EFFECT OF *FANYA JUU* TERRACES WITH VARYING DITCH DIMENSIONS ON SELECTED SOIL PROPERTIES AND CROP YIELDS IN SEMI-ARID EASTERN KENYA

EMERITA NDWIGA NJIRU

(MSc. SOIL SCIENCE)

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN DRYLAND RESOURCES MANAGEMENT

DEPARTMENT OF LAND RESOURCE MANAGEMENT AND AGRICULTURAL TECHNOLOGY(LARMAT)

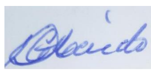
FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

2023

DECLARATION

The thesis is my original work and has not been submitted for a degree in any otheruniversity.

Signature .. ….. Date….28th November2023…

Emerita Ndwiga Njiru

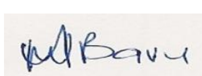
The thesis has been submitted with our approval as University Supervisors.

Signature  ………… Date… 28th November 2023 …

Prof. Charles K. Gachene (PhD)

Department of Land Resources Management and Agricultural Technology

University of Nairobi

Signature  ………… Date …28th November 2023……

Dr. Mary W. Baaru (PhD)

Department of Environmental Studies and Community Development,

Kenyatta University

DECLARATION OF ORIGINALITY

Name of the student: **Emerita Ndwiga Njiru**

Registration Number: **A74/96248/2014**

Faculty: Faculty of Agriculture

Department: **Department of Land Resource Management and Agricultural Technology**

Name of Course: **Doctor of Philosophy in Dryland Resources Management**

Project Title: **Effect of *Fanya Juu* Terraces with Varying Ditch Dimensions on Selected Soil Properties and Crop Yields in Semi-Arid Eastern Kenya**

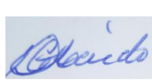
1. I understand what plagiarism is and I am aware of the University's policy in this regard.

2. I declare that this Thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

3. I have not sought or used the services of any professional agencies to produce this work.

4. I have not allowed and shall not allow anyone to copy my work with the intention of passing it off as his/her own work.

5. I understand that any false claim in respect of this work shall result in disciplinary action, in accordance with the University Plagiarism Policy.

Signature:  Date: 28th November 2023

DEDICATION

I dedicate this work to the Almighty God for bringing me this far and to my beloved latemum and dad Dorothea and Nicodemus Dibondo.

ACKNOWLEDGEMENTS

My special thanks go to my supervisors Prof. Charles K. Gachene and Dr. Mary W. Baaru for their exceptional patience, guidance, academic and moral support that significantly contributed to the success of this thesis. My sincere thanks to the European Union through NACOSTI and USAID through NAS under PEER cycle 2 for their support in funding the study. I also thank the farmers in Mua location, Machakos county who provided the land on which trials were established. I am indeed grateful to Peter Musembi, Kimotho and Ferdinard Anyika for their valuable assistance during data collection and laboratory analysis. My gratitude also goes to Dr. Victor Wasike and Mr. John Ayemba for proofreading and typesetting my work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS AND ACRONYMS

AEZ	Agro-ecological zone
ANOVA	Analysis of variance
ASALs	Arid and semi-arid lands
CODs	Cut-off drains
DMRT	Duncan's Multiple Range test
FAO	Food and Agriculture Organization
LGP	Length of Growing Period
IPCC	Intergovernmental Panel on Climate Change
LR	Long rains
LS	Lower slope
LSD	Least significant difference
ML	Middle slope
SMC	Soil moisture content
SR	Short rains
SSA	sub-Saharan Africa
US	Upper slope\
WUE	Water use efficiency

GENERAL ABSTRACT

Fanya juu terracing is a soil and water conservation practice used to control erosion and increase agricultural productivity in sloppy and hilly areas. The practice involves digging ditches and throwing the soil uphill to form embankments that obstruct runoff flow. Scanty information exists on their temporal and spatial effects on soil moisture, nutrients variability and crop yields especially on different types of soils. An on-farm study was, therefore, conducted in both the long rain (LR) and short rain (SR) seasons of 2014 and 2015 on the Luvisols in Mua location in Machakos County in semi-arid Eastern Kenya, to help generate this information. The objectives were to (i) determine the effect of *Fanya juu* terraces with varying ditch dimensions on soil moisture variability along the slope on hard-setting soils (ii) determine the effect of terraces on the spatial variability of selected soil nutrients along the slope and (iii) assess the effect of terraces on maize and bean grain yields on the hard-setting soils of semi-arid Eastern Kenya. A split- split plot design with four replicates was used. Treatments consisted of terraces with 60, 30 and 0 (Control) cm ditch depths and three cropping systems (sole maize, sole beans and maize/bean intercrop). Soil moisture content (SMC), quantities of selected nutrients (nitrogen, phosphorous, potassium, organic carbon) and maize and bean grain yields were monitored at the upper (US), middle (MS) and lower (LS) slope positions of the terraces. Data was subjected to analysis of variance (ANOVA) and means compared across seasons at a 95% level of confidence using the least significant difference of means (LSD). Results showed that SMC and its variability in the different terraces were influenced by the distribution and amount of rainfall. Significant difference ($p \leq 00.001$) was found in the interactions of season, ditch depth and slope position. Treatments with ditches had higher SMC than the control in all seasons. Soil moisture content was higher in terraces with 30 cm ditch depth compared to those with 60 cm in low and poorly distributed rainfall seasons but lower in the high and well-distributed rainfall season. Significantly higher SMC was recorded in the LS position of the terraces compared to the US and MS positions except when seasonal rainfall was high and well distributed. Total nitrogen and available phosphorous were both significantly ($p<0.001$) higher in the LS than in the US positions. Maize and beans grain yields were significantly ($p\leq0.05$) higher in terraced than non-terraced treatments and at the LS position compared to the MS and US positions. Terraces with 30 cm ditch depth produced higher grain yields than those with 60 cm in low and sparsely distributed rainfall seasons. The findings implied that the construction of *Fanya juu* terraces with 30 cm ditch depths was favourable for the conservation of soil moisture, nitrogen and phosphorous contents on hard-setting soils in the marginal rainfall areas of semi-arid Eastern Kenya. Farmers can therefore, save on labuor and still achieve better yields byconstructing terraces with 30 cm ditch depth. The results also implied that spatial variations in contents of N and P caused by *Fanya juu* terraces can be utilized more efficiently through increased intensification of the lower slope position to improve crop production. The study recommends the constructionof *Fanya juu* terraces with a ditch depth of 30 cm and intensification of the lower slope position for increased utilization of the available nutrients and moisture in low and poorly distributed rainfall environments. It further recommends more studies on different soil types, development of technologies that favour efficient utilization of resources without causing degradation at the lower slope, and practices that will increase productivity at the upper position of the slope for improved food security.

CHAPTER ONE: INTRODUCTION

1.1. Background

Terrace construction is a soil and water conservation practice that is adopted for reducing erosion and conserving soil and water in the hilly and sloppy areas of the world. This technique at the same time increases infiltration enabling cultivation and production of cropsin areas of marginal rainfall (Widomski et al., 2011, Rashid et al., 2016, Chen et al., 2021).The practice involves the construction of structures consisting of channels and embankments across the slope that reduce erosion by trapping runoff and allowing water to infiltrate (Widomski et al. 2011, Namirembe et al., 2015, Deng et al., 2021)). This increases soil moisture and improves productivity, especially in arid and semi-arid lands (ASALs) where low soil moisture is a major constraint to crop production.

The arid and semi-arid lands (ASALs) cover over forty percent (40%) of the earth's land area and are a home to about 40% of the global population (Huang et al., 2017; Peng et al., 2020). According to the Food and Agriculture organization (FAO), the ASALs are sections of the drylands which have a length of growing period (LGP) of 1-179 days (FAO, 2000). Soil water deficit in this region mainly result from characteristic low average rainfall with highly variable seasonal and annual amounts and poor distribution within the seasons (Sidahmed, 2000; Wale and Dejenie, 2013). The high variability and uneven distribution are coupled with low soil infiltration rates and high evaporation rates. Much of the rainfall received is lost as runoff with only small amounts of water being harvested for plant growth or future use.

Soil organic carbon and nutrients in the majority of the farms in the ASALs are low partly due to low accumulation of soil carbon and the low inherent soil fertility. Other causes of low soil nutrients are inadequate application of fertilizer inputs in the farming systems and losses resulting from soil erosion (Bernoux and Chevallier, 2014; Rehman et al., 2015). These conditions reduce soil water contents and water availability hence negatively impacting agricultural productivity in the ASALs (Rockstrom and Steiner, 2003; Plaza-Bonilla, 2015; Rashid et al., 2016). The situation is worsened by the fact that the ASALs are already affected and will continue to be affected by global climate change (IPCC, 2007). Some of the predicted impacts of this change include increase in temperature, reduction in available water, loss of natural vegetation and biodiversity, soil fertility degradation, and reduction in locally produced food supplies.

In sub-Saharan Africa (SSA) the ASALs have and continue to experience low crop productivity due to inadequate soil moisture and low nutrient contents. This is because crop production systems in most of the SSA drylands are greatly dependent on rain-fed agriculture with limited or no use of external inputs (AGRA, 2014). Majority of the farms in the region are smallholder, usually degraded and dependent on rainfall with little access, if any, to reliable irrigation (Studer and Liniger, 2013; AGRA, 2014). Droughts and total crop failures are common. Soil fertility in these farms is low partly due to the low inherent soil fertility and low use of fertilizer inputs in the farming systems. Subsequently, crop yields have been and continue to be low, falling below global averages (UNDP, 2009; AGRA, 2014; Munang et al., 2011). Despite the low agricultural production, the African drylands are home to a large percentage of the continent's rapidly growing population, majority of whom are either sedentary and nomadic pastoralists or agro-pastoralists (UNDP, 2009; Adamu and Dejenie (2013), Wale and Dejenie, 2013; AGRA, 2014). Most of the ASAL farming population in SSA are smallholder farmers. These are also the main producers of agricultural outputs in the region. Techniques developed to increase agricultural productivity in ASALs of SSA, therefore, need to be employed in order to increase agricultural production to meet the increasing demand for food while at the same time mitigating on the negative impacts of climate change.. Some of the techniques can be modified to cater for the changes in climate.

Fanya juu terracing has been used for many years to control runoff and erosion in the ASALs of Machakos County of Eastern Kenya (Gichuki, 1991, Mutunga, 2001). This practice was introduced in the 1930s and is widely adapted for soil and water conservation. It is important to note that during the time of its introduction, more emphasis was put on easing their construction for soil conservation without much consideration of requirements for different agroecological zones and soil types. Consequently, their performance under different soils especially in the current circumstances of climate change and increased climate variability is uncertain. It is likely, therefore, that with the incumbent changes in rainfall amounts and distributions, alterations of terrace dimensions could be necessary to improve their efficiency. Despite its widespread application in the drylands of Kenya, little has been done to its effects on soil moisture and nutrient variability in the cultivated area within the terrace and the potential of utilizing such variability for increasing agricultural production in different soil types. This study, therefore sought to determine the terrace effects on soil moisture, nutrients and grain yields of maize and beans on the hard-setting soils of semi-arid

Kenya. This information is essential in developing suitable soil and crop management options for efficient utilization of available moisture and nutrient resources and enhancing productivity per unit of land area especially under the current conditions of climate change.

1.1.1. Terraces as a soil and water conservation measure in the ASALs

Terracing is a soil and water conservation practice that is mostly adopted in hilly, arid and semi-arid areas. The practice involves the construction of structures that consist of channels and embankments of soil developed across a contour slope (Gichuki, 1991; SUSTAINET EA, 2010). These structures intercept the slope of land dividing it into strips. Terraces reduce the length and/or overall steepness of the slope that would otherwise be exposed to erosion. The overall effect is reduced runoff and a decline in soil erosion (Mutunga, 2001; Baptista et al., 2015). The channels and embankments increase infiltration, and maintain soil productivity resulting in sustained crop production (Sheng, 2002; Youssef et al., 2008; Nyamadzawo etal., 2013; Wolka, 2014). Several studies on the use of terraces as a soil conservation measure have reported differences in crop yields between terraced and non-terraced fields as well as within the terraces (Barungi et al., 2013; Binyam et al., 2015; Deng et al., 2021). Studies involving different soils in parts of Kenya have also indicated that terraces have some specific effects on crop yields (Gachene et al. 2011; Wairimu, 2015; Ruto et al., 2015).

A study in the well-drained Luvisols of Machakos County by Gachene et al. (2011) reported an increase in crop yields from the maize rows bordering the terrace ditch compared to the section away from the ditch. The authors attributed these differences to an increase in soil moisture in the area next to the ditch resulting from the lateral flow of water. In the light-textured Andosols in Narok County, Kenya, Ruto (2015) reported retarded growth and low yields of maize next to the ditch compared to those further off. The low yields next to the ditch were attributed to the effect of leaching of nutrients in the light soils caused by increased soil moisture from the water that collected in the ditch. Higher yields further off the ditch were caused by the lateral flow of the water from the ditches to the root zone away from the collection area. A similar study in the heavy-draining Vertisols (Wairimu, 2015) indicated more vigorous growth at the middle of the slope compared to the upper and lower slope positions. These studies gave the implication that terrace effects on crop yields are soil-specific and vary with slope position depending on variability of soil moisture. A study by Ruto, (2015) in Narok, Kenya concluded that the variability of yields in the terraced farms could influence change in the cropping patterns leading to an increase in land productivity. In reference to these observations there is need to carry out studies on effects of terraces in different soil types and slope positions in order to come up with suitable soil and crop management options for increased agricultural productivity. The current study concentrated on terrace effects on soil moisture and nutrient variability and crop yields at different slope positions on the hard-setting soils commonly found in the drylands of semi-arid eastern Kenya.

1.1.2. The hard-setting soils of the arid and semi-arid lands

Soils in the ASALs are generally low in nutrients, especially nitrogen, phosphorous and organic carbon. Low inherent soil fertility, nutrient depletion resulting from leaching, excessive mining and fixation, as well as scarce deposition, accumulation or decomposition of organic materials are some of the reasons for the low soil nutrient status (Bernoux and Chevallier, 2014; Plaza-Bonilla et al., 2015). Most of the dryland soils have hardening and compaction problems combined with surface sealing and crusting properties which together render them susceptible to water and wind erosion (Stewart, 2016).

Hard- setting soils are soils that have an unstable structure that collapses once the soil is wet, then shrinks and hardens as the soil moisture dries up (Giarola et al., 2011; Daniells, 2012). The soils are pulverized and the fine particles disperse when soils are wet and cement the soil surface on drying causing crusting and hardness. The hardening is usually accompanied by surface sealing and compaction. The hard-setting soils are widespread especially in the sub-humid and semi-arid tropics. ,The common soil classifications found in the ASALs include Chromic Luviols, Nitisols, Acrisols and Aridisols (Sombroek et al.,, 1980). In the ASALs of Kenya predominant soils prone to sealing and crusting Luvisols, Acrisols, Lixisols, Ferralsols and Alisols. These soils cover approximately 24% of the total land area (Wanjogu et al., 2006) and are a constraint to agricultural production. In the ASALs of Kenya ponding of hard-setting soils were found to be common when tied ridges were used as a water harvesting practice (Miriti et al., 2012; Karuma et al., 2014) probably due to the sealing of soil pores by dispersed particles. The ponding was followed by soil sealing and crusting as the water dried up. The compaction, sealing and crusting affect infiltration, seed emergence, root penetration and soil work-ability (Giarola et al., 2011, Biamah et al., 2003).

1.2. Problem statement

Fanya juu terracing is a soil and water conservation practice developed for use in increasing agricultural productivity, especially in the drylands. The practice has been used over long periods in the ASALs of Kenya where their adoption is currently considered to be high. *Fanya juu* terraces were developed to reduce soil and nutrient losses through erosion by reducing the speed of runoff flow. However, despite the importance of water in the ASAL crop production, little effort was geared towards studying the effect of these terraces on runoff conservation or the utilization of the water that is collected and stored in the ditches for crop production. Recently few studies have suggested a possibility of moisture variability with slope position in terraced fields. This variability can be employed to ensure maximum utilization of available water and nutrients for crop productivity. The variability could influence changes in the cropping patterns which can be adopted by farmers to maximize on the soil fertility and soil moisture available at different slope positions of the terrace.

A common ditch depth of 50 - 60 cm deep and 50 - 60 cm wide was recommended for ease of adoption by farmers in the ASALs of Kenya (Mati, 2012). Consequently their performance under different soil types or in the current circumstances of climate change and increased climate variability is uncertain. It is likely, therefore, that with the incumbent changes in rainfall amounts and distributions alterations of terraces dimensions could be necessary to improve their efficiency. Results from different locations already show that the variability in crop yields is soil-specific. This brings about the need to carry out studies in different soil types. This study therefore aimed to study the role of terraces on the spatial variability of soil moisture, nutrients and crop yields at different terrace slope positions on the hard-setting soils that are prevalent in the ASALs of Kenya. The purpose was to generate information for use in identifying suitable crop and soil management practices that can result in efficient utilization of soil moisture and/or nutrients available for crop uptake at different positions to improve crop productivity per unit area.

1.3. Justification of the study

Studies have shown variations in crop growth and yield at different positions within the terrace slope giving a possibility of moisture and/or nutrient variability at these positions (Gachene and Baaru, 2011, Rutto, 2015, Wairimu, 2015). These studies also gave an implication that terrace effects on crop yields vary with different soil types. In well-drained Luvisols, for instance, maize rows bordering the terrace ditch were more vigorous in growth and gave higher yields compared to those in the section away from the ditch, a condition that was attributed to an increase in soil moisture next to the ditch resulting from lateral seepage of water (Figure 1.1).

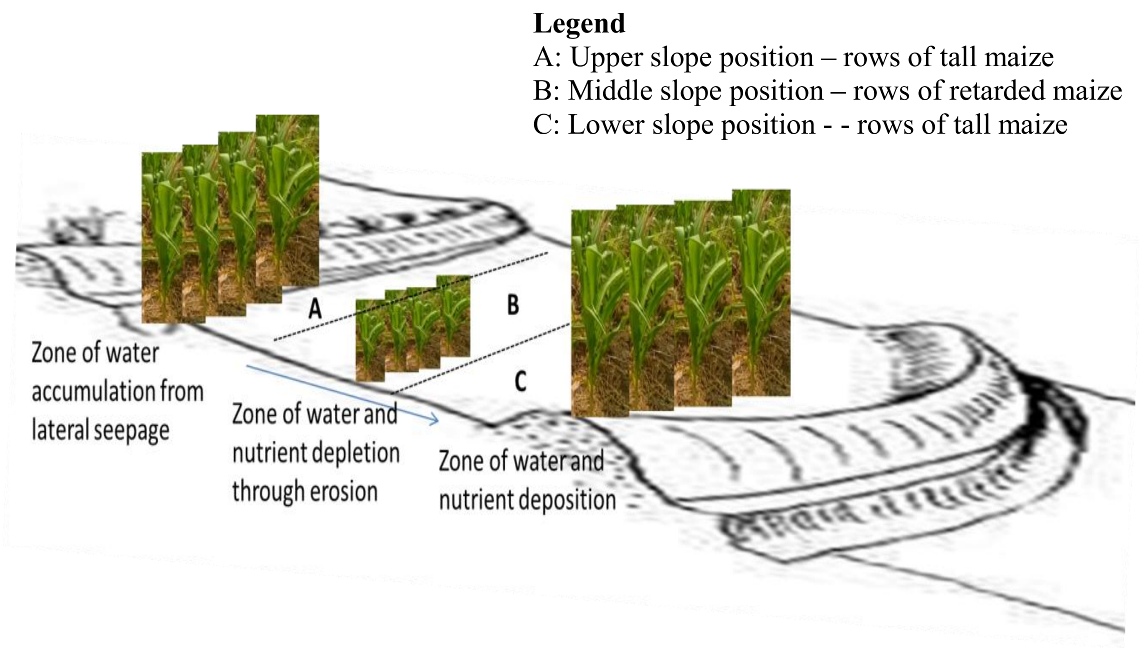


Figure 1.1: Variations in maize height along the terrace slope on the Luvisols **(**Adopted from the description by Gachene and Baaru, 2011, Drawing by E. Njiru**)**

In the light-textured Andosols maize rows next to the ditch had retarded growth and lowyields due to excessive drainage and leaching of nutrients caused by the moisture from the ditch. These were immediately followed by rows of taller maize that benefited from moisture and nutrients drained from the ditch and the first upper row through lateral and surface flows. The tall maize was followed by retarded maize at the depletion zone (Figure 1.2).

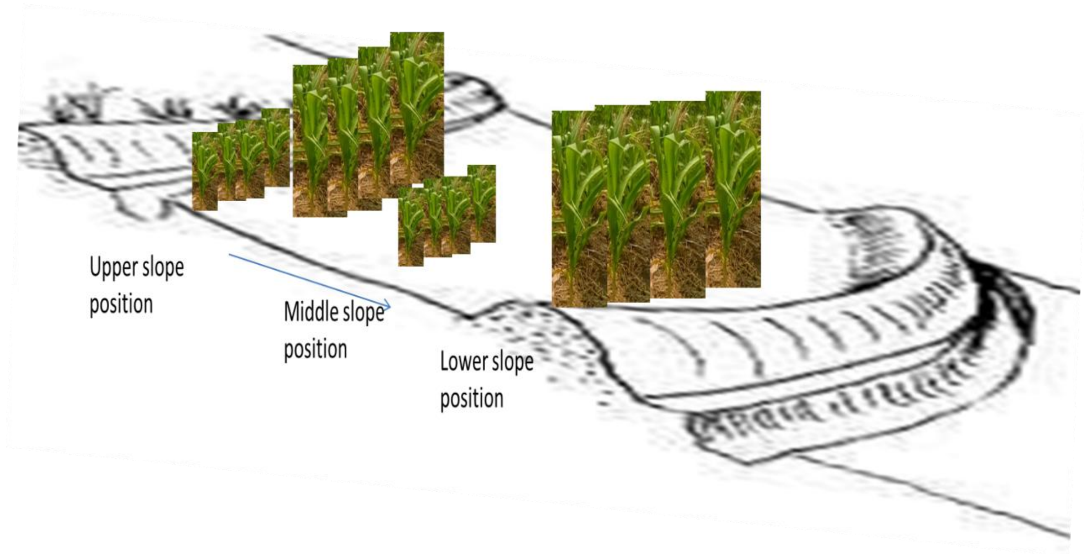


Figure 1.2: Variation in maize plant height along the terrace slope on light-textured Andosols
(Adopted from the description by Ruto, 2015. Drawing by E. Njiru)

A similar study in the heavy-draining Vertisols reported increased yields from rows in thelower position at the furthest end of the slope compared to those next to the ditch. This was attributed to the effect of the lateral flow of moisture (Figure 1.3).

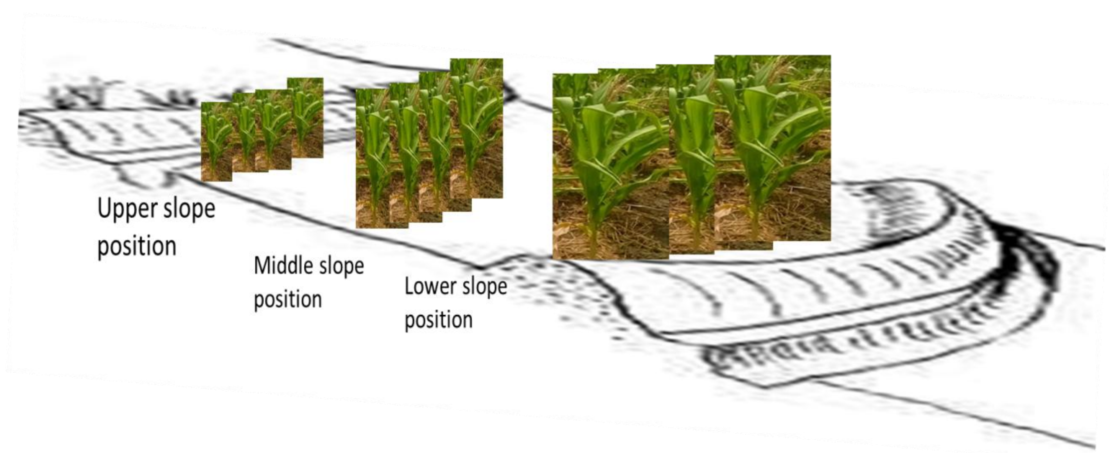
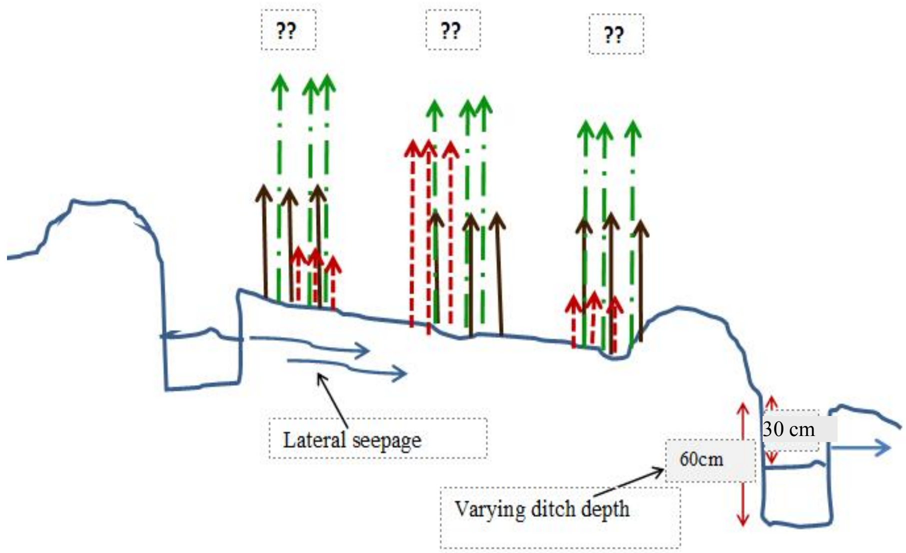


Figure 1.3: Variations in maize plant heights along the terrace slope on heavy textured Vertisols
(Adopted from the description by Wairimu, 2015. Drawing by E. Njiru)

The studies in the three soil types appeared to have a common factor of tall maize in the lower slope position. The studies indicate that farmers can maximize on the lower slope position where maize growth is vigourous and yields are high.

