RAINFALL CHARACTERISTICS AND EFFECT OF SELECTED SOIL MANAGEMENT PRACTICES ON SOIL WATER PRODUCTIVITY IN THE CENTRAL HIGHLANDS OF KENYA

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DECLARATION

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

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DEDICATION

This work is dedicated to my family and friends, especially to my fiancée Rose Wanjiru Mugo for the unwavering support towards my study.

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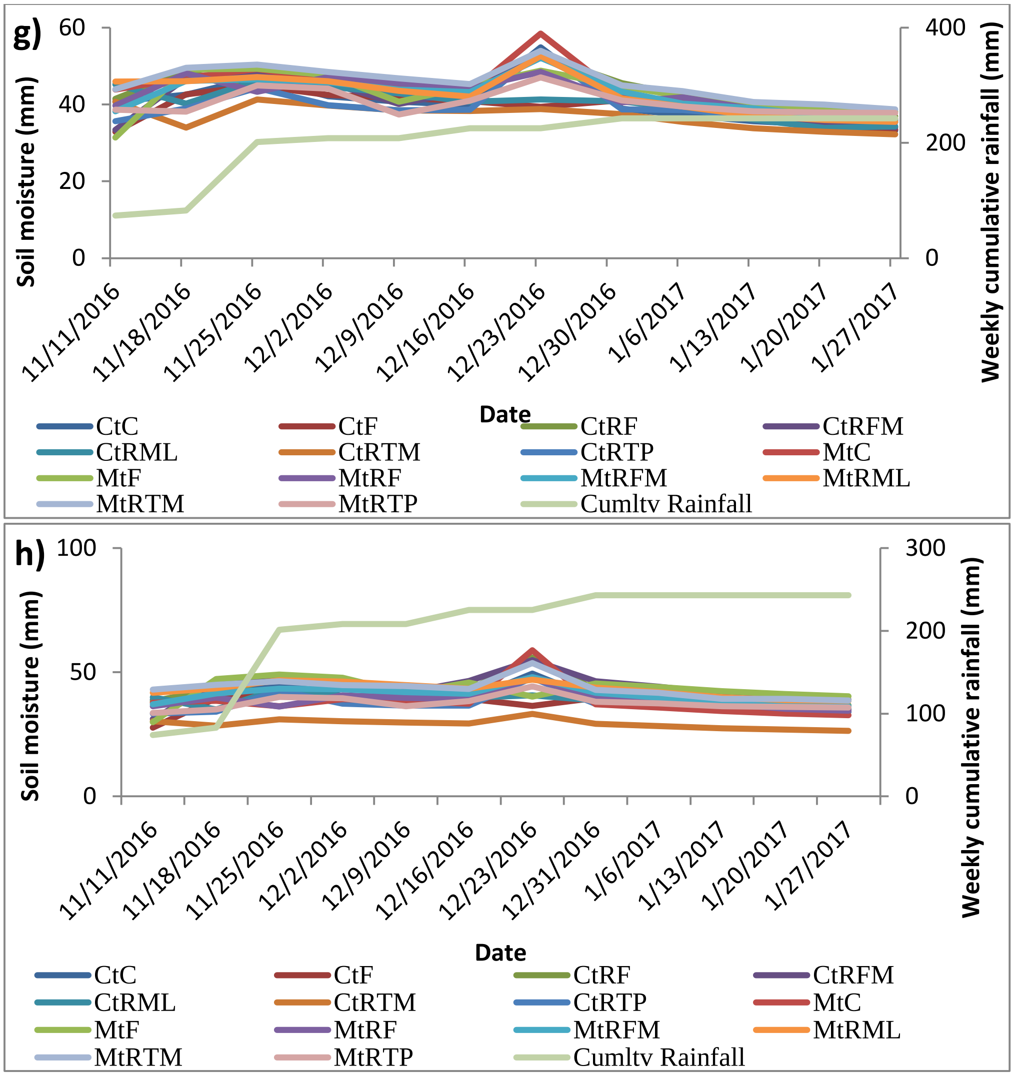
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Cumltv Rainfall

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LIST OF ABBREVIATIONS/ACRONYMS

AEZs	Agro-Ecological Zones
ANOVA	Analysis of Variance
ASL	Above Sea Level
BD	Bulk Density
Ca	Calcium
CDI	Cumulative departure Index
CEC	Cation Exchange Capacity
CHK	Central Highlands of Kenya
CPC	Climate Prediction Centre
CT	Conventional Tillage
CtC	Conventional tillage Control
CtM	Conventional tillage + Sole Mineral fertilizer
CtRF	Conventional tillage + Crop residues + Mineral fertilizer
CtRFM	Conventional tillage + Crop residues + Mineral fertilizer + Animal manure
CtRML	Conventional tillage + Crop residues + Animal manure + Legume intercrop
CtRTM	Conventional tillage + Crop residues + *Tithonia diversifolia* + Animal manure
CtRTP	Conventional tillage + Crop residues +*Tithonia diversifolia* + Phosphate rock
CV	Coefficient of Variation
DEM	Digital elevation model
DMRT	Duncan Multiple Range Test
ENSO	El Niño–Southern Oscillation
ET	Evapotranspiration
GIS	Geographic Information Systems
GPCP	Global Precipitation Climatology Project
IPCC	Intergovernmental Panel on Climate Change
IR	Infiltration Rate
K	Potassium
KALRO	Kenya Agricultural Livestock and Research Organization
KMD	Kenya Meteorological Department
Ks	Saturated hydraulic Conductivity

LH	Lower Highland
LM	Lower Midland
LR	Long Rains
Mg	Magnesium
MS	Microsoft
MT	Minimum Tillage
MtC	Minimum tillage Control
MtF	Minimum tillage + Sole Mineral fertilizer
MtRF	Minimum tillage + Crop residues + Mineral fertilizer
MtRFM	Minimum tillage + Crop residues +Mineral fertilizer + Animal manure
MtRML	Minimum tillage + Crop residues+ Animal manure+ Legume intercrop
MtRTM	Minimum tillage + Crop residues + *Tithonia diversifolia* + Animal manure
MtRTP	Minimum tillage + Crop residues+*Tithonia* diversifolia+Phosphate rock
MWD	Mean Weight Diameter
N	Nitrogen
NASA	National Aeronautics and Space Administration
NE	North East
OM	Organic Matter
ORM	Organic Resource Management
ORs	Organic Resources
P	Phosphorous
POWER	Prediction Of Worldwide Energy Resource
PVC	Polyvinylchloride
PVI	Precipitation Variability Index
RAI	Rainfall Anomaly Index
RCBD	Randomised Complete Block Design
RD	Rainy Days
RF	Actual Rainfall
RMSE	Root Mean Square Error
SE	South East
SOM	Soil Organic Matter

SR	Short Rains
SSA	Sub-Saharan Africa
TMPA	Tropical Multisatellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission
UH	Upper Highland
WG	Working Group
WMO	Word Meteorological Organization
WP	Water Productivity
WUE	Water Use Efficiency

DEFINITION OF TERMS

Rainfall variability	Fluctuations in rainfall amount either temporally, spatially or both.
Water productivity	Crop output per unit volume of water used.
Water use efficiency	Percentage of water supplied to the plant that is effectively taken up by the plant.
Minimum Tillage	Land surface scratched by hand hoe
Conventional Tillage	Land hand hoed to upto 15 cm soil depth
Agricultural Drought	When the cumulative plant available soil water is significantly lower than cumulative crop water requirements and there is absolute water scarcity

ABSTRACT

Water insufficiency due to scarcity, poor distribution and high variability of rainfall in the Central Highlands of Kenya (CHK) and a decline in soil fertility have contributed to a continuous decrease in water productivity. To increase food production to match the growing population, soil management practices that ensure improved water productivity should be embraced. The study, therefore, sought to characterize rainfall and to establish the effects of selected soil management practices on water productivity in Tharaka-Nithi and Murang'a Counties. The field experiments were laid in Meru South sub-County, Tharaka-Nithi County and Gatanga sub-County, Murang'a County. Rainfall characterisation was done in seven Counties in the C; Meru, Embu, Nyeri, Kirinyaga and Kiambu plus the two Counties where the field experiments were laid. Statistical methods and programs used in rainfall characterisation included RAIN software, cumulative departure index (CDI), rainfall anomaly index (RAI), a coefficient of variation (CV), precipitation variability index (PVI), correlation coefficient, root mean square error and scatter plots. The field experiment was laid in a randomised complete block design with tillage and soil inputs as combined treatments. The treatments in each site were: control, sole mineral fertiliser, crop residues plus mineral fertiliser, crop residues plus mineral fertiliser plus animal manure, crop residues plus *Tithonia diversifolia* plus rock phosphate, crop residues plus animal manure plus legume intercrop, crop residues plus *Tithonia diversifolia* plus animal manure. The treatment combinations were laid under both conventional and minimum tillage (MT). Test crop was maize (*Zea Mays L.*), H516. Soil moisture, soil water productivity and soil physical properties (Bulk density, saturated hydraulic conductivity and aggregate stability) under different treatments were subjected to analysis of variance (ANOVA) in SAS 9.3 software. Differences between treatment means were separated using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. Rainfall analysis showed that rainfall in the CHK was highly variable temporally and spatial though fairly distributed. There was a high frequency of dry spell with high probability (93%) of future occurrence. Satellite and observed rain gauge data showed close agreement at seasonal scale than at daily scale. Satellite estimates can be used to substitute observed rain gauge data. The experimental results showed treatments had significant effect on soil moisture at 0-10 cm, 10-20 cm, 20-30 cm and at 30-40 cm depths ($p=0.0001$). Treatment under conventional tillage (CT) plus crop residue plus *Tithonia diversifolia* plus animal manure (CtRTM) had the highest soil moisture. Treatments had a significant effect on soil water productivity at 0-10 cm, 10-20 cm, 20-30 cm and at 30-40 cm depths in Chuka while in Kandara, the significant difference was only at 0-10 cm depth. Treatments under CT plus crop residue plus mineral fertiliser with or without animal manure (CtRFM/ CtRF) had the highest soil water productivity. Treatments had no significant effect on soil bulk density, saturated hydraulic conductivity and aggregate stability in the two sites. The result of the experiment will be used by various stakeholders in agriculture for planning and decision-making purposes regarding water productivity. It will also provide a baseline for further research and development.

Chapter 1

INTRODUCTION

1.1 Background of the study

Water productivity (WP), defined as the net return for a unit of water used (Molden *et al*. 2010) is function of several factors involved in crop production. Factors WP ranges from crop type grown, moisture availability, soil fertility, the agronomic and economic factors (Ali and Talukder, 2008). However, water supply deficiency and low soil fertility are significant limitations to agricultural production (Lal, 1991). Water circulation through the soil-plant-atmosphere system is considered to be among the most critical factors affecting water productivity in the rain-fed farming (Jury, 2002). It has been observed that there is an exponential improvement of water productivity when agricultural water management is improved in low-yielding farming systems (Comprehensive Assessment of Water Management in Agriculture, 2007). In developing countries, especially in arid and semi-arid areas, water is the dominant agricultural constraint (UNEP, 1992). In Kenya, water availability is one of the major limiting factors to agrarian production (Beintema and Stads, 2006). Sources of water used in agriculture and strategies employed for water conservation thus have a direct implication on agricultural production.

Around 80% of the world's agricultural land is rainfed contributing to at least two-thirds of global food production (Alam and Ekhwan, 2011). In Africa, most countries rely on rain-fed farming, for example, 90% of the population in Malawi and Botswana rely on rain-fed agriculture, 70-80% in Zimbabwe and 76% in Kenya with the similar trend throughout Eastern and Southern Africa (Rockström, 2000). Agriculture production system in Kenya is mostly rainfed as the rainfall is the primary water source. Rainfall amounts, distribution, and efficient capture and retention in the soil are thus essential for optimal crop production. However, owing to climatic variation, rainfall, as one of the climatic factors, has been unreliable due to its scarcity, poor distribution and high variability, thus posing problems to agricultural productivity (Özdogˇan, 2011). The poor distribution over time has been the leading cause of soil moisture stress in most smallholder farming systems in

Kenya (Smucker and Wisner, 2008). About 25% of the rain falls within a few rainstorms, making the crops suffer from water stress that might eventually lead to low yield or complete crop failure (Ngetich et al., 2014). Hence, to increas food production in Kenya, water use efficiency becomes vital (Rockström et al., 2002).

While precipitation variation and scarcity have a significant influence on soil moisture balance, soil management practices also impact on available soil moisture which dramatically affects crop yield (Jin et al., 2007). Poor soil management practices have been identified to be among the causes of low water productivity in the CHK (Sanchez and Jama, 2002). These practices include as intensive ploughing and the routine removal of crop residues, soil nutrient mining without adding amendments, non-use of organic resources and inappropriate fertiliser application (Cheruiyot et al., 2001). Apart from intensifying soil moisture stress, these practices contribute to nutrient deficiency, low soil organic matter (SOM), soil acidity, soil aluminium and iron toxicity, soil crusting and loss through erosion (Place et al., 2003). The result is reduced crop yield and consequently low water productivity. Management practices that involve utilisation of locally available and affordable soil moisture conservation practices, and can also avert these problems are the most desirable approaches for addressing soil water productivity in rain-fed agriculture. Such strategies should also ensure that the precipitation received is conserved in-situ within the root-zone and utilised in the most efficient way to get optimal output.

Various soil management practices can be used to enhance water productivity (Evett and Tolk, 2009). Improvement in water productivity can result from improving the provision and management of other factor inputs of crop production like soil moisture, soil fertility plus other agronomic and economic factors (Nangia et al., 2008). One of the approaches is the use of organic inputs which have the potential of conserving soil moisture, modify soil physical properties and improve water use efficiency (Jin et al., 2007). Soil organic matter instigates retention of soil moisture and slow its release over time in a way that enhances crop growth thus increasing yield and water use efficiency (WUE) (Ali and Talukder, 2008). Some of the organic resource management practices that have been identified to enhance WP include cover cropping (Quemada and Cabrera, 2002), mulching (Ji and Unger, 2001) use of animal manure, *Tithonia diversifolia*, *Calliandra calothyrsus* and *Leucaena leucocephala* (Mucheru-Muna et al., 2007).

Tillage systems can also influence water productivity. Tillage affects soil moisture conservation and modifies soil hydro-physical properties such as bulk density, aggregate stability, hydraulic conductivity and infiltration rate (Strudley et al., 2008). For example, Abdullah (2014) reported MT to have enhanced soil moisture. Other soil management practices such as legume intercrop and appropriate use of mineral fertilisers can also help improve the crop output per unit moisture utilised by the crop. Therefore proper tillage practice and proper use of organic and inorganic resources can boost water productivity.

Even though proper tillage practice plus appropriate use of organic and inorganic resources might guarantee success in rain fed agriculture (Hoff et al., 2010), these measures usually are as effective as proper planning and understanding of the climatic patterns that affect agriculture, especially rainfall (Wang et al., 2016). Therefore, prior knowledge of rainfall characteristic is essential. The primary rainfall characteristics are onset and cessation, with rainfall distribution and variation being the other seasonal variables (Stewart, 1991). Thus, the study characterised rainfall in the study area in enhancing soil WP using various soil management practices in the region.

1.2 Statement of the problem

The inadequacy of soil moisture and decline in soil fertility are the major contributors to low water productivity in the rain-fed smallholder farming systems in Kenya. This is due to rainfall related problems such as scarcity, poor distribution and high variability. The decline in soil fertility is due to poor soil management practices where farmers intensively plough their farms during land preparation, inappropriately use mineral fertilisers, routinely remove crop residues during harvest and rarely use organic resources as soil amendments. Lack of proper adaptive capacity to cushion crop from moisture stress condition and soil quality deterioration has intensified the problem. The result has been crop nutrient deficiency, low soil organic matter, soil acidity, soil erosion, soil moisture stress and eventually, reduced water productivity.

Previous studies have shown the use of organic and inorganic resource plus appropriate tillage practices have the potential to remedy soil water productivity. Past studies on the management practices have focused on either enhancing soil fertility or soil moisture conservation. Recommendations have thus been based only on improving one particular factor at a time. Since water productivity is affected by various factors ranging from soil fertility, soil moisture availability, agronomic plus economic factors, there is a need for a holistic approach for amelioration. Integrated soil management that involves the use of both organic and inorganic inputs, plus use of various practices like tillage and legume intercrop have shown the potential of enhancing soil water productivity. Knowledge of rainfall characteristics has also played a major role as the practices are as effective as the understanding of rainfall pattern. Furthermore, while the effect these soil management practices have been investigated in various studies, their success is affected by factors such as climate, soil type, inherent soil characteristics and management. This necessitates the investigation of their effect in the CHK.

1.3 Justification of the study

Use of selected organic and inorganic resources like residue retention and application of locally available organic inputs (crop residue, animal manure and *Tithonia diversifolia*), legume intercropping combined with appropriate tillage method in managing soil fertility and soil moisture retention have the potential to reverse the declining water productivity in the CHK. The organic inputs and proper tillage practices can modify soil physical properties which can enhance WUE. Also, the organic and inorganic inputs can improve soil fertility through nutrient release to the soil. Knowledge of the rainfall characteristics is also vital to the success of using these practices as it will enable farmers plan for the anticipated moisture stress periods that can affect crop growth and yield. The positive results from the implementation of selected soil management practices and proper timing of rainfall will enhance water productivity and consequently lead to improved food security in CHK and similar AEZ in Kenya and rest of the world.

1.4 Research questions

1. What are the rainfall characteristics in the central highlands of Kenya?
2. How do different soil management practices affect soil moisture and water productivity in Tharaka-Nithi and Murang'a Counties?
3. How do different soil management practices affect selected soil physical properties in Tharaka-Nithi and Murang'a Counties?

1.5 Objectives

1.5.1 General objective

To enhance soil water productivity using selected soil management practices in the central highlands of Kenya.

1.5.2 Specific objectives

1. To characterize rainfall in the central highlands of Kenya.
2. To assess the effects of different soil management practices on soil moisture and water productivity in Tharaka-Nithi and Murang'a Counties.
3. To assess the effects of different soil management practices on selected soil physical properties in Tharaka-Nithi and Murang'a Counties.

1.6 Significance of the study

The study contributes to the scientific body of knowledge on the practices that can enhance water productivity in the CHK and similar agro-ecological zones (AEZ). Stakeholders can use the findings in recommending suitable management practices for improving WP in various regions and can also form a basis for further research on the same. Identification of improved soil management practices is expected to contribute to continuous improvement in soil water productivity.

1.7 Conceptual framework

Rainfall scarcity, poor distribution and high variability and poor soil management practices are some of the causes of low water productivity in the CHK. Selected soil management practices such use of organic and inorganic resources and proper tillage can enhance water productivity in rainfed agriculture and improve soil physical properties.

The effectiveness of these practices can be increased by the understanding of the rainfall characteristics of the study region. Use of the selected soil management technologies with proper knowledge of the rainfall characteristics may result in improved water productivity and soil physical properties. Figure 1.1 show interlinks between the research problem, potential interventions and possible output.

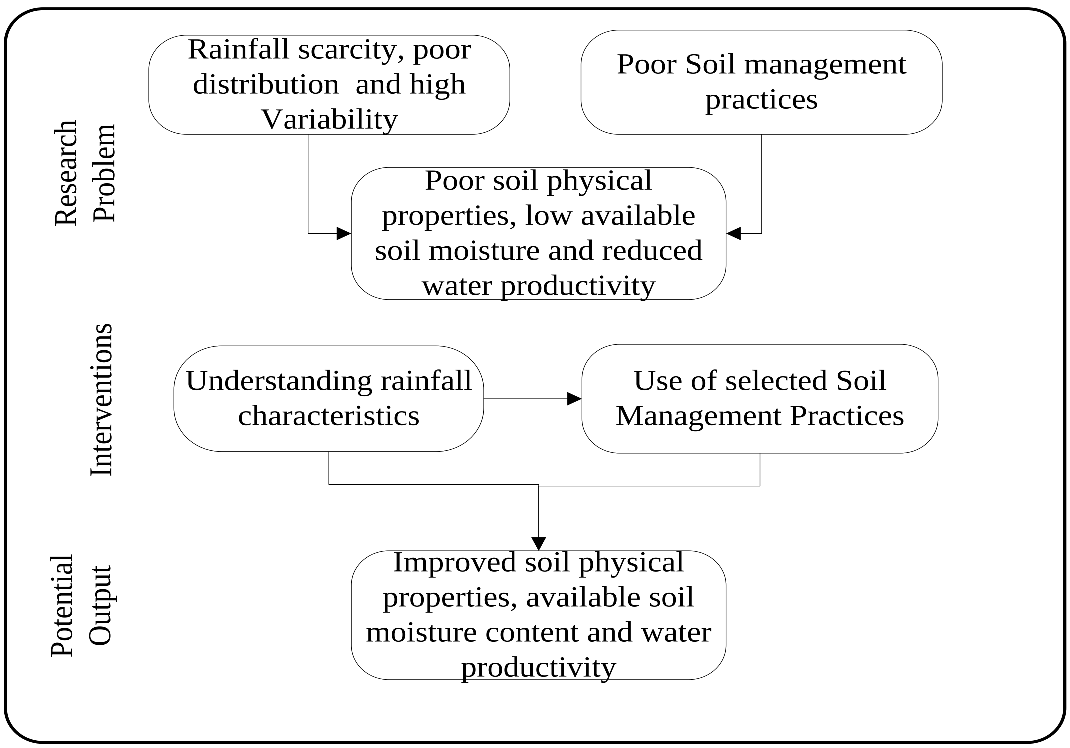


Figure 1.1: framework giving a summary of the study (Source: Author, 2018)

Chapter 2

LITERATURE REVIEW

2.1 Overview

Among the many factors affecting agricultural productivity, soil moisture deficiencies and declining soil fertility cannot be ignored since they dictate success or failure in agriculture (Lal, 1991). Soil moisture insufficiency is generally as a result of high variability, poor distribution and scarcity of rainfall which is the ultimate source of water in rainfed agriculture (Mukhala, 1998). The high rainfall variability and scarcity have resulted in soil moisture stress, causing crop failure in the rain-fed agricultural regions (Özdog˘an, 2011; Ngetich et al., 2014). Soil moisture insufficiency is further intensified by poor soil management practices and lack of an adaptive mechanism to cope with water scarcity (Cheruiyot et al., 2001). Also, poor soil management practices can affected soil quality and lead to soil nutrient deficiency among other soil-related problems. Hence, there is a need to ensure that the available soil moisture is used efficiently and soil quality is improved at the same time.

