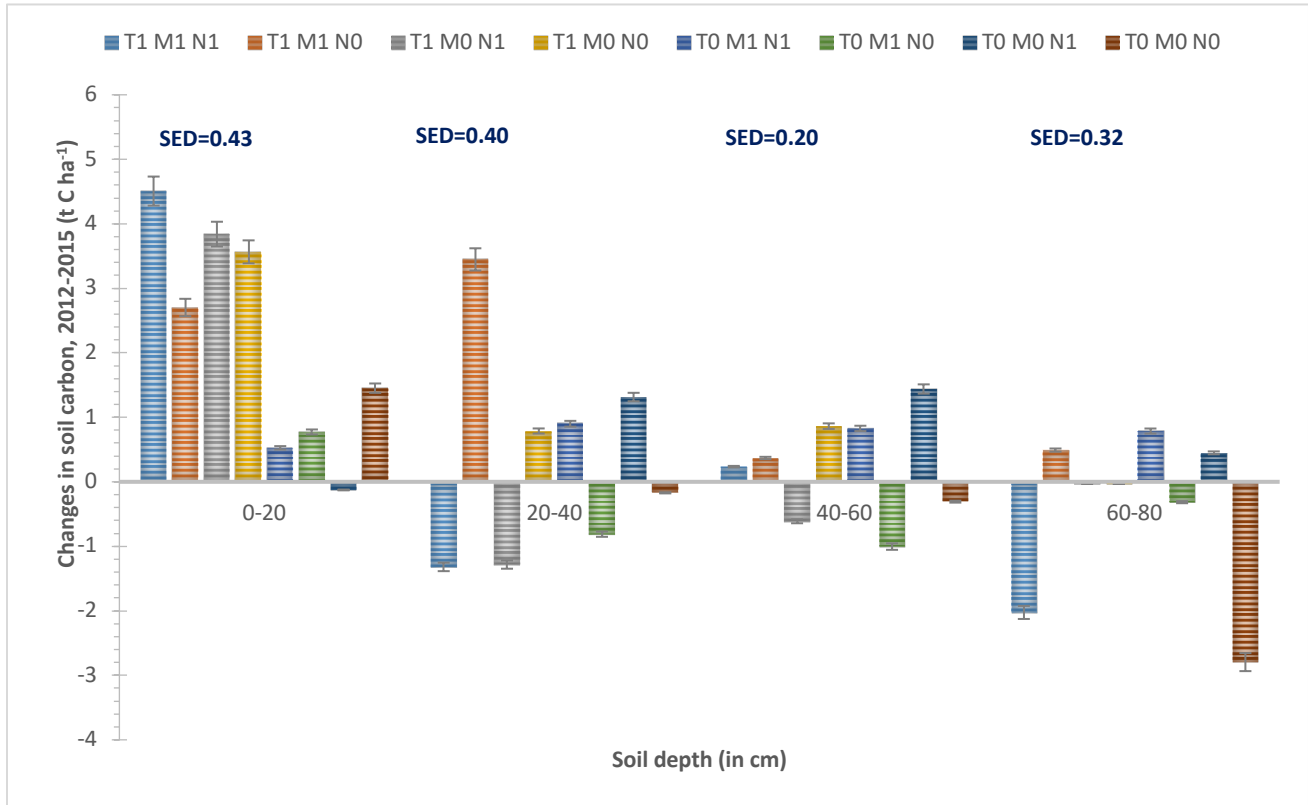


Figure 4.14: Effects of soil tillage, mulch management and nitrogen fertilization treatments on soil carbon changes in soil macro-aggregate class size in 0–80 cm soil profile depths between 2012 (baseline) and 2015 (end-term) in Kirege

Key: T1M1N1= conventional tillage + residue retained + 120 kg N ha⁻¹, T1M1N0= conventional tillage + residue retained + 0 kg N ha⁻¹, T1M0N1= conventional tillage + residue removed + 120 kg N ha⁻¹, T1M0N0= conventional tillage + residue removed + 0 kg N ha⁻¹, T0M1N1= minimum tillage + residue retained + 120 kg N ha⁻¹, T0M1N0= minimum tillage + residue retained + 0 kg N ha⁻¹, T0M0N1= minimum tillage + residue removed + 120 kg N ha⁻¹, T0M0N0= minimum tillage + residue removed + 0 kg N ha⁻¹

