EFFECTS OF CROPPING SYSTEMS ON SOIL QUALITY AND CARBON SEQUESTRATION POTENTIAL IN KAUWI AND ZOMBE WARDS OF KITUI COUNTY, KENYA

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DECLARATION

I understand that plagiarism is an offense and I, therefore, declare that this thesis is my original work and has not been presented to any other institution for any other award.

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Supervisor's Approval

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TABLE OF CONTENTS

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

CHAPTER SIX

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

FAO	**:**	Food Agriculture Organization
GDP	**:**	Gross Domestic Product
UNDP	**:**	United Nations Development Programme
CIDP	**:**	County Integrated Development Plan
NPK	**:**	Nitrogen, Phosphorus and Potassium
SOM	**:**	Soil Organic Matter
SOC	**:**	Soil Organic Carbon
POM	**:**	Particulate Organic Matter
ISFM	**:**	Integrated Soil Fertility Management
RBD	**:**	Randomized Block Design
MBC	**:**	Microbial Biomass Carbon
SSA	**:**	Sub-Saharan Africa
BNF	**:**	Biological Nitrogen Fixation
C	**:**	Carbon
CO_2	**:**	Carbon dioxide
EC	**:**	Electrical Conductivity
CD	**:**	Critical Difference
SLM	**:**	Sustainable Land Management
MAM	**:**	March April May
OND	**:**	October November December
SBD	**:**	Soil Bulk Density
TCS	**:**	Total Carbon Stock
FFAC	**:**	Factory Farming Awareness Coalition
OPSTAT	**:**	Operational Statistics
MOA	**:**	Ministry of Agriculture
ASAL	**:**	Arid and Semi-arid Lands
IPCC	**:**	Intergovernmental Panel on Climate Change
GOK	**:**	Government of Kenya
Ha	**:**	Hactare

ABSTRACT

The use of incorrect agricultural methods and utilization of land, excessive inorganic chemical applications, misguided cultivation, and nutrient mining have all contributed to a considerable deterioration in soil health globally. These factors have resulted in bad soil quality. Soil quality decreases as a result of the adoption of agricultural management practices that farmers have relied on as supplements or replacements for biological functions. This research aimed to determine the geographical and seasonal variation of soil quality under different cropping systems in the Kauwi and Zombe wards of Kitui County, as well as the soil carbon sequestration potential of these systems. Since no attempts were made to influence the outcomes of the study's variables, a descriptive research strategy was used. Vegetable, cereal, fruit, and agroforestry-based cropping systems were chosen on purpose in both the Kauwi and Zombe wards. As a comparison, uncultivated land was chosen as control. During the typical long (MAM) and short (OND) rainfall seasons, composite soil samples were taken from the cropping systems at random. The treatments consisted of five identical sets of the chosen systems planted in the farmers' fields. The OPSTAT statistical analysis tool was used for data coding and analysis. Soil pH and Soil organic carbon were shown to be significantly affected by the interplay between cropping strategies and locations. Zombe's vegetable cropping strategy resulted in the lowest soil pH and electrical conductivity values. Under a vegetable-based cropping scheme, soil organic carbon and NPK were likewise shown to be greatest in Zombe ward. Soil bulk density varied between 1.66 and 1.56 Mg m^{-3} in Kauwi and between 1.66 and 1.80 Mg m^{-3} in Zombe, according to the analysis of spatial variation. Significant differences were seen in soil pH, EC, carbon, and NPK across cropping systems and wet/dry periods. Greater carbon stock (95.52Gg C) was found in the Zombe ward, which corresponded to a greater carbon density (4.55 Mg C ha^{-1}) under vegetable-based cropping system followed by Agroforestry (36.53Gg C). As a result, the maximum capacity to sequester soil carbon was found in the vegetable-based cropping system, regardless of the location, as measured by carbon density, in both the Zombe and Kauwi wards. Because of the high retention of carbon rates achieved by vegetable and agroforestry cropping systems, governments at all levels should educate and encourage farmers to switch to these methods in order to improve soil quality and mitigate effects of climate change.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the study

Soils perform many functions for purposes of supporting agro- ecosystems. Numerous agroecosystem support functions rely on the properties of soils. They provide a structure for plant growth, a reservoir for a wide variety of nutrients necessary for the survival of plants, and a filter that regulates air quality via interactions with the atmosphere. Soils also provide a medium for storing and purifying water as it percolates through, and a location where biological life is engaged in the decomposition and recycling of plant and animal products. Many of these characteristics of soil have been undermined by methods that have failed to account for their interdependence (Oldeman, 1992).

For subsequent generations to enjoy the same level of agricultural output and environmental quality that we have currently, the quality of the soil essentially needs to be preserved and even improved. Agricultural, industrial, and commercial pollution; loss of arable land due to urban expansion, overgrazing, and unsustainable agricultural practices; and long-term climatic changes have resulted to soil degradation (Maximillian *et al.*, 2019). Losses in output resulting from declining soil quality may frequently be compensated for and covered by increased technology and inputs used in today's agricultural production systems. However, the National Research Council (1993), discovered that when agricultural inputs were increased, economic sustainability was reduced and environmental quality was placed at greater risk.

Inappropriate agricultural techniques and land usage have led to a global 12.5% drop in soil health during the previous few decades (Arshad *et al.*, 1997). Inappropriate cultivation, nutrient mining, and overuse of inorganic chemical treatments are some of the activities that may have degraded soil quality (Xiubin *et al.*, 2002). The rising worldwide need for food is a major contributor to these harmful activities. The world's population average annual growth rate was 1.1% between 2015-2020 (Gu *et al.*, 2021). According to the United Nations the global population will grow from the current 7 billon people to 9.3

billion in 2050 and 10.1 billion in 2100 (Lee, 2011). To meet the requirements of a growing inhabitants, farmers have turned to unsustainable methods including monoculture, excessive use of pesticides and fertilizers, and increased agricultural intensification (Tillman *et al.*, 2012).

Agricultural management practices that augment or replace biological functions disrupt the ecological balance and degrade soil quality (Kibblewhite *et al.*, 2008). Large-scale use of highly productive variety of plants and the practice of monoculture, in which only one kind of crop is cultivated at a time on a specific plot, have led to efforts to increase agricultural yields as a consequence of the monetization of agriculture (Pardey *et al.*, 2014). This monoculture farming strategy limits the land's ability to provide essential ecosystem services including soil health and carbon storage (Gebru, 2015). Soil carbon declines, negative soil reactions rise, and nutrients become less available when farmers exclusively plant one crop (Loria *et al.*, 2016).

Intensified cultivation practices, the emergence of crop varieties that are high-yielding, and the greater use of agricultural inputs like herbicides, synthetic fertilizers, irrigation, and automation have all led to a rise in crop output during the past several decades. However, these have led to some unintended consequences, including increased soil erosion, reduced soil fertility, quality, and biodiversity, increased groundwater pollution, lake eutrophication, and a rise in greenhouse gases (Matson *et al.*, 1997). In order to mitigate these negative consequences, soil quality must be (Steffan *et al.*, 2018) improved by the use of conservation tillage, improved organic matter management, and the incorporation of legumes into crop rotations (Lal, 2009a).

Large swaths of Africa are severely nutrient deficient, extremely acidic, or poor in organic carbon as a result of extreme old age, punishing weather, and decades of unsustainable management (Uphoff, 2013). The high rates of child mortality, stunting, and wasting in Africa have long been linked to low soil fertility (Bloss *et al.*, 2004). Soil health may be improved by adding magnesium, zinc, or other frequently deficient elements to soils using specially formulated fertilizers (Jones *et al.*, 2013), but doing so needs knowledge of the soil's specific inadequacies, which can vary greatly even across relatively small distances . Moreover, despite the fact that agriculture is still a vital part of SSA's economy, the region's performance in this area has been dismal and is often regarded as among the worst there is in the world (Otsuka & Larson, 2016; Sanchez *et al.*, 2002). The performance in the sector is poor thus has led to a drop in food output, among other things. There has been a 17% drop in food output per person in SSA since 1970 (Ehui & Pender, 2005). This trend has repercussions for the pervasive rural poverty in SSA (Chamberlin & Ricker-Gilbert, 2016; FAO, 2015), making it one of the areas endangered by food insecurity. It is hardly unexpected that most SSA nations continue to be net food importers given the sector's low performance (Schram *et al.*, 2013).

Most of Kenya's most fertile farmland is located in urban areas where it is at a premium (Ngenoh *et al.*, 2019). Kenya's agricultural industry continues to be an important economic driver, directly accounting for 26% of GDP and indirectly contributing to another 27% of GDP via links to other industries (Alila & Atieno, 2006). More than 70% of the rural population of Kenya works in agriculture (FAO, 2018), and this accounts for more than 40% of all jobs in the country. The number of people globally has also risen dramatically, from 11 million in 1970 to 39.5 million in 2011, and is projected to double in the following 27 years, to 81 million in 2039, at the current growth rate of 2.5% (Amwata, 2020). This fast growth is reducing the amount of available parcels of land in regions with strong agricultural potential, the adverse effects of this phenomenon are reflected in the deterioration of the quality of soil and reduction in agricultural productivity. The potential of the storage of soil carbon to enhance agricultural yields is significant, particularly given the pressing need for increased food production to meet the demands of Kenya's rapidly expanding population. Kitui, a dry and semiarid region, relies on both agriculture and cattle production for its economy. Subsistence farming is the norm, with any excess sold on the market. As a consequence of the region's increasing commercialization, farmers there are now practicing intense crop management and choosing high-yielding crop types, such as green grams. Furthermore, the 'ndegu (Vigna radiata) revolution' is a flagship initiative for the Kitui County Government in 2018, and is promoting such crops as a means of creating wealth for the local populations. However, intensive soil management—which includes practices like mineral fertilization, excessive use of pesticides, and the use of heavy agricultural machinery—results in soil quality being compromised (Loria *et al.*, 2016). This is because monoculture reduces soil carbon and promotes adverse soil reactions. Damage to soil fertility, soil ecosystem services, and reduced nutrient availability results from breakdown of soil structure, deposition of organic materials in the soil, and decrease in fungal community due to rise in bacterial population (Rousk *et al.*, 2010).