Selected tillage practices and use of organic inputs can help ensure proper use of the available moisture and improved soil quality (Strudley et al., 2008). Minimum tillage has a positive influence on various soil physicochemical properties such as soil organic matter, water holding capacity and infiltration rate (Bescansa et al., 2006). These contribute to improved soil water productivity. Some of the soil management practices that affect WP include legume intercrop, use of crop residue, *Tithonia diversifolia*, animal manure, mineral fertiliser all under MT and CT.

This section thus reviews some of these technologies in light of what has been done and their capacity in improving soil moisture, water productivity and soil physical properties. In addition, the effect of various rainfall characteristics on water productivity is reviewed.

2.2 Rainfall characteristics and effect of soil management practices on water productivity

2.2.1 Effect of soil management practices on rain water productivity

Rainfall in the CHK is highly variable, both spatially and temporally (Ngetich et al., 2014). This makes rain-fed agriculture a risky venture. Little can be done to regulate the rainfall pattern and amount received since rain is a natural occurrence. However, the use of the received rainfall water can be controlled. Inefficient use of the seasonally available rain water has been identified to be among the limitation in stabilising and improving crop yields in rainfed agricultural systems (McHugh et al., 2007). Much of the rain water received end up being wasted as runoff due to poor soil hydrological properties that do not encourage soil moisture conservation.

The success of rain water conservation depends on many soil factors such as porosity, bulk density, surface sealing and crusting, surface roughness, hardpans, hydraulic conductivity and infiltration rates as they determine the soil hydrological properties (Strudley et al., 2008). Variations in soil physical characteristic are mostly as a result of soil management. Elder and Lal (2008) pointed out that changes in soil properties differ among the management practices. For example, poor soil management can lead to soil compaction and destruction of soil aggregation (Strudley et al., 2008). These contribute to increased surface runoff, soil erosion and therefore reduced water use efficiency as most of the water is lost. Thus, soil management is fundamental to ensuring efficient utilisation of rain water.

Use of organic materials like crop residue, *Tithonia diversifolia*, and animal manure can enhance soil properties like aeration and soil aggregation (Sanginga and Woomer, 2009). The improved properties enhance rain water infiltration, improve soil moisture retention capacity and reduce water loss through evaporation. The increased water retention capacity ensures efficient use of the water by the plant since water can stay in the root zone of the plant longer before percolating into deeper layers, which consequently ensures increased yield (Ali and Talukder, 2008).

Tillage has been advocated for to be having the capacity to improve the physical and hydro-physical properties of the soils and consequently increase rain water harvesting and crop yields (Gachene and Kimaru, 2003; Strudley et al., 2008; Rockstromet et al., 2009). Conservation tillage, especially MT leads to positive changes in the physical, chemical and biological properties of soil (Bescanca et al., 2006). Some of the soil physical properties influenced by MT include bulk density, infiltration and water retention capacity (Osunbitan et al., 2004). They are also some of the soil properties that govern soil moisture balance. The MT practices concurrently conserve soil and water resources, reduce farm energy and increase yield, soil qualities that are most important in ensuring recapture and retention of rain water into the soil to improve use efficiency. Strudley et al., (2008) mentioned that appropriate tillage practice plus use of organic inputs could ensure proper use of the available moisture and improved soil quality. The selected management approaches, therefore, have the potential of improving rain water use efficiency. The variation on the impact may arise due to differences in rainfall amount and pattern.

2.2.2 Rainfall characteristics and water productivity

Of the many requirements for crop production, climate-related inputs have continously threatened smallholder farming in tropical developing countries due to the constant variations. Lobell and Field (2007) reported precipitation and temperature to account for 30% or more of the year-to-year variation in global average production of the top six crops grown widely. Rainfall, in particular has affected crop production in rain-fed agriculture due to its scarcity, high variability and poor distribution that result to recurrent floods, droughts and dry spells (Mukhala, 1998; Rockström, 2000). These have been some of the major catastrophes in agricultural production, considering rainfall is the primary source of water used in crop production.

About 60% of the world and 90% for sub-Saharan African staple food production are under direct rainfed agriculture (Savenije, 2001; Rockström, 2003b). Like other parts of sub-Saharan African, agricultural production in Kenya is highly dependent on rainfall as irrigation water is scarce or farmers cannot afford the costly technology (Miriti et al., 2013). In the CHK rainfall totals are fairly adequate to support crop growth. For example, Tharaka Nithi and Muranga Counties which receive annual rainfall totals of between 600 to 1400 mm and 900 to 1200 mm respectively have enough to support a wide variety of crops commonly grown in the regions such as maize and beans to maturity (Jaetzold et al., 2007a and b). However, the pattern of distribution and high variation has caused remarkable damage to crops than the absolute totals (Rockström, 2000; Ngetich et al., 2014). This has resulted to undefined onset and cessation date, length of growing season and the occurrence of dry spells within seasons especially at sensitive stages of crop development such as during flowering (Rockstrom and de Rouw, 1997). In the end, low crop yields or total failures have been experienced.

Lack of knowledge on rainfall characteristics has significant repercussions on water productivity. For instance delayed planting date of corn was reported to result in significant loss for every day delayed after the planting date while early planting is associated with problems such as gaping and replanting costs due to germination failures (Nielsen, 2009). Planting close to the optimal planting date has been reported to significantly increase yield (Nyagumbo et al., 2017). Intraseasonal variability of rainfall has made planning for crop production unrealistic and risky. This has caused the risk-averse farmers to abandon agriculture for other less risky ventures (Ngetich et al. 2014). Reduced food production and consequently food insecurity has been the result. Hence, need for the information on the rainfall characteristics.

In trying to cope with the rainfall characteristics related problem, farmers have adopted ways such as digging ridges to trap water, plant and replant due to 'false' start of the season with the view of reducing production risk among others (Wisner (1977). However, these methods increase the production costs of crops, thus not economical for low-value crops like maize. Previous studies also suggest the establishment of climatic institutions to provide services like early warning systems (Sivakumar, 1987; Washington et al., 2006; Vogel et al., 2007). These recommendations aim to reduce the risk of climatic extremes (Stone, 2011). Nevertheless, such studies do not provide the desired information on seasonal variability, the relationship between rainfall and soil moisture retention as influenced by soil surface treatment and soil fertility inputs, and the implication on the distribution of water which finally affect water productivity.

Other studies have analysed rainfall onset dates and rainfall distribution patterns temporally and spatially (Ati et al., 2002; Marteau et al., 2011; Recha et al., 2011; Ngetich et al., 2014; Kisaka et al., 2015). Although these studies can help farmers plan and synchronise their agronomic activities in tandem with rainfall and hence try to reduce the hydrological risks, these analyses are based on observed rain gauge data. Observed rain gauge data usually represent the point rainfall data that cannot be relied on for larger geographical area even upon extrapolation. Also, rainfall characteristics in most regions in Kenya are site-specific (Ngetich et al., 2014 and Kisaka et al., 2015). Thus, for an effective recommendation on water productivity, the rainfall characteristics of the specific study region needs to be determined using more reliable and alternative rainfall data sources.

Unreliability and insufficient observational rainfall data have however limited characterisation of rainfall pattern in the CHK due to low rain gauge density (Franz et al., 2010). In a region where rainfall is highly variable like in the CHK, extrapolating from a sparse and unevenly distributed rain gauge network can lead to inaccuracies (Li and Heap, 2008; Scheel et al., 2011). In central Africa, most substantial disagreement in the data set was reported to have resulted from the low rain gauge density (Herrmann and Mohr, 2011; Maidment et al., 2015). The inadequacy of observed rainfall data has also been a significant barrier to the characterisation of rainfall in sub-Saharan Africa. Most regions are marginalised to install well-maintained rain-gauges. Thus, there is shortage of observable rain gauge data. Characterizations of various rainfall parameters like the spatial variability that is a vital component in agriculture and weather evaluation have been hampered. Despite gauges being considered to be among the most accurate form of local rainfall measurement (Villarini et al., 2009) rain gauge can only capture the variability of small areas and therefore, in many cases, precipitation estimates from rain gauges are subject to improbability when representing a more extensive observation site. Rain gauge use is also confined to the lands and islands as opposed to large water bodies (Levizzani et al., 2007).

Other shortcomings of rain gauges include errors and omissions or power outages from the recording devices, human operators, and data transmission that could also cause valuable data to be lost, damaged, or altered resulting in poor data quality (Kneis et al., 2014). These errors must be the contributors to discrepancies observed between different observed rainfall datasets (Barros, 2014). Use of satellite-based rainfall data can be an alternative data source to bridge the gap (Ward and Trimble, 2003). However, the quality of data from satellite estimations needs evaluation before it can be relied on.

2.3 Effect of soil management practices on soil moisture, water productivity and soil physical properties

2.3.1 Crop residue

Crop residue has had competitive uses, primarily as livestock feed among the smallholder mixed farmers who prefer using it for feed, fuel and construction material as opposed to soil fertility amendment (Fowler and Rockstrom, 2001; Mulumba and Lal, 2008). Crop residue incorporation has favourable effects on soil properties as it improves its quality and productivity, mainly when used as mulch (Lal and Stewart, 1995). Mulching gives water more time to infiltrate into the soil by covering the ground that helps to reduce surface runoff and holds rain water on the soil surface (Mupangwa et al., 2007). This increase water storage in the root zone thus improves utilisation by the plant (Ji and Unger, 2001). Covering the soil also help reduce water loss through evaporation as it moderate soil temperatures (Hatfield et al. 2001; Biamah, 2005; Ramakrishna, 2006; Mulumba and Lal, 2008; Pang et al., 2010). Mulching has been reported to improved water use efficiency by 10-20% (Deng et al., 2006).

By conserving soil moisture in ensuring reduced moisture loss, mulching increased storage of water in the root zone (Ji and Unger, 2001). Crop residue mulch adds nutrients to the soil and modifies the soil biophysical properties upon decomposition (Dudal and Deckers, 1993).

Mulching also has a positive effect on the soil physical properties (Swift and Woomer, 1992). Organic mulching materials upon decomposition improve soil aggregation (Lynch and Bragg, 1985). Organic mulch maintains soil aggregation by shielding the soil surface from direct impact of the rain drops as it decapitates its energy. Mulching also enhances soil moisture infiltration rate (Mupangwa et al., 2007). On soil bulk density, there have been mixed reports on its effect. Some researchers have reported reduced soil bulk density (Oliveira and Merwin, 2001), others have observed increased bulk density (Bottenberg et al., 1999) and yet others found no mulch effect on bulk density (Acosta et al., 1999; Duiker and Lal, 1999). Mulumba and Lal (2008); Kahlon et al. (2013) argued that the differences in the observations may to be due to soil type, antecedent soil properties, type of mulch, climate or land use.

Contradictions have been reported on the effectiveness of crop residue use on soil moisture. Scopelet et al. (1998) reported the effect on yields varied with the type of crop residue and quantity. Mulumba and Lal (2008) attributed the impact on SOM content to be more related to the amount than the kind of residue applied. Erenstein (2003) on the other hand reported placement and the decomposition rate to be more critical. The effectiveness of crop residue as organic input may also vary with soil type, inherent soil properties, climate and management (Mulumba and Lal, 2008). In light of the many equally critical competitive uses, it is crucial that the effect of the use of crop residue in enhancing water productivity is determined if a preferential recommendation is to be made for use by smallholder farmers.

2.3.2 Legume intercrop

Legume-cereal intercropping is a common practice all over East and Southern Africa (Giller, 2001). Throughout the past decade, among the alternative organic practices that have been studied is cereal-legume intercrop (Mugendi et al., 1999). In the central highland of Kenya, nitrogen-fixing legumes (cover crops and trees) are the primary biological resources being promoted (Mugwe et al., 2009). The most common being the maize-bean intercrop. This is because of the poor performance of the herbaceous legumes as they produced little biomass and sometimes reduced maize yields in CHK (Mugwe, 2007; Mugwe et al., 2009).

The practise is mainly is used by farmers to reduce the impact of crop failure and to boost agricultural productivity among other benefits. For example, dual-purpose legumes which may be grown in intercrops or rotations with cereals enhances soil productivity and also produce a second primary product such as a grain for human consumption (Place et al., 2003). Sanginga and Woomer (2009) also reported legume maize intercrop to increase water productivity. Apart from fertility related benefits, intercropping also covers the ground reducing runoff thereby increasing infiltration rate (Olasantan, 1988). This boost soil moisture recharge and consequent increase in water productivity.

2.3.3 *Tithonia diversifolia*

Tithonia diversifolia commonly known as '*Tithonia*' is among the organic resources frequently used for biomass transfer in the CHK (Mugwe et al., 2009). The preference of use is due to its ready availability and affordability among farmers in the region. It naturally grows along the roads and hedges in the homesteads unlike other organic materials like *Calliandra* and *Mucuna* that require care and nurturing (Mugwe et al., 2009). Additionally, it's not as highly palatable to most livestock like other organic materials such as the *Calliandra*. Thus, indecision to prioritise the use as the soil amendment is reduced. Due to the many advantages, it has been among the alternative organic resources being studied in the past decades (Jama et al., 2000).

Studies have reported *Tithonia diversifolia* to be an essential resource in enhancing soil productivity. Vanlauwe et al. (2002) and Bationo et al. (2004) reported on its ability to supplement or even substitute mineral fertiliser in reversing the nutrient depletion in Africa. Ganunga et al. (1998) also reported an increase in maize yield following the use of *Tithonia diversifolia* as biomass. In Kenya, positive responses on crop yield have been reported. For example, in Western Kenya, a yield increase of up to 200% was reported following application of *Tithonia* biomass (Gachengo et al., 1999). In central Kenya, increases in maize with use of *Tithonia* biomass have also been reported by various authors (Mugendi et al.1999; Kimetu et al., 2004). Mucheru-Muna et al. (2007) reported *Tithonia* treatments, sole or in combination with half recommended rate of mineral fertiliser, to have given the highest yields than sole mineral fertiliser in the CHK. Like most organic inputs, the large responses in increasing maize yields upon *Tithonia* application into the soil is attributed to the fact that they contain high amounts of nutrients that are released upon decomposing (Mugwe et al., 2009). Some of the nutrients include Nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) among others.

Apart from *Tithonia* having an impact on soil fertility, it also has a positive influence on other WP parameters like soil quality and soil moisture. For example, long-term study in the CHK, Mucheru-Muna et al. (2007) observed that *Tithonia diversifolia* improved soil physical and biological properties in addition to increasing crop yield. When used as mulch, it enhances soil moisture availability in the soil (Mugwe et al., 2009). These ultimately contribute to improved soil water productivity. Still, its effects on WP need to be established to enable an informed decision on their use.

2.3.4 Animal manure

Animal manure is the solid and liquid excrement from animals, primarily cattle and poultry. In agriculture, animal manure has many important uses ranging from adding nutrients to improving soil physico-chemical properties (Wang et al., 2017). Animal manure has been used as a source of plant nutrients and organic matter to enhance fertility conditions of agricultural lands for a long time (Dao and Cavigelli 2003). It has the capacity to improve soil structural quality, by reducing soil compaction and bulk density while increasing porosity, saturated hydraulic conductivity and water infiltration rates among other benefits (Hati et al., 2007; Fares et al., 2008; Ould Ahmed et al., 2010). Soil physical structure improvement due to animal manure application may be as a result of organic matter content increase, which binds soil particles and increasing soil aggregation (Mosaddeghi et al., 2000). The ability of animal manure to enhance soil fertility and physical properties, improve soil moisture and enhance WUE contributes to improved water productivity.

Although in developed countries manure is seen as a problematic waste, in intensive agricultural systems it is a crucial resource to sustain the productivity of the majority of smallholder farming systems in Africa (Giller et al., 2002). Even though animal manure is limited in Africa both in quality and quantity, it is one of the mostly used organic input (Mafongoya et al., 2006). In the CHK manure is the most widely used organic fertiliser by approximately 80% of households (Mugwe et al., 2009). It is seen as an important resource for soil quality maintenance in the region and other similar areas (Mugwe et al., 2009). However, other uses of animal manure such as fuel and building material have posed stiff competition to agricultural use (Mulumba and Lal, 2008). Again, in CHK animal manure is insufficient in quantity and poor in quality due to poor management (Kihanda, 2003). Thus a clear justification regarding its productivity value is required to advocate for the preferential use in soil management as opposed to other uses and also to justify the need for further research in improving its quality and use efficiency.

2.3.5 Tillage Systems

Tillage is one of the most influential management practices affecting soil physical and hydraulic characteristics (Katsvairo et al., 2002; Lal and Shukla, 2004). Different tillage practices have their advantages and disadvantages. For example, while CT ensures weeds are well controlled, ideal seedbed condition for plants created and the sowing and planting operation can be done excellently (Licht and Al-Kaisi, 2005), it changes soil moisture storage, increase evaporation losses and soil susceptibility to runoff generation and soil loss (Jin et al., 2008). Conventional tillage involves continuous ploughing and disturbance of the soil. It has been reported to lead to the breakdown of soil aggregates, thus exposing SOM to increased microbial activity and mineralisation (Balesdent et al., 2000; Teklay, 2005), thereby leading to losses of SOM and N (Balesdent et al., 2000). Additionally, it leads to structural degradation of soils which may affect infiltration rate (IR) and soil hydraulic conductivity (K) (Six et al., 2000).

Minimum tillage, on the other hand, involves tillage with little or no soil disturbance. The reduced tillage practices have gained interest, especially in the rain-fed crop production where water stress is a severe limitation. Minimum tillage has a positive influence on soil chemical and physical properties such as soil organic matter and soil moisture relations like the water holding capacity (Bescansa et al., 2006). It has proven to increase soil moisture recharge, saves energy, friendly to the environment and enhances soil quality (Acharya et al., 2005; Mrabet et al., 2012; Johansen et al., 2012; Dube et al., 2012). According to Abdullah (2014), MT with residue in the dry season showed a higher overall soil moisture storage capacity compared with the wet season. A study conducted in the semi-arid and sub-humid locations in East and Southern Africa indicated that MT resulted in increased water productivity (Rockstrom et al., 2009). Thus further investigation of MT on soil water productivity is justifiable.

On infiltration rate that directly relates to soil hydraulic conductivity, various studies have reported different results. Vervoort et al. (2001), Bescansa et al. (2006) and Govaerts et al. (2009) reported higher infiltration rate for MT compared to CT. Lindstrom et al. (1984) observed a decrease in infiltration rate while Gomez et al. (1999) reported that there was no significant difference in infiltration rates between conventional and MT. Ji and Unger (2001) postulated that decreased soil disturbance in no-tillage systems leads to the development of bio-pores and improved aggregate stability that give rise to the development of less tortuous and more continuous pores and hence higher infiltration rate. More studies need to be conducted in different regions to ascertain the effect of MT on the rate of infiltration.

Similarly, on soil bulk density (BD), there have been ambivalent reports of tillage effect. Some studies observed higher BD values under MT than CT (Halvorson et al., 2014) while others have reported no effect of tillage on BD (Al-Kaisi et al., 2005). Fowler and Rockstrom, (2001) observed that MT offers an opportunity to reverse land degradation that prevails in many parts of SSA This is due to its positive effects on enhancement of soil physical, biological and chemical properties when compared to CT practices (Wander and Yang, 2000). Like CT, MT also has disadvantages. For example, MT prevents or reduces plant root development in some areas where the soils are hard (Atwell, 1993). This is due to relative compaction of the soil as a result of limited soil disturbance.

As much as the practice of MT has been advocated for based on various positive results from various researchers in Kenya (Ngetich et al., 2008; Mugwe et al., 2009) and other countries in sub-Saharan Africa, MT has not been widely adopted and majority of the smallholder farmers still plough their lands continuously (Rockstrom et al., 2003). This could be because tillage system desirable in one location may not be equally ideal or may fail in another site (Khan et al., 1999). The differences arise due to soil type, climate, land use or even the inherent soil properties. It is therefore essential to select a tillage practice that sustains the soil physical properties required for successful growth of crops in a specific region (Jabro et al., 2009).

2.3.6 Mineral fertilizer

Mineral fertiliser remains the critical supplier of nutrients required by crops for proper growth and development despite its use being considered to have a detrimental effect on human health and the environment (Sanginga and Woomer, 2009). Challenges associated with the use in crop production include reducing soil pH, its high cost and inappropriate use among farmers (Mugwe et al., 2008). Organic inputs that are considered to have the capacity to substitute or supplement mineral fertiliser in reversing nutrient depletion besides other benefits like improving soil quality are being promoted instead (Vanlauwe et al., 2002; Bationo et al., 2004).

A mixture of mineral fertiliser and organic input has proved to be highly productive than when either is solely used (Mugwe et al., 2008). Many long-term studies showed that combinations of both organic and inorganic nutrient sources lead to enhanced nutrient availability and synchronisation of nutrient release and uptake by crops and has positive effects on soil properties (Wallace, 1996; Bekunda et al., 1997; Mugendi et al., 1999). Based on the research findings across numerous countries and distinct agro-ecological zones (AEZs) of the SSA, a mixture of mineral fertiliser and organic input emerged to have the highest and most sustainable gain in water productivity per unit nutrient (Vanlauwe et al., 2001). This is because of the synergistic effects and improved synchronisation of nutrient release and uptake by crop when a mixture of mineral and organic inputs is used (Palm et al. 1997). Bationo et al. (2003) argued that the organic plus inorganic practices can even improve the resilience of the soil's productive capacity. Improved water productivity as a result of using mineral fertiliser also leads to increased crop residue due to high biomass production.

In the CHK, farmers were reported to use organic-inorganic combinations on significantly larger plots than sole organic resources or inorganic fertiliser (Mugwe et al., 2009). Use of sole mineral fertiliser is becoming archaic, but mineral fertiliser use is still very essential in boosting water productivity. Fertilizer use comes at a cost (Mugwe et al., 2009); thus its contribution in enhancing water productivity needs to be evaluated.

2.4 Summary

Low available soil moisture and insufficient nutrient to crops have been among the major limiting factors to water productivity in the CHK. Low soil moisture is attributed to climatic variations, rainfall particularly. High rainfall variability, a poor distribution that is erratic and highly intensive results to agricultural drought, dry spells, floods and soil erosion. Insufficient soil nutrients are as a result of declining soil fertility. The decline in soil fertility is attributed to poor soil management practices. The problem is aggravated by lack of adaptive capacity to avert the low soil water productivity. To overcome the problem, practices that can ensure that the limited precipitation received is utilised efficiently and soil quality related issues are averted to provide improved water productivity is required.