During the introduction of terraces in the ASALs of Kenya a common ditch depth of 0.5 - 0.6 metres deep and 0.5 - 0.6 metres wide was recommended for ease of adoption by farmers (Mati, 2012). Consequently, their performance under different soil types or in the current circumstances of climate change and increased climate variability is uncertain. It is likely, therefore, that with the incumbent changes in rainfall amounts and distributions, alterations of terrace dimensions could be necessary to improve their efficiency. .These observations pointed out the need to carry out studies on the effects of terraces in different soil types to come up with suitable soil-specific management options for different slope positions. It was, therefore, necessary to conduct a study in the hard-setting soils that are common in arid and semi-arid areas of eastern Kenya. The effect of the terraces coupled with the hard-setting conditions of these soils on moisture and nutrient variations is not known and can only be anticipated to result in the maize taking up any one of the scenarios shown in Figure 1.4. The information obtained could help farmers benefit more from the construction of terraces by adopting cropping systems that utilize the variability of nutrients and moisture along the slope to improve yields.



Legend

Maize height in conditions of high rainfall with ponding at upper and lower slope position

Maize height in high rainfall conditions with no terrace effect

Maize height in low rainfall conditions with no terrace effect

Figure 1.4: Possible scenarios of terrace effect on maize growth on hard-setting soils (Drawing by E. Njiru)

Terracing is labour-intensive and the cost of construction is therefore high (Tenge et al., 2005, Atampugre, 2014). Construction cost depends on the slope and stability of the soil (Tenge et al., 2005) and the size of the ditch for *Fanya juu* terraces (Wenner, 1980). Consequently, farmers need to maximize their use, especially concerning spatial variability of soil moisture and nutrients within the terraces. The purpose of this study was, therefore, to establish the effect of terraces on soil moisture, nutrient variability, and maize and bean yieldson the hard-setting soils in the Kenyan ASALs. It is aimed at generating information that can be used for developing suitable management options to ensure efficient utilization of scarce soil moisture and nutrients resources for enhanced crop production per unit of land and water.

1.4. Study objectives

1.4.1. Broad objective

The broad objective was to generate information on the effects of *fanya juu* terraces on soil moisture, nutrient variability and crop yields for efficient use of available resources and enhanced agricultural productivity on the hard-setting soils of semi-arid Kenya

1.4.2. Specific objectives

1. To determine the effectof *Fanya juu* terraces with varying ditch dimensions on soil moisture variability along the slope on hard-setting soils

2. To determine the effect of terraces on the variability of selected soil nutrients along the slope.

3. To establish the effect of *Fanya juu* terraces on maize and bean grain yields on the hard-setting soils of semi-arid Eastern Kenya.

1.5. Hypothesis of the study

1. Varying *Fanya juu* terrace ditch dimensions have no effect on soil moisture variability along the terrace slope on hard-settings soils

2. Terraces do not affect the variability of soil nutrients along the slope

3. *Fanya juu* terraces do not affect maize and bean grain yields on the hard-setting soils of semi-arid Eastern Kenya.

CHAPTER TWO: GENERAL LITERATURE REVIEW

2.1. Soil water and nutrient deficit in the arid and semi-arid lands

Soil water and nutrient conservation and their efficient use is a prerequisite for sustainable agricultural production in arid and semi-arid lands (ASALs) worldwide. This is because water and nutrient deficits are among the major constraints to agricultural production in the ASALs which cover over forty percent (40%) of the earth's land area and are home to about 40% of the world population (Huang et al., 2017). The Food and Agriculture Organization (FAO) of the United Nations describes the ASALs as part of drylands that have a length of growing period (LGP) of between one (1) and 179 days (FAO, 2000). The regions are characterized by low average rainfall which is highly variable in seasonal and annual amounts and poorly distributed within the season. The conditions of high rainfall variability and poor distribution result in recurrent situations of water deficit (Wale and Dejenie, 2013). Much of the rainfall received is lost as runoff due to the characteristic low organic carbon and surface-sealing nature of the soils (Stewart, 2016) which are also low in other nutrients especially nitrogen and phosphorous. Several factors contribute to the low nutrient status of the soils. These include the low inherent soil fertility, nutrient depletion due to leaching, excessive mining of available nutrients with minimum replenishment and losses due to fixation. Soil carbon content is low owing to the scarce deposition, accumulation or decomposition of organic materials (Bernoux and Chevallier, 2014.). Surface sealing, crusting, compaction and hardening make these soils highly susceptible to water and wind erosion (Stewart, 2016). Thus, a combination of soil water deficit, low soil nutrient conditions and negative impacts of climate change contribute to low agricultural production and food insecurity.

Challenges to agricultural production in the ASALs resulting from impacts of water and nutrient deficits are aggravated by a steady increase in population and demand for more food. This has resulted in the cultivation of range-land areas that normally do not have adequate provisional and supportive services such as water and soil fertility (Stewart, 2009). Additionally, the land and water use practices employed by some of the dryland communities are poor and inappropriate for arid environments. This leads to an increase in land degradation and subsequent low crop yields that fall below global averages (Rockstrom and Steiner, 2003; Ngonzo et al., 2013; Omar et al., 2013). Consequently, this has resulted in food scarcity and chronic malnutrition at the household level (Munang et al., 2011; AGRA, 2014). Thus, food insecurity and poverty have since been recognized as the greatest threats to sustainable development in the region (Mati, 2005). Close to 70 % of the population in Africa depends directly on drylands biodiversity for their daily livelihoods. The continuous steady increase in food demand from the increasing population which stood at approximately 325 million by 2009 is anticipated to reach 1.5 billion by 2050 (UNDP, 2009, FAO, 2011, AGRA, 2014). Reports already indicate that approximately 30% of the 800 million people living in SSA are malnourished or suffering from hunger (Clover, 2003; Kidane et al., 2006; Sasson, 2012; AGRA, 2014). Due to these reasons increased agricultural intensification is required in order to keep production in pace with the increasing demand for food (Inocencio et al., 2003). Such intensification demands for effective and efficient use of available water and other resources.

According to the Intergovernmental Panel on Climate Change (IPCC) report (2007), global climate change is already affecting and will continue to affect the semi-arid regions of the world in several ways. Temperature increases, reduction in available water, loss of natural vegetation and biodiversity, soil fertility degradation, and reduction in locally produced food supplies are some of the predicted impacts of this change in the ASALs. This is although the ASALs are already experiencing challenges of erratic and unreliable seasonal and annual rainfall. It is projected that the area under arid and semi-arid conditions in Africa will likely increase by 5 to 8% by 2080 (IPCC, 2007). These climate change predictions also indicate that extreme events of floods and drought coupled with an increase in temperatures will cause additional water stress and result in up to 50% reductions in crop yields in some countries by the year 2020 (IPCC, 2007). Such a reduction in yields will increase the already outstretched supply of food in SSA and worsen current incidences of food insecurity and malnutrition. Given these challenges careful management of water and nutrients is imperative in improving land productivity to cater to the increasing population in the ASAL region of SSA.

2.2. Agriculture in the arid and semi-arid lands of Kenya

In Kenya the arid and semi-arid lands cover approximately 89% of the total land area and receive between 150 to 850 mm of rainfall per year (RoK, 2011, Sigunga and Wandahwa, 2011, UNDP, 2013). Rainfall in these ASALs is highly erratic and varies both seasonally and annually in amounts and distribution. The rains, which at times come in high-intensity storms concentrated over short periods, cause runoff and soil erosion with very little infiltration (UNDP, 2013). Mean minimum and maximum annual temperatures vary from 14 to 22 °C and 26 to 34 °C, respectively (Rao and Okwach, 2005) while infiltration rates are low and evaporation rates are high and exceed rainfall amounts for most of the year. Dry spells during the rainy season are common and frequent droughts result in recurrent crop failures (RoK, 2011, Speranza, 2010). Soils in the ASALs of Kenya are degraded and have low organic matter levels and low water holding capacity (Rockstrom and Steiner, 2003). This is partly due to low vegetative cover and high temperatures. These ASALs are, however, home to over 35% of Kenya's population, the majority of whom are pastoralists and agro-pastoralist farmers who depend on rain-fed agriculture and natural resource base for their livelihood (REGLAP, 2012, UNDP, 2013). The dependency on rain-fed agriculture and natural resource base makes their livelihoods and economic activities highly vulnerable to uncertain rainfall variations and degrading natural resources. Food insecurity is thus common especially in seasons with low rainfall and/or recurrent dry spell usually accompanied by crop failures (Rembold et al., 2014). A report by Food and the Agriculture Organization (FAO, 2011) pointed out that approximately 45% of Kenyans in dry areas were afflicted by chronic malnutrition and over 500,000 children required vitamins due to food shortages. Due to these crop failures and food shortages, the government often has to provide food for people in some areas of the dryland during food deficit seasons, thus increasing resource requirements for the nation.

2.2.1. Soils in the arid and semi-arid lands

According to the Soil Map of Kenya (Sombroek et al., 1980) common soils in the ASALs of Kenya are Luvisols, Lixissols, Ferralisols, Acrisols, Planosols, Alisols Fluvisols Vertisols, Solonchaks and Solonetz. . The soils range from shallow to deep with sandy, medium to fine textures, and low fertility (Osman, 2018). Low soil moisture, sparse vegetation and low production of plant biomass, high temperatures, and low biological activity are some of the factors contributing to low organic carbon in these ASAL soils. The soils are equally faced with both chemical and physical degradation including salinization and alkalinization, wind and water erosion, surface crusting, sealing, hard-setting and compaction (Stewart, 2016). The soils that are most prone to surface sealing in the ASALs of Kenya are Luvisols, Acrisols, Lixisols, Ferralsols and Alisols. Rainfall comes in intensive storms causing water to be lost through runoff, or in low intensities resulting in water loss through evaporation and evapotranspiration especially when the soil surface is dry (UNDP, 2013).

Hard-setting soils

In Africa hard-setting soils are found in large parts of eastern and southern Africa and the Sudan-Sahelian region of West Africa (Monin, 1993). Hard-setting soils are a constraint to agricultural production due to their unstable structure, which collapses once the soil is wet, and then shrinks and hardens as the soil moisture dries up (Daniells, 2012). The soils are pulverized as a result of the instability of the surface layer and detached particles clog and seal pores when soils are wet. On drying, the soils acquires high soil strength and crusting properties and becomes compacted (Giarola et al., 2011). These result in the upper layer of the soil becoming compacted while the surface becomes sealed and crusted. According to Mullins et al (1990), hard-setting soils have a restricted time during which they may be cultivated because once dry, they become difficult or impossible to cultivate until the profileis re-wetted.

The hard-setting condition is usually manifested in the upper horizon. The hardening is accompanied by surface sealing, crusting and compaction as bridging by dispersed soil particles cement the soil surface (Stewart, 2016). These constrain seedling emergence as well as root growth. These soils are however, not permanently cemented but are workable when sufficiently wetted such as during a single intense rainfall event and revert to their hardset state on drying. In the ASALs of Kenya ponding followed by soil crusting as water dried up was reported in hard-setting soils when tied ridges were used as a water harvesting practice (Miriti et al., 2012; Karuma et al., 2014). Hard-setting soils are widespread and are a constraint to agricultural production especially in the sub-humid and semi-arid tropics. In the ASALs of Kenya predominant soils prone to sealing and crusting Luvisols, Acrisols, Lixisols, Ferralsols and Alisols. These soils cover approximately 24% of the total land area (Wanjogu et al., 2006)

2.3. Soil water and nutrient conservation in arid and semi-arid lands

Soil and water conservation measures are described by Mati (2005) and Stewart (2016) as management practices that are used to reduce water losses by runoff and evaporation, while retaining precipitation by increasing infiltration and in-soil moisture storage for crop production. World Overview of Conservation Approaches and Technologies (WOCAT) considers soil and water conservation to include prevention or reduction of soil erosion, compaction and salinity; conservation or drainage of soil water; and maintenance or improvement of soil fertility (FAO, 2004).

Reports on work done over time in arid and semi-arid areas have shown that different field management practices can be used to help reduce water deficit problems in dryland agricultural production systems. These include rain water harvesting (Biamah, et al., 2004, Ibraimo and Munguambe, 2007, Binyam and Asmamaw, 2015), mulching, tillage and soil covers (Gichangi et al., 2004; Gicheru et al., 2004; Jiansheng and Changan, 2012; Miriti etal., 2012, Karuma et al., 2014), supplementary irrigation, crop varieties, and cropping systems (Mutunga, 2001, Itabari et al., 2003). Some of these practices are conservation measures developed to help conserve soil and water for agricultural production (Gachene et al., 2019, Wolka et al., 2021). In Kenya, popular soil and water conservation practices include terracing, conservation tillage, vegetative barriers, runoff harvesting and any other innovative technologies that trap and retain soil, improve its fertility, or facilitate soil-moisture conservation and storage (Mutunga et al. 2001, Biamah and Stroosnijder, 2005). These practices mainly concentrate on the reduction of soil loss through erosion especially from very steep slopes. Any water and nutrient conservation involved is therefore dictated by the type of soil conservation practice (Mati, 2005). The practices have however, been reported to improve crop yield by increasing rainwater harvesting, reducing losses through evaporation and runoff, increasing its infiltration and availability to plants, and conserving soil fertility. These reports come from studies on crop growth and yields and soil fertility status under soil and water conservation (Wezel et al., 2002, Homma et al., 2003). However, little has been reported on the spatial variability of nutrients and moisture in the conserved area and their effects on crop growth.

2.3.1. Soil conservation in the arid and semi-arid lands of Eastern Kenya

Soil and water conservation measures have been used for many years in the aid and semi-arid lands of Machakos County in Eastern Kenya to control runoff and erosion (Mutunga, 2001). One of the common soil conservation practice that was introduced in the area by the colonial government in the 1930s and is used to-date is the construction of terraces on sloppy fields (Gichuki, 1991). Despite a few bottlenecks in the early adoption stages, lack of adequate moisture and decreasing supply of productive land have made farmers over time appreciate the need for terraces for soil and water conservation (http://www.fao.org/doc). Currently over 70% of arable land in the county is terraced. Other soil conservation techniques used include crop rotations and inter cropping (Mutunga, 2001).

2.3.2. Bench terraces for soil and water conservation

A terrace is defined by Gichuki (1991) as “an embankment or ridge of earth constructed across a slope to control runoff and minimize soil erosion”. The channels and embankmentsare built along the contour to reduce the length and/or steepness of the slope. They minimize erosion and conserve soil and water by reducing the quantity and speed of runoff flowing across the soil surface (SUSTAINET EA, 2010). Aklilu, 2016). At the same time they reduce the overland flow and minimize nutrient loss through erosion (Gachene etal. 2019). The reduced speed of runoff and overland flow encourages water retention and increases infiltration (Gichuki, 1991, Mutunga, 2001, Taylor et al., 2008; Baptista et al., 2015). One of the most common type of terraces used for soil conservation worldwide is thebench terrace (Plate 2.1).

(Plate 2.1. a)

(Plate 2.1. b)

Plate 2.1: Old bench terraces in farms in Kimutwa location, Machakos County
(Photo courtesy E. Njiru)

Bench terraces can be classified into different types depending on the method of construction, location and use (Aklilu, 2016) (see Appendix 1 for terrace classification). One classification categorizes bench terraces as (i) excavated and (ii) developed types. Soil-excavated terraces are constructed by excavating soil to create channels/ditches and embankments/walls along the contour. The channels and ditches developed reduce the length and steepness of the slope (SUSTAINET EA, 2010) and thus, the flow of runoff. Terraces can also be developed by the construction of stone bunds/lines, trash lines, or by the use of vegetative barriers such as planting grass strips or leaving unploughed grass strips along the contour to reduce runoff speed and control erosion. In Machakos County the soil excavated terraces are more common than thrash lines or grass strips. This is because trash lines and grass strips take long to establish. They are also easily damaged by termites and droughts or long dry spells which are common in the ASALs (Gichuki, 1991). Excavated terraces are classified as graded or narrow-based bench terraces or level bench terraces (SUSTAINET EA, 2010, Gebreslassie, 2014, Aklilu, 2016).

2.3.2.1. Level bench terraces

This type of terraces are constructed within the farm (cultivated area) to reduce the slope, decrease runoff and increase water retention (SUSTAINET EA, 2010). Different types of bench terraces are found in various parts of the world. The two most common types are the cut-and-fill bench terraces and the "*Fanya juu*" terraces. The cut-and-fill terraces are created through excavating soil to create flat beds supported by walls (embankments) of soil (Plate 2.2). The embankments are planted with a grass cover, especially fodder, to offer support. These beds and embankments run parallel in several series depending on the width of the slope. Cut and fill terraces are recommended in medium to steep slopes of 12-47% (Namirembe et al., 2015). The area should be free of gullies or stones to allow for deep soil excavation.

Plate 2.2: Cut-and-fill terraces in Mbooni sub-county, Makueni County
(Photo courtesy: E. Njiru)

Fanya juu terraces are developed by digging a trench (ditch) along the contour, excavating the soil from the ditch and heaping it to form a compacted embankment that obstructs runoff. The terraces are known as *Fanya juu* in the way they are constructed by heaping the excavated soil uphill (SUSTAINET EA, 2010). A small ledge is maintained between the ditch and embankment to prevent the soil from sliding back. The embankment is sometimes strengthened by a grass cover or fodder crop (SUSTAINET EA, 2010, Studer and Liniger, 2013). The trench collects and retains runoff together with soil sediments. Some farmers plant fruit trees such as pawpaws, bananas and citrus in it to make use of the retained water (Plate 2.3).

Plate 2.3: Fanya juu terraces with banks stabilized with grass (left) and with a fruit tree planted in the ditch (right)
(Courtesy: E. Njiru)

Sediments slowly pile up at the upper part of the embankment while the surface runoff accumulates in the ditch and slowly infiltrates into the soil profile (Tenge et al., 2005). Over time *Fanya juu* terraces develop into benches consisting of a series of level to almost level strips running along the contour (Plate 2.4). The strips divide long slopes into shorter segments reducing erosion and enabling farming in otherwise sloppy areas (SUSTAINET EA, 2010, Namirembe et al., 2015). *Fanya juu* terraces are suitable for areas with deep soils to allow for excavation and slopes below 20% (Namirembe et al., 2015).

Plate 2.4: Fanya juu terraces that have formed a series of strips across the contour (Photo courtesy: E. Njiru)

2.3.2.2. Narrow based terraces

Narrow- based terraces are constructed to contain and remove excess water from a field or a particular area (SUSTAINET EA, 2010, Gebreslassie, 2014). This type of terrace is often constructed on the upper side of the farm to collect excess water and prevent it from flowing into or running over the whole farm. Narrow-based terraces that are constructed to contain excess water are known as retention ditches. When constructed to drain excess water the ditches are often graded and are referred to as cut-off drains (COD). Farmers usually plant different types of fruit trees in the ditches depending on the amount of water retained (Plate 2.5).

Plate 2.5: A retention ditch in Kibwezi East, Makueni County
(Photo courtesy: E. Njiru)

2.3.3. Terrace dimensions

Dimensions of terraces including ditch depth and the intervals from one ditch to the next are calculated using an arithmetic formula based on the type of soil, slope, soil depth, rainfall amounts and intensity (Sheng, 2002, Widomski, 2011, Hussein et al., 2016, Baryla and Zmuda, 2017). However, general measurements are recommended for simplicity and ease of adoption (Mutunga, 2001, Sheng, 2002, Studer and Liniger, 2013). In the ASALs of Kenya *Fanya juu* terraces are constructed at intervals of 10 to 15 meters depending on the slope with channel dimensions ranging from 0.6 to 1.0 meters wide and 0.45 to 1.5 meters deep (Mutunga, 2001). For simplicity, ditch dimensions recommended by the Ministry of Agriculture are 0.6 meters deep and 0.6 meters wide. The recommended dimensions for the CODs on the other hand are 0.9 meters wide and 0.6 meters deep and a gentle ditch slope of 0.5% to drain water to the natural waterways. Some farmers have further modified these dimensions to suit their conditions. For instance, ditch measurements for *Fanya juu* terraces have been modified to up to 1.2

meters width by 0.75 to 0.9 meters deep depending mainly on the farmer's interest and financial situation (labour charges for digging the ditch depends on dimension). The wide ditch is preferred by farmers who plant fruit trees such as mangoes, oranges and bananas in the ditch. Increased uncertainty in the occurrence of seasonal rainfall and the high variability in amounts due to climate change has in the recent past resulted in the gradual reduction or removal of the 0.5% slope of CODs. This enables the trenches to hold more of the limited rain water for longer periods and allow it to flow laterally into the cultivated area as opposed to draining it from the farm.

2.4. Use of cropping systems in soil water management

Cropping systems have been used for decades for soil and water conservation purposes (Mutunga, 2001, Studer and Liniger, 2013, Bashagaluke et al., 2018, Gachene et al., 2019). The systems involve rotations, intercrops, relay cropping and cover crops, most of which include some fast-growing legumes that provide cover to the soil and prevent soil loss (Matusso et al., 2014, Nyawade et al., 2018). Apart from preventing soil loss, cropping systems involving legumes give an extra benefit of nitrogen fixation which improve the soil nutrient status. A review by Mutasso et al. (2012) indicated that cereal-legume inter-cropping systems in SSA had shown improvements in both soil fertility and crop yields particularly for the cereal crop. In most cases the cereal crop involved was the staple food crop for smallholder farmers. Higher water use efficiency (WUE) was reported in maize legume intercrops as compared to the sole crop systems (Ofori et al., 2014). Similarly higher net benefits and land equivalent ratio (LER) were recorded from intercropped plots than from plots under sole systems (Saleem, et al., 2011, Nyassasi and Kisetu, 2014).

Maize (*Zea mays* L.) is a dominant crop in the drylands of SSA. Maize mixed farming systems are common food crop mixture not only in the ASALs of eastern Kenya but also in the country as a whole. Although maize and beans system stands out as a major food basket in the country, their yields have remained low and highly vary with rainfall amounts and distribution (Rao and Okwach, 2005). Maize, being the principal staple crop, is grown in all agro-ecological zones where crop production is carried out (Odendo et al., 2002). It has been recognized as a common component in most intercropping system and is found in 90 per cent of all Kenyan farms (Odendo et al., 2002) where it is grown in pure stands, intercropped with various legumes or in rotation with other crops.

2.5. Research gaps

A large number of soil and water conservation practices have been developed to help increase crop production in the ASALs by increasing rain water harvesting, reducing losses through evaporation and runoff and increasing its infiltration and availability to plants. The majority of these soil and water conservation techniques were however, developed mainly for control of soil and nutrient loss through erosion with little emphasis on their effects on soil water regimes and crop growth in the areas where conservation was carried out (Gichuki, 1991). As a result, scarce information is available on specific relationships between soil and water conservation practices and the status of soil moisture and nutrient variability, crop growth and yields in areas with conservation structures. This information is necessary for the improvement of crop productivity through development of practices that make more efficient use of the available resources.

Terracing is a soil conservation measure that is mostly adopted in hilly, arid and semi-arid areas to reduce soil and water erosion. The structures increase infiltration and maintain soil productivity thus sustaining crop production in sloppy areas (Sheng, 2002, Youssef et al., 2008). Although differences in crop yields have been reported between terraced, non- terraced and within terraced fields, little effort has been focused on the effects of this soil conservation practice on specific soil water and nutrient regimes and crop growth in the conservation area. Terracing as a practice is common in the ASALs of Kenya. Recent studies have reported differences in crop growth and yield at different positions within the terraced fields indicating a possibility of moisture and/or nutrient variability at these positions.

In the well-drained Luvisols of Machakos County Gachene and Baaru (2011) reported an increase in crop yields from the maize rows bordering the terrace ditch comparedto the section away from the ditch and attributed this to an increase in soil moisture next tothe ditch due to lateral seepage from the terrace ditch. In the light-textured Andosols in Narok County, Ruto (2015) reported retarded growth and low yields of maize next to the ditch followed by taller maize rows before the zone of depletion. The retarded growth was attributed to excessive drainage and leaching of nutrients from the section next to the ditch while the taller maize rows were a result of water availability through lateral drainage. A similar study by Wairimu (2015) in the heavy-draining Vertisols showed the crop in thelower slope position having a more vigorous growth compared to that next to the terrace ditch. These studies, other than showing the effect of terraces on the variability of soil moisture and crop yield in the terraced area also showed that the variability was soil-specific. This brings about the need to study the effect of terraces in as many different soils as possible to identify suitable crop and soil management practices that can contribute to efficient crop utilization of the available resources. The studies mentioned above concentrated more on soil moisture variability and constant ditch depths. The effect of varying ditch depths on soil moisture, nutrient variability and crop yields has not been investigated. This study therefore investigated, the effect of varying ditch depths of terraces on both soil and nutrient variability and crop yields at different slope positions.