It is important to examine how various cropping methods affect soil quality. (Hegde, 1996) explains that when we talk about cropping systems, we're referring to a predetermined sequence of crops, a set of crops that make up the system, and the frequency with which these factors interact. In order to quantify soil quality and improve cropping system sustainability (Aparicio & Costa, 2007) a better comprehension of the effects of various agricultural practices on physical and chemical soil parameters and the soil potential for carbon sequestration is essential.

1.2 Statement of the problem

Soil is an essential part of Earth's ecosystem and the most valuable renewable natural resource. Low agricultural productivity, climate change and threatened livelihoods are the result of global vulnerability in ASALs, which is led by damage to the environment, detrimental land use practices, and a lack of awareness on the retention of carbon. This results in low adaptive capacity and increased carbon emissions (Rabach *et al.*, 2020) In addition, soils are under constant stress due to population growth, which is causing deterioration and rendering the soils increasingly unsuited for cultivating crops. The necessity for increased agricultural productivity for increased food production in Kitui County is growing. The monoculture system of growing crops, which diminishes soil quality, has been led by the commercialization of agriculture. The use of heavy gear like tractors, the use of synthetic fertilizers, as well as the application of insecticides and other agro-chemicals are all examples of the intensive soil management that has been utilized to ensure effective output. Soil fertility rates, nutrient imbalances, and environmental quality are all adversely impacted by intensive soil management approaches.

Farmers in Kitui County's Kauwi and Zombe/Mwitika wards use unique cultivation techniques, each with its own distinct effect on crop production and the county's agricultural sector as a whole. Farmers' practices for managing soil have a direct effect on soil quality, thus it's important to analyze and evaluate how different cropping systems affect soil quality. A decrease in soil quality brought on by the commercialization of agriculture and intense soil management may be the cause of the decrease in crop yields seen in both areas.

Soil quality in agricultural systems can potentially be investigated and observed via cropping system analysis, which can then be used to create a sustainable management plan for the protection of soils and, by extension, the generation of sustainable yields. Therefore, the goal of this research was to examine how various cropping systems influence soil quality, and estimate the capacity of soil to absorb carbon dioxide and store it.

1.3 Objectives of the study

1.3.1 General Objective

To evaluate the effects of cropping systems on soil quality and carbon sequestration potential in Kauwi and Zombe wards of Kitui County.

1.3.2 Specific Objectives

i. To assess the spatial variation of soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County.
ii. To determine the seasonal variation of soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County.
iii. To determine the soil carbon sequestration potential of different cropping systems in Kauwi and Zombe wards of Kitui County.

1.3.3 Hypothesis

HO_1: There is no statistically significant spatial variation in soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County.

HO_2: There is no statistically significant seasonal variation in soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County.

HO_3: There is no statistically significant relationship between different cropping systems and soil carbon sequestration potential in Kauwi and Zombe wards of Kitui County.

1.4 Significance of the study

This study has generated knowledge that has helped to develop succinct recommendations that will be used to educate farmers on what cropping systems and nutrient management practices to use in their farms. This study will help educate farmers on the best cropping systems and nutrient management practices to use in their farms. The findings of this study will inform formulation and adoption of policies that will lead to improvement of the quality of the soil consequently increased crop yield. The findings will also be utilized by organizations in the agricultural and environmental sectors to make informed choices on suitable cropping systems and nutrient management methods to promote to enhance soil quality. The findings will lead to food security and economic gains in Kauwi and Zombe wards. Additionally, the identification of cropping systems with the highest soil carbon sequestration potential will guide on the adoption of such systems hence mitigating climate change.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil quality management practices

2.1.1. Overview of soil quality and land degradation among smallholder farmers

In the most productive agricultural regions of Africa, the breakdown of soil is at a staggering 65 percent, as reported by the United Nations Development Programme in 2000. Depleted soil fertility caused by land degradation is a huge contributor to falling production of food per person in the African Continent, particularly among the continent's smallholder farmers (Lal, 2009b). A key danger to sustainable land management is the rising need to expand smallholder agricultural methods to provide for sub-Saharan Africa's fast expanding population. Degradation, high susceptibility, depletion, and ineffectiveness in soils have been led by the adoption of intensive agriculture. Although traditional attempts to enhancing soil management have centered on fewer technologies that end up not being locally accepted by farmers, smallholder farming systems are varied and dynamic (Kuria *et al.*, 2019). Harvests are roughly 2–4 times lower than the potential per capita food production due to poor quality of the soil, which has been ascribed to insufficient nutrition intake from the environment compared to exports, primarily through products that have been harvested, erosion, leaching, and gas loss. For example, (Okwuosa *et al.*) 2006 found that in western Kenya, over 70% of smallholder farmers have poor crop output due to low soil fertility and insufficient financial means to purchase inputs. Organic inputs like animal manures are accessible, but in little quantities and of poor quality, and the expensive cost of fertilizer has led to their infrequent and low use, which cannot boost and maintain output.

Soils in Kenya are often regarded as having diminished levels of nitrogen (N), phosphorus (P), and potassium (K). Additionally, highly inhabited places are where you'll find the most productive arable land, with less than 1 ha available to families of 5-8 people (Smaling *et al.*, 1993). In semiarid regions like Kitui County, for example, people tend to live on enormous, unproductive plots of land that are very fragile.

Sub-Saharan Africa's fertility of the soil is decreasing, which poses a significant challenge to agricultural productivity. This is especially true for smallholder farmers whose wages are modest. During their time spent working in the Mt. Kenya East area, (Wawire *et al.*, 2021) investigated smallholder farmers' approaches to soil fertility management in order to better understand the barriers to widespread adoption of integrated soil fertility management (ISFM) techniques in the region. Agroforestry and fertilizer/manure application were found to be the most often used methods among farmers. The research also found that a number of institutional, farm-related, and socioeconomic variables were strongly connected with farmers' decisions to invest in fertility techniques. On-farm labor and family size were significant predictors of manure and fertilizer consumption. Because farmers' resources, such as money and manpower, influenced the methods they used, it was important to investigate which strategies made the most sense for various farm setups.

The loss of ecosystem function and production over time due to disturbances from which the land is unable to recover naturally is known as land degradation (Bai *et al.,* 2008) . It has been shown to develop gradually and steadily, with regional variations throughout time. Degradation of land is a problem that arises in the context of global development and the environment, as stated by the United Nations Convention to Combat Desertification (UNCCD). Land productivity has been shown to decrease, especially in dry regions, putting local inhabitants in a position where they are more vulnerable to the consequences of climate change. It has been shown that desertification is the most severe form of land degradation. Approximately 64% of Kenya's land area is threatened by mild desertification, according to studies (Macharia *et al.*, 2015).

Many low-income families worldwide, especially in the arid plains of Kenya, rely on commodities and services provided by land ecosystems, and this sector is particularly vulnerable to land degradation. Kenya is an agricultural country, yet its degraded land is home to nearly 12 million people (Bai *et al.*, 2008). Unfortunately, during the last several decades, the country's food crop production development has led population expansion to outpace it (Waswa, 2012). Most smallholder plots produce less than 1 metric ton of the principal grain, maize, per hectare (Muasya & Diallo, 2002; Waswa, 2012). This result has had serious consequences for people's standard of living in rural areas and the economy as a whole because of land degradation and the accompanying "nutrient mining."

It is imperative that nations and communities employ robust measures of land rehabilitation and reclamation in order to halt the current rates of land degradation. Increased funding for research and extension is essential, say (Mulinge *et al.*, 2016), if we are to fulfill the demands of a rising population for food, lumber, fiber, and biomass energy. The need to reverse the development of natural areas into farmlands is also crucial in increasing support for biodiversity protection. If the costs of implementing sustainable land management practices can be decreased by the establishment of connections to carbon markets, then there is a greater likelihood that these practices will be implemented. It is vital for public investments to be raised in environmentally responsible land management if there is to be a reduction in land degradation and an improvement in the rate of reclamation of degraded regions. The degradation of land, which is often a constraint on economic productivity, may further obstruct Kenya's poorest regions' chances for economic development.

2.1.2. Soil Quality Indicators and Management Technologies

Farmers use a wide variety of indicators, such as crop production, soil color, compactness, odor, and plant composition, to determine the fertility of their soils (Odendo *et al.*, 2010). Constant cultivation causes these markers to evolve over time. For instance, as soil fertility declines, the soil's color changes from dark red to brown, the soil's odor fades, and the soil's flora changes. Therefore, it is necessary to apply fertilizers, both chemical and organic, to the soil in order to increase its fertility. However, manure is used seldom since there is rarely enough of it on farms to keep the soil fertile (Odendo *et al.*, 2010). However, smallholder farmers are unable to use mineral fertilizers due to a lack of finance and unpredictable markets for their crops.

The physical, chemical, and biological markers of soil quality in Spanish vineyards subjected to different agricultural methods were studied by (Andrés *et al.*, 2022). He found that the soils of those vineyards had been severely degraded, had low levels of soil carbon, and lacked in biodiversity. In order to mitigate the negative effects of soil degradation on climate change mitigation, water quality, and plant productivity, he foresaw a transition from intensive cultivation to more sustainable management practices, such as limited tillage and regenerative cultivation of the vineyards. This was done in order to combat the negative effects of soil degradation. After comparing the soil quality of three vineyards that were managed in three different ways (intensive management, regenerative strategy, and minimal impact strategy), a researcher found that soil carbon stocks were 2.3 and 3.4 times greater in the regenerative and minimal impact vineyards, respectively, than in the intensive vineyard. This was found after comparing soil quality from the intensive management vineyard. The presence of 26.2% more protists, 3.1% more nematodes, and 29.4% more micro-arthropods in the regenerative vineyard in comparison to the intensive vineyard provides evidence that regenerative viticulture improves soil biota. Degraded agricultural soils in the Mediterranean region may likely be restored by ecological intensification of diverse agricultural systems, as shown by this research.