Conventional tillage enhanced the presence of soil C in the 0-20 cm depth in all the three aggregate fractions, with average increases of 3.5 t C ha⁻¹ in micro-aggregates (Figure 4.12), 2.2 t C ha⁻¹ in meso-aggregates (Figure 4.13) and 3.7 t C ha⁻¹ in macro-aggregates (Figure 4.14). In the 0-20 cm profile, there was an increase in the 2015 end-term soil carbon as compared to the baseline (2012) concentration. The most significant change in the SOC content of the soil micro-aggregates in this depth of 0-20 cm at the end of the research, expressed as the mean t C ha⁻¹ in the soil, was observed in the T1M1N0 treatments (conventional tillage with mulch retained and no nitrogen fertilizer applied), which had seen an increase of 5.4 t C ha⁻¹, which represented a 463% increase from the baseline SOC.

The least increase in this depth of 0-20 cm was noted in T0M1N1 treatments (minimum tillage with mulch retained and nitrogen fertilizer applied), which witnessed an increment of 1.8 C ha⁻¹, representing an increase of only 46%. Generally, there were no significant differences in SOC build-up that was attributable to the type of mulch management regime practiced, except for changes in 0-20 cm in soil micro-aggregates, where there was on average higher soil C content increment noted in mulch retained treatments of 3.1 t C ha⁻¹, as compared to mulch removed. There were marginally higher increments in soil C content under mulch retention levels in 0-20 and 20-40 cm depths, while in the 40-60 and 60-80 cm depths, there were slightly higher increments under minimum tillage treatments (Figures 4.12, 4.13 and 4.14).

While both minimum tillage and conventional tillage were found to be effective in enhancing soil carbon at different depths and in the different soil fractions, the results show a discernible pattern in which in the deeper soil layers, minimum tillage treatments were playing a more significant role in improving carbon content in the soil. This is attributed in part because soil carbon is more stable in deeper layers as microbial respiration declines exponentially with depth (Eilers *et al.*, 2012).

This finding finds support in the assertion by Six *et al.* (2000) that the rate of macro-aggregate formation and degradation (i.e., aggregate turnover) is reduced under minimum tillage systems, as compared to conventional and leads to a formation of stable microaggregates in which carbon is stabilized and sequestered in the long term. This finding in the study tallies with the findings of other researchers such as Baker *et al.* (2007), Yang *et al.* (2008), and Blanco-Canqui and Schlegel (2011). The decrease in soil carbon content with increased depth may have been made possible through the formation of stable organo-mineral complexes. Soil carbon may have also encapsulated within the stable aggregates, thereby offering protection against microbial processes and enzymatic reaction (Lal *et al.*, 2003; Holeplass *et al.*, 2004).

Soil carbon is a significant soil ecosystem constituent affected by continuous cropping in combination with tillage (DuPont *et al.*, 2010). Several studies have indicated that conservation tillage such as minimum tillage can increase the

concentrations of SOC in the surface layer compared with conventional tillage (West and Post, 2002; Franzluebbers *et al.*, 2007; Dalal *et al.*, 2011). Results from this study showed an increase in SOC in the surface layer (0-20 cm depth) to be higher under conventional tillage compared to minimum tillage. Wyngaard *et al.* (2012) also found that SOC concentration was higher in the top layer under conventional tillage system in comparison to the minimum tillage system.

The results from a study by Zhao *et al.* (2015) also showed that the SOC concentrations were higher under minimum tillage for the 0–5 cm depth and decreased more strongly with increases in the soil depth during maize seasons. Total organic carbon has a higher accumulation in the surface layer under no-tillage system but lowers one in deep layers relative to conventional tillage (Murage *et al.*, 2007). Additionally, the soils in the study area were found to have high clay content which could have been protected soil organic matter from decay stored in the first 20 cm (less accessibility to decomposer micro-organisms) under minimum tillage system as suggested by Laudicina *et al.* (2014).