2.6. Scope of the study and structure of the thesis

2.6.1. Scope of the study

The study involved setting up trials in a controlled location with hard-setting soils in Machakos County in semi-arid Kenya where local farmers practice terracing as a soil conservation measure. The aim was to study the effects of terraces on variability of soil moisture, nutrients and crop yield in semi-arid areas. Terraces constructed with different ditch depths were tested for their effects on soil moisture and nutrient variability as well as their effects on growth of maize and beans under different cropping systems. The trial was conducted for four seasons (two long and two short rain seasons) in 2014 and 2015. Findings from this study can be used in other regions with similar soil, climatic, farmer practice and environmental conditions.

2.6.2. Structure of thesis

This Thesis is written in paper format. There is a general abstract at the beginning of the Thesis. Chapters one and two give the introduction and general literature review. They describe the overall aspects of *Fanya juu* terraces, the drylands, constraints to agricultural production in the drylands and some of the technologies employed to solve these constraints. Chapter three addresses objective one of the study, chapter four objective two and chapter five objective three. Chapter six gives the general conclusions and recommendations.

CHAPTER THREE: EFFECT OF VARYING TERRACE DITCH DEPTH DIMENSIONS ON SOIL MOISTURE VARIABILITY ON HARD-SETTING SOILS OF SEMI-ARID EASTERN KENYA

3.1. Abstract

Fanya juu terraces were introduced in semi-arid Eastern Kenya in the 1980s and are used to-date for control of soil erosion. Little emphasis, however, was put on their role in moisture conservation. Although ditch dimensions are governed by several aspects including soil type and depth, slope and amount of precipitation, a constant depth is usually maintained in semi- arid areas for ease of adoption. A study was conducted to establish the effect of terraces on soil moisture content (SMC) and its variability along the slope on the hard-setting soils of semi-arid Eastern Kenya. The experiment was conducted in four seasons during the October- December short rain (SR) and March-May long rain (LR) seasons of 2014 and 2015 in Mua location, Machakos County. The objectives of the trial were (i) to determine the effect of terraces on soil moisture content in the terrace and (ii) to determine the effect of varying ditch depths on soil moisture variability at different positions along the terrace slope. Terraces with two ditch depths, 30 (D_{30}) and 60 cm (D_{60}) were tested against a control of non-terraced or 0 cm (D_0) in a split-plot design. Gravimetric soil moisture content at the 0-30cm soil profile was compared at the upper (US), middle (MS) and lower (LS) slope positions of the terraces with the three ditch depths. Data was subjected to analysis of variance (ANOVA) using Genstat statistical package. Differences between means were separated using the least significant difference at $p \leq 0.05$. Daily rainfall data was recorded and values used to

determine seasonal totals and distribution. Rainfall amounts ranged from 266.4 mm in LR 2014, 149.2 mm in SR 2014, 239.2 mm in LR 2014 and 499.7 mm in SR 2014. Soil moisture results showed that treatments with ditches conserved significantly higher ($p<0.05$) moisture than those without. The effect of ditch depths on soil moisture content varied with rainfall amounts and distribution. There was a significant increase ($p=0.013$) in soil moisture with LS>MS>US positions in treatments with D30. The study concluded that the construction of terraces is required for soil moisture conservation on hard-setting soils of semi-arid lands. It recommended a ditch dimension of 30 cm deep and higher exploitation of soil moisture available at the lower slope position for increased benefits and sustainable productivity of terraces.

3.2. Introduction

Terrace construction is one of the practices that has been adopted in many countries overmany decades to help increase agricultural productivity in hilly or mountainous areas. The structures reduce erosion and conserve soil but are also known to conserve water, especially in regions with low rainfall (Widomski, 2011, Nyamadzawo et al., 2013). The use of terraces isnot only promoted as the best practice for effective soil and water conservation but is also considered the most widely adopted throughout the world (Binyam and Asmamaw, 2015. Terrace structures reduce soil loss from surface runoff thereby reducing nutrient losses through erosion and conserving the soil in both agricultural and non-agricultural areas. They are particularly useful in dry regions for increasing infiltration (Hussein et al., 2016).

Several types of terraces are found and used in different regions depending on local circumstances. The circumstances include the needs of the farmers, the type and depth of soil, slope and precipitation (Widomski, 2011, Namirembe et al., 2015, Wei et al., 2016). The most common type of terrace used in the ASALs where rainfall is low and slopes are moderate is the *Fanya juu* bench terrace. *Fanya juu* terraces are constructed by digging ditches and heaping the soil uphill to form an embankment. The embankment obstructs runoff especially in the hilly or sloppy areas that are prone to widespread erosion. *Fanya juu* terraces are common in the ASALs of Eastern Kenya. Another type of terrace occasionally used together with the *Fanya juu* terrace is the cut-off drains (COD). This type of terrace is constructed to drain excess water from a given area such as the homestead or a cultivated area that is subject to water logging or excess erosion.

Terrace dimensions are determined in consideration of the type of soil, slope, soil depth and rainfall amounts and intensity (Widomski, 2011, Hussein et al., 2016). For simplicity andease of adoption, however, general measurements are adopted from place to place with various modifications by farmers. In the ASALs of Kenya channel dimensions range from 0.6 to 1.0 m wide and 0.45 to 1.5 m deep (Mutunga, 2001) are recommended for *Fanya juu* terraces by the Ministry of Agriculture. Most farmers have modified these dimensions to upto 1.2 m width by 0.75 to 0.9 m deep depending on their interest and financial situation.

A lot of emphasis is put on the effectiveness of terraces in soil conservation. Their role in control of erosion is reported by several authors (Gichuki, 1991, Doreen and

Ray, 2004, Tenge et al., 2006, Widomski, 2011, Adimassu, et al., 2017). However, little has been documented on their importance in runoff conservation, soil moisture retention and the availability of the stored water for crop use. The missing information is critical in the current situation of climate change and especially in the drylands where low and increasingly erratic rainfall affects the farming systems and agricultural productivity. This study aimed at generating information to contribute to the bridging of this knowledge gap. The objectives were to determine the effect of varying ditch depths on soil moisture content and variability in the terraces. The information obtained would be useful in guiding farmers in selecting suitable soil and crop management practices for efficient utilization of available water on hard-setting soils in semi-arid areas in Kenya.

3.3. Materials and methods

3.3.1. Study area

This study was conducted in both the LR and SR seasons of 2014 and 2015. The trial was established on neighbouring farmer's fields in Makyau village, Mua location, Machakos County in semi-arid eastern Kenya. Both farms are in the agro-ecological zone (AEZ) UM4 and are located at 37o15'29.124''E 1o29'40.776S and 37o15'29.1522''E 1o29'40.7112''S on the slopes of Mua hills. They lie at elevations of 1722.20 and 1722.26 m above sea level (Figure 3.1).

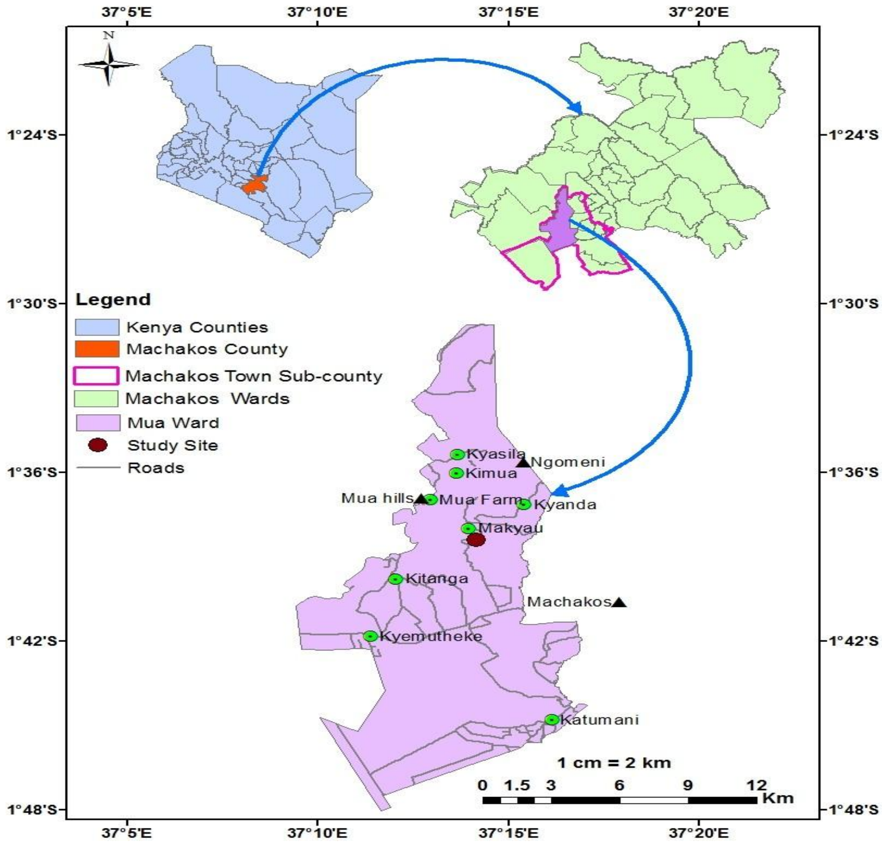


Figure 3.1: A map showing the site of the study

The study area receives an annual average rainfall of 673 mm in two seasons which coincide with the cropping seasons (Jaetzold et al., 2010). The March to May rainfall is referred to as the long rains (LR) season with a mean of 272 mm. October to December rains are referred to as the short rains (SR). These have a mean of 382 mm (Jaetzold et al., 2010). Rainfall is generally unreliable in amount and distribution. Prolonged dry spells and recurrent droughts during the crop-growing seasons are common. These lead to frequent crop failures and food insecurity (Mati, 2012, Jaetzold et al., 2010). Increased variability in onsets, concentration of rainfall in a few rainfall events and increase in extreme/storm rainfall are also common (Speranza, 2010). Annual temperatures range from 24.7°C to 17.3°C with a mean of 20°C. Rates of evaporation (ETo) are high and exceed rainfall amounts (r) in most of the months of the year (Jaetzold et al., 2010).

Soils in the study location are characterized as Luvisols (FAO/UNESCO, 1997), yellow-red sandy clay loam, and shallow with high percent base saturation (Sombroek et al., 1980). Ponds of water easily form on their surface during rainfall events (Miriti et al., 2012). The ponding is followed by sealing and crusting as the water dries up. The major type of farming practiced in the area is mixed cropping/livestock system which combines cultivation of food crops and rearing of livestock. Maize is the most common cereal crop grown as sole a crop or intercropped with beans or pigeon peas.

3.3.2. Experimental design and treatments

A split-plot design with four replicates was used. The main plots consisted of the terrace ditch depths while the slope positions were the sub-plots. The trial was laid out in two adjacent farms where each farm had two replicates. This was because of lack of enough land in a single farm to accommodate the whole experiment. Both farms were in agro-ecological zone (AEZ) UM4. Treatments consisted of terraces of different ditch depths, 0 cm (D_0), 30 cm (D_{30}) and 60 cm (D_{60}) randomly allocated to the main plots (Figure 3.2). The zero (0) cm depth was used as a control since some farmers do not construct terraces on their farms. This had no ditch at the top of the slope and no embankment at the lower side (end) of the cultivated slope. The terraces were measured and ditches dug out to the required depths as per the field plan at the beginning of first season. These were afterwards maintained in the subsequent seasons by removing soil from the ditch before planting. A uniform width of 60 cm was maintained in the 30 and 60cm depth ditches.

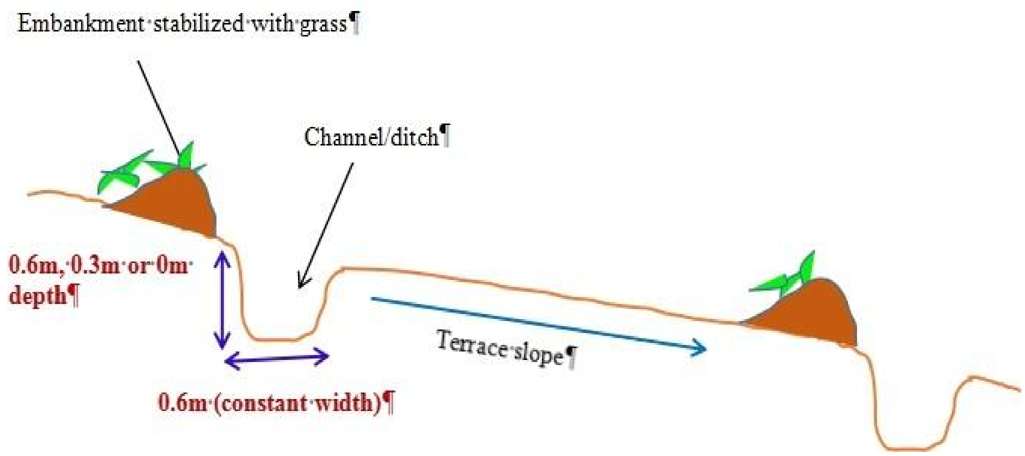


Figure 3.2: Sketch of ditch dimensions tested during the study
(Drawing by E. Njiru)

Each depth occupied a 14 m long plot. A 2-m path separated one main plot from the other to avoid water from the area with one ditch running over to the other The terrace area below each ditch depth was subdivided into three equal sections representing the upper, middle, and lower positions of the slope (Figure 3.3). These sections formed the sub-plots. The terraces were oxen ploughed and planted with maize and beans which were managed as per recommended agronomic requirements until harvesting. The conditions of these crops at different stages of the growing cycle were used to indicate periods of crop moisture stress following days of dry spells. Soil sampling for assessment of moisture contents was conducted during these periods of moisture stress. Grass was planted on the terrace embankments for stabilization.

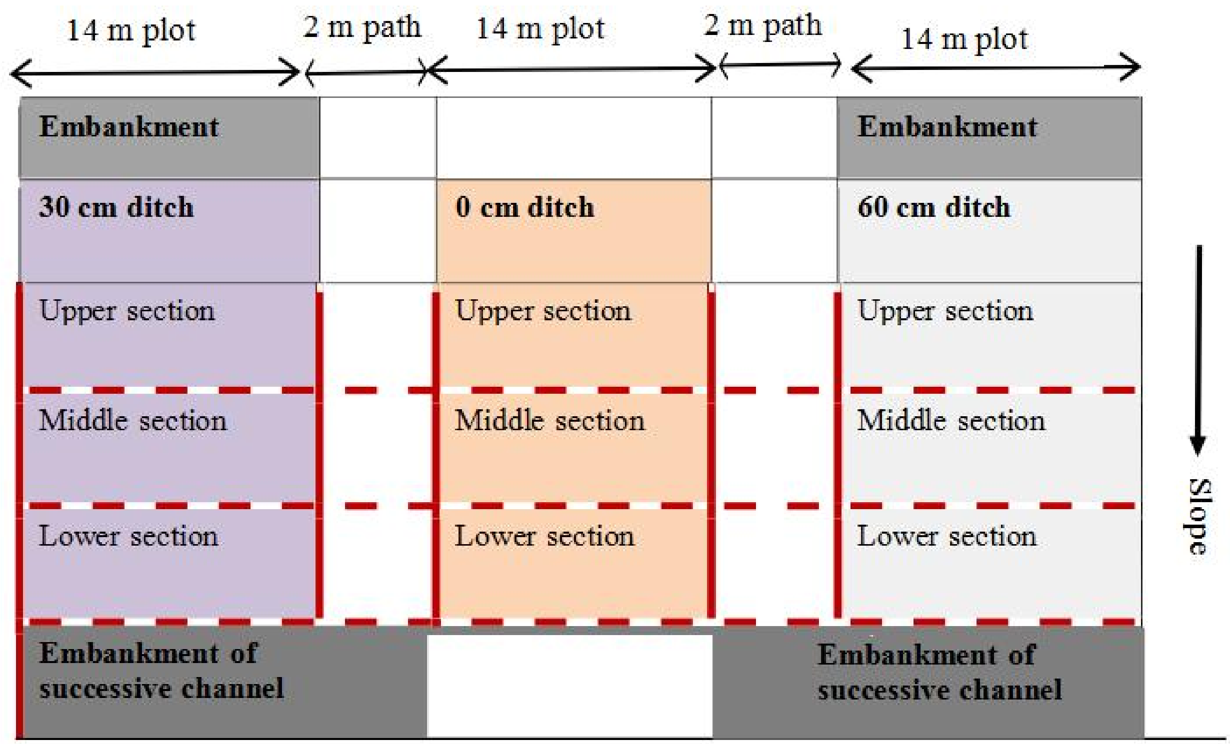


Figure 3.3: Sample of one replicate of the trial (not drawn to scale)

3.3.3. Data collection and analysis

3.3.3.1. Soil sample collection and laboratory analysis for moisture determination

The soil samples were collected from the upper, middle and lower slope positions of each of the terraces defined by the three ditch depths for moisture determination. Samples were collected seasonally for comparison across seasons. Sampling was done at three different stages of maize growth (eighth leaf, tasseling and harvesting stages) during periods of a dry spell when the crop showed signs of moisture stress. The values of soil moisture content obtained from the three sampling stages per season were averaged to get the moisture content in each slope position across the crop growing period. Rainfall data was recorded from daily rain gauge readings and used to determine periods of dry spells. The dry spells were defined according to Stern et al. (2006) as periods of at least ten (10) consecutive days with 0.85 mmof rainfall or less after the last rainfall.

Three random samples were collected from each slope position of every terrace using a soil auger at a depth of 0-30 cm. A sub-sample from a thorough mixture of the three samples was transferred into plastic bags, properly sealed and weighed before being taken to the laboratory. Each sub-sample was placed in a tin of known weight and oven-dried at 105 °C for 24 hours. The dry weights of the soil minus the tins were recorded and used to calculate moisture contents at each slope position of the terraces using the formula:

Vol MC = ((Mt-Ms)/Ms) x Db

Where:

Vol MC = Volumetric moisture content

Mt = Mass of the soil before drying,

Ms=Mass of dry soil,

Db = Soil bulk density

Soil bulk density was determined using metal core rings of known volume. The rings were gently pushed into the soil using a hammer. Intact samples collected in the rings were dried in the oven for two hours at 105^{o}C. The weight of dried soil was taken and soil bulk density was calculated from the formula:

Db = Wd/Vs

Where:

Db = Soil bulk density

Wd = Weight of oven-dry soil

Vs = Volume of soil (= volume of the core ring)

Calculated values for the three sampling stages in each season were averaged to denote soil moisture content across the season.

3.3.3.2. Statistical data analysis

Rainfall data was entered in an Excel spread sheet and total amounts for the seasons were computed. Distribution graphs were derived from the data. Soil moisture data was organized in an Excel spreadsheet and exported to GenStat (2016) statistical package for analysis of variance (ANOVA). Differences between means were determined using Fishers' least significant difference (LSD) of means at $p \leq 0.05\%$ value.

3.4. Results and discussion

3.4.1. Rainfall amounts and distribution

Seasonal rainfall amounts and distribution varied during the study period. Totals of 266.4 mm were recorded during LR 2014 and 239.5 mm during LR 2015. The SR seasons recorded 149.2 mm of rainfall in 2014 and 499.7 mm in 2015. Thes long- term average rainfall amounts for the study area are 272 mm for LR and 382 mm for SR seasons (Jaetzold et al. (2010). Rainfall amounts received in the LR seasons (266.4 mm in 2014 and and 239.5 mm in 2015) were, therefore, both near the normal average (NNA) of 272 mm for the LR seasons. The SR seasons were, however, characterized by below normal average (BNA) in 2014 (149.2 mm) and above normal average (ANA) in 2015 (499.7 mm) compared to the long term average of 382 mm) (Figure 3.4 a, b and c).

Rainfall distribution was poor with regular dry spells during crop growing periods in all seasons except for SR 2015. For instance, out of the 266.4 mm recorded in LR 2014, a total of 207.4 fell within the first month of the season leaving only 44 mm in April and 14.8 mm in May. Monthly rainfall totals in LR 2015 were 17.5, 102.4 and 119.7 mm in March, April and May, respectively. Although rainfall within the first two months (March and April) was fairly distributed, the last month (May) had poor distribution whereby out of the 119.7 mm of rainfall received in nine (9) rain days a total of 100 mm was recorded on a single day. The low rainfall with poor rainfall distribution portrayed in this study are a common occurrence in the semi-arid Kenya with adverse effects on crop yields as ascertained in studies by Miriti et al. (2012) and Speranza (2010) in their previous work in the drylands of Kenya.

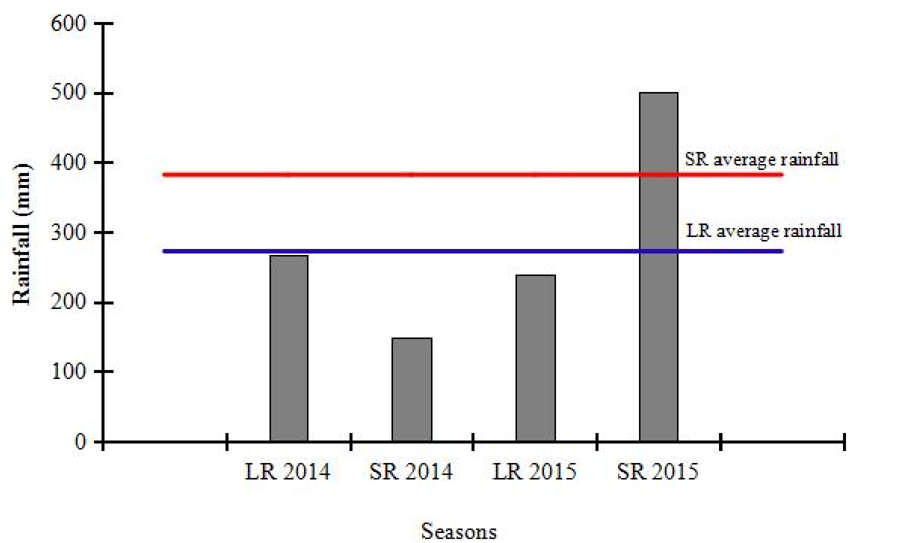


Figure 3.4 a

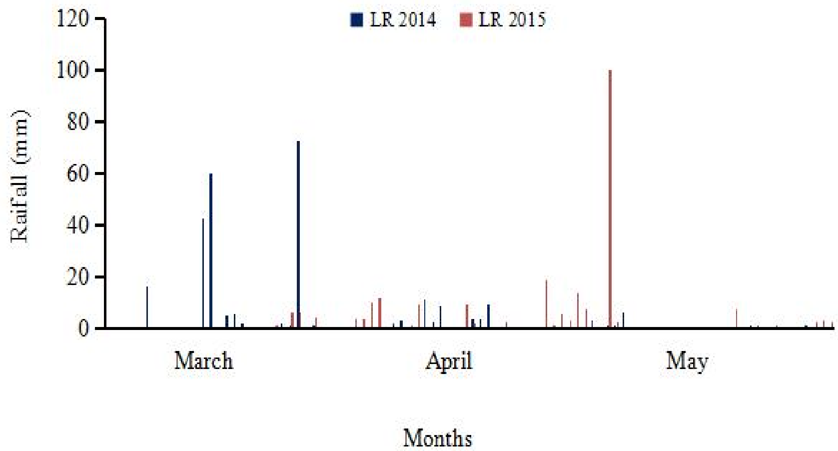


Figure 3.4 b

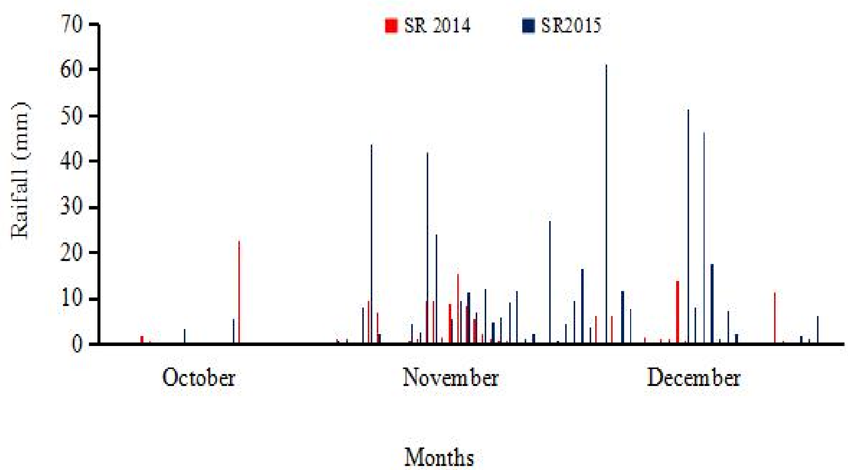


Figure 3.4 c

Figure 3.4: Rainfall (a) amounts during LR and SR seasons in relation to long-term averages, and (b) distributions in LR and (c) in SR seasons in 2014 and 2015

3.4.2. Soil moisture content across seasons

Figure 3.5 shows the average soil moisture contents in the terraces irrespective of the ditch dimensions across the crop growing seasons (see ANOVA results in Appendix 2). Average soil moisture content generally varied from season to season depending on the amount of rainfall received and its distribution. The highest average amount of SMC ($0.35 g^3g^{-3}$) was recorded in SR 2015 when rainfall was high and evenly distributed. Similarly the least average moisture content ($0.12\ g^3g^{-3}$) was recorded in LR 2014 and SR 2014 which also coincided with low and/or unevenly distributed seasonal rainfall.