(Hofny-Collins, 2006) assessed 108 Accra-based farmers using a variety of urban cropping methods. He discovered striking disparities across the cropping systems with regard to the soil fertility management strategies used. Rain-fed crop farmers, such as those who grew maize, traditionally employed techniques including crop rotation, fallowing, and crop residues, supplemented with artificial fertilizer and chicken manure, to maximize yields. Those that raised veggies all year needed a lot of help from other sources. According to the poll, although the majority of farmers (93%) utilized chicken dung to fertilize their crops, just 56% relied on synthetic fertilizers. Cabbage, for instance, received an annual application rate of 75kg/ha to 180kg/ha of the fertilizer NPK 15-15-15, with the precise quantity depending on the farmer's expertise and the soil type.

Previously considered garbage and deposited along roads or burnt (Quansah *et al.*, 2001), Kumasi now routinely applies chicken manure. Farmers believed that manure was superior to artificial fertilizers because it was less expensive, released nutrients slowly, and improved soil quality. The manure's quality notably changes with age and origin (broilers vs. layers), as observed by (Amoah *et al.*, 2006).

According to research by (D. Koné *et al.*, 2010), black soil is highly prized by growers of flowers and other ornamentals. Black soil, as known by Ghanaian farmers, is the dark, humus-rich topsoil that may be found in both forests and degraded garbage dumps.

The term "black soil" is used by Ghanaian farmers to describe the dark, humus-rich topsoil found in places like untouched woods and degraded garbage dumps. High quality black dirt is greatly sought for. The removal of black dirt from natural soils has a detrimental effect on the ecosystem, and its continued harvesting makes it harder to discover. Since 2010, farmers in the Volta region and the Accra plains have experimented with biochar made from rice husks, sugar cane remains, wood chips, and sawdust, and in Kumasi, on red soils (Yeboah *et al.*, 2022), and in Tamale, on sandy loams, they have tried growing both native and exotic vegetables. Human manure is also used seasonally (septage carrying vehicles transport feces to the farmers). This has been seen in peri-urban agriculture, namely in the production of grains other than vegetables, particularly maize. This custom is widespread in the region around Tamale, Ghana.

2.2 Cropping systems impacts on soil quality

2.2.1. Overview

(Emmerling *et al.*, 2002) conducted research that led to the discovery and quantification of chemical and biological soil quality indicators for agroecosystems. Because of the fast reaction that these indicators provide to shifts in soil condition, they are used in the process of assessing the current state of soil quality. According to (Palma *et al.*, 2000), two examples of these markers that have gotten a lot of attention in the literature are features that are microbiological and biochemical in nature. These activities are connected to the accumulation and recycling of soil organic matter (SOM), which is a significant component in determining the quality of the soil (Koutika *et al.*, 2001). Soil organic matter (SOM) is especially important in tropical soils because clay, which has a high exchange capacity, is often lacking in these regions (Ayanlaja & Sanwo, 1991). SOM's importance in preventing nutrient loss, sustainable management practices aimed at keeping SOM levels high are essential (Okpara *et al.*, 2005).

According to the findings of a study by (W. Koné *et al.*, 2008) on the changes in soil biological quality caused by legume- and maize-based agricultural systems, the content of soil organic carbon (SOC) has increased over time in a wet savanna zone in Côte d'Ivoire when legume-based systems were used. Between the beginning of the trial and the end of it, the SOC varied anywhere from 7.5 to 8.6 g/kg (or 14.7%), and it ranged anywhere from 7.2 to 8.3 g/kg (or 15.3%), with the legume-based system exhibiting the biggest comparable increase. Using inorganic fertilizers in combination with mulch made of corn and grass wastes was proven to be an approach to increasing SOC levels in the near run. Microbial biomass carbon (MBC) values did not vary significantly across treatments, even though legume-based systems indicated the highest values. Compared to maize continuous cropping systems (33.111.6 mg C-CO_2/g Corg), legume-based systems had higher mean values for soil C mineralization and soil specific respiration (427.6 and 0.4mg C-CO_2/g biomass C, respectively). The research found that in Côte d'Ivoire's wet savannas, soil quality may be improved to a point where food production can be sustained by including legume-based cover crops into agricultural systems.

The effects of different cropping techniques on selected soil essential features and expected crop yields in Thailand were studied by (Sarwar *et al.*, 2008). This study was to emphasize the influence that residue management and tillage direction have on the decline of chosen soil structural characteristics and, in turn, crop yields across four typical cropping systems (maize-maize, mungbean-maize, cassava, and maize-fallow). The goal of this research was to highlight the impact that residue management and tillage direction have on the decline of selected soil structural properties and, in turn, crop yields. It was discovered that the structural quality of the topsoils produced by the mungbean-maize and cassava systems was higher than that produced by the maize-fallow and maize-maize systems respectively. The soil organic matter value was determined to be greatest for the mung bean–maize system. Only root density and soil shrinkage were shown to be significantly affected by the direction of residue management and tillage. There was little to no difference between the four cropping systems in terms of the specified subsoil structural parameters. In terms of average and second-crop yields, the mungbean-maize and maize-fallow systems considerably outperform the maize-maize system. The study's results also led to the conclusion that cropping practices have both positive and negative impacts on the topsoil's structural qualities and the average crop production in the region. In the cassava plant structure, pore size and SOM decreased, but in the non-dispersed method, soil distortion, permeability, packing thickness, volumetric density, and sand significantly indicated enhanced structural quality. The data showed that the root density, dominant pore size, pore distribution/frequency, and SOM of the mungbean-maize system were all significantly enhanced. This is in contrast to the fact that shrinkage, porosity, and bulk density were all negatively affected.

2.2.2 Tillage-rotation interactions and agronomic sustainability

Crop rotation is a cropping method that is essential for maintaining economic viability in addition to maintaining soil quality by providing increased above- and below-ground residues for soil C input. (Reeves, 1997), summarized a research that found that growing corn and soybeans in rotation reduced the impact of no-till farming on yields on soils with poor drainage. U.S. researcher (Hammel, 1995), discovered that chisel plowing with no-tillage produced much higher yields than moldboard plowing for winter wheat. However, a 3-year wheat-barley-pea rotation resulted in higher wheat yields than a 2-year wheat-pea rotation in both the chisel plow and no-tillage systems. Winter wheat yields increased on the same Ultic Haploxe- roll soil as continuous wheat yields decreased (Young *et al.*, 1994). However, the highest response was shown in a conservation tillage system (chisel plow-no-tillage cycle).

Two-year rotations of red clover and barley, soybean and alfalfa, and soybean and wheat and red clover increased corn yields by 3.9% in conventional tillage and 7.9% in minimal tillage compared to continuous corn in a 10-year trial in Ontario, Canada (Raimbault & Vyn, 1991). When comparing continuous corn versus a rotation based on legumes, the latter is shown to increase aggregate stability. Over the course of eight years, (Bruce *et al.*, 1990) in northern Georgia, USA compared the results of no-tillage, strip-tillage (in-row chisel and no-tillage), and conventional tillage (disk harrow) while growing wheat alongside soybeans and sorghum. Sorghum yields fell when tillage was made more intensive during the second 4-year cropping cycle of the rotations. The incorporation of sorghum into the crop rotation has a beneficial effect on soybean production. (Bruce *et al.*, 1990) dug further and discovered that sorghum improved aggregate stability, air-filled pore space, and bulk density after two or more sequences compared to soybean. After 2 years of sorghum in the no-tillage system, infiltration rates were found to be higher, but with conventional tillage, rotation had no effect on infiltration rates. The results showed that crop rotation's positive benefits on soil physical qualities might be nullified or hidden by tillage. Tillage-induced oxidation of residues may eliminate surface soil characteristics, such as aggregation, that arise from variations in residue amount and quality between crop species in a region. Also, tillage eliminates variances in soil structure caused by rooting patterns and other biological activities connected to a crop rotation's individual plants. (Chan & Heenan, 1996).

(Mikha *et al.*, 2006)conducted research in the Great Plains over a period of four years (1999-2002) in order to determine the effects of cropping systems on soil chemical properties and soil quality. The researchers measured soil carbon (SOC), total nitrogen (TN), particulate organic matter (POM), inorganic nitrogen, electrical conductivity (EC), and soil pH at depths of 0-7.5, 7.5-15, and 15-30 centimeters under conventional and alternative cropping systems. The effects of the treatment were felt most acutely in the upper 7.50 cm of the soil. At five of the eight research sites [Akron, Colorado (CO), Bushland, Texas (TX), Fargo, North Dakota (ND), and Mandan, North Dakota (ND), and Swift Current, Saskatchewan (SK), Canada], no-tillage (NT) and/or the absence of fallow in ALT cropping systems resulted in significantly higher levels of SOC and TN at 0-7.5cm. This was also shown with POM, with four of the eight study sites having considerably (P 0.05) greater POM levels. These locations include Bushland, Texas; Mandan, North Dakota; Sidney, Montana; and Swift Current, Saskatchewan. There was no discernible pattern seen between EC and pH as a direct result of management, despite the fact that soil EC accounted for about 60 percent of the total variation in soil NO_3-N at depths ranging from 0 to 7.5 centimeters across all sites and sampling periods. In this study, the chemical soil characteristics consistently revealed higher values in ALT cropping systems, which were advantageous to crop production and environmental quality, than in CON cropping systems. This was the case even though the CON cropping systems were the control group.

(Mloza-Banda *et al.*, 2016) investigated conservation agriculture (CA) and annual ridge tillage (RT) as cropping systems among small-scale farmers in order to assess the early impacts on soil characteristics in the southern portions of Malawi. The research compared the effects of two and five years of practicing conservation agriculture on the same kind of soil with genetically equivalent maize produced on neighboring ridge tillage plots. The study was carried out in the United States. In order to investigate the chemical and physical qualities of the soil, samples were taken from each of the twenty plots at depths ranging from 0 to 10 centimeters and from 10 to 20 centimeters. There was not a statistically significant difference seen in the soil bulk density or total porosity (POR) between the CA and RT plots, as determined by analysis of variance (ANOVA) and comparison of mean values. However, as compared to CA approaches, RT had a tendency to preserve better soil aggregation and root-zone ventilation properties (air capacity, AC). Plots that were maintained utilizing conservation agriculture had increases in all of the following by the fifth year: soil organic carbon, total nitrogen, accessible phosphorus, and cation exchange capacity. The amount of water that was present in the field at capacity and the relative water capacity (RWC) were both significantly higher when conservation agriculture was used. This was the case over the whole range of years that were analyzed. The benefits of improved soil management are maximized when the attention is placed on the volumetric water content of the soil, the percentage of soil organic carbon, the chemical properties, and the air-water storage capacity of the soil. As a result of these results, it was suggested that pertinent future studies of soil quality be taken into consideration in order to follow the implications of land use change in agroecosystems that are similar to one another.