Based on the previous studies, use of organic and inorganic resource plus appropriate tillage practices has the potential to remedy soil water productivity. Studies on these practices have focused on either enhancing soil fertility or soil moisture conservation, and thus their recommendations have only been based on improving one particular factor. Bearing in mind that water productivity is affected by various factors ranging from soil fertility, soil moisture availability, agronomic plus economic factors, there is a need for a holistic approach for amelioration. Integrated soil management practices that involves the use of both organic and inorganic inputs, plus use of various practices like tillage and legume intercrop have shown the potential of enhancing soil water productivity holistically. This is also supported by knowledge of rainfall characteristics as these practices are as effective as the understanding of rainfall pattern. Additionally, while the effect of these soil management practices have been investigated in various studies, their success is affected by factors such as climate, soil type, inherent soil characteristics and management. This necessitates the investigation of their effect in the CHK.

Chapter 3

MATERIALS AND METHODS

3.1 Overview

This section describes the area of study, the various methods and steps used in achieving the study objectives.

3.2 Study Area

The study was conducted in the CHK. Field experiments were laid in two sites, Chuka in Tharaka-Nithi County and Kandara in Murang'a County. In Chuka, the experiment was established in Kangutu primary school situated at latitude 0°20'19" S, longitude 37°41'06" E, 1468 m above sea level (a.s.l.). In Kandara, the trial was located at Kenya Agriculture and Livestock Research Organization (KALRO) experimental field in Kandara at latitude 0°58'17"S, longitude 37°05'07"E and altitude of 1517 m a.s.l. The soil type in Kangutu site is *Humic Nitisols* which are well drained, extremely deep, dusky red to dark reddish brown, friable clay with acidic topsoil, and moderate to highly fertile. In Kandara site, the soil type is *Ferralsols*, that is highly weathered, have low to very low fertility as a result of low mineral contents and low cation exchange capacity (CEC). Rainfall characterisation was however done in five more Counties apart from the ones the field experiments were laid. Additional Counties were Meru, Nyeri, Embu, Kirinyaga and Kiambu Counties.

Tharaka-Nithi and Meru Counties covers the northern to the eastern slopes of Mt. Kenya. The Counties lie at an average altitude of about 1,500 m above sea level (a.s.l) and have an annual average mean temperature of about 18°C. It receives an average yearly rainfall of about 1500 mm, with a bimodal rainfall pattern. Long rains fall from around March to June and SR from October to February (Jaetzold et al., 2007 a; Smucker and Wisner 2008). The rainfall received is influenced by Mount Kenya (Orographic rain) in combination with latitude, inter-tropical convergence zone, *ENSO* and sea surface temperatures among others (Odingo et al., 2002). The southern part of Meru County is a transition to Tharaka-Nithi County. The prevailing AEZs in the transitional zones are expansive, making quantification of rainfall in these zones vital in the assessment of vulnerability to climate (Recha et al., 2011).

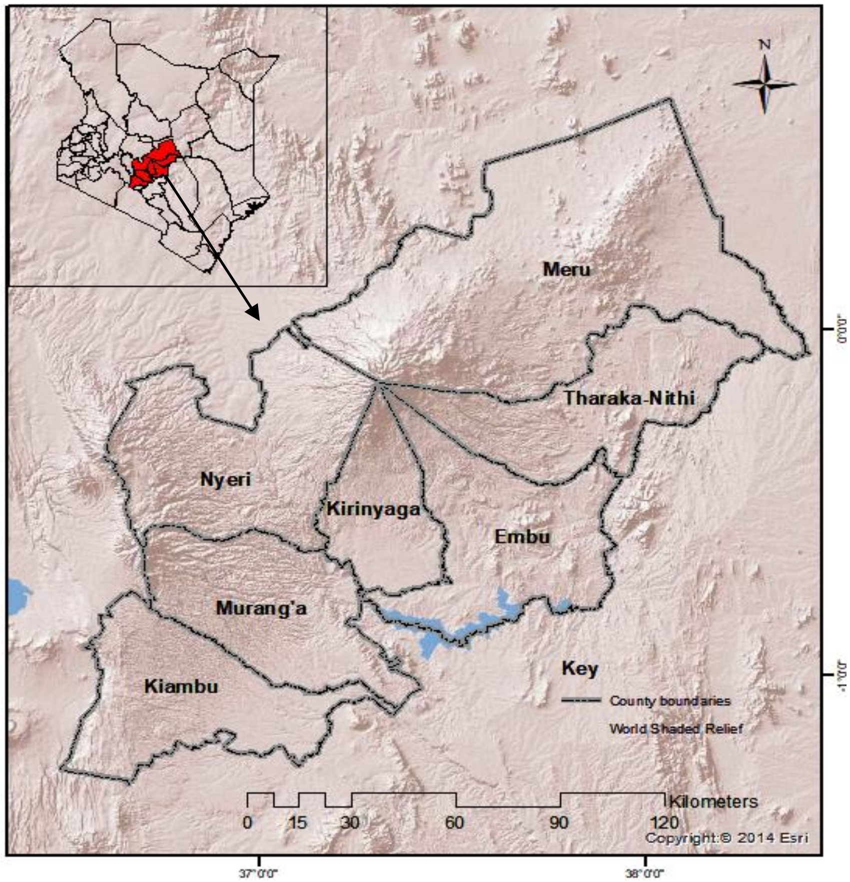


Figure 3.1: Map showing the locations of the Counties under study. Tharaka-Nithi, Nyeri, Murang'a, Embu, Kirinyaga, Meru and Kiambu (Author, 2018)

Embu County is located on the eastern slope of Mount Kenya. It lies at an altitude of about 1,700 m above sea level (a. s. l) and has an annual average mean temperature of 18°C and mean annual rainfall ranging from 450 to 1400 mm. The rainfall type is bimodal with LR falling from around March to June and SR from around October to February (Jaetzold et al., 2007 a). Rainfall is majorly influenced by Mount Kenya in combination with other factors.

Nyeri County is between the Aberdare ranges and Mt. Kenya. It is located on the eastern slope of the Aberdare ranges and the western slope of Mt. Kenya. Average annual rainfall ranges between 700 to 2200 mm. The rainfall pattern is bimodal. The County has high rainfall reliability in both seasons (Jaetzold et al.2007 b). The long dry season is from June to September and short dry season from January to February. Has an average altitude of about 1500 m a.s.l. In the wet areas, the south-easterly trade winds are forced up by the mountains, causing frequent mists and sometimes drizzle above 1500 m a.s.l. during the long dry season at lower altitudes. In the short dry season, the dry north eastern trades wind blow over the region from the Somalian deserts (Jaetzold et al.2007 b). Nevertheless, in the higher areas, there is still enough moisture in the soil to enable permanent cropping possible in the zones.

Kirinyaga County lies on the Southern slope of Mt. Kenya and south-eastern slopes of the Aberdare Range. Annual rainfall ranges from 1600 mm in low altitude areas (1600 m a.s.l.) to 2200 mm in higher altitude areas (2500 m a.s.l.). The rainfall is bimodal and is influenced by Mount Kenya and Aberdare range which affects the southeast trade winds (Jaetzold et al., 2007 b). The reliability of rainfall is high. Average annual temperature is about 20°C.

Murang’a County is located on the eastern slope of the Aberdare Range in the central part of Kenya with altitudes from 900 m to 3300 m a.s.l. It has a mean annual temperature of 26.3°C. Rainfall is bimodal with the long rain period from March to the end of May and short rain from October to December, thus, two cropping seasons. The sub-County receives total annual rainfall of 900 to 1400 mm which is highly variable both spatially and temporally and poorly distributed (Ovuka and Lindqvist, 2000). During the rain periods, most of the precipitation falls as showers late at night or early in the morning. Between June and September, the precipitation mostly falls as drizzle. January and February are the two dry months (Ovuka and Lindqvist, 2000).

Kiambu County is also on the eastern slope of Aberdare ranges. The region has an altitude of between 1300 to 2200 m a.s.l. It receives rainfall of between 900 mm to 1200 mm annually. The rainfall is bimodal with LR from around March to June and SR from around October to February. The rainfall is highly variable. Annual mean temperature is about 18°C.

3.3 Objective 1: Characterization of rainfall

3.3.1 Data Source

Two data sources were used. Daily satellite data was downloaded from Prediction Of Worldwide Energy Resource (POWER) website https://power.larc.nasa.gov/cgi-bin/agro.cgi?na) (Stackhouse, 2015) and observed rain gauge data was obtained from Kenya Meteorological Department (KMD) stations in Embu, Meru and Tharaka-Nithi Counties. The POWER 2017 gives rainfall estimates at any grid point intersection. The estimates at the grid intersect provides an average rainfall for the surrounding area offering more representative readings for the entire region given the spatial interpolation approach used in its derivation. Rain gauge, on the other hand, provides point rainfall readings that do not represent the whole surrounding. Point rainfall data was then used to correct the satellite data. Satellite data obtained covered the region between latitude -1 to 1 and longitude 36 to 38 that covers the whole study area (CHK) from 1997 to 2015 (19 years). In each County, grid point intersection near and within the County boundaries was used to represent the rainfall estimate for that entire County by computing the average. The points were picked at a 1-degree interval that resulted in rainfall data from nine points of grid intersection which were used in computing satellite averages. The points include (1° S, 36° E), (1° S, 37° E), (1° S, 38° E), (0°, 36° E), (0°, 37° E), (0°, 38° E), (1° N, 36° E), (1° N, 37° E) and (1° N, 38° E).

3.3.2 Estimation of missing values in the observed data

A number of methods have been applied in estimating the missing rainfall data depending on whether the data is spatial or temporal. In this case the arithmetic mean method was used (Lu et al., 2016). The missing data were filled using equation 1.

$$X_m = (\frac{\bar{X}}{\bar{Y}})Y_m \qquad \text{(Equation 1)}$$

Where X_m is the missing record at station X, $\bar{X}$ is the long term mean for the station with the missing data in certain year and month, $\bar{Y}$ is the long term mean of the station with complete data and Y_m is the corresponding records of the station Y having complete data.

3.3.3 Homogeneity test and data correction

Homogeneity test for the historical rainfall data from both observed rain gauge and satellite data was conducted. Non-homogeneity usually is due to changes in methods of observation, the recording instrument or biases among other reasons. Data is said to be homogeneous when their characteristic variations are caused only by variation in weather and climate (Conrad and Pollak, 1950). Thus, the test was to ensure that the data is homogeneous and independent as dictated by statistical analysis of rainfall data.

Various methods for testing the homogeneity of rainfall data have been established (Aguilar et al., 2003; Leander and Buishand, 2004). In this study RAINBOW software package (Raes et al., 2007) was used to conduct the homogeneity test. The software package is based on cumulative deviation from the mean. (S_k, k=1, 2, …n,), defined as by equation 2.

$$S_k = \sum_{i=1}^{k}(x_i - \bar{x}) \qquad \text{(Equation 2)}$$

Where S_k is the deviation from the mean, x_i is the annual rainfall records and $\bar{x}$ the mean. The cumulative deviation, S_k should be close to zero for the homogenous rainfall series. The initial value S_k=0 and the last value S_k= n are equal to zero.

The cumulative deviations were rescaled by dividing them with sample standard deviation (s). Then the homogeneity of the rainfall time series was tested by evaluating the maximum (Q) (equation 3) or the range (R) (Equation 4) of the rescaled cumulative deviations. A high value of Q or R was an indication that the data of the time series were not from the same population. The hypothesis of the homogeneity of the dataset was at the 99% probability level. None-homogenous data were transformed before using for further analysis.

$$Q = max\left\lfloor\frac{s_k}{s}\right\rfloor \qquad \text{(Equation 3)}$$

$$R = max\left\lfloor\frac{s_k}{s}\right\rfloor - min\left\lfloor\frac{s_k}{s}\right\rfloor \qquad \text{(Equation 4)}$$

Satellite based rainfall data underestimate total annual averages by a factor of 2. To correct the anomaly, all the satellite data was multiplied by 2 before being used in the rainfall analysis.

3.3.4 Determination of rainfall onset, cessation and the length of growing period

Several methods have been used to determine rainfall onset, cessation and the length of growing period ranging from traditional to semi-empirical to scientific techniques (Ati et al., 2002). For instance, Recha et al. (2011) and Odekunle (2006) used cumulative mean rainfall. Ati et al. (2002) argued that traditional method are unreliable and as they tend to be site specific. Cumulative rainfall methods, on the other hand, could be misleading as they are not based on rainfall–evapotranspiration relationships that consider crop water requirements aside from the inability to detect false start (Ati et al., 2002). RAIN software (Kipkorir, 2005) was therefore used in the determination of onset cessation and the length of growing period.

RAIN is computer model with the ability to determine the rainfall onset, cessation, length and evaluation of the growing season, seasonal crop water shortage and forecasting the relative yield, using soil moisture balance model, for a specified crop on particular soil type (Kipkorir, 2005). Appropriate initial search dates and the corresponding onset window was defined in the RAIN software to eliminate problems of ‘false start’ (Kipkorir, 2005). The onset criteria were regarded to apply the date after which there was a probability of at least 20% that the root zone has adequate soil moisture (Kipkorir et al., 2004).

The onset date was determined by soil moisture balance model based on accumulated rainfall for four days to be at least 25 mm (Raes et al., 2004). This was as per the farmers’ practices on an appropriate wet season showing that at least 25 mm is enough to support seed germination and initial development. Other methods have also been used to determine the onset date like soil moisture at root zone is at field capacity during a maximum of 3 successive days from start of rains (Raes et al., 2004). Lag time of 7 days was set after the onset date of the season. Rainy day threshold was set at 1 mm (Lazaro et al., 2001).

Soil moisture balance also determined the cessation date. It was the date on which the set threshold water stress coefficient was exceeded. The water stress coefficient below 40% was assumed to cause rapid water stress to crops, hence marked the end of a growing season (Mugalavai et al., 2008). The difference between the cessation date and the onset date was taken to be the length of the growing period.

3.3.5 Establishing temporal and spatial pattern of rainfall variation over the years

Long-term trends of annual and seasonal rainfall variation were analysed using CDI and RAI (Tilahun, 2006) in Microsoft Excel program. Cumulative departure index was derived from the normalised arithmetic mean of seasonal and annual rainfall during the period (Equation 5).

$$\mathrm{CDI} = \frac{(\mathrm{r}-\bar{\mathrm{r}})}{\mathrm{S}} \qquad \text{(Equation 5)}$$

Where CDI is cumulative departure index, r the actual rainfall (seasonal or annual) of a given year, $\bar{r}$ the mean rainfall of the total length of the period and S the standard deviation of the total length of the period.

Results of the values were cumulatively added for the entire period and plotted to attain the trends for annual and seasonal rainfall. The RAI was plotted to illustrate inter-seasonal rainfall variations and calculated using equation 6 for positive and equation 7 for negative anomalies.

$$\mathrm{RAI} = +3\left(\frac{\mathrm{RF}-\mathrm{M_{RF}}}{\mathrm{M_{H10}}-\mathrm{M_{RF}}}\right) \qquad \text{(Equation 6)}$$

$$\mathrm{RAI} = -3\left(\frac{\mathrm{RF}-\mathrm{M_{RF}}}{\mathrm{M_{L10}}-\mathrm{M_{RF}}}\right) \qquad \text{(Equation 7)}$$

Where RAI represents the seasonal rainfall anomaly index, RF is the actual rainfall for a given year, M_{RF} mean of the total length of a record, M_{H10} mean of the ten highest values of rainfall on record and M_{L10} the lowest values of rainfall on record.

Coefficient of variation, defined as the ratio of standard deviation to the mean was used to analyse both annual and seasonal rainfall variation and dry spell frequency. The analysis was based on annual and seasonal rainfall amount and rainy days for each County. Use of CV has been applied to analyse annual (Mzezewa et al., 2010) and seasonal (Barron et al., 2003; Seleshi and Zanke, 2004) rainfall and the dry spell variability (Kisaka et al., 2015).

Spatial presentation of rainfall onset, cessation and length of growing period was determined by first getting the seasonal onset cessation dates and the length of growing period for all the grid points within and near the study area over the years under consideration. The dates were used as the input in generating a spatial representation (maps) of seasonal rainfall throughout the study area in ArcGIS 10.5. Ordinary kriging method was used in the interpolation in a semi-variogram model to create the raster layers. The raster layers were then reclassified and extracted by masking to generate digital maps for the onset cessation and the length of growing period.

3.3.6 Establish rainfall distribution and intensity over the years

To establish temporal rainfall distribution pattern over the years, cumulative precipitation amount was calculated for both the long and short rains separately. The cumulative totals were then converted into percentages and graphs of the percentages cumulative precipitation plotted against time.

In the evaluation of rainfall intensity, PVI (Equation 8) that can evaluate both intensity and event spacing of the rainfall (Gu et al., 2016) was used. The PVI has been used by Lu et al. (2016) in the analysis of rainfall intensity in Namibia. The PVI is a dimensionless index defined as the standard deviation of the ratio (R_i) between a time series of cumulative precipitation measurement (C_i) and a time series of cumulative mean precipitation rate (E_i) (Gu et al., 2016).

$$PVI = \sqrt{\frac{\sum_{i=1}^{n}(R-\bar{R})^2}{n}} \qquad \text{(Equation 8)}$$

$$R_i = \frac{C_i}{E_i} \qquad \text{(Equation 9)}$$

$$C_i = \sum_{j=1}^{i} \text{pj}, \quad \text{i} = 1, \ldots, \text{n}. \qquad \text{(Equation 10)}$$

$$\bar{P} = \frac{\sum_{i=1}^{n} pi}{n} \quad \text{(Equation 11)}$$

$$E_i = i\bar{P}, \text{ i=1, …, n.} \quad \text{(Equation 12)}$$

From the daily precipitation measured pj, cumulative rainfall time series C_i (Equation 10) and mean precipitation rate $\bar{P}$ (Equation11) were computed. The time series of cumulative mean E_i (Equation 12) were then computed based on mean precipitation rate $\bar{P}$ (Equation 11), and R_i is the ratio of the cumulative precipitation to the cumulative mean (Equation 9). $\bar{R}$ is the average of R_i over n.

3.3.7 Dry spell analysis

Dry spell frequency was determined by counting. A dry spell has been defined differently depending on the crop and the climatic conditions under consideration. In this study, dry spell was defined as 'n' days without rainfall sandwiched between rainy days (Kumar and Rao, 2005). The 'n' values were taken to be greater than 5, on the basis that consecutive days of more than 5 are enough to cause a significant reduction in water productivity (Shin et al., 2015). A dry day (n) was considered to be any day that receives less than 1 mm of rainfall (Lazaro et al., 2001). This was according to the argument by Angel (2004) that rainfall less than this amount is evaporated back directly to the atmosphere.

To determine the variability of dry spells, the coefficient of variation of the dry spells were computed, and significance of variation evaluated using t test at 95% confidence level. The frequency of the dry spell of 5>10, 10>15 and more than 15 days were also computed. The probability of experiencing a dry spell was determined using the concept by Belachew (2000); that in the Y years of record, the frequency (i) that a dry-spell of duration (t) days occurs was counted on a seasonal basis. Then the number of times (I) that a dry-spell of duration longer than or equal to t occurs was computed cumulatively (Kisaka et al., 2015). The consecutive dry days (1d, 2d, 3d ...) were computed from historical data. The probabilities of consecutive dry days occurrence were estimated by considering the number of days within a given season *d.* The total possible number of days, *D,* for that season over the period of record was computed as *D* = $d * Y$. In this study,

t was taken as 6. The probability, that a dry-spell not longer than t does not occur at a certain day in a growing season was computed by equation 14; probability Q that a dry-spell longer than t days will occur in a growing season was calculated using equation 15, and probability p that a dry-spell exceeding t days would occur within a growing season was computed by equation 16 (Kisaka et al., 2015).

$$P = (\frac{1}{N}) \quad \text{(Equation 13)}$$

$$q = (1 - P) = (1 - \frac{1}{N}) \quad \text{(Equation 14)}$$

$$Q = \left(1 - \frac{1}{N}\right)^n \quad \text{(Equation 15)}$$

$$p = 1 - Q = 1 - \left(1 - \frac{1}{N}\right)^n \quad \text{(Equation 16)}$$

3.3.8 Comparison of satellite and observed data

Cumulative departure index (CDI) was used to compare the trend of rainfall variation. The CDI was computed for both the satellite and the observed rainfall and their graphs plotted against the time of the record. This provided a visual and instant comparison of the two datasets.

Onset-cessation dates and the length of growing period as per each dataset were also compared. The range with which the dates differed was noted and t-test at 95% level of confidence was used to test the significance of the variation. Lack of significance meant the two data sets were in agreement. The ranges with which the dates differ also form part of the evaluation of the two datasets.

Correlation analysis was involved in evaluating the degree of association between satellite estimates and observed rain gauge data using Pearson correlation coefficient in SAS 9.3 software package (SAS Institute, 2011). According to Wilks (1995), higher correlation values implied more association between the variables. Positive correlation indicated that when one quantity increases, the other one increases and vice-versa. Negative correlation inferred that when one quantity increases, the other decreases and vice-versa. A correlation evaluation was done to compare the observed versus satellite estimated at 95% level of confidence. The computation was as per equations 17 and 18.

$$r_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad \text{(Equation 17)}$$

$$t_{n-2} = r\sqrt{\frac{n-2}{1-r^2}} \qquad \text{(Equation 18)}$$

Where r_{xy} is the correlation coefficient, n is the sample size, x_i and y_i are the variables being correlated and $\bar{x}$ and $\bar{y}$ are the mean values of the variables of satellite and gauge based data, respectively and t_{n-2} is the the calculated t value.

Scatter plot was also used to establish the relationship between the two datasets. Satellite estimates and observed rain gauge data were plotted against each other for both daily and monthly rainfall averages. A line of best fit was drawn, and coefficient of determination observed as an indicator of the relationship.

Root Mean Square Error (RMSE), a frequently used measure of the difference between model predicted value and the actual observation was also used in comparing the two dataset. It measures how accurate a model simulates the actual reading value. A lower value of RMSE indicates better fit and vice versa. The computation was as per equation 19.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(s_i - g_i)^2} \qquad \text{(Equation 19)}$$

Where s_i and g_i are the satellite and observed rainfall values, respectively and n is the number of observations.

3.4 Objective 2: Effect of soil management practices on soil moisture and water productivity

3.4.1 Experimental Design

The experiment was laid out in a randomized complete block design (RCBD) replicated four times. Tillage and soil inputs were used as combined treatments (Table 3.1). The treatment combination resulted in fourteen treatments replicated four times. The plots were laid out as shown in figures 3.2 and 3.3 for Chuka and Kandara, respectively.