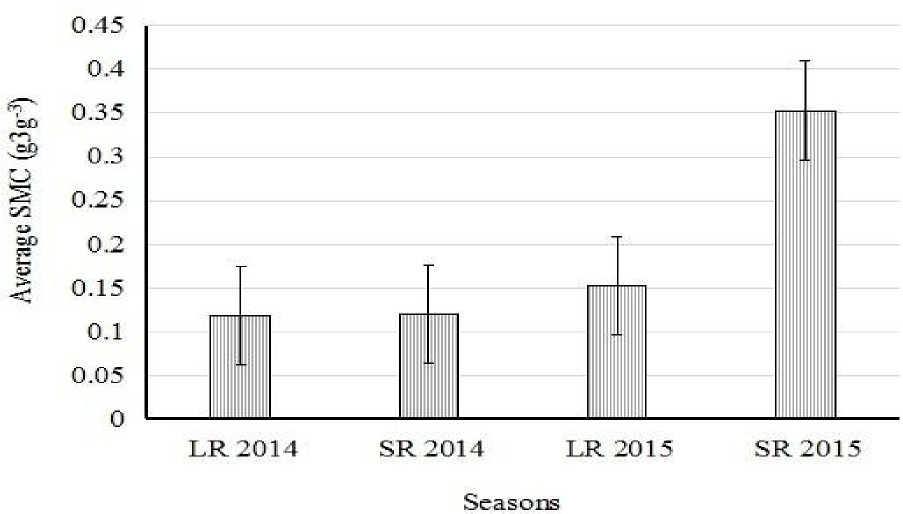


Figure 3.5: Average soil moisture contents in the terraces across the crop growing seasons irrespective of the ditch dimensions

Legend: SMC - Soil moisture content: Error bars denote Standard error bars

3.4.3. Effect of ditch depth and terrace slope position on soil moisture content

Significant difference (p<00.001) was found in the interactions of season, ditch depth and slope position. (Table 3.1). Treatments with ditches (D_{30} and D_{60}) registered higher average soil moisture content than the control (D_0) in all seasons.

Table 3.1: Soil moisture contents at different slope positions of terraces with 0, 30 and 60 cm ditch depth dimensions during LR and SR seasons of 2014 and 2015

		Slope Position		
Season	**Ditch Depth (cm)**	**Lower**	**Middle**	**Upper**
SR 2015	60	0.420 ab	0.406 abc	0.457 a
	30	0.357 abcde	0.356 abcde	0.389 abcd
	0	0.288 abcdef	0.271 abcdef	0.234 abcdef
LR 2015	60	0.251 abcdef	0.175 bcdef	0.184 bcdef
	30	0.183 bcdef	0.160 cdef	0.132 def
	0	0.111 ef	0.091 f	0.083 f
SR 2014	60	0.139 def	0.114 ef	0.108 ef
	30	0.168 bcdef	0.138 cdef	0.124 ef
	0	0.091 f	0.010 ef	0.100 ef
LR 2014	60	0.137 def	0.124 ef	0.125 ef
	30	0.179 bcdef	0.143 def	0.128 def
	0	0.080 f	0.074 f	0.074 f

LSD = o.o33
Means followed by same letter are not significantly different at P ≤ 0.05

The higher SMC in D_{30} and D_{60} than in the control was attributed to a reduction in loss ofrunoff in terraced treatments through its collection in the ditches and interception by the ridges This showed the importance of terraces in reducing rain-water losses in hard-setting soils. Similar results of enhanced soil moisture content through terracing were reported in a study by Li et al. (2012) in Southern Ningxia. The study reported a possibility of 1.13 times more storage of rainfall in terraced than non-terraced landscapes. Lower SMC in non-terraced treatments in the current study could also be attributed to high runoff losses enhanced by the crusting and sealing nature of the soil surface. This implies that loss of rain-water through runoff in these crusting soils was inevitable when conservation structures were not constructed. This possibility is supported by Bresson et al. (2006) in their review on soil crusting in Europe. The authors reported that the slumping of the surface layer of hard-setting soils decreased the porosity of the macro-pores leading to low infiltration and increased erosion. Other authors also emphasized the role of terraces in moisture conservation. Kannan et al. (2009) reported an 85.8% efficiency of water conservation by ridges and furrows in terraces compared to 13.9% in non-terraced fields from their work on Rubirizi farm in Rwanda. Similarly, Shimbahri et al. (2019) found a 110% average increase in soil moisture content in terraced than non-terraced fields in Ethiopia, while Bai et al. (2019) reported a 26.6% reduction in surface runoff in terraces in the Chinese Loess Plateau. Xu et al. (2021) also reported higher soil moisture in terraced than bare slope areas while working in Zhuanglang County in the Chinese Loess Plateau. Wei et al., (2019) similarly reported higher moisture retention in terraces in hilly dry areas of China.

Results of this study revealed that the contents of soil moisture in different ditches and positions of the terraces depended on the amounts and distribution of rainfall. A non-significant difference (p=0.113) in soil moisture content was observed in interactions of ditch depth and slope positions. This could have been caused by the effects of low and poorly distributed rainfall. The rainfall received in season one (LR 2014) was unevenly distributed while the amount in season two (SR 2014) was both low (147.2 mm) and unevenly distributed. The low rainfall and frequent dry spells restricted the amount of water that was collected and conserved in the ditches. The depths of the ditches did not, therefore, have any significant effect on soil moisture content during the below average rainfall seasons. It is however important to note that soil moisture content in D_{30} was higher than in D_{60} during these seasons. The higher but non-significantly different moisture content in D_{30} than in D_{60} was probably because of the differences in depth of the lateral flow of runoff from the two ditches. Lateral seepage in D_{30} occurred at an upper soil profile compared to the flow in D_{60} where runoff was held at a deeper depth. Some of this water was lost through deep percolation at soil depths that were beyond the 0-30 cm soil layer from which sampling was done. A further comparison of similar slope positions across the terraces showed significant differences between treatments with ditches (D_{30} and D_{60}) and the control (D_0) in tthe 3rd and 4th seasons (LR 2015 and SR 2015). Soil moisture content was significantly higher ($P < 0.001$)in D_{60} than in D_{30} at both LS and US positions in season 4 (SR 2015), and at the LS position in season 3 (LR 2015). The rainfall received in the fourth season was 31% higher than the long- term mean (382 mm) with an even distribution across the season. Rainfall in season three was well-distributed in the last two months. It was noted from these results that in high and evenly distributed rainfall soil moisture content was significantly higher in D_{60} than in D_{30}. A significant difference was also found between moisture contents at the US and LS positions. This implied that when rainfall was high and regular the ditches were effective in storing runoff thus increasing soil moisture in the adjacent slope position. At the same time, the ridges were also effective in intercepting the surface flow and storing it at the lower position of the terrace. The deeper ditch (D_{60}) however, collected more water and conserved it for longer periods than the shallow one (D_{30}). This resulted in higher soil moisture contents in D_{60} than in D_{30}.

Significantly higher ($p<0.001$) soil moisture content was found in the US positions than the other positions in terraces with ditches in SR 2015. This was attributed to the effect of water saturation resulting from the high volumes of runoff collected in the ditches during the frequent rainfall events. A review by Dorren and Rey (2004) confirmed that soil saturation can occur in terraces as a result of the retention of too much water. Based on work by Daniells (2012) the unstable surface layer of hard-setting soils is pulverized and detached particles clog and seal the pores when soils are wet. The sealing could have impeded the flow of water through deep seepage and upper lateral flow to the lower slope position thus partially explaining the lower contents in the deposition zone. A significant difference ($p\leq0.05$) in moisture content was however, found between the lower slope and the middle and upper slope positions in D_{30} during these poor rainfall seasons. A combined effect of lateral seepage at the upper soil profile together with interception of surface runoff by the embankments in these poor rainfall seasons accounted for these differences. A report of non-significant effect of ditch depths on soil moisture content was also given by Wairimu (2015) from an experiment conducted for two seasons on the heavy textured Vertisols in Eastern Kenya. He attributed this to the low water levels that collected in the ditches and the poor movement of water in wet Vertisols. However, the results compare positively with reports by Ruto (2017) on light-textured Andosols and Wairiumu (2015) on heavy-textured Vertisols in which higher soil moisture was found at the lower slope compared to the upper slope position of the terraces due to lateral flow of water from the ditch. Higher moisture in the lower slope position was also reported by Shimbahri et al. (2019) on newly constructed terraces in Tigray, Ethiopia. In all these studies, the increase in soil moisture was attributed to the lateral flow of conserved water from the upper to lower slope positions.

3.5. Conclusion and recommendations

Based on the results of this study the role of terraces in conserving soil moisture on hard-setting soils was emphasized. The study revealed that the effect of ditch depths on moisture contents and variability within the slope depend on the amount and distribution of rainfall. Terraces with 30 cm ditch depth conserved more moisture at the 0-30 cm soil profile than those with 60 cm in seasons of low and poorly distributed rainfall. In contrast, when rainfall was high and well distributed in SR 2015 average soil moisture was higher in the terraces with60 cm ditch than in the ones with 30 cm. A higher amount of soil moisture was also conserved at the lower slope position than the upper position. These findings imply that the construction of terraces with shallow ditch depths (30 cm) is recommended to conserve soil moisture on hard-setting soils in the marginal rainfall areas of semi-arid Eastern Kenya. Farmers can also intensify production at the lower slope position to maximize the higher moisture contents available at this slope position for increased productivity.

CHAPTER FOUR: EFFECT OF VARYING TERRACE DITCH DEPTH ON SOIL NUTRIENT VARIABILITY ON THE HARD-SETTING SOILS IN SEMI-ARID KENYA

4.1. Abstract

Terraces control erosion and conserve soil and water in both cultivated and non-cultivated areas. Their effect on nutrient conservation and dynamics in different types of soils has, however, not been explored for use in improving productivity especially in areas with soil fertility problems and when ditch depths are varied. This on-farm field study was conducted to investigate the role of terraces in soil nutrient conservation on hard-setting soils of semi- arid Kenya. The trial was conducted in 2014 and 2015 March-May long rain (LR) and October-December short rain (SR seasons) in Mua location, Machakos County in easternKenya. The objective was to determine the effect of terraces on quantities of selected soil nutrient and their variability within the terrace slope. Terraces with ditch depths of 60 and 30 cm were tested against the control of 0 cm in a split plot design with four replications. Quantities of total nitrogen [%TN], available phosphorous [Av. P], exchangeable potassium [K^+] and % organic carbon [OC] at the 0-30 cm soil depth were measured at the beginning of the trial. At the end of the trial the contents of these nutrients were measured at the upper (US), middle (MS) and lower (LS) slope positions of terraces. Nutrient data was subjected to analysis of variance (ANOVA) and means separated at $p \leq 0.05$ level of confidence using the least significant difference of means (LSD). The final nutrient status was compared to the initial values. Results showed significant ($p = 0.002$) higher quantities of total N at the

end of the two years in terraces with 30 and 60 cm ditches than in the control. Significantly higher ($p < 0.001$) quantities were found at the LS than the US positions of the terraces. There were significant differences ($p=0.004$) in contents of available phosphorous in interactions of ditch depth and slope positions. Quantities in terraces with 30 cm ditch depth increased in the order US=MS<LS. In terraces with 60 cm ditch phosphorous varied in the order US <MS=LS. No significant differences ($p<0.05$) were found in quantities of potassium and organic carbon between the three slope positions or between the contents recorded at the beginning and end of the study. The results implicate that terrace construction is required for the conservation of nutrients N and P. The study recommends intensification of the lower slope position to make use of the available N and P. It also recommends proper soil management of the upper slope position to reduce further deficits and boost the levels of soil organic carbon.

4.2. Introduction

The effects of terracing on erosion control and improvement of crop production have been reported by several authors (Nyamadzawo et al., 2013, Binyam and Asmamaw, 2015, Mwanyoka and Lopa, 2016, Chapagain et al., 2019, Deng et al., 2021). Terrace barriers reduce the flow of runoff thereby reducing erosion. Sediments including the top soil are transported from the upper part of the terrace and deposited next to the barrier (Wolka et al. 2021). This slowly flattens up the slope of the terrace making cultivation on otherwise steep slopes easier. The use of conservation measures has not only been reported to reduce soil erosion but also to produce desirable changes in some soil physio-chemical properties and improved land productivity (Dejene, 2017). Other studies have also reported improvement in soil fertility when terraces were constructed (Hammad et al., 2004, Zhang et al., 2006, Wolka, 2021).

Several types of terraces are adopted by farmers depending on their needs and local circumstances such as soil type, depth and rainfall amounts (Namirembe et al., 2015, Aklilu 2016). The *Fanya juu* type is common in the arid and semi-arid lands (ASALs) of Eastern Kenya (Gichuki, 1991, Mutunga, 2001). Most of the soils of the ASALs of Kenya are deficient in nutrients required for effective crop production. This is partly due to increased nutrient mining with minimal fertilizer addition, low soil cover resulting into low rates of mineralization, and increased nutrient losses through erosion of the top soil. The *Fanya juu* terraces are constructed by digging a trench along the contour and throwing the soil up-slope to form an embankment that traps runoff and soil sediments (Namirembe et al., 2015). This practice was introduced in Machakos District in the 1930s to control erosion on sloppy fields (Gichuki, 1991). Despite some bottlenecks in the early adoption stages, lack of adequate moisture and decreasing supply of productive land have made farmers over time to appreciate the need for terraces for soil and water conservation (FAO, 1991). Currently over 70% of arable land in the county is terraced. Despite their wide adoption and important role in the control of erosion, little information is available on their effects on soil nutrient dynamics in the cultivated area and how this can be utilized to improve production. The effect of terraces on crop production depends on the type of soil (Ruto, 2015, Wairimu, 2015, Gachene and Baaru 2011). This study, therefore, was conducted to investigate the role of terraces in soil nutrient conservation on hard-setting soils of semi-arid Kenya. It aimed at obtaining information that could be used by smallholder farmers who practice terracing to guide in planning for efficient utilization of available nutrients for increased productivity per unit of land area.

4.3. Materials and methods

4.3.1. Study area

The study was conducted on-farm for four seasons in Makyau, Mua location, Machakos County in Eastern Kenya. The trial was set up on two adjacent farms during LR 2014, SR 2014, LR 2015 and SR 2015 seasons. The farms are located on the slopes of Mua hills at 37°15'E 1°29'S at 1722.20 m above sea level (asl) and 37°15'E 1°29'S at 1722.26 m asl in the agro- ecological zone (AEZ) UM4 The area receives an annual average rainfall of 673 mm in two seasons. These are from March to May (long rain [LR]) and October to December (short rain [SR]) seasons). Mean annual rainfall is 320 mm with averages of 272 mm in LR and 382 mm in SR seasons (Jaetzold et al., 2010). Annual mean maximum and minimum temperatures are 24.7°C and 13.7°C, respectively (Jaetzold et al., 2010). The soils are classified as Luvisols (FAO/UNESCO, 1997) which have a sandy clay loam texture, and high percent base saturation. The soils are however low in nitrogen, phosphorous and organic carbon (Table 4.1).

Table 4.1: Soil physical and chemical properties (0-30 cm) of the experimental site (two farms) at the commencement of the study

Farmer 1		Farmer 2	
Soil property	**Values**	**Soil property**	**Values**
pH-H_2O (1:2:5)	6.55	pH-H_2O (1:2:5)	6.6
Organic carbon, (%)	0.6	Organic carbon, (%)	0.66
Total Nitrogen (%)	0.07	Total Nitrogen (%)	0.69
Phosphorous (ppm)	17.91	Phosphorous (ppm)	19.7
Calcium (Cmol/kg)	9.50	Calcium (Cmol/kg)	9.50
Magnesium (Cmol/kg)	1.20	Magnesium (Cmol/kg)	1.22
Potassium (Cmol/kg)	0.40	Potassium (Cmol/kg)	0.49
Sodium (Cmol/kg)	0.30	Sodium (Cmol/kg)	0.51
CEC (Cmol/kg)	15.9	CEC (Cmol/kg)	17.7
Sum me (Cmol/kg)	12.9	Sum me (Cmol/kg)	10.6
Base Saturation (%)	70.3	Base Saturation (%)	70.3
ESP (%)	2.63	ESP (%)	4.35
Bulk density (g/cm3)	1.4	Bulk density (g/cm3)	1.4
Sand (%)	67	Sand (%)	69
Silt (%)	10	Silt (%)	7
Clay (%)	23	Clay (%)	24
Texture Class	Sandy clay loam	Texture Class	Sandy clay loam

Legend: CEC= Cation Exchange Capacity, Sum me - Total milliequivalent of base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), ESP = Exchangeable Sodium Percentage

4.3.2. Experimental design and treatments

A split plot design with four replications was used. Treatments consisted of terraces with three different ditch depths located on the main plots and three slope positions as the sub- plots. The ditch depths were 60 cm, 30 cm and 0 (Control) cm. The three positions were upper, middle and lower slope positions (Figure 4.1). The main plots were each 14 m long with a 2-m path separating adjacent plots. The terrace slope was divided into three equal portions each representing a sub-plot and designated as the upper, middle and lower slope positions.The ditch marked the beginning of a terrace and the embankment of the successive ditch markedthe end.

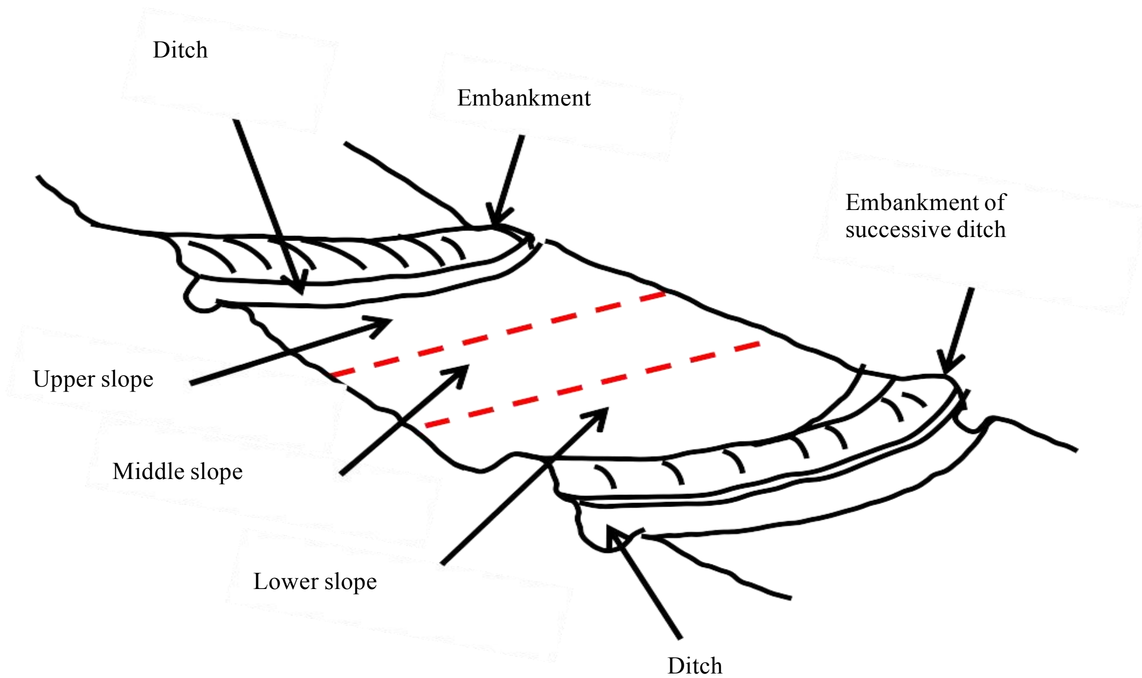


Figure 4.1. A sketch showing the upper, middle and lower slope positions of the terrace

Ditches had a uniform width of 60 cm, while control treatment had no ditch or lower embankment. Terraces served by each ditch depth were cultivated and planted with maize (*Zea mays* L.) and beans (*Phaesolus vulgaris* L.) for the four seasons. Maize was planted with Diammonium phosphate fertilizer (DAP) and top-dressed with calcium ammonium nitrate (CAN) at the recommended rate of 40 kg N and 40 kg P_2O_5 ha^{-1}.

4.3.3. Characterization of soil in the study area

Soil samples were collected for site characterization and initial soil nutrient status. This was done before the commencement of the trial. The site was cleared and initial soil samples collected from the trial field at a depth of 0-30 cm in a zig-zag pattern. The samples collected were mixed into a composite sample and a representative sub-sample packaged. This was taken for laboratory analysis and tabulation of initial soil nutrient status.

4.3.4. Data collection and analysis

4.3.4.1. Sample collection for laboratory analysis of soil nutrient contents

Soil analysis was done at the beginning of the study period for determination of the initial amounts of total nitrogen (TN), available phosphorous (Av. P), exchangeable potassium (K^+), and organic carbon (%OC). Both the major and minor nutrients are low in the ASAL soils. However, the selected major nutrients are easily available in most of the soil amendment products and hence can be accessed by farmers for improvement of their soil. Samples were collected using a soil auger from 0-30 cm depth. Soil was aurgered from different spots on the whole experimental area following a zig-zag pattern and thoroughly mixed into one composite sample in a clean disinfected bucket. Approximately one (1) kg of soil was then drawn from this composite sample for laboratory analysis.

At the end of the study period, soil samples were collected for analysis of total nitrogen (TN), available phosphorous (Av. P), exchangeable potassium (K^+), and organic carbon (%OC) contents at the three slope positions of each terrace. Samples were collected from three random cores in each slope position using an auger at a depth of 0-30 cm. Soils from each position were carefully mixed in a clean disinfected bucket and a representative sub-sample was packaged for laboratory analysis.

4.3.4.2. Laboratory analysis for soil nutrient contents

Representative soil samples were air-dried, ground using a pestle and mortar and sieved using a 2-mm sieve before chemical analysis. Soil total N was determined by the Kjeldahl technique as described by Bremner and Mulvaney (1982). Organic carbon was determined using the Walkley-Black oxidation method as described by Nelson and Sommers (1982). Available P was determined by the Bray 2 method (Olsen and Sommers, 1982) while exchangeable K was determined using the flame photometer.

4.3.5. Statistical data analysis

Data was organized in the Excel spreadsheet and subjected to a two-way analysis of variance (ANOVA) using the GenStat version 14.2 (2016) statistical package. Interactions between ditch depths and slope positions were considered. Differences in means were determined at a 95% level of confidence. Fisher's protected least significant difference (LSD) test was used for post-hoc comparison of means.

4.4. Results and discussion

Quantities of total nitrogen, available phosphorous and organic carbon percent in both the initial and final samples were generally low (Table 4.2) and fell below the required critical levels as stated by Okalebo et al. (2002).

Table 4.2: Soil nutrient status at the beginning and end of the study irrespective of the slope position

	Average nutrient contents		
Soil nutrient	**Initial**	**Final**	**Critical levels**
Total Nitrogen (%)	0.07	0.075	≥0. 21
Phosphorous (ppm)	18.81	22.79	≥30.0
Potassium (Cmol/kg)	0.51	0.58	≥0.24
Organic carbon, (%)	0.63	0.59	≥2.7

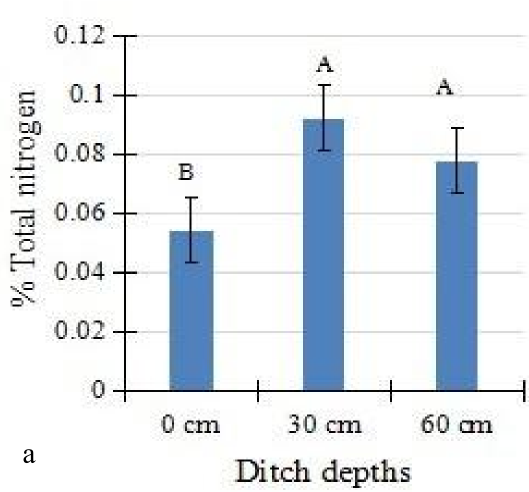
*Critical levels adopted from Okalebo et al. (2002)

4.4.1. Effect of ditch depths and slope position on soil nutrient contents

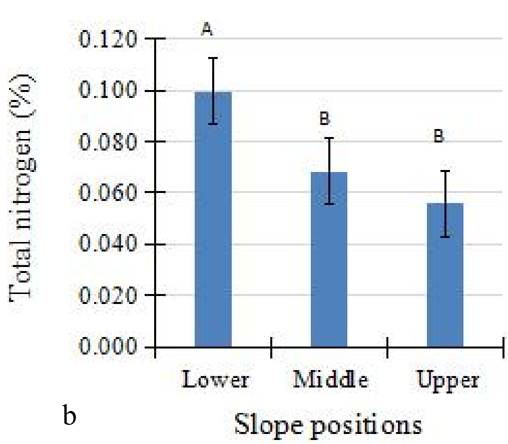
Interactions of ditch depth and slope positions were not significantly different for contents of total nitrogen ($P = 0.063$), exchangeable potassium ($P = 0.548$) and organic carbon ($P = 0.804$) in the soils at the end of the study. However, the interaction was significant ($P = 0.004$) for the contents of available phosphorous.