2.3 Carbon Sequestration Practices

According to (Fowles, 2007), the term "soil carbon sequestration" refers to the process of restoring degraded or severely disturbed soils and increasing their concentration or pools of organic carbon. This is accomplished through a change in land use and the adoption of management practices that are typical in agricultural, pastoral, and forestry ecosystems. In contrast to the confinement of organic carbon in geological formations, the sequestration of organic carbon in soil involves the natural processes of humification to inject carbon into the surface layer to a depth of 0.51 meters. The injection of carbon dioxide to a depth of one to two kilometers is part of the geological sequestration process. The process by which carbon dioxide (CO_2) is removed from the atmosphere and sequestered in a landscape through plants, plant residues, and other organic materials that are then stored or retained in the unit as part of the soil organic matter (humus) is what (Olson, 2013) defined as soil organic carbon (SOC) sequestration. Carbon that has been removed from the atmosphere and stored in the ground, also known as the terrestrial pool, may be held there for decades or even millennia before being returned to the atmosphere.

(Rabach *et al.*, 2020) examined the drylands of Machakos County in Kenya from the perspectives of carbon sequestration, soil fertility, and the economic ramifications of these factors. The purpose of this research was to evaluate the effectiveness of Conservation Agriculture with Trees (CAWT) in dryland agroecosystems in cutting down on the amount of carbon dioxide in the atmosphere. The specific goals of the study were to determine whether or not carbon credits could be earned through the use of conservation agriculture with trees, to compare the amount of carbon sequestered by these systems to that of conventional agriculture with and without trees, and to compare the amount of carbon sequestered by above-ground biomass to the amount of carbon sequestered by below-ground biomass. It has been shown that conventional agriculture as well as conservation agriculture conducted alone do not achieve the same levels of moisture retention in the soil as conservation agriculture practiced with trees. There was a significant link between clay content and cation exchange capacity, with cation exchange capacity being much higher in conventional agriculture compared to conservation agriculture. Increases in nitrogen, organic carbon, sodium, and potassium were also detected, although they did not reach statistical significance when conservation agriculture was used. The results of the research spanning three years showed that practicing conservation agriculture is profitable. In order for farmers to be eligible for carbon credits under the Kyoto Protocol, conservation agricultural practices that included tree planting were implemented. These practices resulted in a large increase in the amount of carbon that was sequestered.

Human actions like as burning fossil fuels, farming and draining grasslands and wetlands, deforestation, and alterations in land use have resulted in an increased focus on developing technologies to store atmospheric CO_2 (Lal, 2009b). According to (Ogle *et al.*, 2012), no-till (NT) systems have been suggested as an alternative to intense plowing techniques such as the use of mould board ploughs (MP) and chisel ploughs (CP) for agricultural land areas. These systems are intended to store carbon dioxide in the soil. However, (Ogle *et al.*, 2012) point out that the transition from MP or CP systems to NT does impact the distribution of SOC across the soil profile, despite the fact that there is a high potential for SOC sequestration while making the transition. If NT, CP, or MP are in a vulnerable condition, then it is possible that none of the three tillage schemes will be successful in sequestering a large quantity of SOC (Olson, 2010). To boost SOC sequestration, often known as the ability of soils to retain carbon, several agricultural practices including as crop rotation, conservation tillage, and NT systems have been used. (Kahlon *et al.*, 2013)found that switching from plow tillage (PT) to no-till (NT) can sequester 0.57 Mg C ha-1 yr-1 over the course of 15 to 22 years. (Kimble *et al.*, 1998), suggested that it could result in a sequestration rate of 0.50 Mg or 106 g C ha-1 yr-1. Both of these findings are based on global analyses of long-term agricultural management experiments. According to(Ozlu & Kumar, 2018), an NT system in Ohio, USA, was responsible for the sequestration of 0.19 Mg C ha-1 yr-1 of soil organic carbon (SOC) in the Hoytville soil and 0.17 Mg C ha-1 yr-1 in the Wooster soil.

(Ndungu *et al.*, 2017) conducted research in the central Himalayas of India to study the effect that mountain cropping systems have on the properties of the soil, the availability of nutrients, and their potential for carbon sequestration. Case studies were conducted on cropping systems for vegetables, fruits, cereals, and agroforestry, while uncultivated land served as the control in these investigations. The research found that the soil properties, nitrogen availability, and carbon sequestration capabilities of the various mountain cropping systems were quite different from one another (p 0.05). Two of the factors that were investigated were the organic carbon content of the soil and the bulk density of the surface soil. The values for these variables ranged from 0.83 to 1.75 percent and 1.25 to 1.27 milligrams per cubic meter, respectively. In addition to this, it was found that the NPK status was different for each cropping strategy. The planting system for vegetables had the greatest available nitrogen level (555.45 kg/ha), whereas the cropping system for fruits had the highest available phosphorus level (43.96 kg/ha) and the highest available potassium level (451.12 kg/ha). The total amount of carbon that was sequestered up to a depth of 30 centimeters and the amount of carbon that was contained in the top 30 centimeters of soil ranged from 1021.52 to 9395Gg. According to the findings of this study, the cropping systems that were used the most often did not have a detrimental influence on the features of the soil or the availability of nutrients in the mid-hills of Himachal Pradesh. On the other hand, a cropping system that was based on fruit had the greatest potential for preserving soil carbon.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Description of the study area

3.1.1 Location of the Study area

The research was conducted in two areas of Kitui County: the Kauwi ward (Kauwi hamlet) and the Zombe/Mwitika ward (Thua River basin). As with all of Kenya, Kitui County sits in the arid and semi-arid lands (ASALs), which constitute around 80% of the country's total land area (MOA, 2007) and are among the most susceptible regions in Kenya. Indeed, ASALs have been designated by IPCC (2000) as being among the most vulnerable and likely to be struck hardest by global warming due to their limited adaptation potential. Natural and human-induced stresses both contribute to soil degradation in ASALs; the most common human-induced stress is land use change, which is responsible for about 20% of greenhouse gas emissions (Solomon, 2007) (IPCC, 2007a). These emissions are primarily carbon dioxide (CO_2) and result from the loss of biomass and increased soil erosion caused by the destruction of vegetation. Farmers in the Kauwi ward of Kitui County still rely on ploughs and other traditional agricultural equipment, which is characterized by a lack of technological advancement and commercialization. Natural manures are often used, and examples include compost, cow dung, and farm waste. Farmers in the Zombe/Mwitika ward in the Thua river valley have chosen intensive agriculture, a strategy that involves a great deal of labor and capital in order to maximize crop production (FFAC, 2021). This usually entails the use of chemical aids like pesticides, fertilizers, and irrigation to crops in order to boost output. The study areas are shown in Figure 3.1 below.