Minimum tillage practice adds soil organic matter and also protects organic molecules from oxidation by providing soil cover and reduced disturbance (Lal, 2004). Management practices influence the soil environment and therefore the habitat of soil microorganisms in various ways. After nine years of minimum tillage implementation, a significant amount of C was sequestered in no-tillage as compared with conventional tillage, particularly in the top 30 cm of soil (Martínez

et al., 2013). Ghuman and Sur (2001) reported that organic carbon content was significantly increased in the minimum tillage with residue and minimum tillage treatments over that of conventional tillage treatment in the surface 0.02 m layer.

The preponderance of soil organic carbon in the initial soil layers in conventional tillage treatments can be attributed to tillage-induced differences in thermal and physical conditions that affect root growth and distribution, and are in agreements with findings posted by de Rouw *et al.* (2010), who concluded that the conventional tillage treatments stored significantly more soil carbon in the initial (0–20 cm) (590 g C m^{-2}) than minimum tillage treatments (133 g C m^{-2}), in their study of the possibilities of carbon and nitrogen sequestration under conventional tillage and minimum tillage cover crop farming in the Mekong valley, Laos. These results also tally with the findings of Angers and Eriksen-Hamel (2008), who undertook a meta-analysis study of full-inversion tillage and organic carbon distribution in the soil profile.

The results of the study, therefore, show that the most significant amount of SOC was stabilized within the micro-aggregate fraction in the conventional tillage systems (which were the most disturbed systems in terms of agricultural land use), while much less SOC was stabilized in the less disturbed minimum tillage systems. This shows the potential role that can be played by smallholder farmers in the breadbasket maize-growing regions of Kenya in improving atmospheric carbon

sequestration in the soils. Therefore, in the long term, the formation of stable micro-aggregates in soils and protection from erosion can act as C sinks.

These results are also supported by findings posted by Han *et al.* (2015) who reported that those conventional tillage treatments improved the storage of soil organic carbon in heavy fractions in the Loess Plateau, China. From the results, there is an indication that while different soil management practices in farmlands can influence the variations of different SOC fractions, conventional tillage land uses significantly improve the storage of SOC by increasing heavy fractions. The results therefore show that management impacts on SOC in smallholder soils can be detected for any soil profile depth (0-80 cm) after 6 cropping seasons of consistent land management and also indicate that the fine particle size soil fraction (soil micro-aggregates) makes an essential contribution to the total SOC distribution at soil plow depths (0-20 cm) in Humic Nitisols.

Crop residue retention in soil is considered a significant factor dynamic in determining soil organic carbon dynamics (Stevenson and Cole, 1999). Increase in SOC in the top depth under minimum tillage, and mulch retention could be attributed to more concentration of crop residues on the soil surface. These results corroborate with a study done by Kandeler *et al.* (1999). They found that reduced and minimum tillage increased the organic carbon content of the fine fraction in the 0-10cm layer while conventional tillage increased organic carbon in the coarse fraction.

These findings are corroborated by previous research findings, including Zhong-du *et al.* (2015), who studied soil carbon storage and stratification under different tillage and mulch management regimes in rice cropping systems, and who reported that macro-aggregate SOC stocks under mulch retained treatments at 0-30 cm were significantly higher than in other systems.

The level of nitrogen fertilizer application had no significant impact on the ability of the soil micro-aggregates in Kirege to retain soil more organic carbon. However, more soil organic carbon was generally built up and retained in treatments with N fertilizer applied, especially in the 0-20 cm depth in the meso-aggregates (Figure 4.13).

The findings with regards to nitrogen fertilization and impact on soil carbon sequestration in the fine particulate macro-aggregate fractions are in alignment with the findings posted by Zhang *et al.* (2009), who carried out a study on long-term fertilization impacts on SOC dynamic from six long-term experiments with maize cropping system. The authors concluded that the application of mineral fertilizer resulted in an increasing trend in SOC storage over the long-term, showing the importance of fertilizers in the overall sequestration of carbon in the soils.

This finding in the research also tallies with the observations by Cenini *et al.* (2015), who reported that 19 years of nitrogen fertilization of soils resulted in significantly enhanced soil C sequestration in the deeper soil profile in heavy soil density fractions. The authors hypothesized that this negative influence occurred due to the altering of biochemical effects between maize crop detritus and soil microbes because of a significant increase in the activity of the C-acquiring enzymes in the soils under these treatments.