4.4.1.1. Total Nitrogen (%TN) contents

Figures 4.2a and 4.2b show the status of average nitrogen contents in treatments with different ditch depths (a) and at different slope positions (b). Contents of total nitrogen were significantly different between ditch depths ($p=0.002$) and slope positions ($p<0.001$) (see also Appendix 3 for ANOVA results).



a



b

Figure 4.2. Average total nitrogen contents in (a) terraces with 0, 30 and 60 cm ditch depths and (b) the upper, middle and lower slope positions of the terraces
Legend: Error bars denote Standard error

Higher nitrogen quantities were observed in plots with ditches compared to the control. These were 0.092% in terraces with 30 cm ditch depth, 0.078% in those with 60 cm ditch and 0.05% in non-terraced treatments (lsd=0.019). Lower nitrogen values in non-terraced plots were partially attributed to the loss of the nutrient through surface runoff. The terrace structures reduced runoff and hence, loss of nitrogen through overland erosion as opposed to treatments where terraces were not constructed. These findings agree with the results from work done by Dercon et al. (2003), Hammad et al. (2004) and Dejene (2017). These authors reported higher concentrations of soil total nitrogen, available phosphorous, and exchangeable potassium together with other soil components such as the cation exchange capacity in terraced than non-terraced fields mainly due to reductions in sediment loss through erosion. Dagnachew et al. (2020) also observed that moisture and nutrients increased when soil water conservation measures were constructed in the Gojeb River catchment in Ethiopia.

Significantly higher ($p<0.001$) nitrogen content was found at the lower compared to the the middle and upper slope positions of all treatments. This may have been caused by losses from the upper to the lower terrace areas through erosion. Most of the eroded nitrogen originated from the fertilizers applied to the crop during planting and topdressing. The embankments of terraces blocked runoff flow resulting in the deposition of sediments and accumulation of nitrogen at the lower slope position. The low content of nitrogen at the upper slope position could also be attributed to leaching due to the water that filled the ditches and saturated the sections adjacent to the ditch in the high rainfall season (Plate 4.1).

Plate 4.1: Ditches holding rain water during the SR 2015 season
(Courtesy: E. Njiru)

This could partially explain the symptoms of nitrogen deficiency noted on the crop especially along the rows bordering the ditches in treatments where ditches were constructed (Plates 4.2 a and b). The deficiency symptoms decreased from the upper to lower positions of the slope similar to observations made by Ruto (2015) from an experiment in the Andosols in Narok County, Kenya.

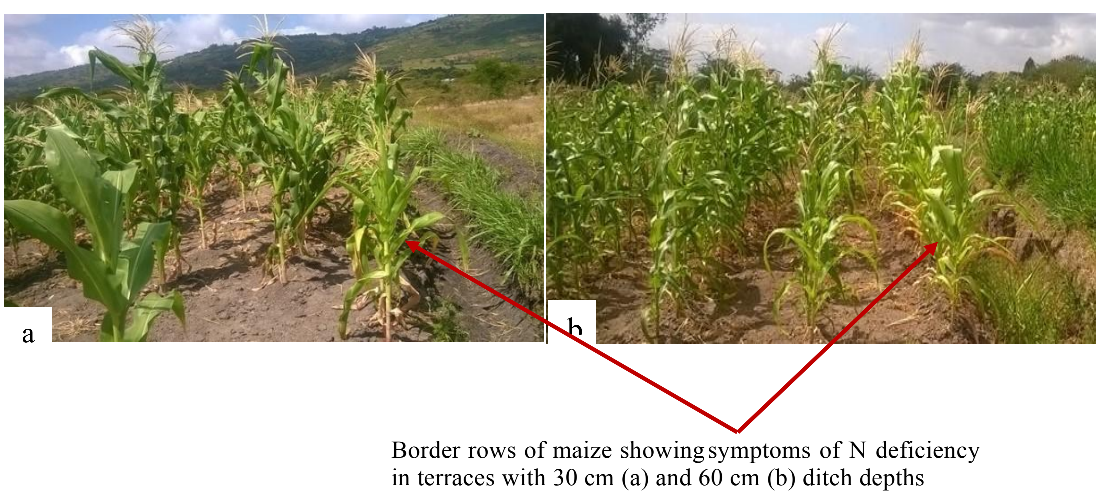


Plate 4.2: Nitrogen deficiency symptoms in maize on rows bordering the channel
(Courtesy: E. Njiru)

Similarly, for the non-terraced plots, higher nitrogen contents in the lower slope position was also attributed to its loss from up slope and flow to lower slope areas through surface runoff (Plate 4.3).

Plate 4.3: Plot showing the reduction in nitrogen deficiency towards the lower slope position
(Photo courtesy E. Njiru)

The results of this study confirm the findings by Siriri et al. (2005) while working on Ferralsols in Western Uganda. The authors reported higher contents of nitrogen in the lower slope compared to the upper areas of the slope resulting from sediment erosion and deposition.

4.4.1.2. Available phosphorous (Av. P)

Figure 4.3 shows the average contents of available phosphorous in the upper, middle and lower slope positions of terraces at the end of the study. Significant differences (p=0.004) in available phosphorous contents were found in interactions of ditch depths and slope positions (seeAppendix 4 for ANOVA results).

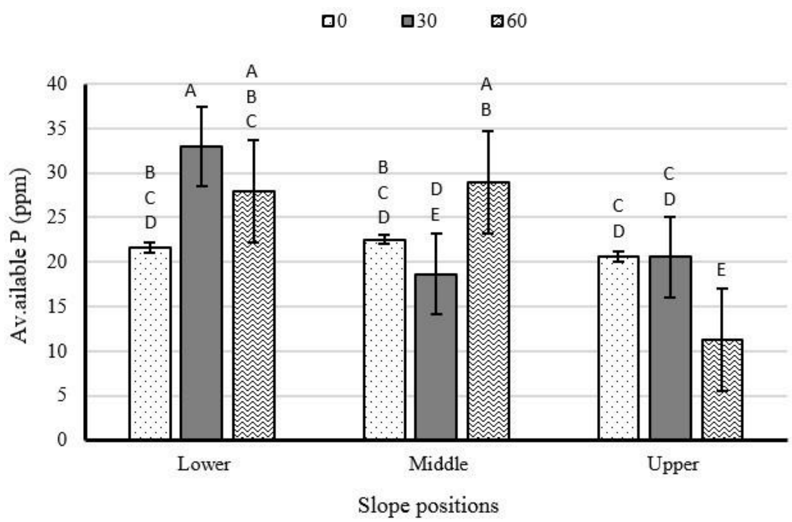


Figure 4.3. Effects of ditch depths and slope positions on quantities of available phosphorous as at the end of the study period
Legend: Error bars denote Standard error

The highest amount of available phosphorous (32.93 ppm) was found in the lower slope position in terraces with 30 cm ditch. This was however, not significantly different from the amounts in the lower slope (27.95 ppm) and middle slope (28.98 ppm) of the 60 cm ditch terraces. This could probably be due to higher surface flow on plots with the shallow ditch compared to those with deeper ditch depth. The shallow ditch was filled with water faster than the deeper one. This resulted in the flow of excess water down the slope thereby transporting phosphorous to the lower part of the slope. Unlike nitrogen which soluble in nature and easily lost through leaching, erosion, runoff, uptake and vaporization, phosphorous is insoluble and fairly remainsat the point of application if not lost through uptake, runoff and erosion, or fixation by clay colloids. Lower quantities were found in the upper slopes in both terraces with 30 cm (20.55 ppm) and 60 cm (11.26 ppm) ditch depths compared to the lower slope positions (32.93 and 27.95 ppm in 30 cm and 60 cm ditch terraces, respectively). The differences in available phosphorous in the three positions was probably caused by the effects of surface erosion of the Di-ammonium phosphate (DAP) fertilizer which was applied to the maize crop in the terraces during planting. The applied phosphorous may have been exposed to sheet erosion and transportation through runoff. The fertilizer might have been eroded down the slope together with soil sediments resulting in higher quantities in the deposition site. Reports by Gachene et al., (1998) during an assessment of the effects of soil erosion on some selected nutrients in clay soil in a sub-humid area of Central Kenya reported high enrichment of P in eroded sediments from fertilized plots in the runoff. This confirms the possibility of erosion of P from the upper slope (depletion site) to the lower slope (deposition site) in the current study. Erosion was higher in treatments with 60 ditch during the high rainfall season leading to higher losses of P. Results of this experiment confirm a report by Ruto (2015) who attributed the higher quantities of phosphorous in the lower slope position to erosion of the applied fertilizers from up-slope and deposition in the lower zone in the Andosols of semi-arid Kenya. On the contrary, Shimeles (2012) reported nearly uniform amounts of soil nutrients in all the slope positions. This was under old terraces that had developed into benches with almost uniform gradient thereby allowing for an equal distribution of runoff and unloading of sediments within the terrace. This confirms the benefits of terracing on the spatial distribution of soil nutrient content

4.4.1.3. Exchangeable potassium

No significant difference was found in the content of exchangeable potassium between terraces with different ditch depths (p=0.606) or between slope positions (p=0.096) (see Appendix 5 for ANOVA results). This could partially be because potassium was not added to the soil during the study and its movement through erosion was minimal. It might also be due to the fact that the soils are well saturated with K (as shown by the 0.51 Cmol/kg in the initial analysis compared to the critical value of ≥0.24 Cmol/kg given by Okalebo et al., (2002)) resulting in insignificant temporal variations. A similar report indicating no significant differences in potassium levels between the slope positions was given by Shimeles et al. (2012) from their study on terraces in Ethiopia. Likewise, Tadele et al. (2011 2013) reported lack of significant differences in exchangeable potassium between different terrace slope positions in separate studies in Ethiopia. On the contrary, Dejene (2017) found significantly higher exchangeable potassium in the accumulation position than in the upper slope position on the shallow soils of Oromia in Ethiopia. This was, however, in old terraces and was attributed to the long-term effects of erosion from the upper slope and deposition in the accumulation zones.

4.4.1.4. Soil Organic Carbon

There was no significant differences in contents of soil organic carbon between terraces with different ditch depths (p=0.414) or within slope positions (p=0.670) (See Appendix 6 for ANOVA results). This could be linked to the short period covered by the experiment which did not allow for sufficient production and accumulation of biomass and hence organic carbon. Studies show that the rate ofsoil organic carbon accumulation under dryland conditions is generally low because of the high temperatures, low soil moisture, and the low and slow production of plant biomass (Bernoux and Chevallier, 2014, Plaza-Bonilla et al., 2015). A study by Laban et al. (2018) indicated that water scarcity constrains plant productivity and accumulation of soil carbon in the drylands. Results similar to those of the current study were reported by Posthumus and Stroosnijder (2010). The authors found no short-term effect of terraces on soil fertility and other properties in the Peruvian Andes. Contrary findings by Million (2003) in North Shoa, Ethiopia, Ofori (2013) in Ahafo Ano South district, Ghana, and Amare et al. (2013) in Anjeni Watershed in Dembecha, Ethiopia, showed higher organic matter and organic carbon contents in the lower slope of the terrace. This was, however, in high rainfall areas where the construction of terraces reduced erosion and allowed biomass accumulation and its transportation from the upper to the lower slope positions through surface runoff and overload flow.

4.5. Conclusion and recommendations

The results of this study highlight the role of terraces in the conservation and spatial variability of total nitrogen and available phosphorous on hard-setting soils of semi-arid lands of Eastern Kenya. Higher contents of the two nutrients were found in plots with terraces than in those without. The effect of terraces on soil nutrients was also seen in higher quantities ofthe nutrients at the lower slope compared to the upper slope positions. These nutrients were trapped together with the overland flow at the lower position by the embankment of the successive terrace. The results indicate that terrace construction is important and therefore recommended for the conservation of soil nutrients N and P on hard-setting soils of semi-arid Eastern Kenya. The higher N and P contents at the lower slope position can be exploited through intensive management of this position especially in regard to mixed cropping patterns. These will improve productivity and increase the benefits of terraces on hard-setting soils.

CHAPTER FIVE: FANYA JUU TERRACE DITCH EFFECTS ON MAIZE AND BEAN GROWTH AND YIELD ON HARD-SETTING SOILS OF SEMI-ARID EASTERN KENYA

5.1. Abstract

Recently, Kenya has been faced with severe droughts and insufficient soil moisture for agricultural production. Most of the water from the scarce rainfall is lost through runoff and erosion leading to low crop yields and food insecurity. Terraces are one of the soil and water conservation practices used to reduce soil and water loss and help increase agricultural productivity. The adoption of the *Fanya juu* type of terraces by smallholder farmers in the Kenyan ASALs is considered to be high. However, only scarce information is available on the effect of these terraces on crop yields along the slope on different types of soils. A trial was established on Luvisols in Mua location, Machakos County in Eastern Kenya during both long rain (LR) and short rain (SR) seasons of 2014 and SR 2015. The objective was to determine the effect of *Fanya juu* terraces on maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.) yields and how these yields differ with slope positions and depth of the ditches. A split-split plot design with four replications in four blocks was used. Treatments consisted of terraces with three ditch depths (60cm, 30cm and 0cm [control]) in the main plots and three cropping systems (maize/bean intercrop, sole maize and sole bean) in the sub-plots. Grain yields were compared across the seasons at the upper, middle and lower slope positions of the terraces using analysis of variance and means separated using the least significant difference (LSD) at $p \leq 0.05$. Significant differences in maize grain yields were observed

in interactions of ditch depth and slope position ($p=0.004$) and ditch depth and season ($p<0.001$). Higher maize yields were realized when ditches were constructed than in the control. Yields were 49.8% higher in the lower position compared to the upper slope in terraces with 30 cm ditch depth and 41.6% in those with 60 cm ditch. Average maize yields from the 30cm ditch were significantly higher than those from the control treatment but non-significant from those in the 60cm ditch in all seasons. There were significant differences in bean grain yields in interactions of ditch depth and slope position ($p=0.037$). Higher yields were harvested from the lower position of the 30 cm ditch than the middle and upper positions. Significant differences ($p=0.033$) in bean yields were also found between interactions of ditch depths, cropping systems and seasons. This study recommends a ditch depth of 30 cm and intensive management of the lower slope position in *Fanya juu* terraces for improved maize and bean production on hard-setting soils.

5.2. Introduction

Hard-setting soils have an unstable structure that collapses when the soil is wet and shrinks and hardens as the soil moisture dries up (Daniells, 2012). These soils are pulverized as a result of the instability of the surface layer and the detached particles clog and seal pores when soils are wet. The surface of the soil easily ponds during rainfall events followed by sealing and crusting as the water dries up (Miriti et al., 2012). On drying, the soils acquire high soil strength and crusting properties and the upper layer gets compacted (Giarola et al., 2011). Repeated cycles of sealing, crusting and compaction result in a hard-setting nature (Bresson et al., 2006, Giarola et al., 2011, Daniells, 2012). The crusting, compaction, ponding and hardness limit crop emergence, development of plant roots and infiltration and increasesurface erosion (Rao et al., 1994, Daniells, 2012).

Hard-setting soils are common in the arid and semi-arid lands (ASALs) of sub-Saharan Africa (SSA). They are found in large parts of Eastern and Southern Africa and the Sudan-Sahelian region of West Africa (Monin, 1993). Most of the soils in the ASALs of SSA are low in moisture and nutrient contents as a result of marginal rainfall, high evaporation and inadequate application of fertilizer inputs (Fries et al., 2020, Masso et al., 2017, Recha et al., 2016). Rainfall is erratic and at times comes in intensive storms with escalated runoff causing further loss of nutrients and rainwater through erosion (UNDP, 2013). Negative impacts of climate change (increased runoff from torrential floods and the associated removal of the topsoil, increased dry spells, uncertainty in predictions of rainfall onsets, cessation and amounts) magnify the situation of water stress and food insecurity. Soil and waterconservation measures are therefore of paramount importance for effective crop production.

Terraces are widely adopted to reduce erosion from the impacts of torrential rainfall and conserve soil and water in low-rainfall areas (Rashid et al., 2016, Widomski et al., 2011). The *Fanya juu* type of terrace is common in the arid and semi-arid areas of Eastern Kenya. These are constructed by digging a ditch and throwing the soil up-slope with the sole purpose of maintaining an embankment to slow down runoff flow and hold soil sediments (Figure 5.1). The ditches and embankments shorten the length of the slope and minimize soil and water loss by reducing the speed and quantity of runoff flow

(SUSTAINET EA, 2010, Aklilu, 2016, Subhatu et al., 2018, Gachene et al., 2019). At the same time the structures increase infiltration and can sustain productivity in sloppy areas with marginal rainfall (Sheng, 2002, Doreen and Rey, 2004, Youssef et al., 2008, Hussein et al., 2016).

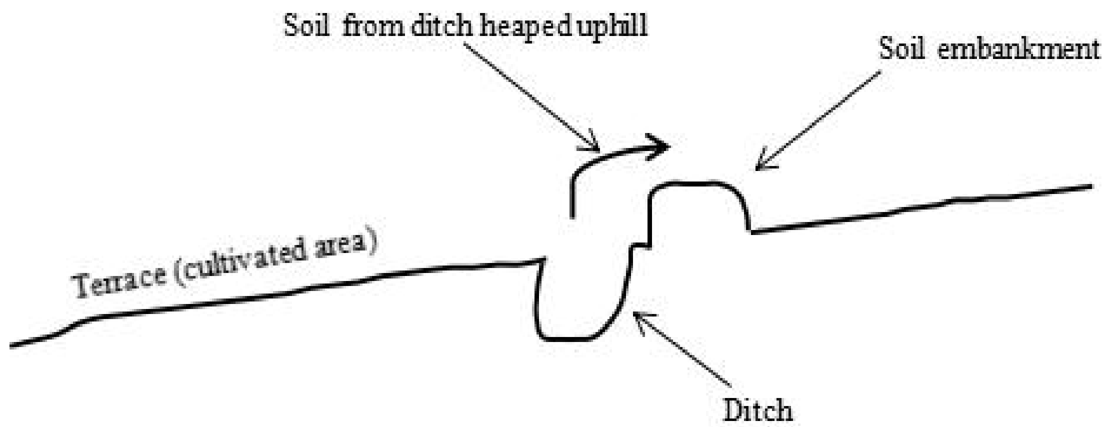


Figure 5.1: A sketch of the cross-section of the Fanya juu terrace
(Drawing by E. Njiru)

Studies have reported differences in crop yields between terraced and non-terraced fields as well as within the terraces (Barungi et al., 2013; Binyam et al., 2015). Some studies have also indicated that crop yields vary along the terrace slope and that this variability is dependent on the type of soil (Gachene and Baaru, 2011; Ruto, 2015; Wairimu, 2015; Ruto et al., 2017b). For instance, in well-drained Luvisols maize rows bordering the terrace ditchwere more vigorous in growth and gave higher yields compared to those in the section away from the ditch (Gachene and Baaru, 2011). This was attributed to an increase in soil moisture next to the ditch resulting from lateral seepage of water. In the light-textured Andosols maize rows next to the ditch had retarded growth and low yields due to excessive drainage and leaching of nutrients caused by moisture that was captured in the ditch (Ruto, 2015). These were immediately followed by rows of taller maize that benefited from moisture and nutrients that flowed laterally from the ditch before another set of rows of retarded maize at the depletion zone. A similar study in the heavy-draining Vertisols (Wairimu, 2015) indicated increased yields from rows in the lower position at the furthest end of the slope compared to those next to the ditch. All these studies attributed the differences in maize yields to variations in soil moisture content along the terrace slope in the different soil types. According to a report by Ruto (2015), the information on variability in crop performance in terraces is crucial in designing appropriate cropping systems for different slope positions to improve productivity in the ASALs. There is, however, a limitation of this knowledge on different types of soils. This brought about the need to study the effect of terraces on crop yields on hard-setting soils that are common in the ASALs of Eastern Kenya in order to generate information that will help enhance exploitation of available moisture and nutrient resources.

5.3. Materials and methods

5.3.1. Description of study location

The study was conducted for four seasons in Mua location, Machakos County in Eastern Kenya. The county is situated between longitudes 36° 45' E and 37° 45' E and latitudes 0° 45' S and 01° 31' S. It lies at altitudes of 1000 to 1600 m above sea level (asl). The trial was set up in two adjacent farms at 37°15'29.124"E 1°29'40.776"S and 37°15'29.1522"E 1°29'40.7112S.

Rainfall is bimodal from March to May (long rains [LR] season) and October to December (short rains [SR] season) (Jaetzold et al., 2010). The experiment was conducted during long rains (LR) 2014, short rain (SR) 2014, LR 2015 and SR 2015 seasons. The mean annual rainfall is 650 mm with seasonal mean of 270 mm in LR and 380 mm in SR. Annual temperatures range from 13 to 24°C (Jaetzold et al., 2010). The rainfall seasons are also the crop-growing seasons in the area. The SR season is more reliable in amount and distribution with a higher probability of occurrence than the LR (Jaetzold et al., 2010). A dry period extending from August until mid-October separates the two rainfall seasons (Figure 5.2).

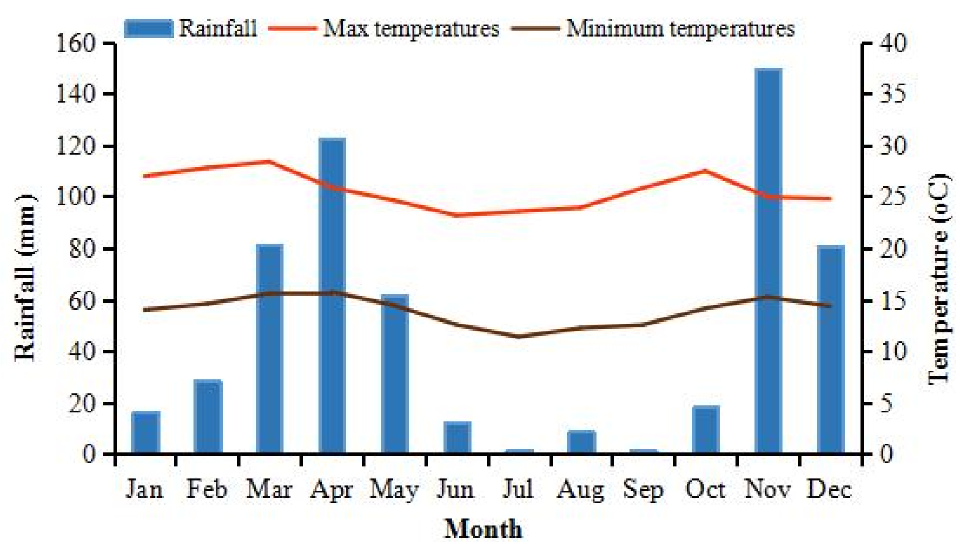


Figure 5.2: Average rainfall, minimum and maximum temperatures of the study site

Evapotranspiration rates are high and exceed precipitation for most of the year (Jaetzoldet al., 2010). Poor distribution of rainfall and recurrent droughts during the crop growing seasons are common. The onsets, cessations, distribution and amounts vary from season to season with considerable effects on crop yields and food security particularly under rain-fed conditions (Mati, 2005, Jaetzold et al., 2010, Omoyo, et al., (2015).

Soils are sandy clay loam in texture with a pH (H_2O 1:2:5) of 6.6. They are classified as Luvisols under FAO/UNESCO soil classification (FAO/UNESCO1997). The soils are shallow and low in water-holding capacity. They are pulverized and prone to surface sealing and crusting. They easily pond during rains especially when ridges are used at planting and crust at the surface when water dries up (Scott et al., 1963, Miriti et al., 2012, Karuma et al., 2014). The soils are low in nutrients contents especially nitrogen and organic carbon (Table 5.1). The major cereal crop grown in the area is maize (*Zea mays* L.) while the major pulses are Common bean (*Phaseolus vulgaris* L.) and pigeon peas (*Cajanus cajan*). The maize is usually grown in a sole crop system or intercropped with the pulses. During the two seasons previous to the study the experimental land was under maize/bean intercrop followed by sole maize system.

Table 5.1: Soil pH, Nitrogen, Phosphorous, Potassium and Organic carbon status at the commencement of the study

Soil property	**Status**	**Soil property**	**Status**
pH-H_2o (1:2:5)	6.60	Potassium (Cmol/kg)	0.51
Total Nitrogen (%)	0.07	Organic carbon (%)	0.63
Phosphorous (ppm)	18.81	CEC) (Cmol/kg)	16.80

Legend: CEC-Cation exchange capacity, ppm-parts per million, Cmol/kg-Centimols per kilogram

5.3.2. Experimental design and treatments

The trial was planted in a split-split plot design with four replications. Each replication was a block. Treatments consisted of terraces with three ditch dimensions; 60, 30 and 0 (control) cm deep (Figure 5.3) in the main plots and three cropping systems in the sub-plots (Plate 5.1). The cropping systems were maize/bean intercrop (M/BI), sole maize (SM) and sole bean (SB). Treatments were combined as summarized in Table 5.2.