Table 3.1: Treatment combinations and fertilizer application rates

Treatments (Combination of tillage and soil inputs)	Rate of mineral fertilizer application	
	N (kg/ha)	P (kg/ha)
Minimum tillage Control		
Minimum tillage + Sole Mineral fertilizer	60	90
Minimum tillage + Crop residues + Mineral fertilizer	60	90
Minimum tillage + Crop residues +Mineral fertilizer + Animal manure	30	90
Minimum tillage + Crop residues+*Tithonia diversifolia* +Phosphate rock (Minjingu)		90
Minimum tillage + Crop residues+ Animal manure+ Legume intercrop (*Dolichos Lablab*)		
Minimum tillage + Crop residues + *Tithonia diversifolia* + Animal manure		
Conventional tillage Control		
Conventional tillage + Sole Mineral fertilizer	60	90
Conventional tillage + Crop residues + Mineral fertilizer	60	90
Conventional tillage + Crop residues + Mineral fertilizer + Animal manure	30	90
Conventional tillage + Crop residues +*Tithonia diversifolia* + Phosphate rock (Minjingu)		90
Conventional tillage + Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*)		
Conventional tillage + Crop residues + *Tithonia diversifolia* + Animal manure		

				Guard zone						
Block 4				Block 1						
	Plot 43- tRFM	Plot 44- MtRTM		Plot 7- CtF	Plot 6- MtRML	Plot 5- CtRML	Plot 4- CtRTP	Plot 3- MtRTM	Plot 2- CtRF	Plot 1- CtC
	Plot 46- CtRFM	Plot 45- MtC		Plot 8- MtC	Plot 9- MtRF	Plot 10- CtRFM	Plot 11- MtF	Plot 12- MtRFM	Plot 13- CtRTM	Plot 14- MtRTP
				Block 2						
Plot 55- CtRTP	Plot 47- MtRTP	Plot 48- MtRML		Plot 21- CtC	Plot 20- CtRML	Plot 19- MtF	Plot 18- MtRFM	Plot 17- CtRTP	Plot 16- CtF	Plot 15- CtRFM
Plot 56- CtC	Plot 50- CtRML	Plot 49- CtRF		Plot 22- MtRML	Plot 23- MtRTM	Plot 24- MtRF	Plot 25- CtRF	Plot 26- CtRTM	Plot 27- MtC	Plot 28- MtRTP
				Block 3						
	Plot 51- CtF	Plot 52- CtRTM		Plot 35- MtRTP	Plot 34- CtRML	Plot 33- CtRFM	Plot 32- MtRTM	Plot 31- MtRFM	Plot 30- MtRML	Plot 29- CtRTM
	Plot 54- MtF	Plot 53- MtRF		Plot 36- CtRF	Plot 37- CtRTP	Plot 38- CtC	Plot 39- CtF	Plot 40- MtC	Plot 41- MtRF	Plot 42- MtF
	Guard Zone			Guard Zone						

Figure 3.2: Experimental layout at Kangutu primary school in Chuka, Tharaka-Nithi County

MtC=Minimum tillage Control; MtF=Minimum tillage+ Sole Mineral fertilizer; MtRF=Minimum; tillage+ Crop residues + Mineral fertilizer; MtRFM=Minimum tillage+ Crop residues +Mineral fertilizer + Animal manure; MtRTP=Minimum tillage+ Crop residues +*Tithonia diversifolia* + Phosphate rock (Minjingu); MtRML=Minimum tillage +Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); MtRTM=Minimum tillage+ Crop residues + *Tithonia diversifolia* + Animal manure; CtC= Conventional tillage Control; CtF=Conventional tillage+ Sole Mineral fertilizer; CtRF=Conventional tillage+ Crop residues+ Mineral fertilizer; CtRFM=Conventional tillage + Crop residues + Mineral fertilizer + Animal manure; CtRTP=Conventional tillage+Crop residues+*Tithonia diversifolia* +Phosphate rock (Minjingu); CtRML =Conventional tillage+ Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); CtRTM=Conventional tillage+ Crop residues + *Tithonia diversifolia* + Animal manure

<table>
<tr><td colspan="14">Guard zone</td></tr>
<tr><td colspan="14">Block 4</td></tr>
<tr><td>Plot 56- CtRTM</td><td>Plot 55- MtRTM</td><td>Plot 54- CtRFM</td><td>Plot 53 MtF</td><td>Plot 52- MtRF</td><td>Plot 51- CtRTP</td><td>Plot 50- CtRF</td><td>Plot 49- MtC</td><td>Plot 48- CtRML</td><td>Plot 47- CtC</td><td>Plot 46- MtRFM</td><td>Plot45- CtF</td><td>Plot 44- MtRML</td><td>Plot 43- MtRTP</td></tr>
<tr><td colspan="14">Block 3</td></tr>
<tr><td>Plot 29- MtC</td><td>Plot 30- MtRML</td><td>Plot 31- MtRTP</td><td>Plot 32- CtF</td><td>Plot 33- MtRF</td><td>Plot 34- CtRML</td><td>Plot 35- MtF</td><td>Plot 36- CtRF</td><td>Plot 37- CtC</td><td>Plot 38- CtRFM</td><td>Plot 39- CtRTM</td><td>Plot 40- CtRTP</td><td>Plot 41- MtRFM</td><td>Plot 42- MtRTM</td></tr>
<tr><td colspan="14">Block 2</td></tr>
<tr><td>Plot 28- MtF</td><td>Plot 27- MtRML</td><td>Plot 26- CtF</td><td>Plot 25MtC</td><td>Plot 24- CtRML</td><td>Plot 23- CtRTM</td><td>Plot 22- MtRTM</td><td>Plot 21- MtRFM</td><td>Plot 20- MtRF</td><td>Plot 19- MtRTP</td><td>Plot 18- CtRTP</td><td>Plot 17- CtC</td><td>Plot 16- CtRF</td><td>Plot 15- CtRFM</td></tr>
<tr><td colspan="14">Block 1</td></tr>
<tr><td>Plot 1- MtRFM</td><td>Plot 2- CtRTP</td><td>Plot 3- CtRFM</td><td>Plot 4- CtF</td><td>Plot 5- MtRML</td><td>Plot 6- CtRML</td><td>Plot 7- MtRTP</td><td>Plot 8- MtRF</td><td>Plot 9- CtC</td><td>Plot 10- CtRF</td><td>Plot 11- MtRTM</td><td>Plot 12- MtF</td><td>Plot 13- CtRTM</td><td>Plot 14- MtC</td></tr>
<tr><td colspan="14">Path</td></tr>
</table>

Figure 3.3: Experimental layout at KALRO farm in Kandara, Murang'a County

3.4.2 Field preparation and input incorporation

Except for sole mineral fertiliser applied plots and both MT and CT control plots, crop residues was surface applied after the crop emergence. In the CT, the land was prepared by hand hoeing to 15 cm soil depth and weeding done at least three times using a hand hoe so at to maintain the plots weed free. Under MT, the land was surface scratched by hand hoe up to 5 cm depth and weeded at least three times per season by hand pulling. The treatment combinations tested and the rate of mineral fertiliser application was as shown in table 1. The plot sizes were six by 4.5 m in Chuka site and 4.5 m by 4.5 m in Kandara site. Test crop was maize (*Zea Mays L.*), H516. The field plots were equipped with soil moisture access tubes to monitor soil moisture.

3.4.3 Planting and crop management

The recommended maize variety H516 was used in both sites. The spacing was 0.75 m by 0.5 m inter and intra-row, respectively. Three seeds were planted per hill to ensure maximum plant population. Two weeks after germination thinning was done to two plants per hole. Legume intercrop (*Dolichos Lablab*) was planted just after maize germination in the plots that had legume intercrop as treatment. The mineral fertiliser was applied using NPK 23:23:0 to supply the required N amount as per the treatments. Phosphorus was supplemented using triple super phosphate (TSP) to a rate of 90 kg ha-1. Crop residue (Maize stover), *Tithonia diversifolia* and animal manure were incorporated into the soil to a depth of 15 cm during land preparation (two weeks to the onset of the season) throughout the experimental period in the CT system. Under MT system, the maize stover was surface applied while *Tithonia diversifolia* and animal manure incorporated into the soil to a depth of 10 cm in the planting holes. Application rates for the various combination of *Tithonia diversifolia* and animal manure were according to Mucheru-Muna et al. (2007) (Table 3.1). For maize stover, the application rate was 5 tons per hectare.

3.4.4 Parameters measured

The parameters measured included soil moisture, grain yield and above ground biomass, rainfall amount and air temperature.

3.4.5 Grain yield and above ground biomass

Grain yield and aboveground biomass were measured at the end of each cropping season at harvest from the net plot. To determine grain yield and above ground biomass per unit area, the following parameters were measured at harvest; actual number of stands per net plot at harvest; fresh weight of all cobs with grains in kilograms (kg) from the net plot; dry weight of all the cobs with grains in kg from the net plot; dry weight of the grains in kg after threshing all the dry cobs from the net plot and fresh weight of all stover from the net plot in kg. The grain yield and aboveground biomass were then converted to a per hectare basis at 12.5% moisture as final grain yield and above ground biomass.

3.4.6 Daily weather data

Daily temperature (minimum and maximum air temperature) values were recorded with an automatic weather station at each study site throughout the experimental period. Daily rainfall measurements were taken using tipping-bucket, data logging rain gauge, Hobo, model; RG3-M (Manufactured by Onset Computer Corporation Company) with a 0.2 mm resolution installed within the research sites. The data loggers were launched, read out, and data exported to excel worksheets for further processing using HOBO-ware Pro Version 3.2.2. Daily rainfall was calculated by multiplying the number of tips per day (09:00 h) by 0.2 mm tipping bucket resolution of the rain gauge.

3.4.7 Determination of soil moisture

For soil moisture, one access tube per plot was installed manually in the middle of each plot in March 2016 during the long rains. The soil was augured to install polyvinyl chloride (PVC) tubes to a depth of 80 cm below the soil surface with a protrusion of about 20 cm above the soil surface to prevent run off water from entering the tubes. The top of the tubes were covered by plastic cups to prevent water entry. The bottoms of the tubes were also covered by a watertight lid during the installation to prevent water entry into the tubes from below. Five extra calibration tubes both in Kandara and Chuka were also installed in the guard rows alongside the plots in representative position. Slurry method of re-filling was used to aid and hasten intimate contact between the tubes and the soil. The access tubes were left to acclimatize with the soil from March 2016 until the beginning of the short rains seasons in October 2017 when soil moisture monitoring begun. Soil moisture measurements was taken weekly starting from planting time until harvesting using portable Diviner 2000 (Evett et al., 2009) through the pre-installed access tubes. The reading was taken at 10 cm depth interval. Diviner 2000 recorded data from all levels in the soil profile up-to 80 cm depth, however only up-to 40 cm depth was considered for analysis. This was because the treatments were not expected to have caused significant changes in deeper soil layers within the short period. Data was downloaded at the end of the season and processed in MS excel.

3.4.8 Determination of soil water productivity

Water productivity was calculated in accordance with Ali and Talukder (2008) using equations 20 and 21. The ETo values were calculated with the FAO ETo calculator program (FAO, 2012).

$$\mathrm{WP} = \frac{\mathrm{B}}{\sum WU} \qquad \text{(Equation 20)}$$

$$\sum WU = \sum \mathrm{SM} - \sum \mathrm{ETo} \qquad \text{(Equation 21)}$$

Where WP is the soil water productivity, B is the total crop biomass, WU is water used, SM the soil moisture and ETo, the water loss through evapotranspiration.

3.4.9 Data Analysis

Soil moisture and soil water productivity were subjected to analysis of variance (ANOVA) in SAS 9.3 software (SAS Institute, 2011), to obtain an F value for each of the model effect at 95% significance level. Differences between treatments means were separated using DMRT (Buysse et al., 2004) at $p \leq 0.05$.

3.5 Objective 3: Determining the effect of the soil management practices on selected soil physical properties

3.5.1. Bulk Density

Undisturbed soil sampling for bulk density in the 0–5 cm layers was done using the core rings. One sample was taken at the middle of each plot at the end of the second cropping season. Stainless steel core sampler of dimension 5 cm diameter by 5 cm height was used to sample the soil carefully to avoid compaction. The collected soil cores were trimmed to the exact volume of the cylinder and oven dried at 105^{o} C for 24 hours. Bulk density was determined gravimetrically from the ratio of the mass of dry soil per unit volume of soil cores (Equation 22).

$$p_b = \frac{m_s}{v_t} \qquad \text{(Equation 22)}$$

Where p_b is the bulk density, m_s the mass of soil solids, and v_t is the total core volume.

3.5.2 Saturated hydraulic conductivity

Laboratory measurements of the Ks-value were conducted on undisturbed soil samples. The core rings were used for sampling at the middle of each plot vertically at the end of the second cropping season as per the method described by Wit (1967). The core rings of dimension 5 cm diameter by 5 cm height were used and the samples taken at 0-5 cm depth. At the laboratory, the constant-head method was used (Klute and Dirksen, 1982). The pressure was kept constant at the top of the sample with a one-dimensional flow created through the sample. The calculation was done using equation 23.

$$k_s = \frac{VL}{Aht} \qquad \text{(Equation 23)}$$

Where, k_s is the saturated hydraulic conductivity coefficient, V the collected volume of water, L is the length of soil column, A is the area of the soil column, h is the head difference and t, the time required to get V volume.

3.5.3 Aggregate stability

For aggregate stability, disturbed soil sample of about 0.5 kg was sampled at the centre of each plot within 0-5 cm depth. Sampling was done using a spade. The samples were air-dried and large clods broken by hand and sieved through 4 mm sieve. Rotary dry sieving method was used Lyles et al. (1970). The resistance of the aggregates to abrasion was determined by pouring the weighed aggregates back into the drying pan, sliding them off this pan back into the feed bin of the rotary sieve, sieving and weighing again, and determining the changes in aggregate size distribution. The soil material was transferred to a 75 µm aperture sieve that had previously been immersed in ethanol and was gently moved up and down in ethanol five times to separate fragments less than 75 µm diameter from the bigger ones. The greater than 75 µm diameter action was oven-dried and gently dry-sieved by hand on a column of seven sieves with 75, 150, 250, 500, 1000, 2000 and 3000 µm apertures. The weight of each size fraction was calculated as follows: the fraction less than 63 µm diameters were derived as the difference between initial weight and the sum of the weights of other six fractions. Aggregate stability of each fraction was expressed by calculating the mean weight diameter (MWD) of the seven classes, which is the sum of the weight fraction of soil remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent mesh. The aggregate stability was determined as per equation 24.

$$MWD = \sum_{i=1}^{8} \bar{x}_i w_i \qquad \text{(Equation 24)}$$

where, MWD is mean weight diameter (mm), w_i is total weight fraction of aggregates in the size class I with a diameter $\bar{x}_i$

3.5.4 Data analysis

Soil bulk density, saturated hydraulic conductivity and aggregate stability were subjected to ANOVA in SAS 9.3 software (SAS Institute, 2011) to obtain an F value for each of the model effect at p=0.05. Differences between treatment means were examined using DMRT (Buysse et al., 2004) at $p \leq 0.05$.

Chapter 4

RESULTS

4.1 Overview

The section presents the result as per the stated objective.

4.2 Weather conditions during the experimental period

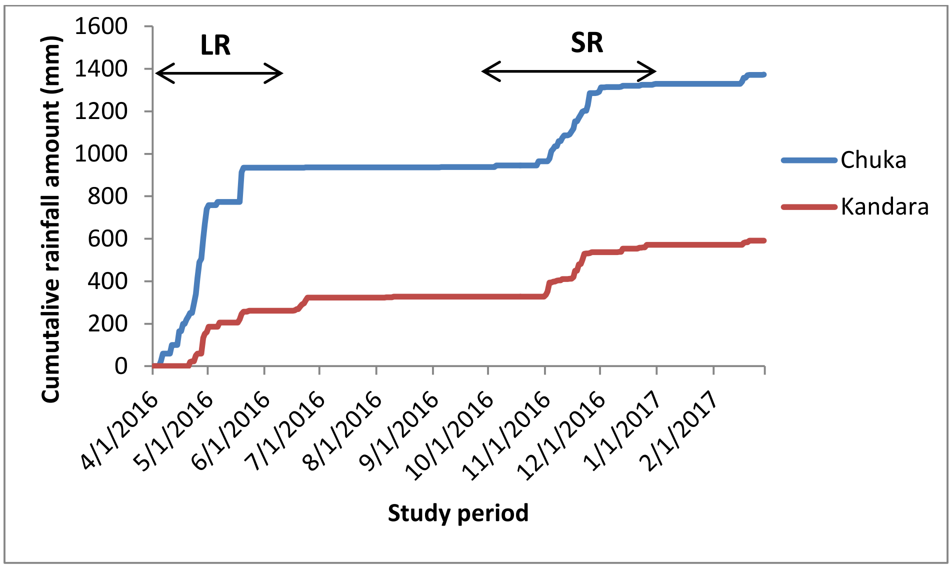


Figure 4.1: Cumulative rainfall during long and short rains 2016 in Chuka, Tharaka-Nithi County and Kandara, Murang'a County

Table 4.1: Weather condition on monthly basis during the study period in Chuka, Tharaka-Nithi County (Automatic weather station)

Date	Max Temp (°C)	Max RH (%)	RH 6am (%)	Min Temp (°C)	Min RH (%)	RH 3pm (%)	Average Tempe (°C)	Average RH (%)	Monthly Rainfall (mm)
3/2 016	30.4	47.9	87.2	16.2	38.7	41.3	22.7	18.4	0.0
4/2016	27.3	41.7	79.4	17.3	57.9	34.6	21.2	10.7	161.0
5/2 016	25.0	40.0	81.5	15.5	45.0	29.8	19.4	10.2	101.0
6/2016	24.5	45.3	85.9	14.1	53.2	40.4	19.6	16.1	60.5
7/2016	24.4	83.0	66.7	12.5	49.2	66.6	17.8	35.0	0.0
8/2016	25.6	95.5	88.7	12.6	62.4	62.1	18.1	80.5	5.6
9/2 016	26.9	94.8	96.9	13.4	53.4	61.8	19.2	76.3	0.0
10/2016	29.5	94.4	88.0	14.7	46.4	52.1	21.4	80.5	0.2
11/2016	26.0	91.2	79.0	16.0	51.7	52.0	19.7	76.3	208.5
12/2016	26.7	96.0	79.4	14.3	38.7	43.3	19.8	63.5	34.5
1/2017	28.8	46.0	81.5	12.3	37.9	67.5	20.5	70.1	0.0
2/2017	29.9	57.0	85.9	14.1	42.6	66.9	21.6	70.1	20.0

Table 4.2: Weather condition on monthly basis during the study period in Kandara, Murang'a County (Automatic weather station)

Date	Max Temp (°C)	Max RH (%)	RH 6am (%)	Min Temp (°C)	Min RH (%)	RH 3pm	Average Tempe (°C)	Average RH (%)	Monthly Rainfall (mm)
3/2 016	29.4	93.7	92.1	16.8	49.2	52.5	22.7	73.2	740.1
4/2016	27.0	97.4	96.9	17.6	62.4	66.9	21.4	83.6	194.1
5/2 016	27.6	98.7	88.0	15.5	53.4	66.6	20.1	80.5	1.7
6/2016	24.9	98.0	79.0	14.5	46.4	62.1	18.8	76.3	0.4
7/2016	24.3	95.5	87.2	13.7	51.7	61.8	18.2	63.5	0.3
8/2016	25.9	94.8	79.4	13.7	38.7	52.1	18.8	70.1	1.1
9/2 016	26.1	94.4	81.5	13.6	37.9	52.0	18.9	70.1	27.2
10/2016	29.0	91.2	85.9	14.8	37.3	43.3	21.4	64.9	326.7
11/2016	25.1	96.0	66.7	16.1	38.7	67.5	19.7	71.9	38.3
12/2016	24.5	91.4	88.7	15.1	57.9	62.6	19.5	77.5	0.0
1/2017	27.2	85.5	78.6	13.8	45.0	48.9	20.2	65.1	42.9
2/2017	27.3	91.1	86.6	14.9	48.6	52.6	20.9	70.7	71.0

4.3 Object 1: Rainfall Characterization

4.3.1 Data quality

There were no missing values in the satellite rainfall estimates. However, the missing values in the observed rain gauge data were estimated as described in section 3.2.2, using equation 1. Results of the homogeneity test from rainbow software for the two sets of data showed that the data sets were homogenous and were accepted at 99% probability since the deviation from the zero mark did not cross the 99% probability line. The data was then used for further analysis.

4.3.2 Seasonal rainfall onset, cessation and the length of growing period

Spatially, the onset dates for the LR ranged from 25th of February to 3rd of April across all the seven Counties. Onset dates for the SR ranged from 12th of September to 10th of October. The range for onset date was at least 38 days for LR and 28 days for the short rains indicating high variation both spatially and temporally. Long rains, however, had high variability in the onset dates than the SR portraying higher uncertainty. The onset was early from the western towards eastern part and from the south towards the northern parts of the study area during the long rains. For SR, the onset dates were earlier from the western towards the eastern and from north to the southern part of the study area (Figure 4.2).

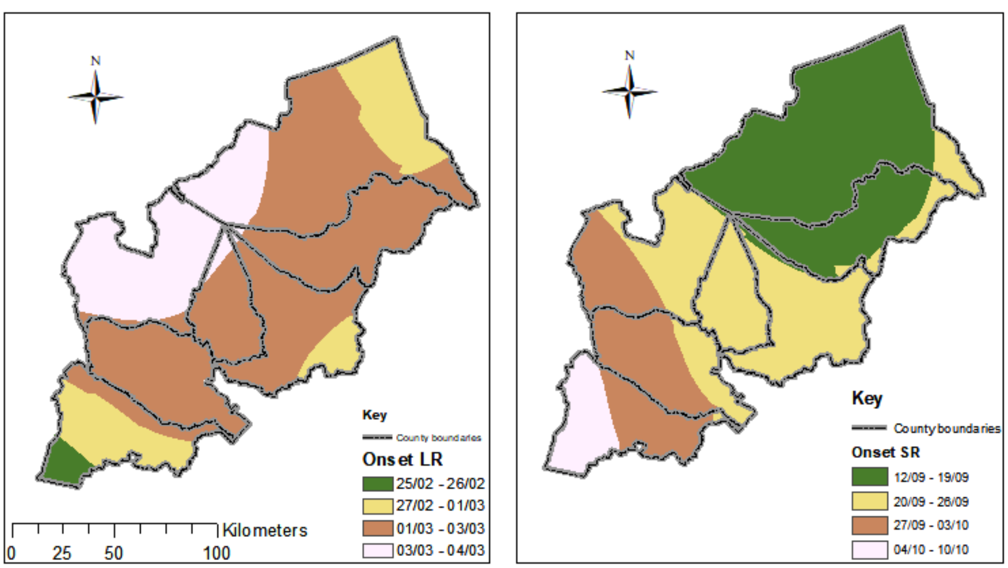


Figure 4.2: Map showing onset dates for LR and SR

Cessation dates varied from 21st May to 2nd June for LR and from 3rd to 26th of January for SR across the Counties. The cessation dates were spread for 12 days for LR and a period of 23 days for short rains. Unlike the onset dates, cessation dates were more heterogeneous during the SR than the LR. Cessation was earliest from the eastern to the western part of the study area during the LR. During the SR, cessation was earliest from the south towards the northern part of the study area (Figure 4.3).