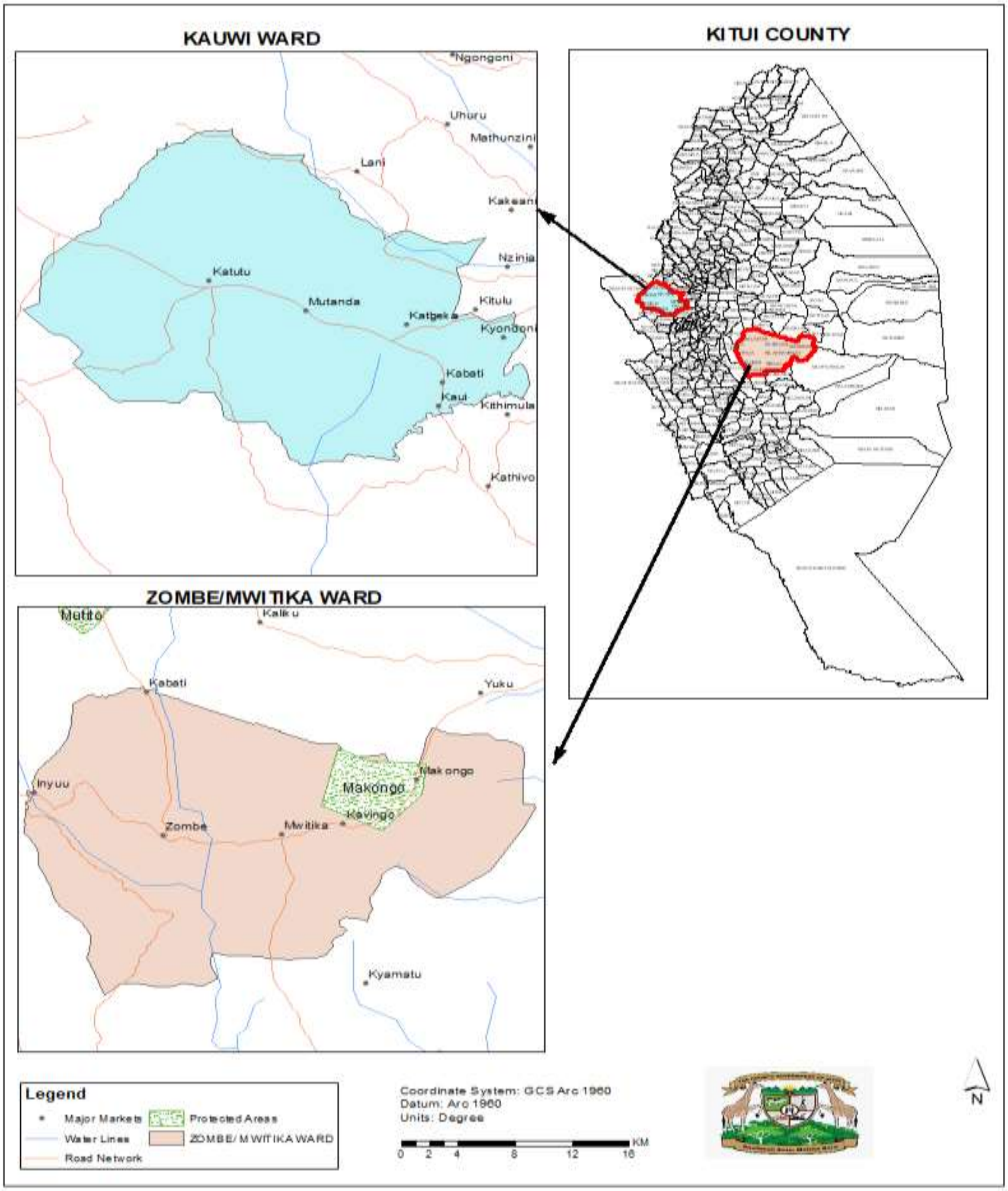

Figure 3.1 Map of Kitui showing the location of study areas

1.1.2 Climate and Topography

The elevation of Kitui County ranges from 400 to 1,839 meters above sea level, with the highest points being in Kitui central and Mutito hills (Republic of Kenya, 2002). The average annual rainfall in the county is 881 millimeters (34.7 inches) (climate data.org), making for a hot and dry environment. Most of the County is considered to have an arid climate (Njoroge & Obiero, 2014), one of two climate types in the area. Highs average between 15 and 40 degrees Celsius (59 and 104 degrees Fahrenheit) year-round. Typically, September/October through January/February are the warmest months of the year. The average annual high is about 26 degrees Celsius, while the average annual low is around 14 degrees Celsius, with a wide range in between. July has the lowest average temperature of 14 °C, while September sees the highest average temperature of 34 °C. Due of the high average temperatures, evaporation occurs at a rapid pace. There are two wet periods every year, creating a bimodal rainfall pattern. From March through May, we get the lengthy rains. These are notoriously unpredictable and inconsistent. The second rainy season, comprised of shorter but more consistent precipitation, occurs between October and December. The opposite half of the year is often dry. Long rains are 40% dependable and short rains are 66% reliable, with an average annual rainfall of 250mm-1050mm. Annual precipitation forecasting is often imprecise. Seasonal rivers only flow during the rainy season and dry up as soon as the rains stop.

The soils have a high moisture-storing capacity and poor nutrient availability; they are well-drained; moderately deep to very deep; dark reddish brown to dark yellowish brown; friable to hard; and sandy clay to clay. Loamy sand to sandy loam makes up the topsoil in most areas.

3.1.3 Population

The population density of Kitui County is anticipated to rise to 39 people per square kilometer from its 2009 level of 33 people per square kilometer, according to the Kenya National Population and Housing Census. Hilly topography and several valleys where agriculture grows well support a high population density in the county, and these factors all contribute to the county's overall pattern of population distribution.

Table 3.1: Population per sub-county in Kitui County

Sub-County	Number of wards	Population (2009)	Density (persons/Km^2)	Population (2018)	Density (persons/Km^2)	Population (2020)	Density (persons/Km^2)	Population (2022)	Density (persons/Km^2)
Mwingi North	5	139,902	29	155,267	32	158,904	33	162,627	34
Mwingi West	4	103,726	96	115,117	106	117,813	109	120,573	112
Mwingi Central	6	141,141	34	156,641	38	160,311	39	164,066	40
Kitui West	4	102,266	153	113,497	170	116,155	174	118,876	178
Kitui Rural	4	104,394	67	115,859	74	118,573	76	121,351	78
Kitui Central	5	131,653	197	146,112	219	149,535	224	153,038	229
Kitui East	6	123,181	24	136,708	27	139,910	27	143,188	28
Kitui South	6	165,972	27	184,200	30	188,515	31	192,931	31
Total		**1,012,236**	**33**	**1,123,401**	**37**	**1,149,717**	**38**	**1,176,650**	**39**

Source: Kitui County Integrated Development Plan 2017-2022

With an annual rate of 2.1%, the county's population is projected to be 1,176,650 people in 2022. The population has been growing rapidly due to the county's high fertility rate of 5.1 children per woman which is higher compared to the national average rate of 4.6 children per woman. The high population growth in the county impacts food production with low resilience to climate change due to agricultural intensification to increase food production to feed the rising population. The labour force age group of between 15-64 years in the county account for about 50%, with a high unemployment rate of 65% among the youth presenting a challenge to the realization of meaningful development in the county. There is a general lack of vocational skills as per the available employment opportunities and the economy. Rural-urban migration is high among these youth, the majority of whom lack the skills for meaningful employment, (GOK, 2014).

3.1.4 Socio-economic activities and livelihoods strategies

The main source of income in the county is Agro-pastoralism. Agriculture is the mainstay for the majority of smallholder farmers with 87.3% of the households. The total labor force is 514,133 (15-64 year olds), where the vast majority of the county's population is unemployed. The County has approximately 18,228 wage earners most of whom are from the public sector and approximately 388,431 self-employed people. Subsistence crop production forms the greatest percentage in the county with mixed crop, monoculture farming, and livestock production being the most common farm types. The common food crops grown include maize, sorghum, millet, beans, cowpeas, green grams, and pigeon peas. Cash crops include sisal, sweet potatoes, vegetables, and fruits (such as mangoes and bananas). The average farm size acreage is 5 acres, with intermittent large-scale farming emerging comprised of sorghum and green grams, especially in Kitui rural, Kitui East, Kitui West, and Mwingi North sub-counties. The average farm acreage under these crops is estimated to be about 60 acres. Agriculture in the County is characterized by low mechanization. Ox plough is the most commonly used method of farming. In all these farm types family labour dominates (GOK 2014). In Kauwi Location, the areas under maize crop, green grams, mango fruit, agroforestry, and uncultivated land are 2,180Ha, 2,540Ha, 200 Ha, 1530 Ha, and 2,450Ha respectively (Ministry of Agriculture, County government of Kitui).

The other major economic activity after agriculture is small-scale business for the majority of the population involved in vegetables and fruit/food vending. In the county, small-scale businesses exist in marketplaces and kiosks in the rural as well as in the urban centres. Traditional animal husbandry is widely practiced in free-range systems. Cattle, sheep, goats, donkeys, chicken, and bees are the most important animals in the area. Dairy farming for cattle and goats is also practiced in Kitui central, Mwingi central, and Mwingi West sub-counties. It is commonly in zero-grazing and semi-zero-grazing supplemented with crop residues, nappier grass, and preserved pasture. Majority of the household practice poultry farming, apiculture, pig, rabbit farming, and fisheries are emerging as other viable options for livestock production.

Generally, all these activities are weather dependent, hence not commercially viable to the majority of smallholder farmers. The county's major economic activities thus are exposed to common weather changes which have negatively continued to impact on livelihood sources. The over-dependence on rainfed agriculture in the County, environmental degradation, and the rising population compromise livelihood options for the majority of these households. Unsustainable livelihood strategies such as charcoal burning, sand harvesting, and over-extraction of forest resources impacts on the environment with reduced food production and climate resilience. (GOK 2014).

3.2 Research design

The study followed a descriptive research design since there was no manipulation of the variables. Four cropping systems i.e. vegetable, cereal, fruit, and agroforestry based were purposefully selected in both Kauwi and Zombe wards of Kitui County. Uncultivated land was selected as control. Composite soil samples were randomly collected from the cropping systems during conventionally long (MAM) and short (OND) rains seasons. The selected systems constituted the treatments and were replicated five times in the farmers' fields. The details of the cropping systems are given in the table below.

Table 3.2: The cropping systems and seasons

	Cropping Systems		Seasons
T_1	Cereal (maize)	T_1	Long rain
T_2	Vegetables	T_2	Short rain
T_3	Orchard (mango)		
T_4	Agroforestry (mango+maize)		
T_5	Uncultivated land (control)		

3.2.1: Treatment Combinations

5*2= 10

Replications= 5

3.2.2: Target Population

The target population for this study was composed of farmers from Kauwi ward in Kitui West and Zombe ward of Kitui East Sub-County.

3.3 Soil Samples and sampling procedure

Each farming system had surface soil samples obtained from a depth of 0 to 15 centimeters throughout the long and short rains seasons for laboratory examination. Composite soil samples were selected from each farming method to ensure their inclusion. For the various cropping systems, soil samples were taken during the long rain season (March–May) and the short rain season (October–December) for analysis of selected soil indicators. Bulk density, organic carbon, total nitrogen, phosphorus, potassium, electrical conductivity, and pH were also measured in the soil.

3.4 Preparation of the soil by sampling

In March 2019, before the MAM long rains, in May 2019, after the MAM rains, and in February 2020, after the OND short rains, composite soil samples were produced from five subsamples, randomly obtained in each experimental unit from 0-15 cm deep using a soil auger. The samples were taken to the Muguga laboratory where they were dried (50°C) and sieved (2 mm mesh). The samples were then analyzed for soil parameters using standard laboratory methods as outline in Table 3.3.

Table 3. 3 Method of Analyzing Soil Parameters

S/No.	Parameter	Method of measuring
	Soil Organic carbon	Rapid titration method (Walkley & Black, 1934)
	Nitrogen	Alkaline potassium permanganate (Subbaiah & Asija, 1949)
	Phosphorous	Olsen's method (Olsen, 1954)
	Potassium	Ammonium acetate (Merwin & Peech, 1951)
	Electrical conductivity	1:2.5 soil: water suspension method (Sims & Jackson, 1971)
	pH	pH meter
	Soil bulk density	Standard core method (B. Singh, 1980)
	Soil organic carbon stock	Computed by multiplying soil carbon content (%)with bulk density (D/gM^3), volume fraction of coarse fragment and expressed as MgCha^1 by the formular Q1=ECiDiEi(1-Gi)

3.5 Statistical analysis

Data obtained was analyzed after the experiments and critical examination was done for ease of interpretation. In order to evaluate the geographical and seasonal changes in soil quality in Kitui County's Kauwi and Zombe wards under various cropping systems on soil physical-chemical characteristics, nutrient contents, and carbon stocks, an analysis of variance (ANOVA) was carried out. This allowed the researchers to determine whether or not there were significant differences in the means of the treatments. The statistical tests were conducted with the aid of OPSTAT statistical software and means compared at a critical difference of $p<0.05$.