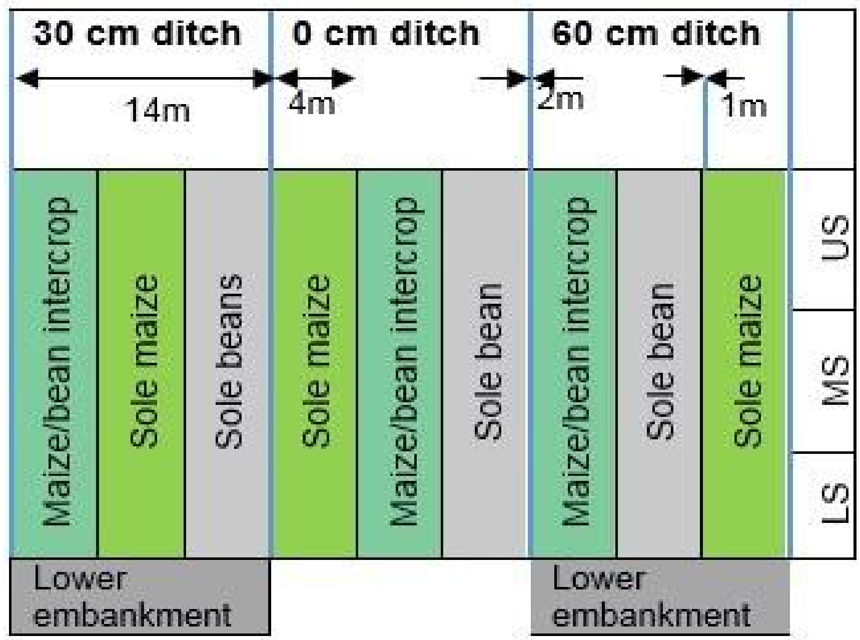


Figure 5.3: Layout of a single replication of the trial showing measurements and allocations of ditches, cropping systems and slope positions

Legend: US Upper - slope position, MS - middle slope position, LS – lower slope position

Plate 5.1: Arrangement of crops on the main plots

Table 5.2: Treatment combinations studied in a split-split plot design

Treatment	Combination
T1	60 cm ditch + maize/bean intercrop
T2	60 cm ditch + sole maize
T3	60 cm ditch + sole bean
T4	30 cm ditch + maize/bean intercrop
T5	30 cm ditch + sole maize
T6	30 cm ditch + sole bean
T7	0 cm ditch + maize/bean intercrop,
T8	0 cm ditch + sole maize
T9	0 cm ditch + sole bean

The main plots were 14 m wide with a two (2) meter path separating adjacent plots. Each main plot had three sub plots of 4 m and a one (1) meter path between subsequent sub-plots. The length of the terraces depended on the slope and ranged from 14 to 17 m. The terrace area below each ditch was subdivided into three equal sections which were designated as the upper (next to the ditch), middle (at the centre of the terrace) and lower (adjacent to the embankment of the subsequent ditch) positions of the slope (Figures 5.4). These sections formed the sub-sub-plots from which data for analysis was collected.

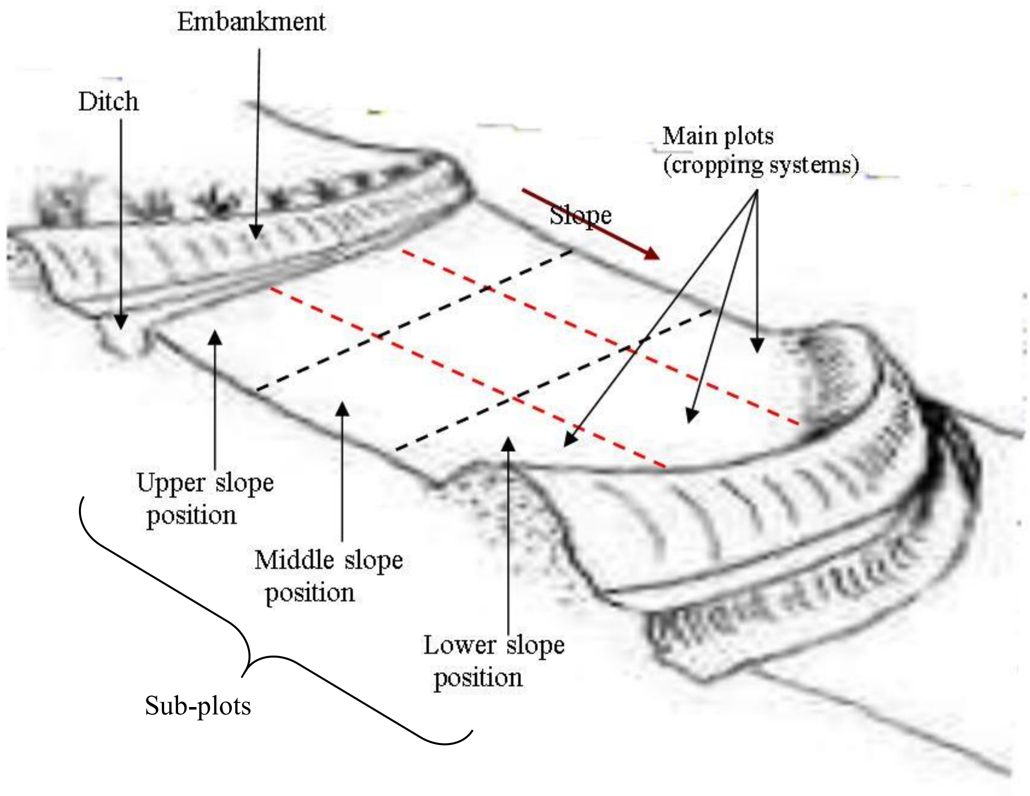


Figure 5.4: A sketch of the terrace showing the ditches and slope positions

5.3.3. Land preparation and planting

The land was prepared by clearing, ploughing and digging out the ditches before onset of rains. The locations of the ditches were identified using rod and string method and the three ditch treatments randomly allocated to the main plots along the identified positions. The 30 and 60 cm trenches were measured and the soil dug out by hand at the beginning of the first season. The first and subsequent land preparation was done using oxen plough (common farmer practice). The field leveled out by hand hoes before planting. Planting was done every season at on-set of rains to maximize available rainfall. During planting the cropping systems (maize/bean intercrop, sole maize or sole beans) were randomly allocated to the sub-plots. Maize (*Zea mays* L.) variety Duma 43 and common bean (*Phaseolus vulgaris* L.) variety Kat B1 were used as the test crops. Maize was planted at a spacing of 90 x 30 cm. Beans were planted at 45 x 20 cm in the sole crop system and at 90 x20 cm (one row between two maize rows) in the mixed system. Two seeds were planted per hill and the seedlings thinned to one plant per hill two weeks after emergence. Maize was planted with Di-ammonium phosphate (DAP) and later top-dressed with calcium ammonium phosphate (CAN) at the recommended rate of 40 kg P_2O_5 and 40 kg N ha^{-1}. Napier grass was planted on the terrace embankments for soil stabilization and ditches maintained in subsequent seasons by scooping out any soil filing up the trench and heaping it back on the embankment. Standard agronomic practices were adopted for weeding, pest and disease control and the general management of the crop until harvest time.

5.3.4. Data collection and analysis

Crop data was collected from the upper, middle and lower slope positions of each of the sub- plots. The data included dates of planting, percent germination and stand after thinning for both maize and beans. At physiological maturity yield data was collected from a net plot area within each slope position. Yield data included the number of plants harvested (both maize and beans), number of maize cobs harvested, field weights of cobs, grain weights of maize and beans per plot, and moisture contents of maize and bean grains at harvest. Dimensions of net plot areas were 13.5 m^2 for maize (5 rows) in both sole and intercropped systems and 10.8 m^2 for beans (8 rows in pure stand and 4 rows under intercropped system). Data was entered in Excel spreadsheets for ease of management. The yield and field grain moisture content data were used to compute the final grain yields in t ha^{-1} corrected to 12% moisture content. Crop data was subjected to GenStat (2016) statistical package for two-way analysis of variance (ANOVA). Means were separated at a 95% level of confidence. The Fishers' protected least significant difference of means (LSD) was used for the separation of means.

5.4. Results and discussions

5.4.1. Amounts and distribution of rainfall during the study period

Rainfall varied in amounts and distribution in the four crop-growing seasons. Three of the seasons had low or poorly distributed rainfall with frequent dry spells (Figure 5.5). Both LR 2014 and 2015 seasons had poorly distributed rainfall despite the amounts recorded (266.4 and 239.6 mm in 2014 and 2015, respectively) being close to the long-term mean of 272 mm. A total of 149.2 mm of rainfall was received in SR 2014. This was below the SR long-term mean of 382 mm stated by Jaetzold et al., (2010). In SR 2015, however a total of 499.7 mm was received which was above the seasonal mean.

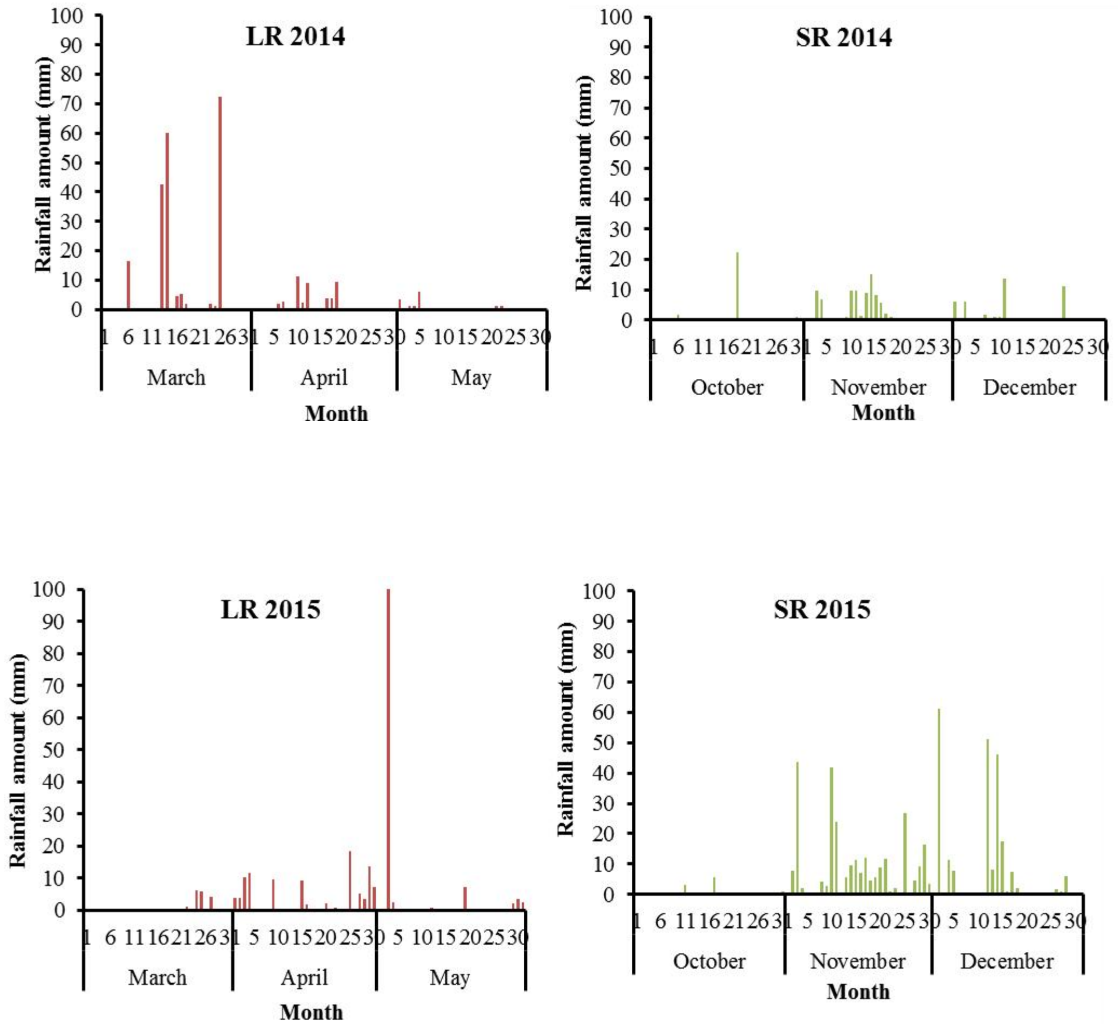


Figure 5.5: Rainfall distribution in long rain (LR) and short rain (SR) 2014 and 2015 seasons

5.4.2. Effect of terraces on maize grain yields

Results of analysis of maize grain yields are given in Figure 5.6 (see Appendix 7 for ANOVA results). Treatments with ditches (30 and 60 cm) recorded higher maize grain yields both in intercrop and sole crop systems than the control in all the seasons.

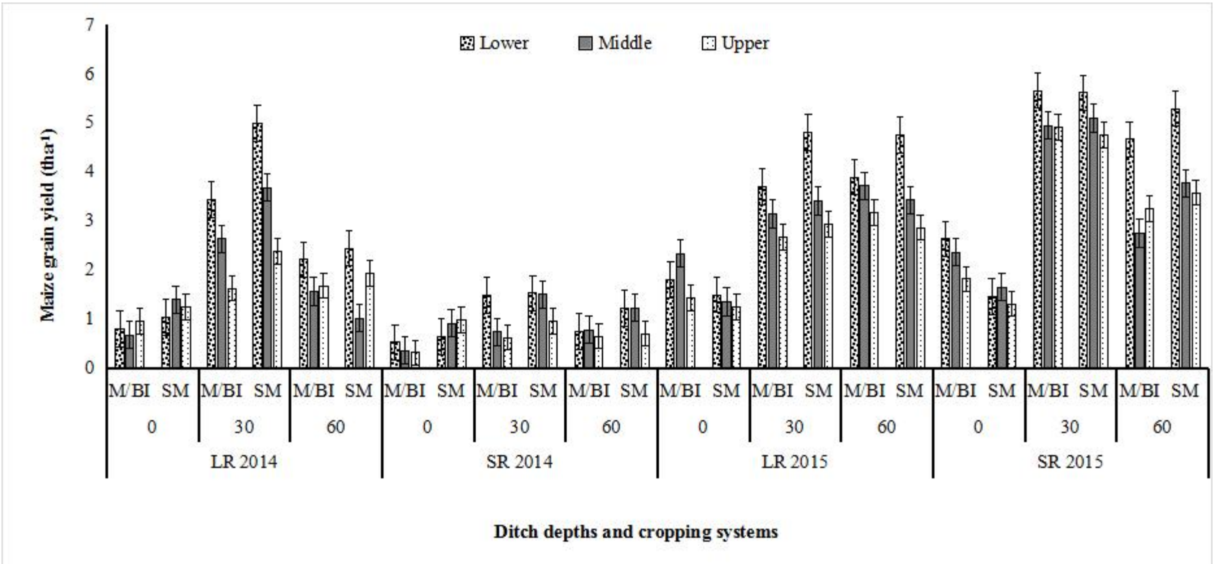


Figure 5.6: Maize grain yields as affected by ditch depths, cropping systems and slope positions during LR and SR 2014 and 2015 seasons

Legend: M/BI -Maize and bean intercrop system, SM - Sole maize system

The average maize grain yields over the four seasons were significantly higher ($p<0.001$) in treatments with terraces than in the control. These were 3.24 t ha^{-1} in terraces with 30 cm ditch depth, 2.55 t ha^{-1} in those with 60 cm, and 1.28 t ha^{-1} in non-terraced plots. The differences in yields between terraced and non-terraced plots could partially be attributed tothe surface crusting and compacting nature of hard-setting soils. This could be caused by increased water and nutrients losses in non-terraced treatments through runoff aggravated by the surface crusting and compacting nature of the soils. As discussed by Giarola et al. (2011) once dry, the surface of hard-setting soils easily crusts and seals. This impedes rain water infiltration and accelerates erosion. Such hardening could have increased the loss of water and nutrients through runoff resulting in a reduction in maize yields especially in the control treatment where terraces were not constructed. Several authors (Dorren and Rey, 2004, Tenge et al., 2011, Subhatu et al., 2018) have demonstrated that *Fanya juu* terraces are effective in reducing water and soil losses. The structures increase infiltration when water is held in the trenches for longer periods. Maize in treatments with ditches therefore, benefited from increased availability of soil moisture from the lateral flow of water held in ditches and the nutrients that were retained in the terraces. The low yields in the non-terraced treatment inform what the farmers who have not constructed terraces get in this area. This would mean that a ditch depth of 0 cm in unfavourable for crop production. Farmers in marginal areas, therefore, require to construct terraces terraces to improve on grain yields. The results imply that farmers can benefit from the little rainfall by constructing terraces to capture runoff and using it in their farms to improve production. The results confirm those by Kosmowski (2018) indicating an increase in yields in terraced fields in Ethiopia. Rashid et al. (2016) also reported an increase in wheat grain resulting from a 16% increase in soil moisture content when terraces were constructed in the sloppy rain-fed areas of Pakistan.

Seasonal average maize yields from terraces with 30 cm ditch depth (irrespective of the cropping system) were significantly ($p<0.001$) higher than those from control treatment. They were, however, not significantly different from those obtained from treatment with the60 cm ditch (Figure 5.7).

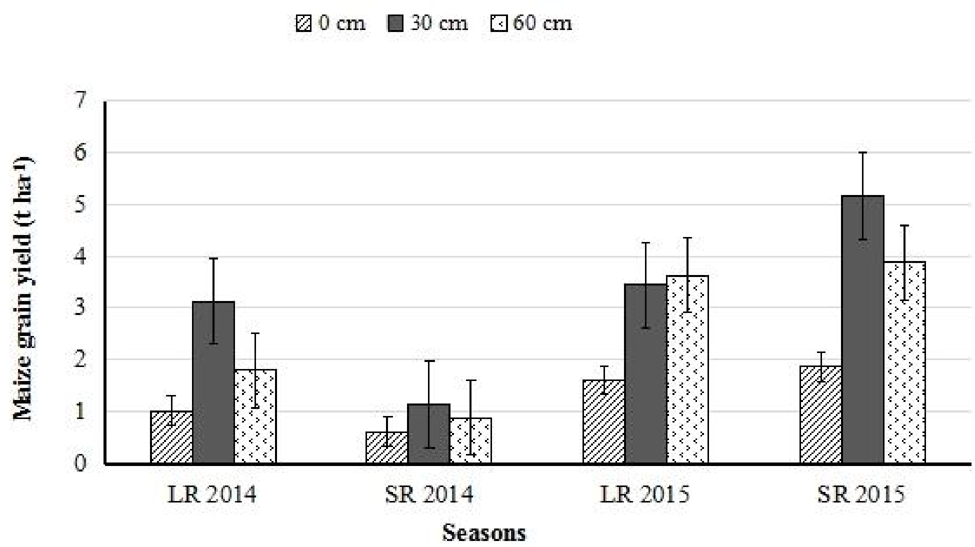


Figure 5.7: Effects of ditch depth dimensions on maize grain yields during LR and SR 2014 and 2015 seasons
Legend: LR - long rain, SR- short rain

This implied that varying the depth of the ditch from the recommended 60 cm to 30 cm did not significantly affect maize grain yields. However, the conditions provided by the shallow ditch were more conducive for the maize performance than in the deeper one. It could be argued that the 30 cm ditch held the runoff at an upper soil depth compared to the 60 cm ditch. The lateral flow of water in the shallow ditch was closer to the upper soil horizon making it more available to the crop at the zone with high root concentration. This was more evident in seasons with low or poorly distributed rainfall (LR and SR 2014). As observed by Rossato et al. (2017), the response of plants to rainfall in the top layers of the soil is better compared to that in deeper profiles. Water in the deeper ditch was held at lower depths and could have been lost through deep percolation and lateral flow below the root zone. In SR 2015 the amount of rainfall received was high and evenly distributed. This may have caused the leaching of nutrients in terraces with 60 cm ditch depth and lower yields than those from terraces with 30 cm ditch. This is an indication that the construction of terraces with 30 cm ditch depth can be beneficial to the farmers since it is less laborious and has higher chances of soil moisture availability at the crop root zone for improved crop productivity. Contrary to these findings, Mbugua et al. (2019) reported no differences in maize yields from terraces with different ditch depths in a trial conducted on Vertisols in semi-arid Kenya. This was attributed to an impediment to the movement of water in wet Vertisols.

The lower slope position of treatments with ditches generally recorded higher maize yields than the upper and middle positions in all seasons. Yields increased from the upper to the lower slope position by 49.8% in the 30 cm and 41.6% in the 60cm ditch terraces. There were significant differences (p=0.004) in maize yields between the three slope positions in terraces with 30 cm ditch. Yields increased from the upper position (2.60 t ha^{-1}) to the middle position (3.14 t ha^{-1}) by 20.8%. An increase of 49.6 % was recorded from the upper (2.60 t ha^{-1}) to the lower positions (3.89 t ha^{-1}) of the slope of the same terrace. In terraces with 60 cm ditch maizegrain yield from the lower slope position (3.15 t ha^{-1}) was significantly higher than from the middle (2.28 t ha^{-1}) and upper position (2.23 t ha^{-1}) (LSD=0.053). Higher yields in the lower slope position may have resulted from the effect of soil moisture and nutrients trapped by the embankment as well as from the lateral seepage of the water in the ditches. Gicheru et al. (2004) reported an increase crust strength when soil water content decreased. The increased moisture could have reduced the strength of the crust at the lower slope position providing a conducive environment for the maize to grow. Maize performance is affected by lack of water at all stages of growth and especially during the flowering period when the crop is most sensitive to drought (Spitkó et al., 2014, Aslam et al. 2015). The availability of soil moisture at the lower slope position in treatments with ditches may have contributed to reducing this stress. Earlier studies reported that higher water content in the ditch can lead to efficient use of nitrogen and that increases in soil moisture can improve nitrogen absorption, transportation and accumulation resulting in enhanced crop yields (Dijkstra and Cheng, 2008, Zoca et al., 2012, Huang et al., 2022). In view of this the maize crop therefore benefited from nitrogen uptake in the roots through mass flux facilitated by the presence of water. Higher grain yields at the lower slope position compared to the upper could also be attributed to the phosphorous that was deposited through runoff and sediment loss from the upper slope to the lower slope positions. It was also noted that quantities of potassium in the study area were not limiting for crop growth. Potassium regulates the opening and closing of the stomata, and hence the exchange of water vapor, oxygen, nutrients and carbon dioxide in the plant. Its abundant presence in the soil coupled with the availability of moisture in the lower slope position may have facilitated uptake of nitrogen and phosphorous resulting in higher crop vigour and grain yields.The conducive environment created by the presence of moisture can be exploited through intensification of the lower slope position to increase production and the benefits of constructing terraces in hard-setting soils.

The results of this experiment concurred with reports from studies conducted by Amare et al. (2013) in the Central Highlands of Ethiopia. The authors found higher maize and wheat yields at the lower slope position than at the upper slope and attributed it to increased fertility in the deposition zone. Ruto et al. (2017b) similarly reported an increase in yields at the lower slope of the terrace compared to the upper slope as a result of accumulation of nutrients and moisture at this site. In the current study, no significant difference ($p<0.05$) was found between the yields of maize in the three slope positions in the control treatment. This was because the runoff was not trapped in a particular area and there were no variations in the accumulation of moisture or nutrients. This is what is expected in the study area on farms where terraces have not been constructed.

There were no significant differences ($p \leq 0.05$) in maize grain yield between the sole maize and maize/bean intercrop systems or in interactions of cropping systems, ditch depth and slope positions. Maize grain yields were not significantly affected by the type of cropping system (sole maize or maize/bean intercrop). This was probably because of lack of effective competition from the bean crop. Rainfall during the study seasons was either too low and/or sparsely distributed for the beans to survive and compete with maize for resources, or well distributed and high enough to provide sufficient soil water for both crops.

5.4.3. Effect of terraces on bean grain yields

No bean grains were obtained in SR 2014. This was partially caused by the low (149.2 mm) and unevenly distributed rainfall. As reported in several studies (Boutraa and Sanders, 2001, Molina et al., 2001, Robel et al., 2019) moisture stress reduces bean yields with severity depending on the stage at which the stress occurs. According to Ntukamazina (2017) even brief periods of dry spell affect both the quality and quantity of bean yield. Such dry spells were common during the season. The ditches captured too little or no runoff to create any changes in soil moisture and subsequently on the yields of beans.

Results of bean data analysis (Figure 5.8) showed that there were significant differences between bean green yields in the interaction of ditch depth and slope positions (p=0.015) and between cropping systems and slope position (p=0.037) (see Appendix 8 for ANOVA results). Significantly higher (p=0.019) bean grain yields were obtained from treatments with 30 cm (0.497 t ha^{-1}) and 60 cm (0.469 t ha^{-1}) ditch depths compared to the control (0.359 t ha^{-1}).