Tivet *et al.* (2013), found no significant difference in total organic carbon. In the absence of N fertilization, Nivelles *et al.* (2016) found the soil C input from crop residues were significantly higher in conventional tillage compared to no-tillage in 2 mm sieved soils. The significant effects between tillage and crop residues associated with no-tillage could be ascribed to the reduced decomposition of the organic matter input in the soil hence contributed to increased soil carbon stock (Pandey *et al.*, 2014).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study evaluated the role that low-cost, sustainable agricultural practices, involving tillage and retention of mulch on the surface, can play in order for maize farming systems to make better use of N from organic and inorganic sources and soil water. While more rains fell during the SR seasons, the LR seasons were more critical in terms of higher grain and stover yields: there is, therefore, need to adjust farming systems to this reality. In the light of changing climate variability, for instance, this study has shown that retention of mulch significantly contributed to conserving water below 50 cm, away from potential evaporation. This means that the water so conserved will be available for buffering the maize crop in case of seasonal water stress, which is increasingly becoming a reality for smallholder farmers in the Central Highlands of Kenya.

The study showed variation in both maize and stover yields during different seasons. While minimum tillage with mulch removed and nitrogen fertilizer applied (T0M0N1) treatment combination had the highest maize yields compared to all the other treatments during the trial period for three cropping seasons, generally conventional tillage treatments performed better in terms of yields season-on-season. Conventional tillage, mulch retention and nitrogen fertilizer applied

(T1M1N1) combination treatment was superior for stover yields in four out of the six cropping seasons.

The study demonstrated that the grain and biomass WUE of maize under conventional tillage was superior compared to minimum tillage, suggesting that tillage played a significant role in water use efficiency improvement. The research also showed that conventional tillage systems and crop mulch retention practices, when combined, significantly enhanced both maize grain and stover yield, with up to 30% more grain yields for conventional tillage as compared to minimum tillage. There was a consistent pattern where maize grain yields under conventional tillage plots were consistently higher than under minimum tillage plots. However, maize grain yield response to tillage varied substantially across years, and this could be ascribed to the prevailing weather conditions, particularly the rainfall amounts in specific growing seasons.

Mulching had much more influence than tillage systems on soil nitrogen mineralization, especially in the top soils and season's start. Nitrate-N and ammonium-N concentrations were high at the topsoil at the beginning of the cropping seasons in the treatments with no mulch retention. However, in the same trend (with no residue) the mineral nitrogen concentration declined faster hence the effects with mulch retention had more $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentration at the end of the season. Both conventional and minimum tillage systems had no significant effect on nitrate-N ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) concentration over the

seasons. Nitrogen concentration tended to be more in the top depths at the beginning of a cropping season under minimum tillage system compared to the conventional tillage systems.

The study concluded that the type of tillage practices implemented (conventional tillage and minimum tillage) does not necessarily influence the amount and distribution of soil nitrate-N, except at the depths beyond 60cm, and later in the season. Further, the study showed that mulching had much more influence than tillage systems on the soil mineral N concentrations, especially at top soils and early periods of the season up to seven weeks after planting. Also, it was observed that tillage and mulch management combination had no significant impact on agronomic nitrogen use efficiency (aNUE).

Mulching ensures more soil moisture availability, thus more plant-available soil water and higher buffering in the event of water stress. The study has confirmed the value of retaining residue on the surface with regards to soil water conservation in the soil profile to a depth of 100 cm. Results showed that mulch retained treatments significantly conserved more soil moisture, in the process resulting in more plant-available soil water and ensuring higher buffering in the event of water stress during the maize growing season, a scenario that is getting increasingly likelier in a country plagued by droughts like Kenya. Also, the study has shown that there was significantly higher soil water content under minimum tillage treatments in the depths to 100cm than conventional tillage, indicating that a reduction of

primary soil tillage intensity (through the minimum tillage practices) increased the amount of moisture and level of soil moisture conservation in the deeper soil layers.