CHAPTER FOUR

4.0 RESULTS

The findings of this study were presented in this chapter.

4.1 Spatial (Location-Wise) Variation of Soil Quality under Different Cropping Systems in Kauwi and Zombe Wards of Kitui County

The influence on soil quality by various cropping systems was determined through analysis of soil samples in the laboratory using different methods as outlined earlier in chapter three. Opstat, a statistical data analysis software was then used to analyze the data and results presented as indicated hereunder.

4.1.1 Locational variation in status of pH, Electrical Conductivity, and Soil Organic Carbon in Soils under different cropping systems in the study area

Results presented in table 4.1 indicated that in Zombe and Kauwi wards of Kitui County, vegetable-based, cereal-based, orchard-based and agroforestry-based cropping systems have significant effects on soil properties. Soil organic carbon ranged from 2.53% in vegetable-based cropping systems and 0.90% in uncultivated land in Zombe while in Kauwi it ranged from 1.26% in vegetable-based to 0.48% in uncultivated land. The cropping system-wise trend of soil organic carbon in the soil was; vegetable-based (2.53%) > orchard based (1.50%) > cereal-based (1.44%) > agroforestry based (1.18%) > uncultivated-land (0.90%) in Zombe while the trend in Kauwi was; vegetable-based (1.26%) > agroforestry based (1.21%) > cereal-based (1.05%), > orchard (0.97%) > uncultivated land (0.48%). The interaction between cropping systems and locations was found to have a significant ($p<0.05$) influence on soil organic carbon.

The soil pH ranged from 2.73 in vegetable-based to 6.45 in uncultivated land in Zombe ward. It followed the ascending order; vegetable (2.73) < cereal-based (4.42) < orchard based (5.32) < agroforestry based (6.08) < uncultivated land (6.45) under the different cropping systems, while in Kauwi ward, the soil pH followed the ascending order; vegetable-based (5.16) < orchard based (6.77) < cereal-based (6.87) < agroforestry based

(7.32) < and uncultivated land (7.71). The interaction between cropping systems and locations was found to have a significant influence on soil pH in the region.

The Electrical Conductivity in soil ranged from 347.75 dSm^{-1} in the vegetable-based cropping system to 206.68dSm^{-1} in uncultivated land in Zombe location. It followed the descending order, vegetable-based (347.75dSm^{-1}), > orchard based (315.25 dSm^{-1}), >agroforestry based (284.71dSm^{-1}) > cereal-based (267.88dSm^{-1}), and > uncultivated land (206.68dSm^{-1}) in Zombe ward while in Kauwi ward it followed the following descending order; vegetable-based (326.15 dSm^{-1}) > orchard based (304.58 dSm^{-1}) > cereal-based (258.18 dSm^{-1}) > agroforestry based (249.11 dSm^{-1}) and > uncultivated land (194.47 dSm^{-1}) across the cropping systems.

Table 4.1: Locational Variation in Status of pH, Electrical Conductivity, and Soil Organic Carbon in Soils under Different Cropping Systems in the Study Area

Cropping System	Soil quality parameter								
	pH			EC (dSm^{-1}) micro siemen			Soil Organic Carbon (Units %)		
	Zombe	**Kauwi**	**Mean**	**Zombe**	**Kauwi**	**Mean**	**Zombe**	**Kauwi**	**Mean**
Vegetable-based	2.73	5.16	3.94	347.75	326.15	336.95	2.53	1.26	1.89
Cereal based	4.42	6.87	5.64	267.88	258.18	263.03	1.44	1.05	1.25
Agroforestry based	6.08	7.32	6.90	284.71	249.11	266.91	1.18	1.21	1.19
Orchard based	5.32	6.77	6.05	315.25	304.58	309.915	1.50	0.97	1.23
Uncultivated land	6.45	7.71	6.89	206.68	194.47	200.58	0.90	0.48	0.69
Mean	5.0	6.77		284.454	266.498		1.51	0.99	

CD $^{0.05}$

Cropping systems 0.00

0.00 0.00

Locations 0.00

0.00 0.00

Cropping systems X Locations 0.002

NS 0.002

4.1.2 Location-wise variation in the status of Soil NPK under different cropping systems in the study area

Results presented in table 4.2 revealed that soil nutrients were significantly influenced by cropping systems in both Zombe and Kauwi wards. Total Nitrogen ranged from 0.79 kg ha^{-1} to 0.23 kg ha^{-1} and 0.32kg ha^{-1} to 0.16 kg ha^{-1} in both Zombe and Kauwi wards respectively. It followed the trend; vegetable-based (0.79 kg ha^{-1}) > orchard based (0.56 kg ha^{-1}) > cereal-based (0.44 kg ha^{-1}) > agroforestry based (0.36 kg ha^{-1}) > uncultivated land (0.23 kg ha^{-1}) and cereal-based (0.32 kg ha^{-1}) > agroforestry based (0.30 kg ha^{-1}) > orchard based (0.298 kg ha^{-1}) > vegetable based (0.25 kg ha^{-1}) > uncultivated land (0.16 kg ha^{-1}) in Zombe and Kauwi wards respectively. The overall soil nitrogen levels were found to be substantially greater in the Zombe wards and lower in the Kauwi wards. Total Nitrogen was greatest in the vegetable-based farming system (0.79kg ha^{-1}) in Zombe ward, and was statistically equal to the cereal-based (0.32 kg ha^{-1}) cropping system in Kauwi. The lowest rates were recorded in Zombe and Kauwi's uncultivated areas, at 0.23 and 0.16 kilos per hectare per year, respectively. There was a considerable effect on total Nitrogen from the interplay between cropping systems and geographic regions. Data obtained showed that available phosphorus in Zombe was significantly higher across the cropping systems as compared to Kauwi ward. It followed the descending order; vegetable-based (267.53kg ha^{-1}) >orchard based (224.69 kg ha^{-1}) > agroforestry based (201.29 kg ha^{-1}) > cereal-based (183.03 kg ha^{-1}) >uncultivated land (139.67 kg ha^{-1}) and orchard based (209.75 kg ha^{-1}) > uncultivated land (153.15 kg ha^{-1}) > cereal-based (134.44kg ha^{-1}) > vegetable based (93.64 kg ha^{-1}) and > agroforestry (83.27kg ha^{-1}) in Zombe and Kauwi wards respectively. It was observed that vegetable-based cropping system had the highest level of phosphorus in Zombe while in orchard-based system observed levels of available phosphorus was at par as observed in Kauwi ward. Phosphorus availability was also shown to be significantly impacted by the interplay between cropping systems and geographic regions.

Available potassium was observed to be higher in Zombe ward across all the cropping systems compared to Kauwi ward. It followed the order; vegetable-based (570.79kg ha^{-1}) > orchard based (440.94 kg ha^{-1}) > agroforestry based (429.37kg ha^{-1}) > cereal-based

(343.67 kg ha^{-1}) > uncultivated land (275.51 kg ha^{-1}) in Zombe ward and agroforestry based (303.26 kg ha^{-1}) > cereal-based (303.01kg ha^{-1}) > vegetable based (271.63 kg ha^{-1}) > orchard vegetable (261.81 kg ha^{-1}) > uncultivated land (212.19 kg ha^{-1}) in Kauwi ward. Irrespective of cropping systems, the maximum soil available potassium of 570.79 kg ha^{-1} was recorded in Zombe ward and minimum in Kauwi ward (212.19 kg ha^{-1}). It was also observed that the interplay between cropping methods and locations had a substantial impact on the amount of potassium that was readily accessible in the soil.

Table 4.2: Locational variation in status of Nitrogen, Phosphorus and Potassium in Soils under different cropping systems in Kitui County

Cropping System	Soil quality parameter Nitrogen % (total)			Phosphorus ppM (available)			Potassium ppM (available)		
	Zombe	Kauwi	Mean	Zombe	Kauwi	Mean	Zombe	Kauwi	Mean
Vegetable based	0.79	0.25	0.52	267.53	93.64	180.585	570.79	271.63	421.21
Cereal based	0.44	0.32	0.38	183.03	134.44	158.733	343.67	303.01	333.34
Agroforestry based	0.36	0.30	0.33	201.29	83.27	142.28	429.37	303.26	366.32
Orchard based	0.56	0.298	0.43	224.69	209.75	217.22	440.94	261.81	351.37
Uncultivated land	0.23	0.16	0.19	139.67	153.15	146.41	275.51	212.19	243.85
Mean	0.48	0.26		203.24	134.85		416.06	270.38	

CD $^{0.05}$

Cropping systems 0.00

0.00 0.00

Locations 0.00

0.00 0.00

Cropping systems X Locations 0.00

0.00 0.00

4.1.3 Location-wise variation in the status of Soil Bulk Density under different cropping systems in the study area

Locational variation status showed that soil bulk density ranged from 1.8 to 1.64 Mg m^{-3} in Zombe while in Kauwi it ranged from 1.66 to 1.56 Mg m^{-3}. Soil bulk density decreased when farming systems changed; vegetable-based (1.8 Mg m^{-3}) > cereal-based (1.76 Mg m^{-3}) > agroforestry based (1.72 Mg m^{-3}) > orchard based (1.68 Mg m^{-3}) > uncultivated land (1.64 Mg m^{-3}) and vegetable-based (1.66 Mg m^{-3}) > cereal-based (1.63 Mg m^{-3}) > agroforestry based (1.61 Mg m^{-3}) > orchard based (1.58 Mg m^{-3}) > uncultivated land (1.56 Mg m^{-3}) in Zombe and Kauwi wards respectively, (Table 4.3). It was discovered that soil bulk density was significantly ($p<0.05$) affected by the interaction between cropping systems and locations.