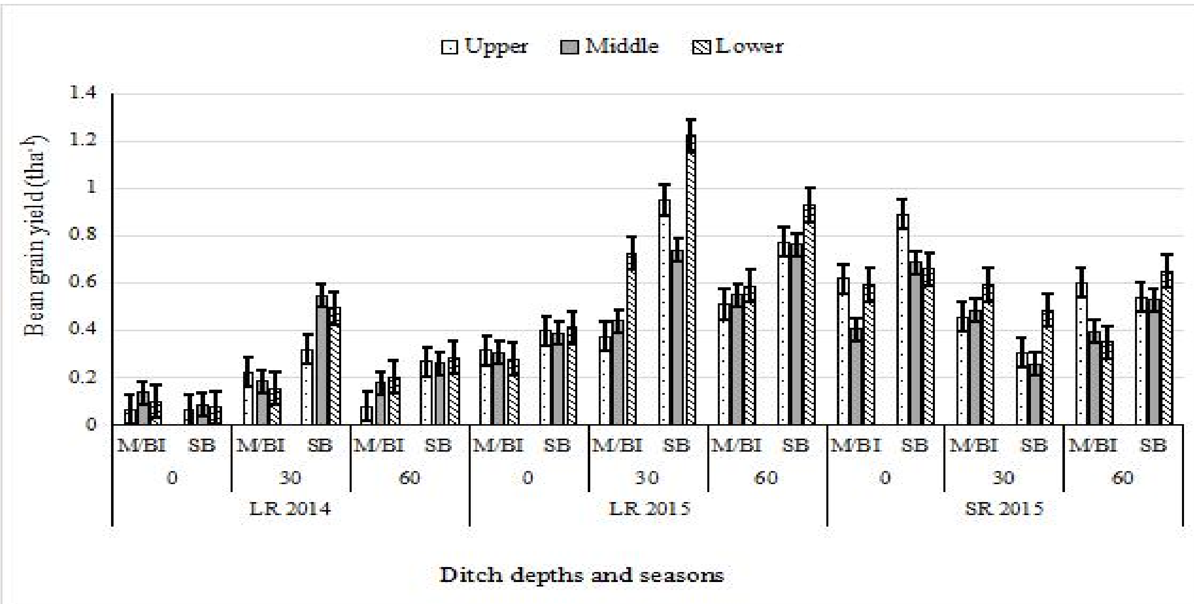


Figure 5.8: Bean yields as affected by ditch depths, cropping system, and slope positions during LR and SR 2014 and 2015 seasons

Legend: M/BI -Maize and bean intercrop system, SB - Sole bean cropping system

Higher and significantly different mean bean yield (0.61t ha^{-1}) was recorded in the lower slope position in treatments with 30 cm ditch depth than in the upper slope position of the control (0.33 t ha^{-1}). Yields from the lower slope in terraces with 30 and 60 cm deep ditches were higher than those from the middle and upper slope positions of the respective terraces. Higher yields in treatments with ditches in the lower slope compared to the middle and upper positions were probably a result of the availability of water and nutrients trapped by the terrace embankments. The water and nutrients are transported down the slope in soil sediments. The long-term process of sediment transfer results in the final leveling of the terraces and a reduction in runoff and erosion. The results of this study concur with the findings by Ruto et al. (2017b) who reported higher bean yields in the lower slope position as a result of the deposition of nutrients from the terrace through surface runoff in light-textured Andosols, Narok. Siriri et al. (2005) similarly found an increase in sorghum yields from 0.4 t ha^{-1} in the upper area of the slope to 2.4 t ha^{-1} in the lower position. Yields obtained from treatments with ditches were lower than from the control during the SR 2015 season. A comparison between similar positions of the terraces also indicated that average bean grain yields in the lower slope position were significantly higher (p=0.015) in treatments with ditches than in the control treatment except in SR 2015. Lower yields in treatment with ditches during SR 2015 season could be attributed to the effect of excessive rainfall. Conditions of high soil moisture contents can be unfavorable for proper bean performance because of the imbalances in oxygen levels in the root area and the increase in infestation by pathogens which both cause losses in yields Ntukamazina (2017). Results on beans yields were, therefore, inconsistent. The crop was affected by both moisture stress in the low rainfall season of SR 2014 and water logging during SR 2015. Periods of dry spell affect both the quality and quantity of bean yield, whereas excess water in the root zone are unfavourable due to oxygen imbalances and increased chances for fungal infections.

5.5. Conclusions and Recommendations

Terracing can significantly improve maize and bean grain yields on hard-setting soils in the marginal areas of semi-arid Kenya. This study showed that the practice increased maize yields in both low and high rainfall seasons in the drylands. Terraces improved bean yields in LR 2014 and LR 2015 when rainfall amount was close to the long-term average but depressed yields in SR 2015 when rainfall was above the normal long-term average of the area. This implies that farmers in marginal rainfall areas can improve their maize and bean grain yields by constructing terraces to capture runoff on hard-setting soils. The practice may, however, not be recommendable for bean production in high-rainfall areas due to the effect of increased water saturation at the crop root zone. Yields of maize in sole or bean-intercropped systems on hard-setting soil were not significantly affected by the construction of terraces. However, higher bean yields in the terraces were obtained from the sole bean system compared to when beans were intercropped with maize. This study recommends a sole cropping system for bean production in terraces on hard-setting soilsin areas of low rainfall. The study observed that terraces with 30 cm ditches yielded higher than those with 60 cm ditches. At the same time, the lower slope position of the terraces was capable of providing a more conducive environment for maize and bean production resulting in higher yields than the upper position. Farmers can therefore, save on labour and still achieve better yields by constructing terraces with a shallow ditch depth (30 cm). The practice of constructing terrace with 30 cm deep ditches dimension in low rainfall areas is sustainable in the long-term since it saves on costs of construction and gives the same maize yields as the one with 60 cm ditch depth. The conducive environment at the lower slope position created by the presence of the ditches can be exploited through increased intensification to enhance production and increase the benefits of constructing terraces in hard-setting soils.

CHAPTER SIX: GENERAL CONCLUSION AND RECOMMENDATIONS

This study has highlighted the role of *Fanya juu* terraces in conserving soil moisture, nitrogen and phosphorous in hard-setting soils of semi-arid Eastern Kenya. It concludes that the influence of ditch depths on moisture content and its variability within the slope depends on distribution and amount of rainfall. In seasons of low and poorly distributed rainfall, terraces with 30 cm ditch depth conserve more moisture at the 0-30 cm soil profile than those with 60 cm. In contrast, in high and well-distributed rainfall, soil moisture is higher in the terrace with a 60 cm ditch than that of 30 cm. The moisture increases linearly from the upper to lower slope positions. *Fanya juu* terraces also increase the amount of total nitrogen and available phosphorus at the lower slope position of terraces compared to the other positions. The study further concludes that terraces have a significant effect on crop yields on hard-setting soils in semi-arid Eastern Kenya. Terracing increase maize grain yields in both low and high rainfall seasons. However, the terrace positively impact bean grain yields only when amount of seasonal rainfall is near the normal long-term average Farmers in low rainfall areas can thus increase crop production by constructing terraces to capture runoff. Increasing the depth of the ditch from 30 cm to 60 cm does not significantly affect maize grain yields. Yields are however, higher in treatments with 30 cm than the 60 cm ditches. Additionally, the study shows that maize grain yields on terraced hard-setting soils are not affected by the type of cropping system (sole or intercropped). Terraces increase bean yields in the sole system compared to the intercrop. The lower slope position has higher moisture and nutrients N and P levels. This provides a more conducive environment for maize and bean production that results in higher yields than at the upper slope position.

The study recommends the construction of terraces with shallow ditch depth of 30 cm to conserve both soil moisture and the nutrients nitrogen and phosphorous on hard-setting soils in the marginal rainfall areas of semi-arid Eastern Kenya. This management practice will ensure that farmers sustainably exploit available moisture and nutrients in lower terrace positions consequently enhancing the efficient use of these resources for increased crop productivity. Farmers can also save on labor and still achieve better yields by constructing terraces with the shallow ditch depth (30 cm). The conducive environment at the lower slope position can be exploited through increased intensification to enhance production and increase the benefits of constructing terraces on hard-setting soils. Growing beans in a sole system is recommended for production on terraced hard-setting soils in areas with marginal rainfall.

Generally, this study recommends the construction of *Fanya juu* terraces with a ditch depth of 30 cm and intensive management of the lower slope position for enhanced crop production on hard-setting soils. It also recommends further research with a focus on how to manage the upper and middle slope positions to minimize nutrient and moisture losses to increase the productivity in these positions. Similarly, technologies and management practices that increase productivity of the lower slope position without causing over- utilization of the available resources and land degradation need to be developed, validated and disseminated to end users. Finally, similar research investigating the effects of terraces on the variability of soil moisture, nutrient and crop yields need to be conducted in different types of soils. This will help in generating information on the best management practices on terraces for improved productivity in different types of soils. Adoption of the generated information will enable smallholder farmers to reap the benefits of the otherwise laborious construction of terraces for increased productivity and household food security.

REFERENCES

Adamu, H.W. and Dejenie, T. (2013). Dryland ecosystems: their features, constraints, potentials and managements. Review. *Agricultural and Environmental Management: 2*(10): 277-288.

Adimassu, Z., Langan, S., Johnston, R., Mekuria, W. and Amede. T. (2017). Impacts of soil and water conservation practices on crop yield, run-off, soil loss and nutrient loss in Ethiopia: Review and synthesis. *Environmental Management 59*, 87-101. https://doi.org/10.1007/s00267-016-0776-1SN - 1432-1009.

Aklilu, M. (2016). A field guideline on bench terrace design and construction. Ministry of Agriculture and Natural Resources. Natural Resource Management Directorate; 2016. Accessed 20 June 2022. Available: https://www.researchgate.net

Alliance for a Green Revolution in Africa. (AGRA). (2014). Africa agriculture status report 2014: Climate change and smallholder agriculture in sub-Saharan Africa, Nairobi, Kenya, (No. 2) (p. 218).

Amare, T., Terefe, A., Selassie, Y.G., Yitaferu, B., Wolfgramm, B. and Hurni, H. (2013). Soil properties and crop yields along the terraces and toposequece of Anjeni watershed, Central highlands of Ethiopia. *Journal of Agricultural Science*, *5*(2):1916-9760.https://doi.org10.5539/jas.v5n2p134

Aslam, M., Maqbool, M.A. and Cengiz, R. (2015). Drought stress in maize (*Zea mays* L.): Effects, resistance mechanism, global achievements and biological strategies for improvement. Springer International, DOI: 10.1007/978-3-319-25442-5.

Atampugre, G. (2014). Cost and Benefit Analysis of the adoption of Soil and Water Conservation methods, Kenya. *International Journal of Scientific and ResearchPublications*, *4*(8), August 2014 1 ISSN 2250-3153

Bai, J., Yang, S., Zhang, Y., Liu, X. and Guan, Y. (2019). Assessing the impact of terracesand vegetation on runoff and sediment routing using the Time-Area method in the Chinese Loess Plateau. *Water*, *11*(4), p. 803

Baptista, I., Fleskens, L., Ritsema, C., Querido, A., Tavares, J., Ferreira, A. D. and Varela, A. (2015). Soil and water conservation strategies in Cape Verde (Cabo Verde in Portuguese) and their impacts on livelihoods: an overview from the Ribeira Seca watershed. *Land, 4*: 22-44.

Barungi, M., Ng'ong'ola, D.H., Edriss, A., Mugisha, J., Waithaka, M. and Tukahirwa, J. (2013). Factors influencing the adoption of soil erosion control technologies by farmers along the slopes of Mt. Elgon in eastern Uganda. *Sustainable Development, 6*(2): 9–25.

Baryla, A. and Zmuda, R. (2017). Determining the spacing of ridge terraces on arable land in central and south-western *Poland. Land Reclamation, 49*(2), 57-68. 10.1515/sggw- 2017-0005

Bashagaluke, J.B., Logah, V., Opoku, A., Sarkodie-Addo, J. and Quansah, C. (2018). Soil nutrient loss through erosion: Impact of different cropping systems and soil amendments in Ghana. PLoS One. 2018 Dec 19;13(12):e0208250. doi: 10.1371/journal.pone.0208250. PMID: 30566517;

PMCID: PMC6300324.

Bernoux, M. and Chevallier, T. (2014). Carbon in dryland soils. Multiple essential functions. Les dossiers thématiques du CSFD. N 10. June 2014. CSFD/Agropolis International, Montpellier, France. 40 pp.

Biamah, E.K. and Stroosnijder, L. (2005). Watershed conservation in semi-arid Kenya. In. Coping with drought: Options of soil and water management in semi-arid Kenya. Weaginenin University and research centre publications. *Tropical resource management papers, 58*: 91-107.

Biamah, E.K., Sterk, G. and Stroosnijder, L. (2003). Tillage and farmyard manure effects on crusting and compacting soils art Katumani, semi-arid Kenya. In. Tulberg, J. and Hoogmoed, W. (eds.). Proceedings of 16th International soil tillage research organization conference. 13-18 July, 2003, Brisbane, Australia. Pp.150-158.

Binyam, A.Y. and Asmamaw, D. (2015). Rainwater harvesting : An option for dry land agriculture in arid and semi-arid Ethiopia. *Water Resources and Environmental Engineering, 7*(2): 17-28.

Boutraa, T. and Sanders, F.E. (2001). Influence of water stress on grain yield and vegetative growth of two cultivars of bean (*Phaseolus vulgaris* L.) *Journal of Agronomy and Crop Science, 187*(4):251-257. DOI: 10.1046/j.1439-037X.2001.00525.x

Bremner, J.M, and Mulvaney, C.S. 1982. Nitrogen- total. In: Page, A.L, Miller, R.H. and Keeney, D.R. (eds). Methods of Soil Analysis, Part 2-Chemical and microbiological Properties, Second Edition, Soil Science Society of America, USA. pp. 595-624.

Bresson, L.M., Bissonnais, Y. and Andrieux, P. (2006). Soil surface crusting and structure slumping in Europe. In: Boardman, J. and Poesen, J. (eds). Soil erosion in Europe. John Wiley & Sons, Ltd; 2006. ISBN: 0-470-85910-5

Chapagain, T., Ghimire, B., Pudasaini, R., Gurung, K., Choi, K., Rai, L., Magar, S., Bishnu, B. K. and Raizada, M.N. (2019). The underutilized terrace wall can be intensified to improve farmer livelihoods. *Agron. Sustain. Dev. 39*(29)3 https://doi.org/10.1007/s13593-019-0574-2

Chen D., Wei W., Chen L. (2021). Effects of terracing on soil properties in three key mountainous regions of China. *Geography and Sustainability journal*, 2021. 2(3) pp 195-206

Clover, J. (2003). Food security in sub-Saharan Africa. *African Security Review, 12*(1).

Dagnachew, M., Moges, A., Kebede, A. and Abebe, A., 2020. Effects of soil and water conservation measures on soil quality indicators: The case of Geshy sub-catchment, Gojeb river catchment, Ethiopia. *Applied and Environmental Soil Science,* Vol. 2020, 16 p. ID 1868792, 16 p

Daniells, I.G. (2012). Hardsetting soils: a review. *Soil Research, 50*(5): 349-359.

Dejene, T. (2017). The Effectiveness of stone bund to maintain soil physical and chemical properties: The Case of Weday Watershed, East Hararge Zone, Oromia, Ethiopia. *Civil and Environmental Research* ISSN 2224-5790 (Paper) ISSN 2225-0514 (Online) Vol.9, No.12, 2017.

Deng, C., Zhang G., Liu Y., Nie, Y., Li, Z., Liu, J. and Zhu, D. (2021). Advantages and disadvantages of terracing: A comprehensive review. *International Soil and Water Conservation Research, 9*(3) pp 344-359.

Dercon, G., Deckers, J., Govers, G., Poesen, J., Sanchez, H. and Vanegas, R. (2003). Spatial variability in soil properties on slow forming terraces in the Andes region of Ecuador. *Soi. Till. Res*, *72*: 31-41.

Dijkstra, F.A. and Cheng, W. (2008). Increased soil moisture content increases plant N uptake and the abundance of ^{15}N in plant biomass. *Plant and Soil. 302*(1/2):263-271. http://www.jstor.org/stable/42951770

Dorren, L. and Rey, F. (2004). A review of the effect of terracing on erosion. In: Boix- Fayons, C. and Imeson, A. (eds). Briefing papers of the 2nd Soil Conservation and Protection for Europe (SCAPE) Workshop. Cinque Terre, Italy. 97-108.

Food and Agriculture Organization. (FAO). (1991). Soil conservation. https://www.fao.org/3/X5301E/x5301e06.htm. Accessed 20/9/2021

Food and Agriculture Organization of the United Nations/United Nation Educational, (FAO/UUNESCO). (1997). Scientific and Cultural Organization. Soil Map of the World. Revised Legend. World Soil Resources. Report 60. FAO: Rome. 1997; 41 pp.

Food and Agriculture Organization. (FAO). (2000). Manual on integrated soil managementand conservation practices. FAO Land and Water Bulletin No. 8. Rome. Italy: FAO. (214 p)

Food and Agriculture Organization (FAO) (2004). Soil and water management. http://www.fao.org/soils-portal/soil-management/soil-conservation/en/. Accessed

20/9/2021

Food and Agriculture Organization. (FAO). (2011). The state of food and agriculture, 2010- 2011. Women in Agriculture. Closing the gender gap for development. Food and Agriculture Organization of the United Nations. Rome, Italy. (p. 160).

Food and Agriculture Organization. (FAO). (2015). The state of food and agriculture. Social protection and agriculture: breaking the cycle of rural poverty. Food and Agriculture Organization of the United Nations. Rome, Italy. (p. 151).

Fries, A., Silva, K., Pucha-Cofrep, F., Oñate-Valdivieso, F. and Ochoa-Cueva, P. (2020). Water Balance and Soil Moisture Deficit of Different Vegetation Units under Semiarid Conditions in the Andes of Southern Ecuador Climate, 8:30. doi:10.3390/cli8020030

Gachene, C.K. and Baaru, M. (2011). Effects of vegetative macro contour lines on moisture conservation and crop performance in Kathekakai, Machakos District. A paper presented during the 4th National conference for dissemination of research results and exhibition innovation. 3-6 May 2011. National Council of Science and Technology.

Gachene, C.K.K, Mbuvi, J.P. Jarvis,N.j. and Linner, H., (1997) Soil erosion effects on soil properties in a highland area of Central Kenya. *Soil Science Society of America Journal, 61*(2). pp559-564https://doi.org/10.2136/sssaj1997.03615995006100020027x.

Gachene, C.K.K., Nyawade, S.O. and Karanja, N.N. (2019). Soil and water conservation: An overview. In: Leal Filho, W., Azul, A., Brandli, L., Özuyar, P. and Wall, T. (eds). Zero Hunger. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. 2019. https://doi.org/10.1007/978-3-319-69626-3_91-1

Gebreslassie, H. (2014). Opportunities of bench terracing in Tigray, Ethiopia: Taking land to water perspective. *Advances in Life Science and Technology, 22*: 33-39.

GENSTAT. (2016). Release 14.2. Lawes Agricultural Trust-IACR. Rothamsted Experimental Station, U.K; 2016.

Giarola, N.F.B., de Lima, H.V. and da Silva, A.P. (2011) Hardsetting Soils: Physical properties. In: Gliński J., Horabik J. and Lipiec J. (eds). Encyclopedia of Agrophysics. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-3585-1_261

Gichangi, E.M., Njiru, E.N., Itabari, J.K., Wambua, J.M., Maina, J.N. and Karuku, A. (2004). Assessment of improved soil fertility and water harvesting technologies through community-based on-farm trials in the ASALs of Kenya. In: Andre Bationo, Boaz Waswa, Job Kihara and Joseph Kimetu (eds). Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and opportunities. *Springer.* pp. 759- 765.

Gicheru, P., Gachene, C., Mbuvi, J.P. and Mare, E. (2004). Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. *Soil and Tillage Research. 75*(2):173-184. DOI: 10.1016/S0167-1987(03)00161-2

Gichuki, F.N. (1991). Environmental change and dryland management in Machakos District, Kenya 1930-90. Conservation profile. Results of ODI Research presented in preliminary form for discussion and critical comment. Nairobi.

Hammad, A.A., Haugen, L.E. and Borresen, T. (2004). Effects of stonewalled terracing techniques on soil-water conservation and wheat production under Mediterranean conditions. *Environment Management Journal, 34*.

Homma, K., Horie, T., Shiraiwa, T., Supapoj, N., Matsumoto, N. and Kabaki, N. (2003). Toposequential variation in soil fertility and rice productivity of rainfed lowland paddy fields in mini-watershed (Nong) in Northeast Thailand. *Plant Production Sci*ence; *6*:147-153. https://doi.org/10.1007/s00267-016-0776-1

Huang, D., Chen, X., Zhang, S., Zhang, Y., Gao, Y. and Zhang, Y. (2022). No-tillage improvement of nitrogen absorption and utilization in a Chinese Mollisol using 15N- tracing method. *Atmosphere, 13*(4):530. https://doi.org/10.3390/atmos13040530

Huang, J., Li, Y., Congbin, F. and Wang, G. (2017). Dryland climate change: Recent progress and challenges. *Reviews of Geophysics, 55*(3).

Hussein, M.H., Amien, I.M and Kariemb, T.H. (2016). Designing terraces for the rainfed farming region in Iraq using the RUSLE and hydraulic principles. *International Soil and Water Conservation Research journal* 4: 39-44.

Ibraimo, N. and Munguambe, P. (2007). Rainwater harvesting technologies for small scale rainfed agriculture in arid and semi-arid areas. Integrated Water Resource Management for Improved Livelihoods. CGIAR Challenge

Program on water and food. (p. 25).

Inocencio, A., Sally, H. and Merrey, D.J. (2003). Innovative approaches to agricultural water use for improving food security in sub-Saharan Africa. Colombo: SriLanka. International water management institute.

IPCC. (2007). Climate Change 2007. Synthesis Report: Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. [Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds)]. IPCC, Geneva, Switzerland. (p. 104)

Jaetzold, R., Helmut, S. and Shisanya C. (2010). Farm Management Handbook of Kenya Vol. II. Atlas of agro-ecological zones, soils and fertilizing by group of districts in eastern province. Subpart C. Machakos and Makueni County; 2010.

Kannan, N., Senthivel, T., Rayar, A. S. and Mutesa, F. (2009). Analysis of soil moisture conservation techniques with dry season maize crop on hill land at Rubirizi, Rwanda. *https://www.researchgate.net/publication/47416606*.

Karuma, A., Mtakwa, P., Amuri, N., Gachene, C.K. and Gicheru, P. (2014). Enhancing soil water content for increased food production in semi-arid areas of Kenya - Results from an on-farm trial in Mwala District, Kenya. *Agricultural Science, 6*(4): 125-134.

Kidane, W., Maetz, M. and Dardel, P. (2006). Food security and agricultural development in sub-Saharan Africa- Building a case for more public support. Policy assistance series 2. FAO regional office for Africa (p. 122).

Kosmowski, F. (2018). Soil water management practices (terraces) helped to mitigate the 2015 drought in Ethiopia. *Agricultural Water Management. 31*(204): 11-16. doi: 10.1016/j.agwat.2018.02.025

Laban, P., Metternicht, G. and Davies, J. (2018). Soil biodiversity and soil organic carbon: keeping drylands alive. Gland, Switzerland: IUCN. viii + 24p

Li J., Zhang W. J., and Zhang J. P. (2012). Comparative Analysis of water reduction benefits between terrace and slope land in southern area of Ningxia: Taking Haoshuichuan Watershed as an example. Advances in Hydrology and Hydraulic Engineering, Pts 1and 2, 212-213, 83-87.

Masso, C., Nziguheba, G., Mutegi, J., Galy-Lacaux, C., Wendt, J. and Butterbach-Bahl, K. (2017). Soil fertility management in sub-Saharan Africa. Sustainable Agriculture Reviews book series (SARV). 2017;25

Mati, B. M. (2005). Overview of water and soil nutrient management under smallholder rainfed agriculture in East Africa. Working Paper 105. Colombo, Sri Lanka: International Water Management Institute (IWMI). p. 105.

Mati, B. M. (2012). Soil and Water Conservation Structures for Smallholder Agriculture. Training Manual 5. Nile Basin Initiative (NBI), Nile Equatorial Lakes Subsidiary Action Programme (NELSAP) - Regional Agricultural and Trade Programme (RATP), Bujumbura, Burundi.

Matusso, J.M.M., Mugwe, J.N. and Mucheru-Muna, M. (2014). Potential role of cereal- legume intercropping systems in integrated soil fertility management in smallholder farming systems of Sub-Saharan Africa, *Agriculture and Environmental Management,3*(3): 162-174

Matusso, J.M.M., Mugwe, J.N., and Mucheru-Muna, M. (2014). Potential role of cereal- legume intercropping systems in integrated soil fertility management in smallholder farming systems of Sub-Saharan Africa, Agriculture and Environmental Management; 3(3): 162-174

Mbugua H.1., Baaru M. W., and Gachene C. K. (2019). Soil moisture variability effects onmaize crop performance along a toposequence of a terraced vertisol in Machakos, Kenya. *Journal of Soil Science and Environmental Management*. 10(1), pp. 21-28.

Million, A. (2003). Characterization of indigenous stone bunding (kab) and its effect on crop yield and soil productivity at Mesobit-Gedba, North Showa Zone of Amhara Region. Master's thesis, Alemaya University, Ethiopia.

Miriti, J.M., Kironchi, G., Esilaba, A.O., Heng, L.K., Gachene, C.K.K. and Mwangi, D.M. (2012). Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. *Agricultural Water Management, 115*, 148-155.

Molina, J.C., Moda-Cirino, V., Da N., Junior, F.S., Faria, R. and Destro, D. (2001). Response of common bean cultivars and lines to water stress. *Crop Breeding and Applied Biotechnology, 1*(4). DOI: 10.13082/1984-7033.v01n04a05

Monin, J. (1993). Soil crusting and sealing (1993), Soil tillage in Africa: needs and challenges. Food and Agriculture Organization of the United Nations. FAO soils bulletin. 69: 95-128

Mullins, C.E., MacLeod, D.A., Notthcote, K.H., Tisdall, J.M. and Young, I.M. (1990). Hardsetting soils: Behaviour, occurrence and management. In: Soil degradation, Lal, R. and Stewart, B.A. (eds). *Advances in Soil Science, 11*: 37-108.

Munang, R.T., Thaw, I. and Rivington, M. (2011). Ecosystem management: Tomorrow's approach to enhancing food security under a changing climate. *Sustainability:* Open Access.

Mutunga, K. (2001). Water conservation, harvesting and management - Kenyan Experience. In: Sustaining the global farm, D.E. Stott, R.H. mohtar and G.C. Steinhardt (eds). (pp. 1139-1143).

Mutunga, K., Critchley, W., Lameck, P., Lwakuba, A. and Mburu, C. (2001). Farmers' initiatives in land husbandry: Promising technologies for the drier areas of east Africa. Technical Report No. 27. RELMA, Nairobi.