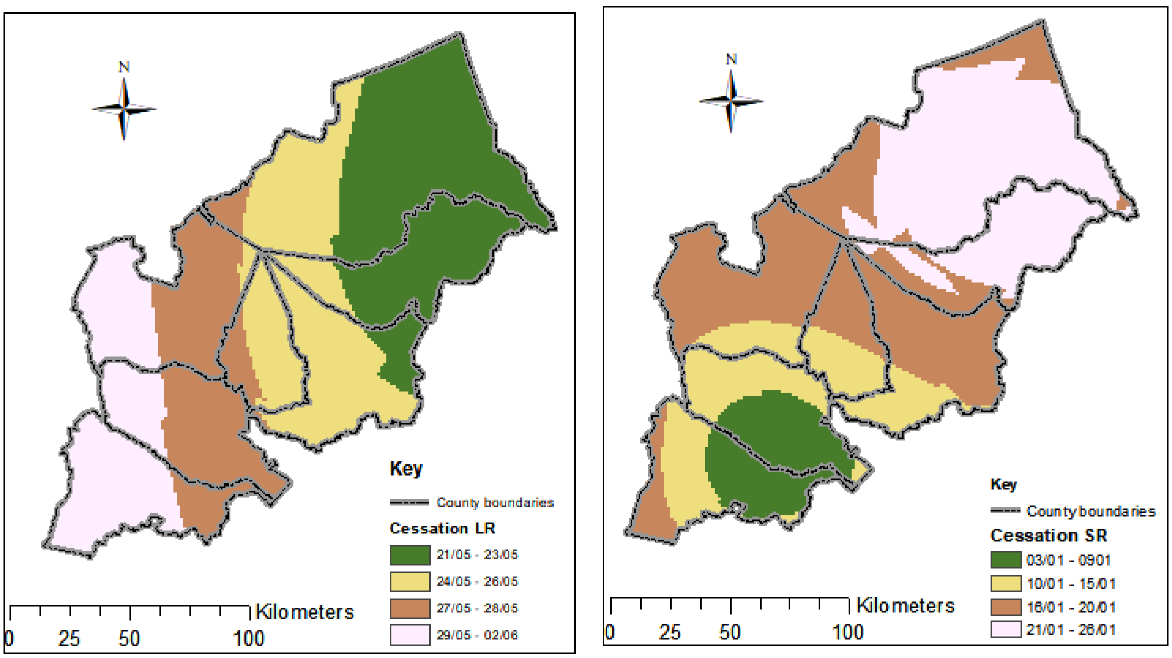


Figure 4.3: Map showing cessation dates for LR and SR

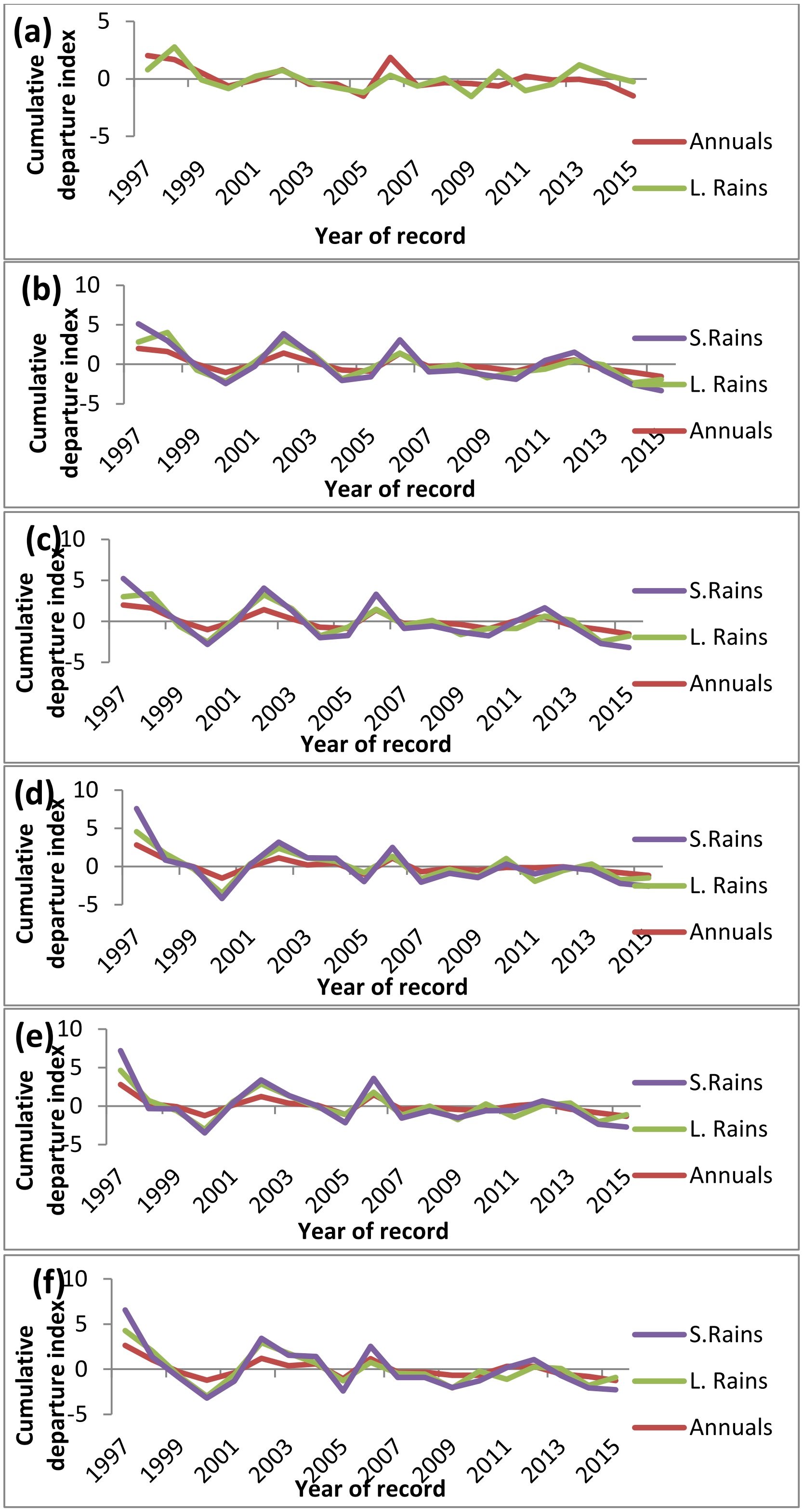
The length of the growing season was also highly variable, the averages ranging from 81 to 92 days during the LR and from 97 to 133 days during the SR. Generally, SR had a longer length of growing period than the LR, thus could support a broader range crop. Table 4.3 summarises the average onset, cessation and the length of growing period across the Counties.

Table 4.3: Average onset cessation dates and the length of growing period across the Counties from 1997 to 2015

County	Onset		Cessation		Length (Days)	
	LR	SR	LR	SR	LR	SR
Embu	29-February	20-September	24-May	13-January	84	115
Kiambu	28-February	8-October	30-May	19- January	92	103
Kirinyaga	2-March	22- September	26-May	9- January	85	109
Murang'a	1-March	26- September	27-May	1- January	87	97
Meru	1-March	11- September	24-May	22- January	84	133
Nyeri	2-March	22- September	26-May	9- January	85	109
Tharaka-Nithi	28- February	14- September	19-May	24- January	81	132

4.3.3 Spatial and temporal rainfall variation

The departure from the mean as exhibited by CDI reduced across the period from 1997 2015 (Figure 4.4) indicating that rainfall pattern becomes more stable and less variable in the past 19 years period. From 2007 to 2013 the rainfall was oscillating around the average indicating minimal variation until 2014-2015 when the trends significantly drop to below average (CDI<-2). Between the periods 1999-2000 and 2005, the pattern was consistently below average in the all the seven Counties. Both seasonal and annual rainfall was consistently above the average between 1997 and 1999 in all the Counties except Embu where the short rains in 1998 were below average. In all other Counties, SR was the most variable followed by LR, with annuals having the least variation, while in Embu County the annual rainfall had the highest variability, then long rains with the SR being the least variable. A similar trend was detected by RAI (Figure 4.5). Short rain emerged to be the most variable rainfall period across the years and the Counties in general with the highest positive anomaly (RAI=+13) in Kirinyaga County in 2006 being the wettest across the seasons and years of the record. The driest (RAI=-8) in Murang'a County in 2000. For LR rains the highest positive anomaly was +12, and the highest negative anomaly was -8. For SR highest positive anomaly was +13, and the highest negative anomaly was -7. Short rains showed more variation than the LR.


(a)
Cumulative departure index
5
0
-5
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year of record
Annuals
L. Rains
(b)
Cumulative departure index
10
5
0
-5
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year of record
S.Rains
L. Rains
Annuals
(c)
Cumulative departure index
10
5
0
-5
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year of record
S.Rains
L. Rains
Annuals
(d)
Cumulative departure index
10
5
0
-5
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year of record
S.Rains
L. Rains
Annuals
(e)
Cumulative departure index
10
5
0
-5
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year of record
S.Rains
L. Rains
Annuals
(f)
Cumulative departure index
10
5
0
-5
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year of record
S.Rains
L. Rains
Annuals

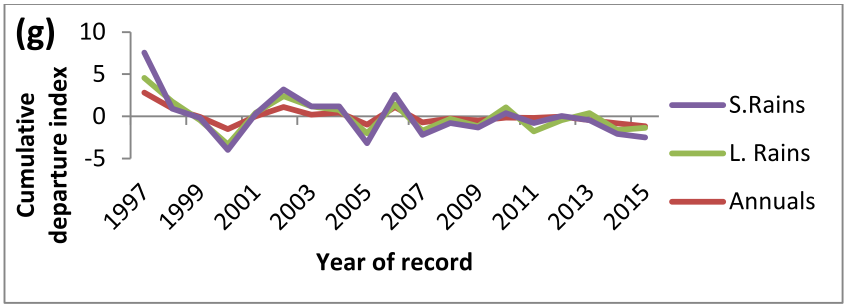
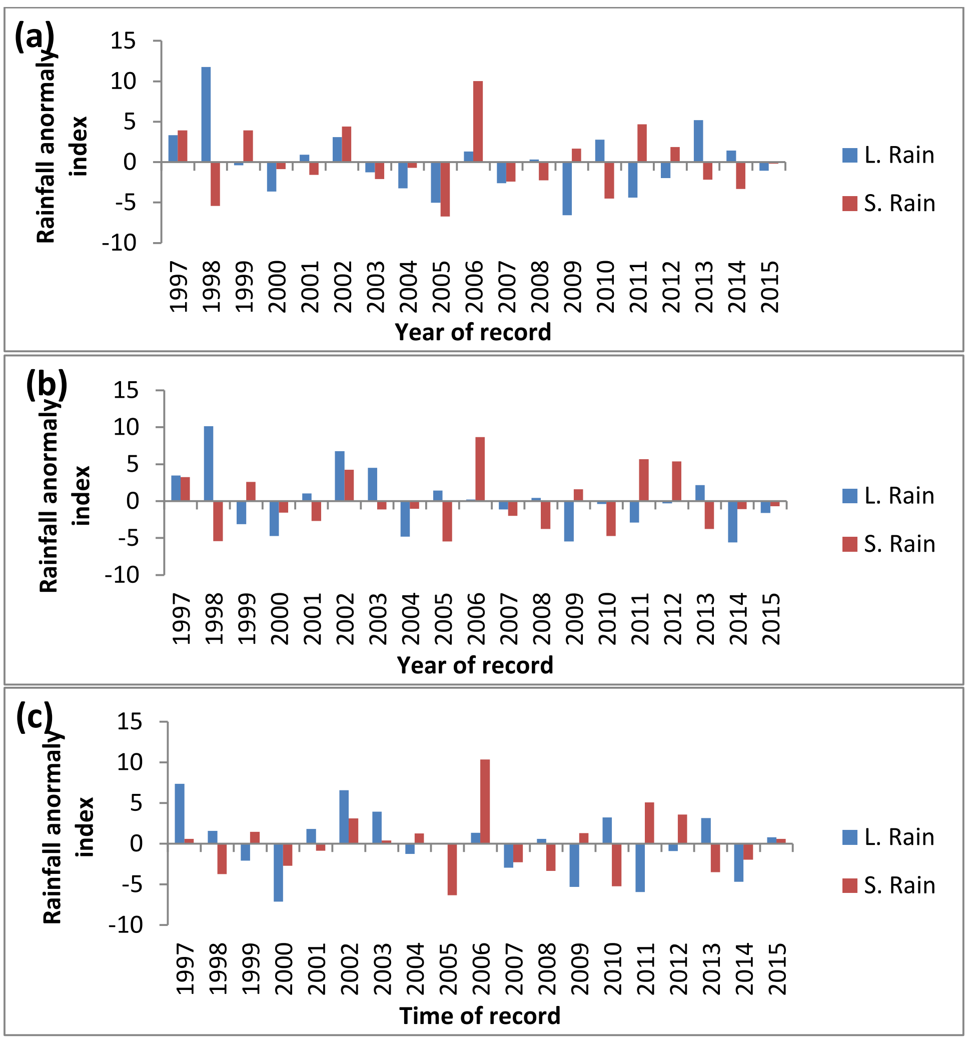


Figure 4.4 Times series of Cumulative departure index for annual, long rains and short rains in (a) Embu, (b) Kiambu, (c) Murang'a, (d) Meru, (e) Kirinyaga, (f) Nyeri and (g) Tharaka-Nithi Counties



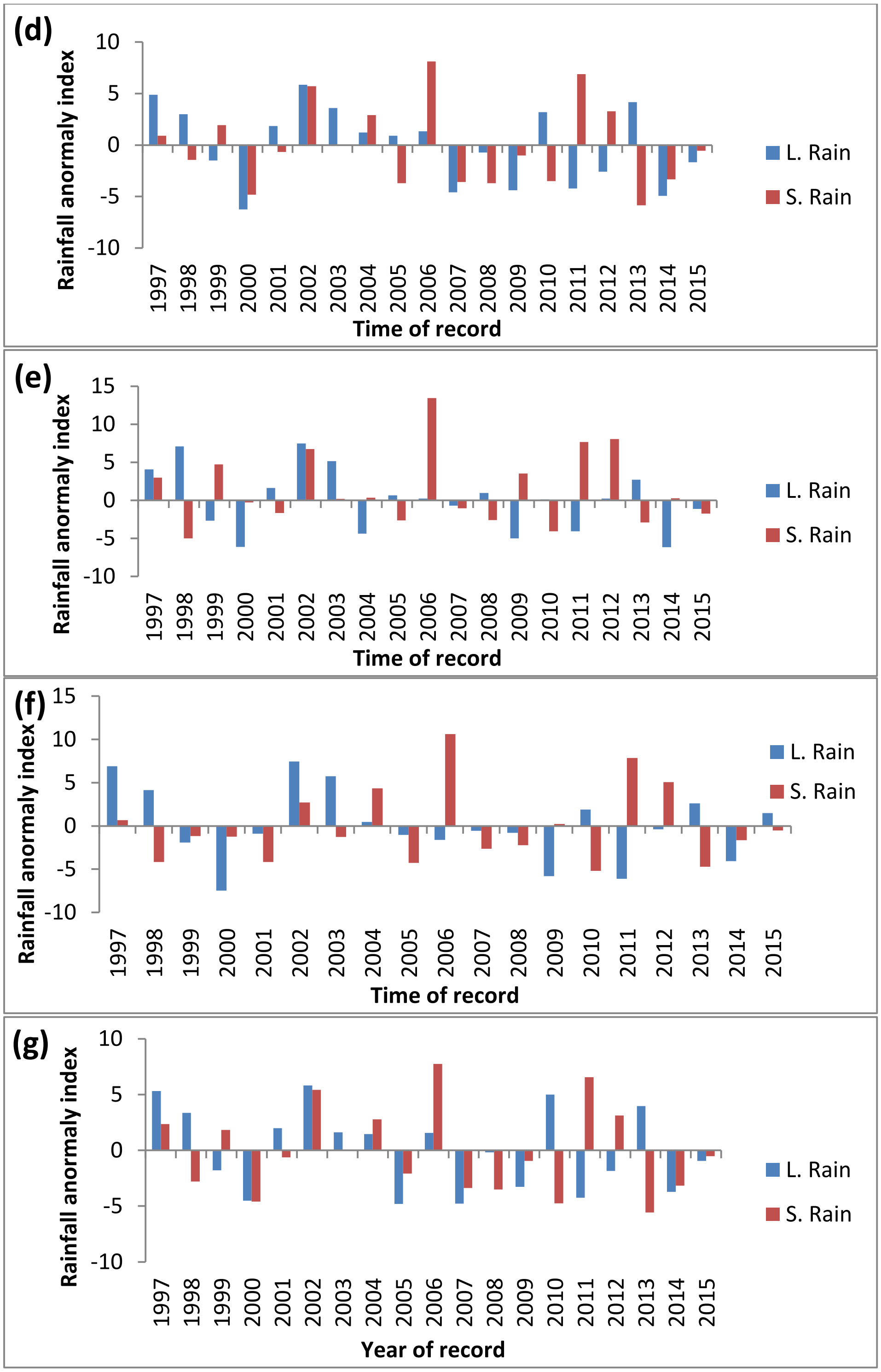


Figure 4.5: Time series of RAIfor long rains and short rains in (a) Embu, (b) Kiambu, (c) Murang'a, (d) Meru, (e) Kirinyaga, (f) Nyeri and (g) Tharaka-Nithi

The CValso showed high rainfall variability (Table 4.4). The CV value of more than 0.3 (30%) was considered to be indicating high variation (Araya and Stroosnijder, 2011). The

CV for annual rainfall varied from CV=0.29 to 0.42 across the Counties indicating high rainfall variability. For LR the range was between CV=0.33 to 0.48, and for SR it ranged between CV=0.56 to 0.69. Again, this portrayed SR to be the most variable followed by LR and then the annual rainfall. A number of rainy days within the season also indicated similar pattern with the CVs ranging between CV=0.23 to 0.40 and CV=0.36 to 0.48 for the LR and SR, respectively (Table 4.5).

Table 4.4: Variability of annual and seasonal rainfall amounts across the Counties from 1997 to 2015

County	**Coefficient of variation (CV)**		
	Annual	**LR**	**SR**
Embu	0.34	0.37	0.57
Kiambu	0.29	0.33	0.56
Kirinyaga	0.32	0.36	0.63
Meru	0.42	0.33	0.57
Murang’a	0.29	0.44	0.68
Nyeri	0.32	0.39	0.60
Tharaka-Nithi	0.42	0.48	0.69

Table 4.5: Seasonal rainy days variability from 1997 to 2015

County	**LR**		**SR**	
	No. of rainy days (RD)	**CV-RD**	**No. of rainy days (RD)**	**CV-RD**
Embu	403	0.23	505	0.44
Kiambu	614	0.23	597	0.36
Kirinyaga	554	0.26	586	0.46
Muranga	572	0.27	595	0.36
Meru	318	0.35	419	0.45
Nyeri	505	0.32	556	0.40
Tharaka-Nithi	285	0.40	426	0.48

4.3.4 Rainfall distribution pattern and intensity

Rainfall distribution pattern showed a bimodal rainfall pattern in the CHK. For both the long and short rains, the distribution pattern did not vary much across the different Counties (Figures 4.6a and b). For the LR, the month of April receives about 60% of the season's rainfall, with March receiving around 20% and the remaining 20% spread from the month May to July. For the SR, the month of November and December receives about 70% of the seasonal rainfall in all the Counties. October receives 20% while remaining 10% is spread between January and February. The months of April and November during the long and rains short, respectively, received the more significant chunk of the seasonal rainfall. This is ideal as these are the months within the season where active vegetative growth takes place. Thus, rainfall distribution is suitable for the growth of many crops such as maize, where the onset month receive sufficient rainfall that allows for germination and initial crop growth. Much of the rainfall is received during the heavy crop vegetative stage and the least amount received towards the harvesting of the crop. This is an indication of a well-distributed rainfall pattern.

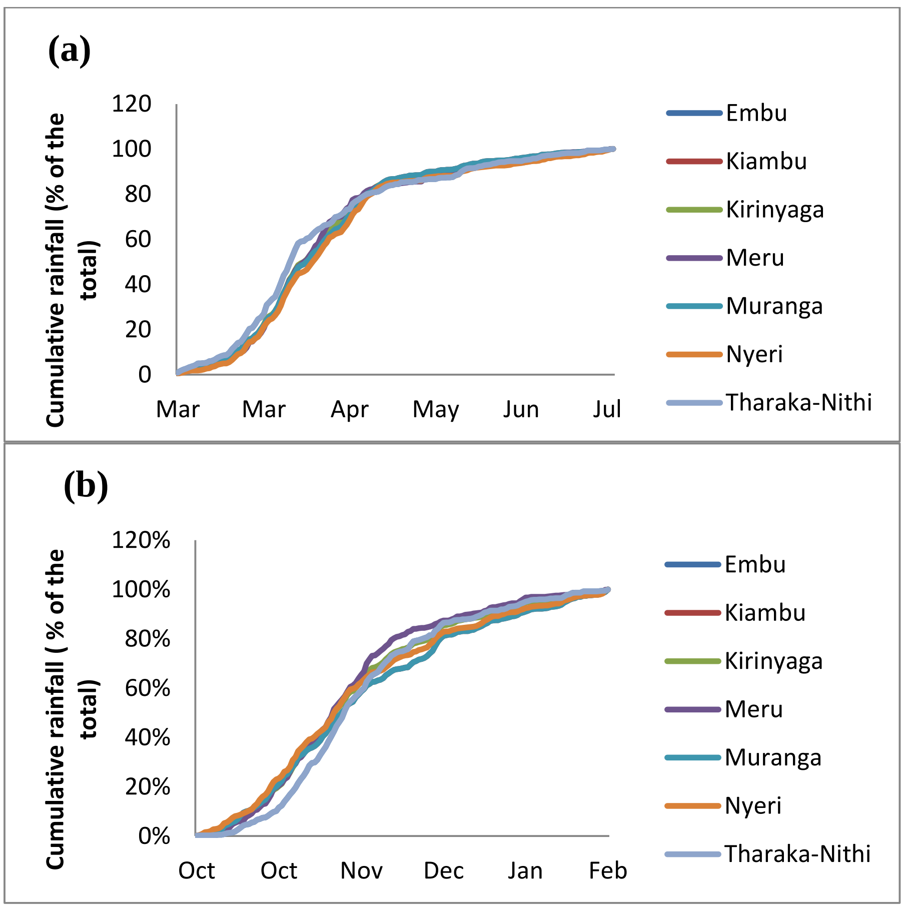


Figure 4.6: Temporal distribution of average daily rainfall as a percentage of the total rainfall received over the long rains (a) and short rains (b) seasons across the Counties

On rainfall intensity, the results showed low PVI ranging from PVI=0.09 to 0.27 in the study area indicating low intensity (Table 4.6). This means there are no high incidences of extreme rainfall events.