Overall, the study showed that SOC concentrations decreased with increase in soil depth. In all the three fractions, the highest increases in the SOC storage were noted in the 0-20 cm depths, with higher increments observed in soil macro-aggregates. The highest increases in SOC storage and retention in both soil macro-aggregates and meso-aggregates between the two years (2012 and 2015) were observed in T1M1N1 treatment combination (conventional tillage with mulch retained and nitrogen fertilizer applied).

The study demonstrated that management impacts on SOC in smallholder soils can be detected for any soil profile depth (0-80 cm) after 6 cropping seasons of consistent land management and also indicated that the fine particle size soil fraction (soil micro-aggregates) makes an essential contribution to the total SOC distribution at soil plow depths (0-20 cm) in Humic Nitisols. The study has shown that the largest amount of SOC was stabilized within the micro-aggregate fraction in the conventional tillage system (which were the most disturbed systems in terms of agricultural land use), while much less SOC was stabilized in the less disturbed minimum tillage systems. This shows the potential role that can be played by smallholder farmers in the breadbasket maize-growing regions of Kenya in improving atmospheric carbon sequestration in the soils.

The results of the study have shown that rate of macro-aggregate formation and degradation (i.e., aggregate turnover) is reduced under minimum tillage systems, as compared to conventional and leads to a formation of stable microaggregates in which carbon is stabilized. Therefore, in the long term, the formation of stable micro-aggregates in soils protected from erosion can behave as C sinks. The results therefore show that management impacts on SOC in smallholder soils can be detected for any soil profile depth (0-80 cm) after 6 cropping seasons of consistent land management and also indicate that the fine particle size soil fraction (soil micro-aggregates) makes an essential contribution to the total SOC distribution at soil plow depths (0-20 cm) in Humic Nitisols.

The sustainability of maize production in the Central Highlands of Kenya is in question now more than ever before, especially in the light of changing climates. A major reason for this phenomenon is severe soil degradation, often manifested in low soil N fertility, and which has sent plummeting maize yields. The situation is exacerbated by the financial inability of most farmers to purchase N fertilizer for supplementation. In these dire conditions, a straightforward approach that can be followed to improve maize productivity sustainably is to integrate cropping practices that allow maize to make better use of N from organic and inorganic sources and ensures better yields for farmers, while at the same time improving soil properties.

Overall, the findings of this doctoral research support the statement that climate change can also offer opportunities for the smallholder agriculture sector and associated food security if the right adaptation measures are implemented and necessary farm resources and inputs provided. These adaptations include switching to more suitable tillage and mulch management regimes. This research confirms that while conventional tillage improves SOC sequestration and overall soil quality in the surface depths, the evidence obtained points to the importance of minimum tillage practices in promoting deep C sequestration and improving soil quality in smallholder maize-based farming systems in Humic Nitisols.

5.3 Recommendations

From the findings of the study, the following recommendations were derived:

- Conventional tillage, mulch at 1 ton per ha, and application of N fertilizers at 120 kg per ha is recommended as an appropriate land use system, which can deliver better maize yields for smallholder farmers practicing maize mono cropping.
- Adoption of this package by smallholder farmers means higher incomes and better food security.
- It is crucial to manage to mulch at season's start in order to ensure better mineralization of nitrogen.

- In order to buffer farming systems from the spectre of mid-season water stress, smallholder farmers need to adopt mulching.
- Conventional tillage, mulch at 1 ton per ha, and application of N fertilizers at 120 kg per ha is recommended for stabilization of soil carbon and improving the soil quality of smallholdings.
- Overall, T1M1N1 suite (which represents conventional tillage, mulch at 1 ton per ha, and application of N fertilizers at 120 kg per ha) is suitable for sustainable agricultural intensification in Kenya's Central Highlands.

5.4 Suggestions for further research

Based on the findings of the research, the following areas are recommended for further research:

- Future crop modelling studies that will use latest modelling practices in order to undertake a deeper evaluation of the impact of elevated atmospheric CO₂ on maize crop yields across the Central Highlands of Kenya
- Characterization of losses of fertilizer N through volatilization, leaching and denitrification from the Nitisols when subjected to both tillage practices for maize production.
- Performance modelling of the use of N-efficient maize genotypes used for maize production in similar geographies globally.

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