Namirembe, S., Nzyoka, J.M. and Gathenya, J.M. (2015). A guide for selecting the right soil and water conservation practices for small holder farming in Africa. ICRAF Technical manual No.24. Nairobi, Kenya: World Agroforestry Centre (ICRAF)

Nelson, E. W. and Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter. In: Page, A. L., Miller, R. H. and Keeney, D. R. (eds) *Methods of soil analysis: Chemical methods,* Part 3. Soil Science Society of America. Madison WI, USA. pp. 542-560.

Ngonzo, C.L., Shisanya, C.A. and Obando, J.A. (2013). Climate change, excess land–uses and farmers' water demand : An induction from smallholder farms of Muooni dam site, Kenya. *Agri-Food and Applied Sciences, 1*(2): 24-36.

Ntukamazina, N., Onwonga, R.N., Sommer, R., Mukankusi, C.M., Mburu, J.

and Rubyogo, C. (2017). Effect of excessive and minimal soil moisture stress on agronomic performance of bush and climbing bean (*Phaseolus vulgaris* L.). *Cogent Food and Agriculture, 3*(1). DOI: 10.1080/23311932.2017.1373414

Nyamadzawo, G., Wuta, M., Nyamangara, J. and Gumbo, D. (2013). Opportunities for optimization of in-field water harvesting to cope with changing climate in semi-arid smallholder farming areas of Zimbabwe. *Springer*; Open access. At http://www.springerplus.com/content/2/1/100

Nyassasi, B.T. and Kisetu, E. (2014). Determination of land productivity under maize- cowpea intercropping system in agro-ecological zone of mount Uluguru in Morogoro, Tanzania. *Agricultural sciences, 2*(2): 147-157.

Nyawade, S., Gitari. H., Karanja, N., Gachene, C., Schulte-Geldermann, E. and Parker, M. (2018). Intercropping potato with grain legumes for enhanced productivity and climate change adaptation in smallholder farms, Kenya. Regional Universities Forum for Capacity Building in Agriculture (RUFORUM) Biennial Conference, October 22-26, 2018. Nairobi, Kenya.

Odendo, M., De Groote, H., Odongo, O. and Patrick, O. (2002). Participatory rural appraisal of farmers' criteria for selection of maize varieties and constraints to maize production in moist mid-altitude zone of western Kenya - A case study of Butere-Mumias, Busia and Homa Bay Districts. Kenya Agricultural Research Institute, Nairobi

Ofori, E., Atakora, E., Kyei-Baffour, and Antwi, B.O. (2013). Relationship between landscape positions and selected soil properties at a Sawah site in

Ghana. Departmentof Agricultural Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.*African Journal of Agricultural Research.* 8(27), pp. 3646-3652.

Ofori, E., Oteng-Darko, P., Berchie, J.N., Nimako, F.O., Yeboah, S. and Owusu, E.D. (2014). Monitoring of soil moisture regime and water use efficiency under maize cowpea cropping system. *Current microbiology and applied science, 3*(10): 837-848.

Okalebo, J.R. Gathna, K.W. and Woomer, P.L. (2002). Laboratory methods of soil and plant analysis: A Working Manual. 2nd Edn., Nairobi: Tropical Soil Fertility and Biology Program.

Olsen, S.R. and Sommers, L.E. (1982). Phosphorus. In: Page, A.L., Miller, R.H. and Keeney, D. R. (eds). Methods of soil analysis, Part 2. Chemical and microbiological properties, 2nd Ed. Soil Science Society of America. USA. pp. 403-427.

Omar, A.A., Edinam, K.G. and O.L. (2013). Causes and impacts of land degradation and desertification : Case study of the Sudan. *Agriculture and Forestry, 3*(2): 40-51.

Omoyo, N.N., Wakhungu, J. and Oteng'i, S. (2015). Effects of climate variability on maize yield in the arid and semi arid lands of lower eastern Kenya. *Agriculture and Food Security, 4*:8. https://doi.org/10.1186/s40066-015-0028-2

Osman, K.T. (2018). Dryland Soils. In: Management of soil problems.

10.1007/978-3- 319-75527-4

Peng, Y., Fu, B., Zhang, L., Yu, X., Fu, C., Diop, S., Hirwa, H., Guisse, A. and Li., F. (2020). Global Dryland Ecosystem Programme (G-DEP): Africa consultative meeting report. *Journal of Arid Land 12*(3): 538-544.

Plaza-Bonilla, D., Arrúe, J.L., Cantero-Martínez,C., Fanlo, R., Iglesias, A. and Álvaro-Fuentes, J. (eds). (2015). Carbon management in dryland agricultural systems. A review. Agron. *Sustain. Dev. 35*, 1319-1334. https://doi.org/10.1007/s13593-015-0326-x.

Posthumus, H. and Stroosnijder, L. (2010). To terrace or not: The short-term impact of bench terraces on soil properties and crop response in the Peruvian Andes. *Environment Development and Sustainability.* 12(2)

Rao, K.P.C. and Okwach, G.E. (2005). Enhancing productivity of water under variable climate. Proceedings of the East Africa integrated river basin management conference. Ed. Bruce A. Lankford and Henry F. Mahoo. 7-9 March. Sokoine University of Agriculture, Morogoro, Tanzania.

Rao, K.P.C., Cogle, A.L., Srinivasan, F.T., Yule, D.F. and Smith, G.O. (1994). Effect of soil management practices on runoff and infiltration processes of hardsetting Alfisol in semi-arid tropics. 8th ICSO conference, 1994, New Delhi, India. 1287-1293.

Rashid, M., Obaid ur R., Alvi, S., Kausar, R. and Akram, M.I. (2016). The effectiveness of soil and water conservation terrace structures for improvement of crops and soil productivity in rainfed terraced system. *Pak. J. Agri. Sci., 53*(1), 241-248. DOI: 10.21162/PAKJAS/16.1502

Recha, J.W., Mati, B.M., Nyasimi, M., Kimeli, P.K., Kinyangi, J.M. and Radeny, M. (2016). Changing rainfall patterns and farmers' adaptation through soil water management practices in semi-arid eastern Kenya. *Arid Land Research and Management. 30*(3): 29- 238. DOI: 10.1080/15324982.2015.1091398.

REGLAP. (2012). Regional learning and advocacy programme for vulnerable dryland communities. Key statistics on the drylands of Kenya, Uganda and Ethiopia (p. 42).

Rehman, O., Rashid, M., Kausar, R., Alvi, S. and Sajjad, M.R. (2015). Assessment of runoff and sediment losses under different slope gradients and crop covers in semi-arid watersheds. Soil Science Society of Pakistan. *Soil Environ. 34*(1): 75-81.

Rembold, F., Nkunzimana, T. and Kayitakire, F. (2014). Analysis of the food security situation in Kenya at the end of the 2013-2014 short rains season. Drought conditions affecting dry lands in northern and northeastern Kenya, below average crop production in southwestern marginal agricultural areas. JRC scientific and policy reports. (p.46)

Republic of Kenya. (RoK). (2011). Vision 2030 Development strategy for northern Kenyaand other arid lands. Nairobi. (p.121)

Robel, A., Addisu, A., Minda, T. (2019). Effect of growth stage moisture stress on common bean *(Phaseolus vulgaris* L.) yield and water productivity at Jimma, Ethiopia. International journal of environmental science and natural resources, *16*(1): 555929. DOI: 10.19080/IJESNR.2019.16.555929.

Rockstrom, J. and Steiner, K. (2003). Conservation farming–a strategy for improved agricultural and water productivity among smallholder farmers in drought prone environments. In: Water conservation technologies for sustainable dryland agriculture in Sub- Saharan Africa. Beukers, D., de Villiers, M., Mkhize, S., Sally, H. and L. Van Rensburg (eds). Proceedings of the Symposium and Workshop held in Bloemfontein, South Africa, 8-11 April 2003. pp. 200-208.

Rossato, L., Alvalá, R.C.A., Marengo, J.A., Zeri, M., Cunha, A.P.M. and Pires, L.B.M. (2017). Impact of soil moisture on crop yields over Brazilian semi-arid. *Frontiers inEnvironmental Science, 5* https://www.frontiersin.org/article/10.3389/fenvs.2017.00073

Ruto, A., Gachene, C., Gicheru, P., Mburu, D. and Khali, Z. (2017b). Crop yields along the toposequence of terraced Andosols in Narok, Kenya. Tropical and Subtropical *Agroecosystems, 20*: 35-47

Ruto, A.C. (2015). Optimizing moisture and nutrient variability under different cropping patterns in terraced farms for improved crop performance in Narok County, Kenya. PhD Thesis. University of Nairobi. Accessed 10 June 2022. Available: http://erepository.uonbi.ac.ke

Ruto, A.C., Gachene, C.K., Gicheru, P.T., Mburu, D.M. and Zeinab, K. (2017a). Soil moisture variability and uptake of selected nutrients by maize along the toposequence of terraced andosols in Narok, Kenya. *Journal of Agricultural Science and Food Technology, 3*(5), pp. 78-87, October, 2017. ISSN: 2465-7522. http://pearlresearchjournals.org/journals/jasft/index.html

Saleem, R., Ahmed, Z.I., Ashraf, M., Arif, M., Malik, M.A., Munir, M. and

Khan, M.A. (2011). Response of maize-legume intercropping system to different fertility sources under rainfed conditions. *Sarhad Agric*., *27*(4): 503-511.

Sasson, A. (2012). Food security for Africa: an urgent global challenge (pp. 1–16).

Sheng, T.C. (2002). Bench terrace design made simple. In 12th ISCO Conference (pp. 500- 504)

Shimbahri, M. G., Almeida, O. L. A., Yazew, E., Bresci, E. and Castelli, G. (2019). Spatial variability of soil moisture in newly implemented agricultural bench terraces in the Ethiopian Plateau. *Water.* 11(10) pp. https://www.mdpi.com/2073-4441/11/10/2134.

Shimeles Damene, Lulseged Tamene and Paul L.G. Vlek, (2012). Performance of farmland terraces in maintaining soil fertility: A case of Lake Maybar Watershed in Wello, Northern Highlands of Ethiopia. *Journal of Life Sciences, 6*: 1251-1261.

Sidahmed, E.A. (2000). The rangelands of arid and semi-arid areas: challenges and hopes for the 2000s. Keynote address to Symposium. The International Conference on Desert Development in the Arab Gulf Countries, Kuwait Institute for Scientific Research, Kuwait, 23-26 March 1996. IFAD Technical Advisory Division. Staff Working Paper No. 29.

Sigunga, D.O. and Wandahwa, P.J. (2011). Land and soil resources and their management for sustainable agricultural production in Kenya: Current position and future challenges. *Egerton Science and Technology,* 66-85.

Siriri, D., Tenywa, M.M, Raussen, T. and Zake, J.K. (2005). Crop and soil variability on terraces in the highlands of SW Uganda. *Journal of Land Degradation and Development, 16*(6): 569-579. https://doi.org/10.1002/ldr.688

Sombroek, W.G.and Pauw, B.J.Avan der . (1980). Exploratory soil map of Kenya. Republic of Kenya. Ministry of Agriculture. Kenya Soil Survey, Nairobi.

Speranza, C.I. (2010). Drought coping and adaptation strategies: Understanding adaptations to climate change in agro-pastoral livestock production in Makueni District, Kenya.*European Development Research,* 22: 623-642.

Spitkó, T., Nagy, Z., Tóthné Zsubori, Z., Halmos, G., Bányai, J. and Marton, L.C. (2014). Effect of drought on yield components of maize hybrids (*Zea mays* L.). *Maydica, 59*(2):161-169.

Stern, R., Rijks, D., Dale, I. and Knock, J. (2006). INSTAT climatic guide. *Statistical services centre.* The University of Reading, UK. pp. 230.

Stewart, B.A. (2016). Dryland Farming. Reference Module in Food Science.

https://doi.org/10.1016/B978-0-08-100596-5.02937-1

Stewart, R. (2009). Land degradation in arid regions. Our ocean planet. Oceanography in the 21st century. A New Oceanography Book for College Students (1st ed).

Studer, R.M. and Liniger, H. (2013). Water harvesting: Guidelines to good practice. Centre for Development and Environment (CDE), Rainwater Harvesting Implementation Network (RAIN), The International Fund for Agricultural Development (IFAD), Rome. (p.210).

Subhatu, A., Speranza, C.I., Zeleke, G., Roth, V., Lemann, T., Herweg, K. and Hurni, H. (2018). Interrelationships between terrace development, topography, soil erosion, and soil dislocation by tillage in Minchet Catchment, Ethiopian Highlands. *Land degradation and development, 29*(10):3584-94.

SUSTAINET EA. (2010). Technical manual for farmers and field extension service providers: Soil and water conservation. *Sustainable agriculture information initiative, Nairobi. 16*. ISBN 978-9966-1533-8-8. Accessed 20 June 2022. Available: https://wocatpedia.net

Tadele, A., Selassie, Y. G., Haile, M. and Yamoh, C., (2011). Effect of soil and water conservation measures on selected soil physical and chemical properties and barley (Hordeum spp.) yield. *Journal of Environmental Science and Engineering 5*(11): 1483-1495

Tadele, A., Terefe, A., Selassie, y.G., Yitaferu, B., Wolfgramm, B. and Hurni, H. (2013). Soil properties and crop yields along the terraces and toposequece of Anjeni Watershed, Central Highlands of Ethiopia. *Journal of Agricultural Science, 5*(2): 1916-9760.

Tenge, A.J., De Graff, J. and Hella, J.P. (2005). Financial efficiency of major soil and water conservation measures in West Usambra highlands, Tanzania. *Applied Geographic, 25*: 348-366.

Tenge, A.J., Sterk, G. and Okoba, B.O. (2011). Farmers' preferences and physical effectiveness of soil and water conservation measures in the East African highland. *Journal of social sciences, 1*:84-100. Accessed 20 June 2022. Available: https://www.researchgate.ne

Tessema B., Sommer R., Piikk K., Söderström M., Namirembe S., Notenbaert A., Tamene L., Nyawira S and Birthe P. (2019). Potential for soil organic carbon sequestration in grasslands in East African countries: *A review. Grassl Sci., 66*: 135- 144. https://doi.org/10.1111/grs.12267.

UNDP, UNCCD and UNEP. (2009). Climate Change in the African Drylands: Options and opportunities for adaptation and mitigation. (p. 58).

UNDP, UNCCD and UNEP. (2009). Climate Change in the African Drylands: Options and opportunities for adaptation and mitigation. (p. 58).

United Nations Development Programme. (UNDP). (2013). Combating Desertification in Kenya: Emerging lessons from empowering local communities. Nairobi, Kenya. 2013:44.

Wairimu, H.M. (2015). Effect of soil moisture variability on crop performance in a terraced vertisol, Machakos County. Master's Thesis. University of Nairobi. 2015.

Wale, H.A. and Dejenie, T. (2013). Dryland ecosystems : Their features, constraints, potentials and managements. *Agricultural and Environmental Management, 2*(10): 277- 288.

Wanjogu, S. N., Muya, E. M., Macharia, P. N. and Kamoni, P. T. (2006). Sustainable land management in Kiambindu, Kiarukungu, Kyeekolo and Kisioki smallholder irrigation schemes (Mbeere, Kirinyaga, Makueni and Kajiado Districts). Kenya soil survey advisory site evaluation report. December, 2006 Kenya Agricultural Research Institute. National Agricultural Research Laboratories. Kenya Soil Survey. pp 98

Wei W, Feng X, Yang L, Chen L, Feng T, Chen D. (2019). The effects of terracing and vegetation on soil moisture retention in a dry hilly catchment in China. Sci Total Environ. 10(647) pp1323-1332.

Wei, Z., Chen, D., Wang, L., Daryanto, S., Chen, L., Yang, Y., Lu, Y., Sun, G. and Tianjiao F. (2016). Global synthesis of the classifications, distributions, benefits and issues ofterracing. In: Earth-Science Reviews. pp. 159.

Wenner, C. (1980). Soil conservation in Kenya especially in small-scale farming in high potential areas using labour intensive methods'. Ministry of Agriculture, Nairobi.

Wezel, A., Steinmuller, N. and Friederishen, J.R. (2002). Slope position effects on soil fertility and crop productivity and implications for soil conservation in upland Northwest Vietnam. *Agric. Ecosystem Environment, 91*:113-126.

Widomski, M.K. (2011). Terracing as a measure of soil erosion control and its effect on improvement of infiltration in eroded environment. In: Soil erosion issues in agriculture. Godone, D. (ed). Shanghai, China: InTech. pp:315-334.

Wolka, K. (2014). Effect of soil and water conservation measures and challenges for its adoption: Ethiopia in Focus. *Journal of Environmental Science and Technology*, 7, pp. 185-199.

Wolka, K., Biazin, B., Martinsen, V. and Mulder, J. (2021). Spatial variation in soil properties and crop yield on stone bund terraces in southwest Ethiopia. Soil use and management. https://doi.org/10.1111/sum.12777

Xu, Y., Zhu, G., Wan, Q., Yong, L., Ma, H., Sun, Z., Zhang, Z. and Qiu, D. (2020).

Effect of terrace construction on soil moisture in rain-fed farming area of Loess Plateau. Journalof Hydrology, Regional Studies 37(2021), 100889

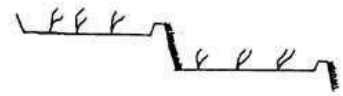
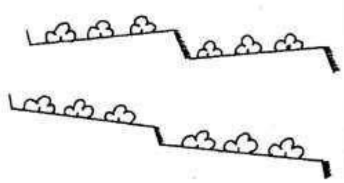
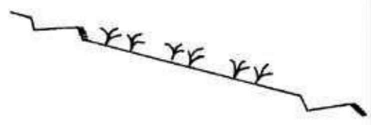
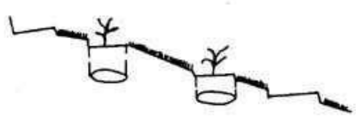
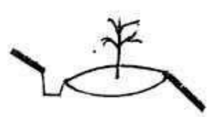
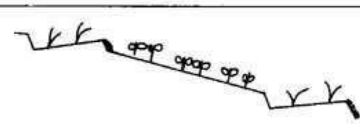
Youssef, A.A., Touma, J., Zante, P., Slah, N. and Albergel, J. (2008). Water and sediment balances of a contour bench terracing system in a semi-arid cultivated zone (El Gouazine, central Tunisia). *Hydrological Sciences, 53*(4): 37-41.

Zhang, J.H., Quine, T.A. and Ni, S.J. (2006). Stocks and dynamics of SOC in relation to soil redistribution by water and tillage erosion. *Global Change Biol., 12*: 1834-1841.

Zoca, S., Lollato, R. and Meeks, K. (2012). Influence of Agricultural Terraces on Soil Water and Physical Properties in Oklahoma.

APPENDICES

Appendix 1. Classification of bench terraces (Aklilu, 2016)

Land Use & Crop	Cross-sectional View	Type
A. Continuous type (on deep soils and slopes of 7° to 25°)		
1. For rice or for flood irrigation		Irrigation or level bench terraces
2. For mainly rain-fed crops or irrigated crops in dry season		Upland bench terraces: a. Reverse sloped b. Outward sloped
B. Discontinuous type (on shallow to deep soils and slopes of 7° to 30°)		
3. For upland crops, especially semi-permanent crops		Hillside ditches
4. For tree crops or fruit trees on steep slopes		Orchard terraces
5. For planting individual trees or plants		Individual basins
C. Transitional type (on deep soils and slopes of 7° to 25°)		
6. For mixed farming or for flexible future land use		Convertible terraces
7. For completing full bench terraces over a period of time		Intermittent terraces

Appendix 2. Analysis of variance (ANOVA) table for volumetric soil moisture content(g^3g^{-3}) across the seasons

Source of variation	d.f.	s.s.	m.s.	v.r.	p value	
Rep stratum	2	0.1729753	0.0864876	2.23		
Season	3	1.0263428	0.3421143	8.82	0.013	*
Residual	6	0.2327207	0.0387868	16.26		
Depth	2	0.1562804	0.0781402	32.76	<.001	***
Season.Depth	6	0.0568275	0.0094713	3.97	0.013	*
Residual	16	0.0381646	0.0023853	6.83		
Slope	2	0.0111683	0.0055841	15.98	<.001	***
Season.Slope	6	0.0068785	0.0011464	3.28	0.009	**
Depth.Slope	4	0.0027635	0.0006909	1.98	0.113	
Season.Depth.Slope	12	0.0147094	0.0012258	3.51	<.001	***
Residual	48	0.0167709	0.0003494			
Total	107	1.7356019				

Appendix 3. Analysis of variance table for nitrogen content (%) at end of trial period

Source of variation	d.f.	s.s.	m.s.	F	p-value	
Rep	3	0.0025911	0.0008637	1.83		
Depth	2	0.0087227	0.0043614	9.25	0.002	**
Slope	2	0.0120208	0.0060104	12.75	<.001	***
Depth.Slope	4	0.0051628	0.0012907	2.74	0.063	ns
Residual	17	0.0080155	0.0004715			
Total	28	0.0293241				

Appendix 4. Analysis of variance (ANOVA) table for available phosphorous content(ppm) at the end of the trial period

Source of variation	df	s.s	m.s.	F	p value	
Rep	3	1371.69	457.23	16.19		
Depth	2	36.26	18.13	0.64	0.539	ns
Slope	2	608	304	10.76	<.001	***
Depth. Slope	4	671.75	167.94	5.95	0.004	**
Residual	17	480.12	28.24			
Total	28	1711.23				

Appendix 5. Analysis of variance table for exchangeable potassium (Cmol kg^{-1}) contentat end of study

Source of variation	d.f.	s.s.	m.s.	F	p-value	
Rep	3	0.15072	0.05024	1.47		
Depth	2	0.03526	0.01763	0.52	0.606	ns
Slope	2	0.18434	0.09217	2.7	0.096	ns
Depth. Slope	4	0.10779	0.02695	0.79	0.548	ns
Residual	17	0.58077	0.03416			
Total	28	0.94172				

Appendix 6. Analysis of variance table for organic carbon (%) content at end of study

Source of variation	d.f.	s.s.	m.s.	F	p-value	
Rep	3	0.08523	0.02841	0.88		
Depth	2	0.06019	0.03009	0.93	0.414	ns
Slope	2	0.02661	0.01331	0.41	0.67	ns
Depth.Slope	4	0.05226	0.01306	0.4	0.804	ns
Residual	17	0.5512	0.03242			
Total	28	0.72152				

Appendix 7. Analysis of variance table for maize grain yields (t ha^{-1}) across seasons

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Rep stratum	3	20.823	6.941	5.08		
Rep.Depth stratum						
Depth	2	185.726	92.863	67.93	<.001	***
Residual	6	8.202	1.367	1.3		
Rep.Depth.CS stratum						
CS	1	3.491	3.491	3.33	0.101	
Depth.CS	2	4.599	2.299	2.19	0.168	
Residual	9	9.44	1.049	1.36		
Rep.Depth.CS.Slope stratum						
Slope	2	30.569	15.285	19.76	<.001	***
Depth.Slope	4	14.599	3.65	4.72	0.004	***
CS.Slope	2	0.331	0.166	0.21	0.808	
Depth.CS.Slope	4	1.742	0.436	0.56	0.691	
Residual	36	27.849	0.774	0.63		
Rep.Depth.CS.Slope.*Units* stratum						
Season	3	305.722	101.907	83.22	<.001	***
Depth.Season	6	63.783	10.631	8.68	<.001	***
CS.Season	3	3.794	1.265	1.03	0.38	
Slope.Season	6	5.182	0.864	0.71	0.646	
Depth.CS.Season	6	9.085	1.514	1.24	0.291	
Depth.Slope.Season	12	11.317	0.943	0.77	0.68	
CS.Slope.Season	6	3.292	0.549	0.45	0.845	
Depth.CS.Slope.Season	12	2.048	0.171	0.14	1	
Residual	141	172.658	1.225			
Total	266	840.526				

Appendix 8. Analysis of variance table for bean grain yields (t ha^{-1}) across seasons

Source of variation	d.f	s.s.	m.s.	v.r.	F pr.	
Rep stratum	3	0.60458	0.20153	4.29		
Rep.Depth stratum						
Depth	2	0.76681	0.38341	8.17	0.019	**
Residual	6	0.28168	0.04695	0.37		
Rep.Depth.CS stratum						
CS	1	1.23111	1.23111	9.64	0.013	**
Depth.CS	2	0.09113	0.04556	0.36	0.709	
Residual	9	1.14914	0.12768	4.83		
Rep.Depth.CS.Slope stratum						
Slope	2	0.25226	0.12613	4.77	0.015	**
Depth.Slope	4	0.30369	0.07592	2.87	0.037	**
CS.Slope	2	0.02506	0.01253	0.47	0.627	
Depth.CS.Slope	4	0.06132	0.01533	0.58	0.679	
Residual	36	0.9525	0.02646	0.29		
Rep.Depth.CS.Slope.*Units* stratum						
Season	2	6.1584	3.0792	34.19	<.001	***
Depth.Season	4	2.60947	0.65237	7.24	<.001	***
CS.Season	2	0.46286	0.23143	2.57	0.084	
Slope.Season	4	0.33846	0.08462	0.94	0.447	
Depth.CS.Season	4	1.00552	0.25138	2.79	0.033	
Depth.Slope.Season	8	0.27397	0.03425	0.38	0.927	
CS.Slope.Season	4	0.04915	0.01229	0.14	0.968	
Depth.CS.Slope.Season	8	0.2757	0.03446	0.38	0.926	
Residual	65	5.85326	0.09005			
Total	172	20.02947				