Table 4.6: Rainfall intensity across the Counties from 1997-2015

County	PVI
Embu	0.15
Kiambu	0.09
Kirinyaga	0.13
Meru	0.27
Murang’a	0.09
Nyeri	0.12
Tharaka-Nithi	0.26

Dry spell frequency during the LR for the 19 year period was highest in Embu with 83 occurrences and lowest in Murang’a with 57 occurrences (Table 4.7). During SR frequency of dry spell was highest in Nyeri with 88 occurrences and lowest in Embu with 69 occurrences during the 19 years of record (Table 4.8). The frequency of dry spell of between 5 to 10 days was consistently highest in all Counties in all the seasons while the dry spell frequency of more than 15 days was the least. On average there is at least a dry spell within a season for both long and short rains.

The CVanalysis of the dry spell indicated high seasonal variability in Kirinyaga, Murang’a, and Nyeri Counties during the LR. Kiambu, Kirinyaga and Murang’a had high variability during the SR (Table 4.9). Embu is the only County with low dry spell variability thus allow for easy planning and subsequent mitigation.

Table 4.7: Frequency of dry spell across the Counties during the long rains from 1997-2015

Year	**County**																				
	Embu			**Kiambu**			**Kirinyaga**			**Murang'a**			**Meru**			**Nyeri**			**Tharaka-Nithi**		
	>5	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**
1997	0	3	1	0	0	2	0	0	2	0	0	2	0	0	1	2	0	2	0	0	2
1998	1	1	2	0	2	1	0	2	1	0	2	0	1	2	0	1	2	0	0	1	1
1999	5	1	0	3	0	0	4	0	0	3	0	0	2	1	0	4	0	0	3	0	0
2000	2	1	2	3	2	1	2	0	2	2	1	1	0	0	3	4	0	0	0	1	2
2001	1	2	2	1	1	1	2	0	2	2	1	1	1	0	2	0	1	1	1	0	2
2002	1	2	1	1	1	0	2	1	0	1	1	0	2	2	0	1	1	0	3	1	0
2003	2	0	2	2	1	1	3	0	1	3	0	1	2	0	2	3	0	1	2	1	1
2004	0	1	1	1	1	1	2	3	1	1	2	1	3	1	2	2	1	1	2	2	0
2005	1	1	1	2	2	2	1	2	2	1	1	1	2	2	3	1	1	2	2	2	3
2006	1	2	0	2	0	0	1	2	0	2	0	0	3	1	1	2	0	0	3	0	1
2007	4	3	0	3	1	0	3	1	0	5	1	0	3	2	2	4	2	0	1	1	2
2008	2	0	2	2	0	1	2	0	2	2	0	1	1	1	2	1	1	2	1	1	1
2009	1	1	2	3	1	0	0	1	1	3	1	0	0	0	2	0	1	2	0	0	2
2010	2	1	1	1	2	0	2	1	0	1	1	0	2	1	0	1	2	0	1	2	0
2011	1	0	2	3	0	1	1	0	1	3	0	0	1	1	2	1	1	1	1	1	2
2012	2	1	1	1	0	1	2	1	1	0	1	1	2	0	1	2	0	1	2	0	1
2013	5	0	3	1	2	0	0	2	0	0	1	0	0	1	2	1	1	0	0	2	1
2014	4	2	0	1	0	3	3	1	0	1	2	0	2	2	0	3	1	0	2	2	0
2015	0	1	2	0	0	3	2	0	1	2	0	1	4	1	0	1	1	0	4	1	0
Totals	**35**	**23**	**25**	**30**	**16**	**18**	**32**	**17**	**17**	**32**	**15**	**10**	**31**	**18**	**25**	**34**	**16**	**13**	**28**	**18**	**21**

Table 4.8: Frequency of dry spell across the Counties during the short rains from 1997-2015

Year	**County**																				
	Embu			**Kiambu**			**Kirinyaga**			**Murang'a**			**Meru**			**Nyeri**			**Tharaka-Nithi**		
	>5	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**	**>5**	**>10**	**>15**
1997	4	0	0	1	1	0	0	0	0	1	0	1	2	0	0	2	0	0	2	0	0
1998	2	1	1	1	1	1	2	0	2	3	1	1	2	0	3	3	3	0	2	0	3
1999	0	0	1	4	1	1	2	0	1	3	0	1	2	0	2	3	0	0	2	0	2
2000	1	1	3	4	2	1	5	2	0	4	2	0	2	1	3	4	0	2	2	1	3
2001	3	0	1	3	1	1	4	0	1	2	1	1	0	2	2	2	1	1	1	2	1
2002	1	3	0	2	0	2	1	1	1	2	0	1	0	1	2	0	1	2	0	1	2
2003	2	1	1	0	1	1	1	2	1	0	2	0	1	1	1	1	3	1	2	0	3
2004	1	2	0	1	0	1	2	1	1	0	0	1	2	1	1	2	1	2	2	1	1
2005	1	1	2	2	0	3	4	3	0	3	1	1	1	2	3	3	3	0	1	0	3
2006	0	1	0	1	0	1	4	1	0	1	0	1	2	0	1	1	3	1	3	0	1
2007	2	1	1	5	0	0	2	0	0	4	0	0	2	1	0	2	3	0	2	1	0
2008	1	1	2	2	0	2	2	0	1	1	0	1	2	0	1	3	0	2	1	1	1
2009	1	1	1	5	0	0	1	1	1	5	0	0	3	1	2	1	0	2	3	1	1
2010	2	1	2	2	3	0	3	1	1	3	2	0	2	2	1	4	1	0	1	2	2
2011	2	3	0	3	4	1	2	1	1	5	0	1	0	1	2	1	1	3	1	1	2
2012	1	0	2	0	4	0	2	0	1	0	3	0	2	1	1	3	1	1	2	1	1
2013	2	2	0	2	1	2	2	2	1	3	0	2	1	1	1	1	3	1	0	1	2
2014	1	1	2	1	1	3	2	2	3	1	1	3	2	0	2	3	1	2	2	1	2
2015	2	1	0	2	0	1	0	0	0	1	1	1	0	1	2	0	3	1	0	1	1
Totals	**29**	**21**	**19**	**41**	**20**	**21**	**41**	**17**	**16**	**42**	**14**	**16**	**28**	**16**	**30**	**39**	**28**	**21**	**29**	**15**	**31**

Table 4.9: Dry spell analysis across the Counties for both long and short rains from 1997 to 2015

County	Seasonal dry spell analysis			
	LR		SR	
	Dry spell Frequency	CV	Dry spell Frequency	CV
Embu	83	0.19	69	0.19
Kiambu	49	0.29	82	0.35
Kirinyaga	66	0.32	74	0.47
Murang'a	57	0.50	72	0.53
Meru	74	0.22	74	0.25
Nyeri	63	0.44	88	0.25
Tharaka-Nithi	67	0.19	75	0.28

The probability analysis of the dry spell (Table 4.10) showed that the probability that a dry-spell may be equal to or longer than 5 days ranged from 4 to 5% for LR and was 4 % for the SR. The probability of a dry spell less than 5 day does not occur at a certain day in a growing season ranged from 95 to 96% for LR and 96% for the SR. The probability that a dry spell longer than 5 days will not occur at a certain day in a growing season ranged from 1 to 5% for the LR and 1 to 2% for the SR. Finally the probability that a dry spell exceeding 5 days would occur within a growing season ranged from 97 to 99% for LR and was 98% for the SR. Generally, there was a high probability of dry spell occurrence in future.

Table 4.10: Dry spell probability analysis for both long and short rains seasons across the Counties

County	Dry spell probabilities							
	P*		R**		Q***		L****	
	LR	SR	LR	SR	LR	SR	LR	SR
Embu	0.05	0.04	0.95	0.96	0.01	0.02	0.99	0.98
Kiambu	0.04	0.04	0.96	0.96	0.03	0.01	0.97	0.99
Kirinyaga	0.04	0.04	0.96	0.96	0.03	0.02	0.97	0.98
Murang'a	0.04	0.04	0.96	0.96	0.05	0.02	0.95	0.98
Meru	0.05	0.04	0.95	0.96	0.02	0.02	0.98	0.98
Nyeri	0.04	0.04	0.96	0.96	0.03	0.01	0.97	0.99
Tharaka-Nithi	0.04	0.04	0.96	0.96	0.03	0.02	0.97	0.98

*Probability that a dry-spell starts on a particular day within a growing season
**Probability that a dry-spell less than 5 does not occur at a certain day in a growing season
***Probability that a dry-spell longer than 5 days will not occur in a growing season
****Probability that a dry-spell exceeding 5 days would occur at least once in a growing season

4.3.6 Comparison between grid points satellite estimates and the meteorological stations (ground observations) rainfall data

The visual and statistical trend portrayed by the CDI show the satellite data consistently underestimating observed rain gauge values (Figure 4.7). However, the data sets had similar trend indicating they are in agreement.

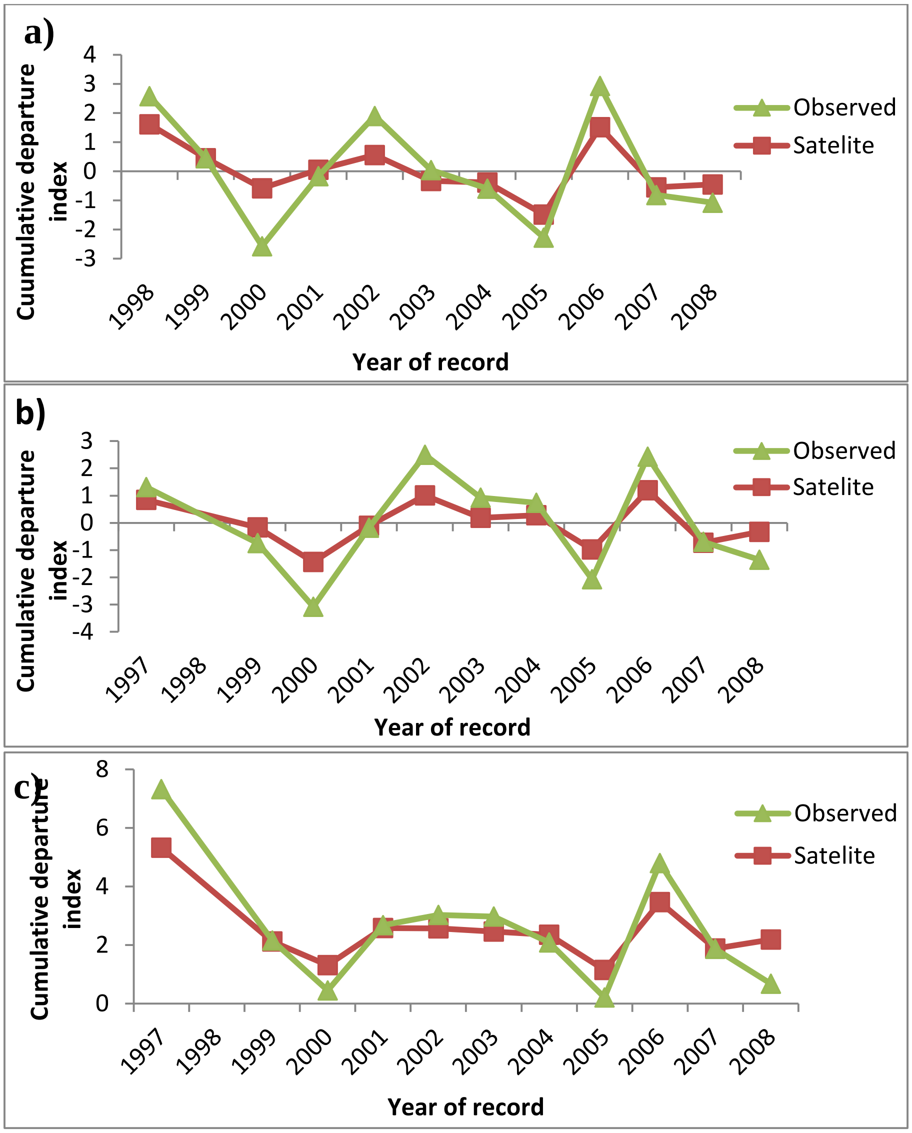


Figure 4.7: Times series of Cumulative departure index for observed and satellite estimates in Embu (a), Meru (b), and Tharaka-Nithi (c) Counties across the years

Pearson correlation of the onset cessation and the length of growing period between the satellite and observed gauge data were as per the tables 4.11, 4.12 and 4.13. In Embu County, SR showed stronger agreements on the onset, cessation and the length of growing period where the CV ranged between 0.56 to 0.59 than the ones during the long rains that ranged between 0.02 to 0.19. The t-test, however, showed the two data sets were significantly different from each other at 95% level of confidence. A similar pattern was observed in Meru County with SR having the correlation coefficient ranging between 0.17 to 0.63 and the ones for LR ranging between 0.08 to 0.35. In Tharaka-Nithi County, on the other hand, onset and cessation dates for both the long and short rains showed stronger agreement between the data sets with the correlation coefficient ranging from 0.54 to 0.83 than the agreement for the length of growing period that ranged from 0.16 to 0.33. Similarly, the t-test showed the two data sets were significantly different from each other at 95% level of confidence. Comparison of the onset, cessation and the length of growing period showed that the two data sets are in agreement regarding predicting these rainfall parameters, especially during the short rains.

The daily correlation comparison between the two datasets indicated that there was an agreement between the two data sets though not very strong. The correlation coefficient ranged from 0.4428 to 0.6245 with the t-test showing the datasets were significantly different from each other across all the three Counties (p=0.0001) (Table 4.14).

Root mean square error showed high positive values indicating the satellite underestimate the observed rain gauge data (Table 4.14). The values ranged from 2.842 to 4.310 across the Counties under study.

Table 4.11: Comparison of satellite rainfall estimate and observed rain gauge at onset, cessation and length of growing period during LR and SR in Embu County

Year	LR						SR					
	Onset (J^th day)		Cessation (J^th day)		Length(J days)		Onset (J^th day)		Cessation (J^th day)		Length (J days)	
	Observed	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**
1999	62	71	154	134	92	63	279	269	387	371	108	102
2000	78	64	146	134	68	70	280	269	367	367	87	98
2001	83	53	150	134	67	81	277	265	359	367	82	102
2002	78	62	150	142	72	80	280	275	387	375	107	100
2003	78	43	162	139	84	96	278	275	359	367	81	92
2004	58	54	146	134	88	80	280	273	355	367	75	94
2005	82	60	166	134	84	74	280	273	355	367	75	94
2006	57	60	147	138	90	78	277	272	379	379	102	107
2007	83	60	166	134	83	74	280	275	355	375	75	100
2008	82	60	146	134	64	74	277	266	355	367	78	101
Mean	**74**	**59**	**153**	**136**	**79**	**77**	**279**	**271**	**366**	**370**	**87**	**99**
Corr coeff	**0.19813**		**0.03729**		**0.02849**		**0.5615**		**0.59277**		**0.57630**	
P value	**0.5832**		**0.9185**		**0.9377**		**0.0912**		**0.0709**		**0.0812**	

Table 4.12: Comparison of satellite rainfall estimate and observed rain gauge at onset, cessation and length of growing period during LR and SR in Meru County

Year	LR						SR					
	Onset (J^th day)		Cessation (J^th day)		Length (J days)		Onset (J^th day)		Cessation (J^th day)		Length (J days)	
	Observed	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**	**Observed**	**Satellite**
1999	76	76	145	146	86	70	284	269	378	358	94	89
2000	76	76	141	146	75	70	291	269	369	358	78	89
2001	76	76	141	146	85	70	283	269	365	362	82	93
2002	62	62	146	146	93	84	280	269	389	370	109	101
2003	62	62	141	146	84	84	290	269	361	358	71	89
2004	72	72	141	146	101	74	287	269	393	359	106	90
2005	60	60	141	159	73	99	291	272	357	358	66	86
2006	74	74	161	146	83	72	262	266	397	370	135	104
2007	60	60	141	146	83	86	280	275	389	358	109	83
2008	60	60	141	146	74	86	277	275	357	358	80	83
Mean	**57**	**68**	**141**	**147**	**84**	**79**	**283**	**270**	**376**	**361**	**93**	**91**
Corr coef	**0.08309**		**0.16181**		**0.35894**		**0.171190**		**0.56908**		**0.63153**	
P value	**0.8195**		**0.6552**		**0.3084**		**0.6363**		**0.0860**		**0.0502**	

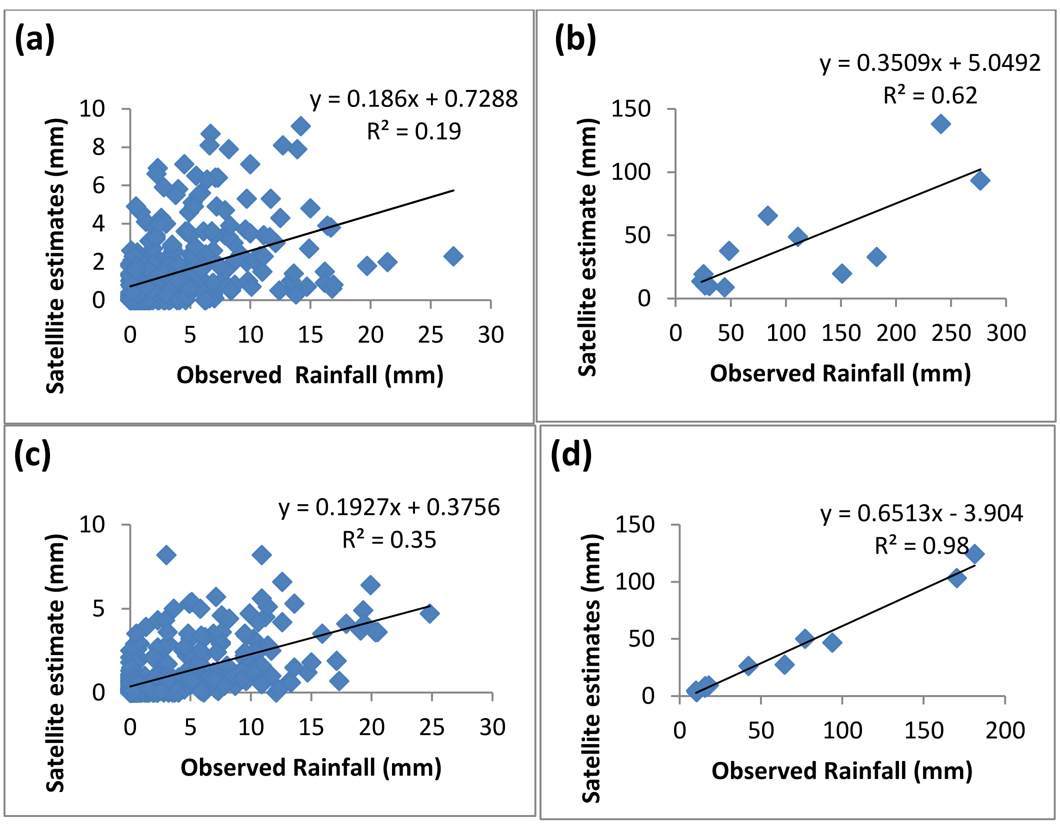
Table 4.13: Comparison of satellite rainfall estimate and observed rain gauge at onset, cessation and length of growing period during LR and SR in Tharaka-Nithi County

Year	LR						SR					
	Onset (J^th day)		Cessation(J^th day)		Length(J days)		Onset(J^th day)		Cessation(J^th day)		Length(J day)	
	Observed	Satellite	Observed	Satellite	Observed	Satellite	Observed	Satellite	Observed	Satellite	Observed	Satellite
1999	47	76	168	144	121	68	292	281	384	364	92	83
2000	47	76	176	144	129	68	271	281	368	360	97	79
2001	65	76	164	144	99	68	273	281	361	360	88	79
2002	61	62	164	144	103	82	279	278	376	369	97	91
2003	61	62	164	144	103	82	290	278	356	360	66	82
2004	77	72	164	144	87	72	290	278	360	360	70	82
2005	80	60	184	160	104	100	290	272	356	360	66	88
2006	58	74	164	144	106	70	289	272	404	369	115	97
2007	61	60	164	144	103	84	278	283	396	360	118	77
2008	82	60	164	144	82	84	275	279	356	360	81	81
Mean	**64**	**68**	**168**	**146**	**104**	**78**	**283**	**278**	**372**	**362**	**89**	**84**
Corr coef	**0.54769**		**0.83327**		**0.33057**		**0.54098**		**0.62758**		**0.16105**	
P Value	**0.1012**		**0.0028**		**0.3509**		**0.1064**		**0.0521**		**0.6567**	

Table 4.14: Pearson correlation and Root mean square error comparison of daily satellite rainfall estimates and observed rain gauge data

County	Correlation analysis		RMSE
	Correlation Coefficient	P value	
Embu	0.4427	0.0001	4.310
Meru	0.5935	0.0001	2.978
Tharaka-Nithi	0.6245	0.0001	2.842

Scatter plot shows poor agreement between the data sets at daily basis with the coefficient of determination (R^2) ranging from R^2=0.19 to 0.98 (Figure 4.9). On a monthly scale, however, there was substantial agreement with the R^2 ranging between R^2 =0.62 to 0.98. This indicates that at the daily scale, the satellite rainfall estimates cannot represent the observed rainfall adequately while at monthly scale, the observed rainfall can be represented fully by the satellite estimates.