Table 4.3: Locational variation in status of Soil Bulk Density in Soils under different cropping systems in Kitui County

Cropping System	**Soil quality parameter**		
	Soil Bulk Density (Mg m^{-3})		
	Zombe	**Kauwi**	**Mean**
Vegetable based	1.798	1.66	1.73
Cereal based	1.76	1.63	1.699
Agroforestry based	1.72	1.61	1.67
Orchard based	1.68	1.58	1.63
Uncultivated land	1.64	1.56	1.599
Mean	1.72	1.61	

$CD^{0.05}$

Cropping systems 0.00

Locations 0.00

Cropping systems X Locations 0.009

4.2 Seasonal Variation of Soil Quality under Different Cropping Systems in Kauwi and Zombe Wards of Kitui County

4.2.1 Seasonal variation of Soil pH, Electrical Conductivity and Soil Organic Carbon under different cropping systems in the study area

Data revealed that Soil pH ranged from 3.43 to 6.65 during the short rains and followed the ascending order; vegetable-based (3.43) > cereal-based (5.48) > orchard based (6.42) > agroforestry based (6.56) > uncultivated land (6.65). During the long rain season soil pH ranged from 4.19 to 6.75 and followed the ascending order; vegetable-based (4.95), > cereal-based (6.41), > orchard based (6.52), > agroforestry based (6.67) > and uncultivated land (6.75). The soil pH was lower during the relatively short rainy season than the long rainy season under different farming systems. The study area's soil pH also proved to be notably impacted by the relationship between cropping practices and seasons.

Further, the results showed that under the different cropping systems, the EC did not vary much during the seasons. It ranged from 345.95dSm^{-1} under vegetable-based cropping system to (206.68dSm^{-1}) in uncultivated land during the short rains. It followed the order vegetable based (345.95dSm^{-1}), < orchard based (319.05dSm^{-1}) < agroforestry based (293.91dSm^{-1}) < cereal-based (245.34dSm^{-1}), and < uncultivated land (206.68dSm^{-1}) across the cropping systems. The electrical conductivity followed the order: vegetable-based (364.15 dSm^{-1}), < orchard based (318.29 dSm^{-1}), < agroforestry based (300.31 dSm^{-1}), < cereal-based (274.38 dSm^{-1}) and < uncultivated land (211.87 dSm^{-1}) during the long rains season.

The study's results revealed that soil organic carbon ranged from 0.87 % to 0.40 % during the short rain season and 1.89 % to 0.69 % during the long rain season which was rated low under the different cropping systems. During the long rains season soil organic carbon was highest in vegetable-based (1.89%) followed by cereal-based (1.25%) orchard based (1.23%) agroforestry based (1.19%) and uncultivated land (0.69%). Cereal-based cropping systems exhibited the highest soil organic carbon (0.87%) followed by orchard and agroforestry based at (0.70%). Vegetable-based was lowest at (0.40%) during the short rain season. The study area's soil organic carbon levels were shown to be significantly impacted by the interactions between agricultural practices and seasons. (Table 4.4).

Table 4.4: Seasonal variation in status of pH, Electrical Conductivity and Soil Organic Carbon in Soils under different cropping systems in the study area

Cropping System	**Soil quality parameter**								
	pH			**EC (dSm^{-1})**			**Soil Organic Carbon (%)**		
	Short rains	**Long rains**	**Mean**	**Short rains**	**Long rains**	**Mean**	**Short rains**	**Long rains**	**Mean**
Vegetable based	3.43	4.95	4.19	345.95	364.15	355.05	0.40	1.89	1.15
Cereal based	5.48	6.41	5.94	245.34	274.38	259.86	0.87	1.25	1.06
Agroforestry based	6.56	6.67	6.66	293.91	300.31	297.11	0.70	1.19	0.95
Orchard based	6.42	6.52	6.55	319.05	318.29	318.67	0.70	1.23	0.97
Uncultivated land	6.65	6.75	5.99	206.68	211.87	209.28	0.62	0.69	0.65
Mean	5.47	6.2643		282.186	293.80		0.66	1.25	

CD $^{0.05}$

Cropping systems 0.00

0.000 0.00

Seasons 0.00

0.005 0.00

Cropping systems X Seasons 0.02 NS

0.00

4.2.2 Seasonal variation of Soil NPK status under different cropping systems in the study area

Seasonal variation of Soil NPK status of cropping systems, (Table 4.5) found that the cropping systems and seasons had a major impact on the soil's available nutrient status. Total nitrogen in soil ranged from 0.36 to 0.19 kg ha^{-1} during the short rain season. Cereal based cropping system was the highest at (0.36 kg ha^{-1}) followed by > agroforestry based at (0.34 kg ha^{-1}) followed by > orchard based (0.33 kg ha^{-1}) then > vegetable based (0.3 kg ha^{-1}) > uncultivated land (0.28 kg ha^{-1}), (Table 4.5).

During the long rain season vegetable based was highest at (0.51kg ha^{-1}) followed by > orchard based at (0.43kg ha^{-1}) while > uncultivated land was least at (0.19 kg ha^{-1}). During the extended rains season, total soil nitrogen was found to be 0.52 kg ha-1 greater across all cropping systems. On soil nitrogen content in general, it was found that the interaction between cropping systems and seasons had no discernible effect.

Available phosphorus ranged from 217 kg ha^{-1} to 114.22 kg ha^{-1} across the seasons which was rated as medium under the different rain seasons. Under vegetable-based available phosphorus was lower during the short rains at (114.22 kg ha^{-1}) and higher at (180.59 kg ha^{-1}) during the long rain season. Likewise, cereal-based (128.47 kg ha^{-1}), agroforestry based (118.35 kg ha^{-1}), orchard based (139.28 kg ha^{-1}), and uncultivated land (144.48 kg ha^{-1}) cropping systems had lower available phosphorus during short rain season compared to the long rain season at cereal-based (158.73 kg ha^{-1}), agroforestry based (142.28 kg ha^{-1}), orchard based (217.22 kg ha^{-1}) and uncultivated land (146.41 kg ha^{-1}). The condition of soil accessible phosphorus was also significantly impacted by interactions between cultivation techniques and seasonality. During the long rains season, the orchard-based cropping system had the greatest soil available P (217.22 kg ha^{-1}), whereas during the short rains season, the vegetable-based cropping system had the lowest (114.22 kg ha^{-1}).

Under the various agricultural systems and seasonal patterns, soil accessible potassium varied from 540.13 to 211.05 kg ha^{-1} and followed the order; cereal-based (540.13 kg ha^{-1}) > uncultivated land (507.29 kg ha^{-1}) > agroforestry based (472.32 kg ha^{-1}) > vegetable based (395.00 kg ha^{-1}) > orchard based (360.03 kg ha^{-1}) and vegetable-based (367.21 kg ha^{-1}) > orchard based (324.37 kg ha^{-1}) > agroforestry based (238.32 kg ha^{-1}) > cereal-based (234.88 kg ha^{-1}) > uncultivated land (211.05 kg ha^{-1}) during the short rains and long rains seasons respectively. Regardless of agricultural systems, the short rains season had the highest soil accessible potassium levels (540.13 kg ha^{-1}) and the long rains season saw the lowest (211.05 kg ha^{-1}). It was discovered that soil accessible potassium was significantly influenced by the interactions between cropping systems and seasons. During the short rain season (540.13 kg ha^{-1}), the cereal-based farming system was found to have the most soil accessible potassium, whereas during the long wet season (211.05 kg ha^{-1}) it had the lowest.

Table 4. 5: Seasonal variation in status of Nitrogen, Phosphorus and Potassium in Soils under different cropping systems in the study area

Cropping System	Soil quality parameter								
	Nitrogen (total)			Phosphorus (available)			Potassium (available)		
	Short rains	Long rains	Mean	Short rains	Long rains	Mean	Short rains	Long rains	Mean
Vegetable-based	0.3	0.52	0.41	114.22	180.59	147.40	395.003	367.208	381.106
Cereal based	0.36	0.38	0.37	128.47	158.73	143.60	540.13	234.88	387.504
Agroforestry based	0.34	0.33	0.33	118.35	142.28	130.31	472.317	238.317	355.317
Orchard based	0.33	0.43	0.38	139.28	217.22	178.25	360.034	324.374	342.204
Uncultivated land	0.28	0.19	0.24	144.48	146.41	145.48	507.291	211.051	359.171
Mean	0.32	0.37		128.96	169.05		454.955	275.165	

CD $^{0.05}$	Nitrogen	Phosphorus	Potassium
Cropping systems	0.044	0.01	NS
Seasons	0.028	0.00	0.00
Cropping systems X Seasons	NS	0.02	0.001

4.2.3 Seasonal variation of Soil Bulk Density under different cropping systems in the study area

Results revealed that soil bulk density ranged from 1.68 Mg m^{-3} to 1.56 Mg m^{-3} during short rains and 1.78 Mg m^{-3} to 1.64 mg m^{-3} during the long rains. Soil bulk density was lower during the short rain season across the cropping systems and relatively higher during the long rain seasons across the cropping systems. During the short rains soil bulk density was as follows across the cropping systems; vegetable-based (1.68 Mg m^{-3}) > cereal-based (1.64 Mg m^{-3}) > agroforestry based (1.62 Mg m^{-3}) > orchard based (1.59 Mg m^{-3}) > uncultivated land (1.56 Mg m^{-3}) compared to the long rain season whereby the soil bulk density was as follows vegetable based (1.8 Mg m^{-3}) > cereal-based (1.75 Mg m^{-3}) > agroforestry based (1.72 Mg m^{-3}) > orchard based (1.68 Mg m^{-3}) > uncultivated land (1.64 Mg m^{-3}). Soil bulk density was lowest during the short rains under uncultivated land, (Table 4.6).

Table 4.6: Seasonal variation in status of Soil Bulk Density in Soils under different cropping systems in the study area

Cropping System	**Soil quality parameter**		
	Soil Bulk Density (Mg m^{-3})		
	Short rains	**Long rains**	**Mean**
Vegetable-based	1.68	1.78	1.73
Cereal based	1.64	1.75	1.699
Agroforestry based	1.62	1.72	1.67
Orchard based	1.59	1.68	1.63
Uncultivated land	1.56	1.64	1.599
Mean	1.62	1.71	

$CD^{0.05}$	
Cropping systems	0.00
Seasons	0.00
Cropping systems X Seasons	NS

4.3 Evaluation of Carbon Sequestration Potential of Different Cropping Systems in the Study Area

The cropping systems in Zombe and Kauwi wards of Kitui County have been found to significantly influence the soil carbon sequestration potential in the region, (Table 4.7 and 4.8).