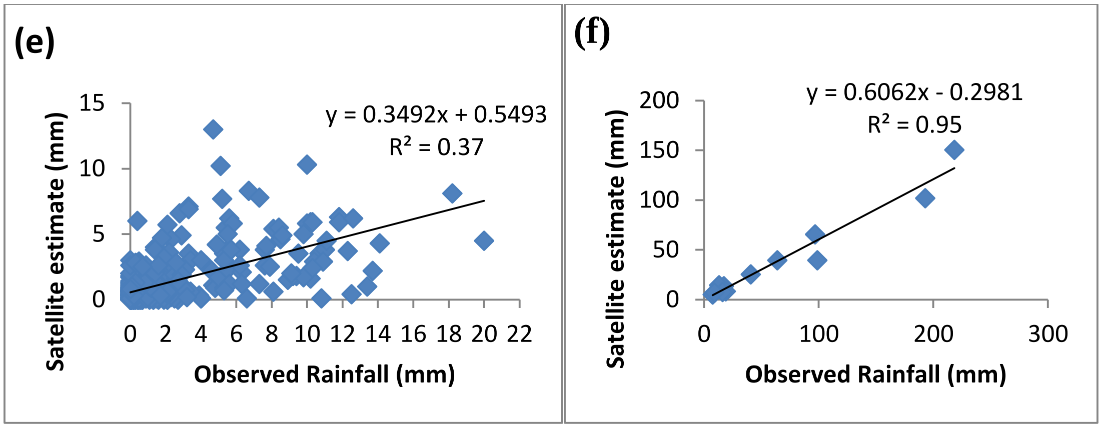


Figure 4.8: Scatter plots comparing satellite estimates and observed raingauge data set at daily (a), (c) and (e) for Embu, Meru and Tharaka-Nithi respectively and monthly (b), (d) and (f) for Embu, Meru and Tharaka-Nithi respectively from 1999 to 2008

4.4 Objective 2: Treatment effect on soil moisture and water productivity

4.4.1. Treatment effect on soil moisture

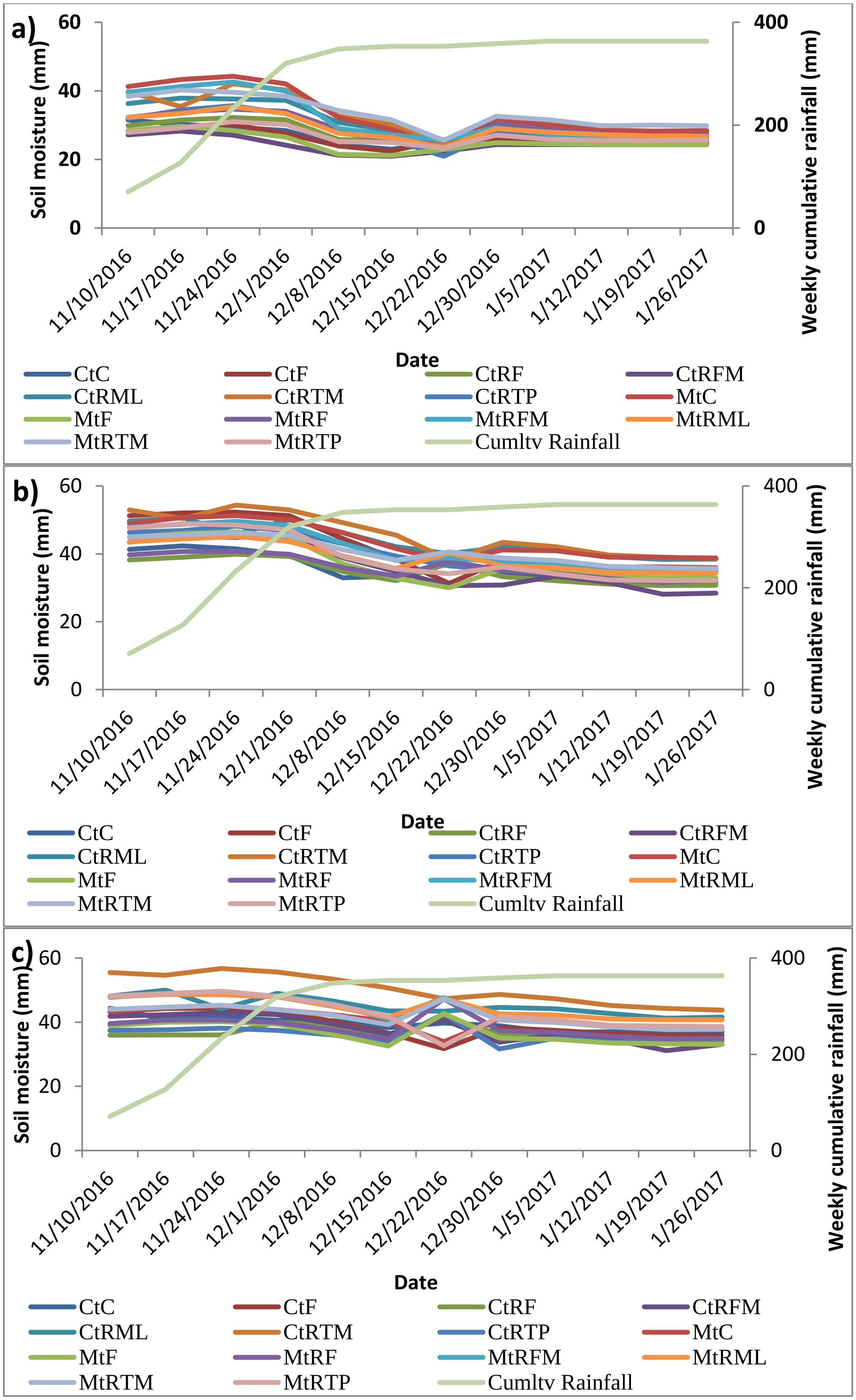
Treatments had no significant effect on soil moisture in Kandara $p \leq 0.05$. In Chuka treatment under CT with crop residue plus *Tithonia diversifolia* plus animal manure (CtRTM) had the highest soil moisture content at all depths except at 0-10 cm depth where MT control had the highest soil moisture (Table 4.15). Generally, CtRTM was the best in enhancing soil moisture in the *Humic Nitisols* in Tharaka-Nithi during the experimental period. This was followed by the treatment under CT plus crop residue plus animal manure with legume intercrop (CtRML) which had the second highest soil moisture across the soil depths. On the other hand treatments under CT plus crop residue plus mineral fertiliser with animal manure and without animal manure (CtRF and CtRFM) had the lowest soil moisture across the depths. This is also supported by the time series showing a trend where CtRTM had the highest soil moisture reading with CtRF and CtRFM having the lowest readings most of the times during the growing season (Figure 4.10). Therefore in *Humic Nitisols* in Chuka, Tharaka-Nithi County, CtRTM was the best treatment combination in enhancing soil moisture during the two cropping seasons while CtRF CtRFM were the least in improving soil moisture under short-term consideration.

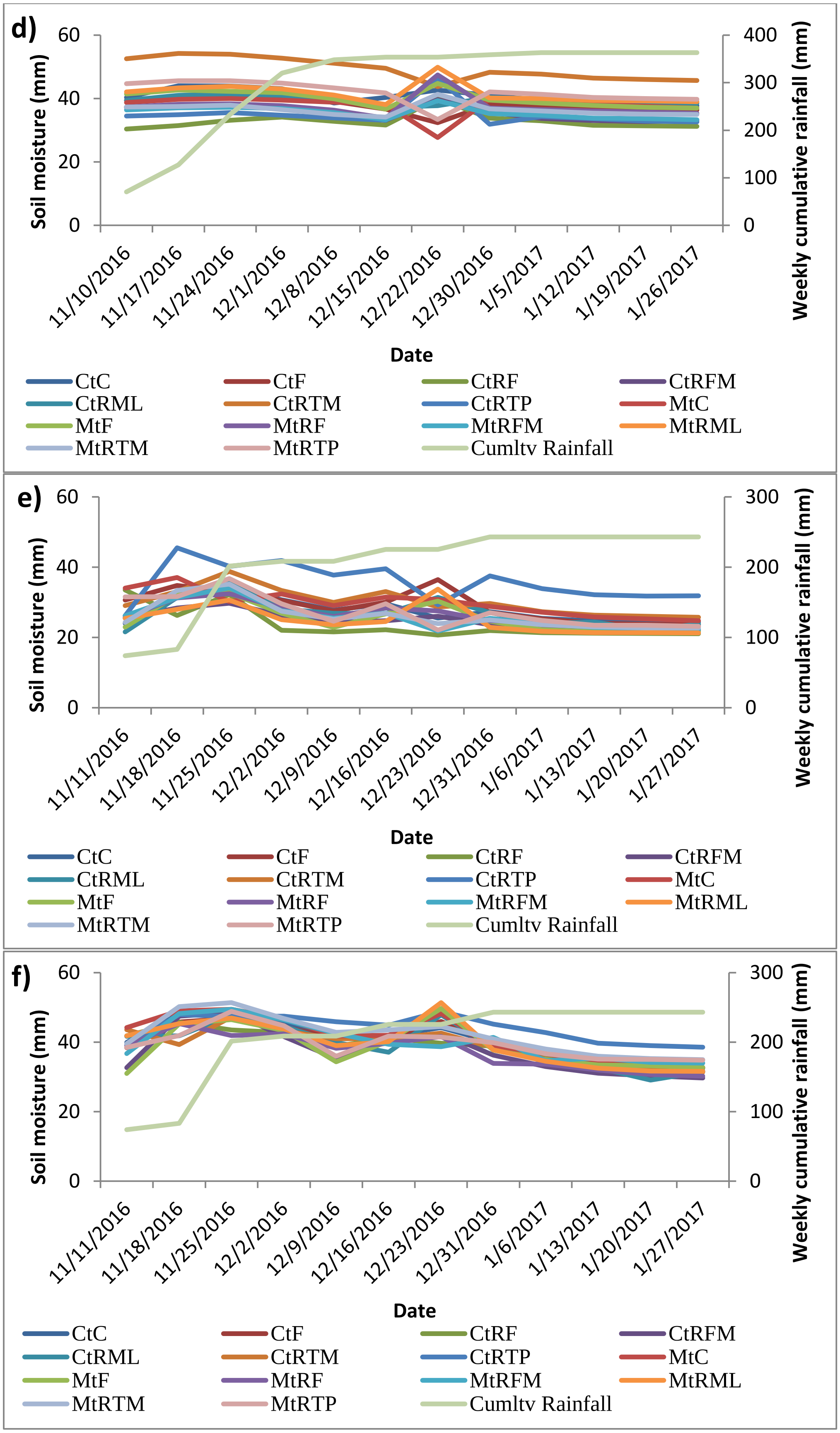
Table 4.15: Treatment effect on soil moisture (mm) at different depths during long rains 2017 in Chuka, Tharaka-Nithi County

Treatment	Depths			
	10 cm	**20 cm**	**30 cm**	**40 cm**
CtC	26.73[bcd]	36.09[de]	39.39[cd]	40.76[a]
CtF	26.123[cd]	42.10[abc]	39.00[cd]	37.94[a]
CtRF	27.85[abcd]	34.993[e]	36.63[bc]	42.98[a]
CtRFM	24.42[d]	36.28[de]	37.90[cd]	35.61[a]
CtRML	31.43[abc]	43.69[ab]	44.95[ab]	39.54[a]
CtRTM	32.60[ab]	45.55[a]	50.27[a]	49.37[a]
CtRTP	23.69[abcd]	40.54[abcde]	35.86[c]	34.91[a]
MtC	33.54[a]	43.78[ab]	40.78[bc]	37.87[a]
MtF	25.10[d]	37.64[cde]	36.62[bc]	40.00[a]
MtRF	29.52[abcd]	26.19[ed]	38.32[bc]	37.50[a]
MtRFM	31.79[abc]	41.18[abcd]	43.79[abc]	35.55[a]
MtRML	29.16[abcd]	38.98[bcde]	44.52[ab]	41.62[a]
MtRTM	33.52[a]	40.60[abcd]	41.77[abc]	36.51[a]
MtRTP	26.81[bcd]	38.99[bcde]	42.82[abc]	41.92[a]
P Value	**0.0031**	**0.0007**	**0.0354**	**0.1460**

Means with the same letter(s) within the column are not significanlty different at $p \leq 0.05$

MtC=Minimum tillage Control; MtF=Minimum tillage+ Sole Mineral fertilizer; MtRF=Minimum; tillage+ Crop residues + Mineral fertilizer; MtRFM=Minimum tillage+ Crop residues +Mineral fertilizer + Animal manure; MtRTP=Minimum tillage+ Crop residues +*Tithonia diversifolia* + Phosphate rock (Minjingu); MtRML=Minimum tillage +Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); MtRTM=Minimum tillage+ Crop residues + *Tithonia diversifolia* + Animal manure; CtC= Conventional tillage Control; CtF=Conventional tillage+ Sole Mineral fertilizer; CtRF=Conventional tillage+ Crop residues+ Mineral fertilizer; CtRFM=Conventional tillage + Crop residues + Mineral fertilizer + Animal manure; CtRTP=Conventional tillage+Crop residues+*Tithonia diversifolia* +Phosphate rock (Minjingu); CtRML =Conventional tillage+ Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); CtRTM=Conventional tillage+ Crop residues + *Tithonia diversifolia* + Animal manure


a)
b)
c)
Soil moisture (mm)
Weekly cumulative rainfall (mm)
60
40
20
0
400
200
0
11/10/2016
11/17/2016
11/24/2016
12/1/2016
12/8/2016
12/15/2016
12/22/2016
12/30/2016
1/5/2017
1/12/2017
1/19/2017
1/26/2017
Date
CtC
CtF
CtRF
CtRFM
CtRML
CtRTM
CtRTP
MtC
MtF
MtRF
MtRFM
MtRML
MtRTM
MtRTP
Cumltv Rainfall


d)
Soil moisture (mm)
Weekly cumulative rainfall (mm)
Date
11/10/2016
11/17/2016
11/24/2016
12/1/2016
12/8/2016
12/15/2016
12/22/2016
12/30/2016
1/5/2017
1/12/2017
1/19/2017
1/26/2017
CtC CtF CtRF CtRFM
CtRML CtRTM CtRTP MtC
MtF MtRF MtRFM MtRML
MtRTM MtRTP Cumltv Rainfall
e)
Soil moisture (mm)
Weekly cumulative rainfall (mm)
Date
11/11/2016
11/18/2016
11/25/2016
12/2/2016
12/9/2016
12/16/2016
12/23/2016
12/31/2016
1/6/2017
1/13/2017
1/20/2017
1/27/2017
CtC CtF CtRF CtRFM
CtRML CtRTM CtRTP MtC
MtF MtRF MtRFM MtRML
MtRTM MtRTP Cumltv Rainfall
f)
Soil moisture (mm)
Weekly cumulative rainfall (mm)
Date
11/11/2016
11/18/2016
11/25/2016
12/2/2016
12/9/2016
12/16/2016
12/23/2016
12/31/2016
1/6/2017
1/13/2017
1/20/2017
1/27/2017
CtC CtF CtRF CtRFM
CtRML CtRTM CtRTP MtC
MtF MtRF MtRFM MtRML
MtRTM MtRTP Cumltv Rainfall

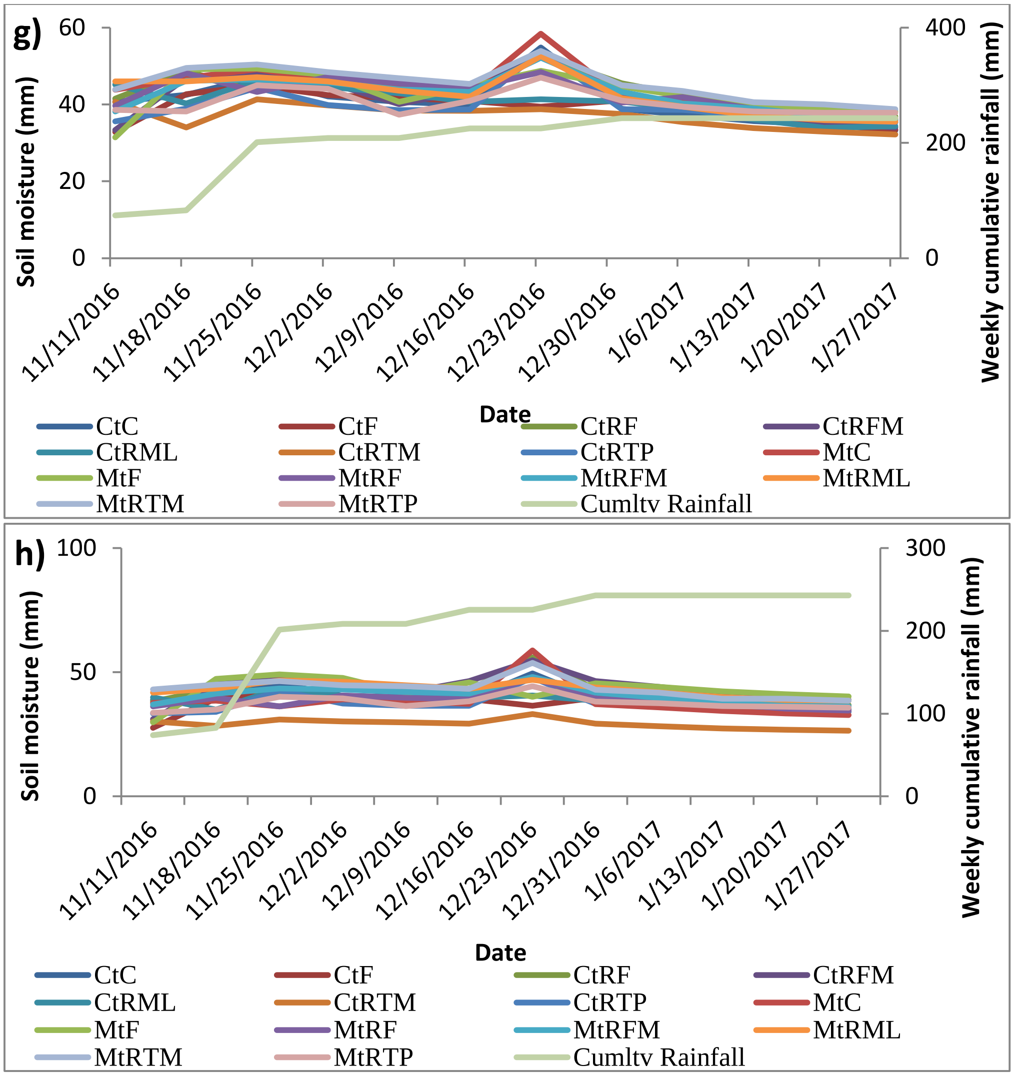


Figure 4.9: Time series on treatment effect on soil moisture content (mm) in Chuka a, b, c and d at depths 10cm, 20 cm, 30 cm and 40 cm, respectively and Kandara e, f, g and h at at depths 10cm, 20 cm, 30 cm and 40 cm, respectively during SR season 2016/2017.

MtC=Minimum tillage Control; MtF=Minimum tillage + Sole Mineral fertilizer; MtRF=Minimum; tillage+ Crop residues + Mineral fertilizer; MtRFM=Minimum tillage+ Crop residues +Mineral fertilizer + Animal manure; MtRTP=Minimum tillage+ Crop residues +*Tithonia diversifolia* + Phosphate rock (Minjingu); MtRML=Minimum tillage +Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); MtRTM=Minimum tillage+ Crop residues + *Tithonia diversifolia* + Animal manure; CtC= Conventional tillage Control; CtF=Conventional tillage+ Sole Mineral fertilizer; CtRF=Conventional tillage+ Crop residues+ Mineral fertilizer; CtRFM=Conventional tillage + Crop residues + Mineral fertilizer + Animal manure; CtRTP=Conventional tillage+Crop residues+*Tithonia diversifolia* +Phosphate rock (Minjingu); CtRML =Conventional tillage+ Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); CtRTM=Conventional tillage+ Crop residues + *Tithonia diversifolia* + Animal manure; C.Rainfall=Cumulative rainfall.

4.4.2. Treatment effect on soil water productivity

In Chuka site, treatments had a significant effect on soil water productivity at all depths under consideration (Table 4.16). Treatments under CT with crop residue plus mineral fertiliser with and without animal manure (CtRFM and CtRF) had the highest soil water productivity after the two cropping season in the Humic nitisols of Chuka in Tharaka-Nithi Counties. On the other hand, MT control (MtC) had the lowest soil water productivity followed by conventional tillage control (CtC).

Table 4.16: Treatment effect on soil water productivity (Kg/m^3) at different depths in Chuka Tharaka-Nithi County

Treatment	**Depth**			
	10 cm	**20cm**	**30 cm**	**40 cm**
CtC	1.76^{bc}	2.04^{bc}	1.77^{c}	1.48^{e}
CtF	2.59^{bc}	2.54^{bc}	2.73^{bc}	2.89^{cde}
CtRF	5.91^{a}	4.01^{a}	5.87^{a}	4.99^{abc}
CtRFM	6.22^{a}	4.06^{a}	4.55^{ab}	6.52^{a}
CtRML	2.31^{bc}	2.14^{bc}	3.24^{bc}	2.37^{de}
CtRTM	3.12^{bc}	2.59^{bc}	2.73^{bc}	2.95^{cde}
CtRTP	3.53^{b}	2.88^{b}	2.93^{bc}	5.82^{ab}
MtC	1.16^{c}	1.52^{c}	1.80^{c}	1.15^{e}
MtF	3.39^{b}	2.23^{bc}	3.58^{bc}	4.11^{bcd}
MtRF	3.42^{b}	2.95^{b}	3.32^{bc}	5.13^{abc}
MtRFM	3.55^{b}	3.06^{ab}	4.45^{bc}	4.98^{abc}
MtRML	3.00^{bc}	2.07^{bc}	2.39^{bc}	3.97^{bcd}
MtRTM	2.72^{bc}	2.32^{bc}	2.87^{bc}	3.33^{cde}
MtRTP	3.28^{bc}	2.50^{bc}	2.03^{c}	2.35^{de}
P-Value	**0.0001**	**0.0004**	**0.0160**	**0.0001**

Means with the same letter(s) within the column are not significanlty different at $p \leq 0.05$

MtC=Minimum tillage Control; MtF=Minimum tillage + Sole Mineral fertilizer; MtRF=Minimum; tillage+ Crop residues + Mineral fertilizer; MtRFM=Minimum tillage+ Crop residues +Mineral fertilizer + Animal manure; MtRTP=Minimum tillage+ Crop residues +*Tithonia diversifolia* + Phosphate rock (Minjingu); MtRML=Minimum tillage +Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); MtRTM=Minimum tillage+ Crop residues + *Tithonia diversifolia* + Animal manure; CtC= Conventional tillage Control; CtF=Conventional tillage+ Sole Mineral fertilizer; CtRF=Conventional tillage+ Crop residues+ Mineral fertilizer; CtRFM=Conventional tillage + Crop residues + Mineral fertilizer + Animal manure; CtRTP=Conventional tillage+Crop residues+*Tithonia diversifolia* +Phosphate rock (Minjingu); CtRML =Conventional tillage+ Crop residues + Animal manure + Legume intercrop (*Dolichos Lablab*); CtRTM=Conventional tillage+ Crop residues + *Tithonia diversifolia* + Animal manure; C.Rainfall=Cumulative rainfall.

In Kandara, the treatments had no significant effect on soil water productivity except at 10 cm depth (Table 4.17). At 10 cm depth, treatments under CT with crop residue plus mineral fertiliser with and without animal manure (CtRFM and CtRF) again had the highest soil water productivity with MtC having the lowest.

Table 4.17: Treatment effect on soil water productivity (Kg/m^3) at different depths during LR 2017 in Kandara Murang'a County

Treatment	**Depth**			
	10 cm	**20cm**	**30 cm**	**40 cm**
CtC	1.64^{c}	1.68^{a}	1.49^{a}	1.67^{a}
CtF	2.11^{bc}	2.35^{a}	1.91^{a}	1.89^{a}
CtRF	3.56^{a}	2.57^{a}	3.31^{a}	2.17^{a}
CtRFM	3.39^{ab}	2.63^{a}	2.32^{a}	2.77^{a}
CtRML	1.56^{c}	1.44^{a}	1.74^{a}	1.91^{a}
CtRTM	2.22^{abc}	2.40^{a}	3.57^{a}	2.38^{a}
CtRTP	1.65^{c}	2.80^{a}	2.15^{a}	1.98^{a}
MtC	1.48^{c}	1.44^{a}	1.34^{a}	1.63^{a}
MtF	3.34^{ab}	2.46^{a}	2.50^{a}	3.62^{a}
MtRF	3.44^{ab}	2.38^{a}	3.15^{a}	3.17^{a}
MtRFM	2.70^{abc}	2.61^{a}	2.21^{a}	2.58^{a}
MtRML	1.71^{abc}	1.47^{a}	1.41^{a}	1.34^{a}
MtRTM	1.96^{c}	2.67^{a}	1.96^{a}	2.81^{a}
MtRTP	2.15^{bc}	1.68^{a}	1.75^{a}	1.72^{a}
P-Value	**0.0024**	**0.1200**	**0.1676**	**0.1073**

Means with the same letter(s) within the column are not significanlty different at $p \leq 0.05$

4.5 Objective 3: Treatment effect on soil physical properties

In both Chuka and Kandara sites, the treatments had no significant effect on soil bulk density, saturated hydraulic conductivity and aggregate stability at $P \leq 0.05$ at the end of the second cropping season.

Chapter 5

DISCUSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Overview

The section outlines the findings and placing them within the context of the scientific body of knowledge. The general conclusion and the recommendation from the study is outlines. Area for further research is also pointed out.

5.2 Objective 1. Discusion on rainfall characteristics

5.2.1 Seasonal rainfall onset, cessation and the length of growing period

Onset range of at least 38 days for LR and 28 days for the SR makes the onset windows long enough to cause uncertainties in onset dates and consequently planting dates. This verifies findings by Ngetich et al. (2014) that rainfall onset in the CHK is highly variable. The uncertainty in the onset dates has often led to poor timing of planting date among farmers which has had remarkable repercussion in agricultural production. Early planting before the onset date or dry planting could hamper seed germination and plant growth should the rains delay. On the other hand, late planting was reported to cause up to 10kg/ha yield loss after every single day of delayed planting date (Nielsen, 2009). Timely planting, therefore, is vital for the farmers as it helps increase the yield (Nyagumbo et al., 2017).

Cessation dates were spread for 12 days for LR and a period of 23 days for SR. Unlike the onset dates, cessation dates were more heterogeneous during the SR than the LR. The findings are similar to those of Camberlin and Okoola (2003) who observed high onset variability than the cessation in Eastern Africa. On the other hand, in northern Ethiopia Araya and Stroosnijder (2011) established, that over the study area, rainfall cessation date was more varying than the onset date. Like the onset, variation in cessation dates affects crop production as it makes the planning of farming activities strenuous among the farmers.

Late-onset and early cessation shorten the length of growth period which in turn may decrease water productivity (Jury, 2002). Studies conducted in semi-arid parts of West Africa also indicated that there is a significant relationship between the start of rains and the length of the rainy season (Sivakumar, 1988). Earlier onsets date and late cessation indicate a longer length of growing period. In the central highland of Kenya, the length of growing period was long enough to support the growth of a variety of crops to maturity. Portraying, the region as one of the high potential areas in Kenya categorised by Jaetzold (2007) as humid areas. However, short rains had a longer length of growing period than the long rains making it more reliable. The reliability of the SR over LR has been observed in various studies (Amissah-Arthur et al., 2002; Hansen and Indeje, 2004; Ngetich et al., 2014). The SR is the main growing season in Eastern Kenya on which annual crops such as maize, sorghum, green grams and finger millet are dependent on. Thus, farmers should focus more on the SR period as the main cropping season in the CHK to boost their productivity.

The high variability in the rainfall onset and cessation was associated with local factors and position of sites in relation to the amplitude of inter-tropical convergence zone (Recha et al., 2011). In the humid region of western Kenya, Mugalavai et al. (2008) pointed on the local effect (escarpments and Lake Victoria) plus atmospheric winds (NE and SE monsoon) to be the contributors of onset and cessation for the LR and SR. The causes being natural, farmers can only hope for precision in the climatic forecast (Recha et al. 2008; Cooper et al. 2008) to efficiently utilise the rainfall in their agricultural productivity. In the bimodal rainfall regions of Kenya, Stewart (1985) suggested growing of maize when there was early onset while millet and sorghum to be favoured over maize during late onset to reduce the impact of early planting. While the suggestion could help cut losses, maize still stand to be the staple food and farmers are willing to risk planting it even when the conditions are not favourable. Other soil moisture conservation measures that can ensure efficient utilisation of the available rainfall should be recommended to the farmers to cushion them from the losses due to the high rainfall variability in the region.

5.2.2 Spatial and temporal rainfall variation

The results show high rainfall variation both temporally and spatially. The high rainfall variation was also reported by Recha et al. (2011) in Tharaka-Nithi, where he observed year-to-year and season-to-season rainfall variation. Short rains were highly variable than the LR and the annuals as observed similar to the observation by Recha et al. (2011) in Tharaka County stating the SR as significant determinant of annual rainfall variability. Hansen and Indeje (2004) eported that the LR to be the most reliable and could be predicted with a reasonable degree of accuracy, unlike the SR. The high variability of the seasonal rainfall has thus impacted on agriculture negatively considering agricultural production in SSA is heavily hinged on the seasonal rainfall than the annual. This has made planning for agrarian production difficult. Farmers are not sure of what to expect of the rainfall pattern every year. However, there is hope that constant monitoring of rainfall pattern can help in the prediction of the expected rainfall events that could reduce the uncertainty related risks.

5.2.2 Rainfall distribution and intensity

The well-distributed rainfall pattern observed (Figure 4.6) is similar to the findings by Recha et al. (2011) in Tharaka district in the CHK over the short rain period. Recha et al. (2011) argued that the fair spread has the potential of reducing the impact of high rainfall variability. On the contrary, in Muranga County, Ovuka and Lindqvist (2000) reported poor rainfall distribution. The sparse distribution was reported to have contributed to reduced water productivity in the region. Farmers in the study area where rainfall is well distributed should, therefore, capitalise on the good rainfall distribution to balance out the impact of high rainfall variability.

Low rainfall intensity observed on the other hand is inconsistent with the global findings that there are increasing extreme precipitation events (Alexander et al., 2006). The last report from the Working Group 1 (WG1) of the International Panel on Climate Change (Summary for Policy Makers, SPM WG1-IPCC 2007) reported that heavy precipitations have increased on most of the planetary land surface during the 20th century. Groisman et al. (2005) also showed a widespread increase in the frequency of very heavy precipitations during the past 50–100 years. In Namibia, Lu et al. (2016) reported extreme precipitation events such as heavy rainfall and drought on analysing rainfall intensity. The observed low rainfall intensity thus should constantly be monitored to establish any changes in the coming years. This will help in averting the tragedies associated with extremities of rainfall such as droughts and floods which all significantly affect crop production.

The low intensity and evenly distributed rainfall in the CHK is a characteristic of relief rainfall common in the mountainous region (Elvis et al., 2015). The regions experience this type of rainfall due to the effect of Mount Kenya and the Aberdare Ranges. The Counties are all on the windward side of the Mt. Kenya and Aberdare range thus receive high rainfall amounts. On the leeward side of Mt. Kenya, the regions receive low rainfall amount with cold temperature due to the dry cooling winds that blow over the area. The low rainfall intensity is ideal for agricultural production since there is no crop destruction as a result of either droughts or floods that are common in the regions of high rainfall intensity. While there are low frequencies of rainfall extremities in the CHK, farmers still need to be equipped with control measures in preparation for such.

5.2.3 Dry spell analysis

There were high occurrences and variability of dry spell across the Counties during the years under consideration. The probability analysis also shows high chances of dry spell incidences, similar to the ones reported by Hulme (2001) and Mzezewa et al. (2010). The results indicate a high incidence of a dry spell in the study region vindicating report by Rockstrom et al. (2003) that intra-seasonal dry spells have become a common feature. Barron et al. (2003) and Mzezewa et al. (2010) reported dry spell to disrupt crop growth and lower crop yield. Mzezewa et al. (2010) associated dry spells with poor seasonal rainfall distribution that is common in most parts of the world. However, the dry spells observed across the Counties in the present study were of low magnitude considering most of the incidences were a dry spell of fewer than ten days. Depending on the severity or magnitude of the dry spell and the stage of crop growth, dry spell can cause significant damage to the crop (Ngigi et al., 2005). While even dry spell of more than five days is enough to cause a reduction in crop yield, dry spell of more than 15 days can reduce yield up to 50% or cause complete crop failure especially when the crop is at its critical growth stage (Shin et al., 2015). Even though the most frequently observed dry spell across the Counties was of low magnitude, farmers should cushion themselves from the drought-related calamities by adopting some of the cost-effective soil moisture conservation practices that are being promoted in the region. Some of the technologies include the use of organic resources and appropriate tillage practices among others (Cai and Wang, 2002; Huang et al., 2003; Wang et al., 2003; Huang et al., 2005, Lenssen et al., 2007). The practices have shown the potential of enhancing the use efficient use of the available soil moisture.

5.2.4 Comparison of satellite and observed rain gauge data

The two data sets showed consistency in the pattern of behaviour as portrayed by the visual graphical representation of the CDI. This is further supported by the Pearson correlation that also showed an agreement between the datasets with a high significance level ($p=0.001$). The correlation coefficient of onset cessation and the length of growing period also showed agreement between the datasets, implying that the satellite estimates can be used as a substitute of the observed gauge data in the prediction of onset, cessation and the length of growing period. This can be a solution to the data scarcity problem that has been experienced in the CHK and other regions that are considered remote as the satellite estimate can give rainfall reading of any particular point of interest.

Scatter plot showed an agreement between the data sets that were strongly correlated at monthly scale while weak at daily scale corroborating the findings by Lu et al. (2016) and Sungmin et al. (2016). This indicated that at a daily scale, satellite estimates are not reliable as a representation of rainfall, but at monthly scale, they can be used as either a substitute or complementary to the observed rain gauge data depending on how well such data are managed. Various studies had also established the existence of an agreement between the satellite estimates and observed rain gauge data (Mohamed, 2013; Lu et al., 2016; Sungmin et al., 2016). This gives an indication that the satellite estimates can be used not only as a complementary to the observed rain gauge data but as a substitute when properly corrected. However, correction is site specific and should be customised as per the agroecological zone.

The spatial and temporal variation in the degree of agreement observed across the Counties could be associated with the findings of various studies. The studies reported the agreement to be affected by factors such as proximity to large water bodies like oceans (Mohamed, 2013), satellite–ground misregistration (Kidd et al., 2003) and spatial and temporal resolution. For instance, satellite–ground misregistration and low spatial and temporal resolution can cause a change in both place and time of precipitation. This could result in significant differences between the satellite estimates and observed rain gauge data. Displacement in time of the precipitation leads to differences observed in the onset, cessation and length of growing period. Spatial displacement of the precipitation might also mean precipitation reading recorded in one region might be received in another region. The poor temporal resolution also explains the stronger agreement of the data sets at monthly scale than at daily scale. This is because, at monthly scale, the systematic error arising from the low temporal resolution is reduced by averaging the daily readings. Reducing the causes of such errors is essential in improving the reliability of satellite estimates.

Satellite estimate was observed to underestimate rainfall values as portrayed visually by CDI and statistically by the root mean square error that had high positive values. The finding supports the observation made by Sungmin et al. (2016) in southeast Austria while comparing the daily rainfall data from WegenerNet and observed rain gauge data that the WegenerNet data underestimated the observed rainfall. Mohamed (2013) also reported similar finding while comparing the satellite estimates from African Rainfall Climatology Project of the Climate Prediction Centre and the observed rain gauge from various regions of Tanzania. The underestimation by the satellite-based rainfall estimation was also observed by Sanchez et al. (2014) when comparing the rainfall estimates from TRMM with observed rain gauge data in Cape Verde Islands. These reports indicate that all satellite-based rainfall estimates tend to underestimate the observed rainfall. The underestimation could be as a result of physical differences between satellite retrievals and validation retrievals (Mohamed, 2013) among other factors, both statistical and environmental. While some of these causes can be improved by statistical adjustment of the various parameters involved, others are as a result of the surrounding environment, and thus correction is environment specific. This, therefore, requires further investigation to accurately come up with customised correction factor as per the region of interest.

5.3 Objective 2: Discussion on treatment effect on soil moisture and soil water productivity

5.3.1 Treatment effect on soil moisture

There was a lack of significant effect of the soil management practices on soil moisture in Kandara site ($p \leq 0.05$). In Chuka site, the observed significant effect ($p \leq 0.05$) could be due to the differences in soil types. Differences in soil types have been among the factor affecting the soil management practices response on soil hydrological properties (Mupangwa et al., 2007; Mulumba and Lal, 2008; Kahlon et al., 2013). In Chuka site, the soil was *Humic Nitisols* that is highly weathered with inherent fertility (Jaetzold et al., 2007 b) while in Kandara site the soil were *Ferralsols* characterised by low fertility and CEC. The high fertility and CEC of the *Humic Nitisols* could have resulted to the faster integration of the organic inputs to the soils thus faster response of the treatment effect. The *Ferralsols* on the other hand has low fertility and CEC that do not enhance quick integration of the organic matter with the soils causing the delay in the treatment response.

Treatments under CT had higher soil moisture compared with the minimum tillage. The high performance in the conventionally tilled soil as opposed to MT in enhancing soil moisture was unlikely. This contradicts findings reported by Bescanca et al. (2006), that MT is the best tillage method in boosting soil hydrological properties as opposed to CT as the soil pores remain continuous due to minimised disturbance. This could have been contributed by the tillage combination with organic residues and the length of time under consideration. In the short-term period, the crop residues under minimum tillage might not have wholly integrated with the soil as opposed to CT where the residues were physically mixed with the soil during the incorporation. This corroborates the findings by Bescansa et al. (2006) that in the short-term, tillage has a greater influence on soil moisture conditions than crop residue.

The physical mixing up of the crop residues and *Tithonia diversifolia* hastened the process of the organic residue incorporation with the soil thus faster improvement in soil hydrological properties under CT than under MT. The rate of organic residue integration with the soil also explains why treatments with *Tithonia diversifolia* show improvements in soil hydrological properties in short-term period than other organic materials like animal manure. This is because the rate of decomposition of *Tithonia diversifolia* is fater than other organic materials used in the treatments. Treatment combination with mineral fertiliser had the least amount of soil moisture. This could be due to an increased rate of soil moisture utilisation by the crops. Addition of mineral fertiliser leads to faster crop growth and development, which translates to a high rate of soil moisture depletion. This could have led to the low amount of soil moisture detected on treatments with mineral fertiliser. It is therefore prudent that all factors of production are adjusted to the optimal levels if the combined effects are to be realised in full capacity.

It can be postulated that the practices which quickly enhance soil hydrological properties might not hold the positive results for the long-term period as their effectiveness may fade as fast. This is due to the high rate of biomass loss in the soil due to quick decomposition as a result of the physical disintegration of the organic input during CT. The labile nature of some of the organic inputs also allows for the fast decomposition. Examples of some practices include CT and use of high decomposing organic residues like *Tithonia diversifolia*. Thus the use of MT and more recalcitrant organic materials might take long before being effective, but the impact can last for a long time. While instant results are good, sustainability is more important. Thus practices that are more sustainable are better promoted like continuous use of the organic resource as they can boost soil quality in a more sustainable manner.

5.3.2 Treatment effect on soil water productivity

Differences in the soil types between the two sites could be the reason for lack of significance of treatment effect in Kandara site in most of the depths as opposed to the significant effect observed in Chuka in all the depths under consideration. Soils in Chuka site categorized as *Humic Nitisols* that are deep, well drained and have inherent fertility unlike the *Ferralsols* in Kandara that are strongly weathered of the humid tropics with low fertility due to low mineral contents and a low CEC of less than 16 me/100g of clay (Jaetzold et al., 2007 a). The low CEC affect even the adsorption of the applied nutrients into the soil as they are leached into the deeper soil layers before being sufficiently taken up by plants. Nutrient use efficiency is therefore low in such soils. Continuous application of the organic resources on such soils could boost the CEC. Therefore in long-term basis, the management practices could have a significant effect on Kandara site just like in Chuka.

The high water productivity realized on treatments under CT with crop residue plus mineral fertilizer with or without animal manure (CtRFM and CtRF) which recorded low amount of soil moisture is due to high yield realized under these treatments. Water productivity defined as the net return for a unit of water used (Molden et al., 2010a). In crop production, higher water productivity could be due to either the same production from less water resources or higher production from the same water resources (Zwart and Bastiaanssen, 2004). In this case, there was high production from the same water resource.

The inclusion of mineral fertilizer known for boosting the crop yield, especially when used together with the organic input resulted in increased crop yield. Organic plus inorganic inputs have been known to have positive synergies that improve agricultural productivity (Mugwe et al., 2008). The effect is also almost instant and can be realized within a short period. The increase in yield thus contributed to improved WP even after two cropping seasons. The organic inputs enhanced water productivity value as it ensured the available moisture was utilized in the most efficient way and reduced the soil moisture losses. This is consistent with the findings of Mupangwa et al. (2007) that organic resources enhance WUE as it ensures water is held on the soil surface long enough to allow for sufficient water infiltration. The same water available was used efficiently with minimal loss, therefore, contributed to the observed increase in WP. Conventional tillage performed better than the MT under the short term period as it enhanced decomposition and integration of organic residues in the soil via the physical mixing during tillage. Improved hydro-physical properties and release of organic nutrients into the soil was therefore realised faster than under the MT making it the best at least for the short term duration. While CT has been reported to reduce soil moisture infiltration rate and water holding capacity among other shortcomings about soil moisture conservation (Jin et al., 2008), in this study, the role it plays in enhancing organic resources integration with the soil outweighed its shortcomings on the short term. This soil management practices, however, needs further investigation in the long term to identify a more sustainable and effective practice.

5.4 Objective 3: Discussion on treatment effect on soil physical properties

Lack of significant differences across the treatments on soil bulk density, saturated hydraulic conductivity and aggregate stability could be due to the short study period. Significant changes of the treatment effect can be expected under long-term study. For example, organic matter takes an estimate of 10 to 12 years to cause observable change in the soil at 20 cm depth (Hejazi et al., 2010). Observable changes are also influenced by soil type, depth, climate and management practices being implemented. Considering the vital role played by soil physical properties on soil quality, practices that will enhance the soil properties sustainably should be investigated and advocated for to ensure improved soil quality (Wright and Hons, 2005). Therefore, long-term study of the soil management practices on the soil physical properties should be conducted.

5.3 Conclusions

Rainfall in the CHK is highly variable, but well distributed with a low incidence of precipitation extremities. Dry spells are common in the region with high probabilities of future occurrence but of low magnitude. Rainfall characteristics should be continuously monitored, and the findings relayed to the farmers to reduce some of the hydrological risks associated with rain-fed agriculture. Satellite rainfall estimates have a strong agreement with the observed rain gauge data especially at monthly scale, aside from the underestimation. Thus the satellite estimates can be as a reliable data source in place of the rain gauge data that are scarce and needs high maintenance upon proper correction. This will boost the efficiency and reliability of rainfall prediction that in turn makes planning for agricultural activities more feasible and practical.

Use of organic and inorganic input plus appropriate tillage has a significant impact on soil moisture and WP even under short-term period. Soil management practices that are under convention tillage with organic residue performed better than the ones under MT with or without organic residue in enhancing soil moisture. Practices that had mineral fertiliser recorded the lowest soil moisture reading while they boosted water productivity than the ones without. Again treatments under CT performed the best in enhancing soil water productivity under a short-term period of the study. However, practices under CT might not maintain the high performance on the long run as the faster rate of organic residue integration might mean the higher rate of losing the residue thus not sustainable in the long run. Soil disturbance due to tillage has been reported to discontinue the soil pores affecting most of the soil hydrological and physical properties like hydraulic conductivity, water holding capacity, bulk density and aggregate stability among others.

The treatments had no significant effect on soil physical properties. For any significant change to be noticed, the study should be conducted on a long-term basis. For sustainability purposes, use of both organic and inorganic inputs should be encouraged as this will ensure improved water holding capacity, water use efficiency, increased in crop yield and enhanced soil physical properties. The effectiveness of these soil management practices also proved to vary with the soil type and the climatic conditions making them site specific.

5.4 Recommendation

- Farmers to capitalize on the well distributed rainfall with low intensity to reduce the impact of the high rainfall variability.

- CtRTM to be promoted for improved soil water content and CtRFM and CtRF to be promoted for improved soil water productivity under short term
- Use of organic and inorganic inputs plus tillage practices to be investigated under long term to come up with practices that can sustainably improve available soil moisture, water productivity and soil physical properties (Bulk density, aggregate stability and hydraulic conductivity) in Chuka, Tharaka-Nithi County and Kandara, Murang'a County.

5.5 Areas of further research

Continuous characterisation of rainfall should be conducted to detect any changes that might arise to ensure those changes do not affect rain-fed agriculture. Further validation should be performed on the satellite estimates and customised for every region to boost the accuracy with which the satellite rainfall estimates represent the observed rain gauge data.

The effect of organic and inorganic inputs plus the tillage practices should be investigated under long-term study to establish the most sustainable method that can enhance soil moisture, soil water productivity and soil physical properties.

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