Table 4.7: Status of Carbon Density and Total Stocks under Different Cropping Systems in Zombe Ward

Cropping system	Carbon density ($Mg\ C\ ha^{-1}$)	Area (Ha)	Total Carbon stock (Gg C)
Vegetable-based	4.5489	21,000	95.52
Cereal based	2.5344	14,000	35.48
Agroforestry based	2.0296	18,000	36.53
Orchard based	2.52	7,000	17.64
Uncultivated land	1.476	23,000	34.39
Total			**219.57**

Table 4.8: Status of Carbon Density and Total Stocks under Different Cropping Systems in Kauwi Ward

Cropping system	Carbon density ($Mg\ C\ ha^{-1}$)	Area (Ha)	Total Carbon stock (Gg C)
Vegetable based	2.0916	2540	5.313
Cereal based	1.7115	2180	3.731
Agroforestry based	1.9481	1530	2.981
Orchard based	1.5326	200	0.307
Uncultivated land	0.7488	2450	1.834
Total			**14.166**

In Zombe ward, carbon density followed the descending order; vegetable-based (4.55Mg C ha^{-1}) > cereal-based (2.53Mg C ha^{-1}) > orchard-based (2.52Mg C ha^{-1}) >agroforestry based (2.03Mg C ha^{-1}) uncultivated land (1.48Mg C ha^{-1}) under the different cropping systems. Total carbon sequestered ranged from (95.52 Gg C) to (17.64 Gg C) and followed the trend vegetable based (95.52 Gg C), > agroforestry based (36.53 Gg C) > cereal-based (35.48 Gg C) >uncultivated land (34.39 Gg C) >and orchard based (17.64 Gg C).

In Kauwi ward carbon density followed the descending order; vegetable-based (2.09Mg C ha^{-1}) > agroforestry-based (1.95Mg C ha^{-1}) > cereal-based (1.71Mg C ha^{-1}) > orchard-based (1.53Mg C ha^{-1}) > uncultivated land (0.75Mg C ha^{-1}) under the different cropping systems. Average carbon stored followed the trend, ranging from 5.31 Gg C to 0.31 Gg C.; vegetable-based (3.31 Gg C) > cereal-based (3.73 Gg C) > agroforestry based (2.98 Gg C) > uncultivated land (1.83 Gg C and > orchard based (0.31 Gg C).

Season-wise, carbon density was higher during long rain seasons than in short rain season. All the cropping systems under study had high carbon density during the long rain season than the short rain season and took the order cereal (1.427Mg C ha^{-1}) > agroforestry (1.134Mg C ha^{-1}) > orchard (1.113Mg C ha^{-1}) > uncultivated land (0.967Mg C ha^{-1}) > vegetable (0.672Mg C ha^{-1}) while during the long rain season, the order was vegetable (3.36Mg C ha^{-1}) > cereal (2.188Mg C ha^{-1}) > orchard (2.066Mg C ha^{-1}) > agroforestry (2.047Mg C ha^{-1}) > uncultivated land (1.132Mg C ha^{-1}), (Table 4.9).

Table 4.9: Status of Carbon Density and Total Stocks under Different Cropping Systems during Different Rain Seasons

Cropping system	**Carbon density (Mg C ha^{-1})**		**Area (ha)**	**Rain season wise carbon stock (Mg C)**		**Total carbon stock (Gg C)**
	Short rains	**Long rains**		**Short rains**	**Long rains**	
Vegetable	0.672	3.364	23540	15.82	79.19	95.01
Cereal	1.427	2.188	16180	23.09	35.40	58.49
Agroforestry	1.134	2.047	19530	22.15	39.98	62.13
Orchard	1.113	2.066	7200	8.014	14.875	22.889
Uncultivated land	0.967	1.132	25450	24.61	28.81	53.42
Total						**291.931**

CHAPTER FIVE

5.0 DISCUSSION

5.1 Spatial (Location-Wise) Variation of Soil Quality under Different Cropping Systems in Kauwi and Zombe Wards of Kitui County

5.1.1 Locational variation in status of pH, Electrical Conductivity, and Soil Organic Carbon in Soils under different cropping systems in the study area

Vegetable, cereal, and fruit-based cropping systems had a lower (acidic) soil pH than the other cropping systems and control in both the Kauwi and Zombe wards, as determined by the current research. The continual use of acid-forming chemical fertilizers is responsible for the lower soil pH found in vegetable, cereal, and fruit. Vegetable-based cropping systems also heavily relied on synthetic fertilizers. Soil acidity is most likely caused by farmers using chemical fertilizers, particularly those high in nitrogen. Nitrification, the process by which ammonium-containing compounds are converted to nitrate in the soil, is responsible for acidity. Soil acidity decreases when ammoniacal nitrogen fertilizer is applied in greater quantities. Soil pH was found to be within a normal range, indicating that long-term cropping techniques in the study region had not had a deleterious effect on soil quality. Further, the study results revealed that the soil pH under vegetable-based, cereal-based, and orchard based was lower in Zombe ward as compared to Kauwi ward. The current trend of results can be attributed to the intensive agriculture practiced along the Thua river basin in Zombe ward where farmers use chemical fertilizers on their small pieces of land to get high farm yields. Inorganic fertilizers commonly used by the farmers are CAN and DAP. On the other hand farmers in Kauwi ward practice traditional agriculture whereby organic fertilizers such as animal waste, compost, and plant residues are used to increase crop yields on the farms.

The results also revealed that Electrical Conductivity (EC) was lowest under control, followed by cereal and agroforestry cropping systems in both Kauwi and Zombe wards. The highest EC was observed under vegetable-based and orchard-based cropping systems. The study also established that on average the application of inorganic fertilizers impacted on soil quality with significantly increased EC as compared to manure application. The possible explanation for this trend is the high application of fertilizers on vegetable and orchard-based cropping systems which leads to excess nitrification that accelerates soil salinization under such systems. Salinization tempers with nitrogen uptake, which slows plant development and causes yield loss. It also causes ionic stress in crops when harmful ions in soil salts e.g. chloride or sodium impede the acquisition of other positively charged ions vital for crop growth particularly potassium and calcium leading to crop loss. The low EC observed under control, cereal, and agroforestry cropping systems can be attributed to the low soil disturbance under such systems. The results agree with findings by (Ram *et al.*) (2022) who studied the effects of different land use systems on soil pH, Electrical conductivity, and micronutrients in Mollisols of Uttarakhand, India, whereby EC was found low on agroforestry-based treatments. The results of this study are also in contrast with the findings of (Ozlu & Kumar, 2018)on the application of manure and inorganic fertilizer impacts on soil quality whose study found out that on average manure treatments significantly increased EC compared with fertilizer treatments.

Further, the results revealed that electrical conductivity was higher in Zombe ward compared to Kauwi ward. This can be attributed to the dry climate and low precipitation hence excessive salts are not flushed out of the soils. The higher EC in Zombe can also be attributed to intensive agricultural activities along the Thua River basin where irrigation of crops is done probably with salt-rich water, which amplifies salt content in the soils.

The highest soil organic carbon observed in vegetable-based compared to the other cropping systems and uncultivated land in Zombe was maybe due to the regular application of inorganic manure under intensive agriculture in Thua valley, Zombe ward. Intensive farming aims at increasing the productivity and profitability of a piece of land by high-level inputs of different factors that help with yields, such as capital, labor, fertilizers, insecticides, pesticides, herbicides, and others. High SOC observed in orchard-based and cereal-based as compared to agroforestry and uncultivated land may also associate to the high use of inorganic fertilizer below an intensive structure of agriculture. Inorganic fertilizer consists of mineral-based nutrients manufactured for immediate application on crops and does not need to decompose over time to supply nutrients to plants. Most inorganic fertilizers contain balanced amounts of nitrogen, potassium, and phosphorus to feed plants and foster growth. The results are in consonance with (Bhavya *et al.*, 2017) found the highest SOC stocks in the mango orchard. The relatively high SOC in vegetable-based compared to the rest in Kauwi which is associated with the application of compost under traditional form of farming. Litter is the source of soil organic matter, and the more the litter that is produced by the plantations, the higher will the content and amount of soil organic carbon in the plantation. Litter production contributes to primary productivity because it continues the nutrient cycle and the export of nutrients and organic detritus to the ecosystem(Hossain & Hoque, 2008; Mfilinge *et al.*, 2005). Absorption of nutrients by plants and their capacity to return these to the soil through litter brings about changes in chemical and physical soil properties (Rawat, 2005); thus, quantification of soil carbon store is useful for estimating the total soil carbon sink (Shukla *et al.*, 2015). This trend may be attributed to intensive cultivation under such systems which might have resulted in the decomposition of soil organic matter.

5.1.2 Location-wise variation in the status of Soil NPK under different cropping systems in the study area

The results of the study revealed that the effect of interaction between cropping systems and locations had a positive correlation between soil total Nitrogen and soil quality. In Zombe ward, vegetable-based cropping system recorded the highest soil total nitrogen, followed by orchard and cereal-based came third. The lowest amount of total nitrogen was recorded under uncultivated land and agroforestry cropping systems. These trends can be attributed to the application of inorganic fertilizers on vegetable, orchard, and cereal-based systems under intensive agricultural practices. The pressure to get high yields on a small piece of land along Thua River, compels farmers to use chemical fertilizers on vegetables, fruits, and cereals. In Kauwi ward, the highest amount of nitrogen was observed under cereal, agroforestry, and orchard-based cropping systems. The possible explanation for this is that there is high nutrient cycling due to litter fall under agroforestry and orchard cropping systems. Moreover, the results show trends of high total nitrogen under all the cropping systems in Zombe ward compared to Kauwi ward. This is because farmers in Zombe ward practice intensive agriculture while farmers in Kauwi practice traditional agricultural practices with minimal or no use of agrochemicals. The findings are in tandem with similar studies by (Chen *et al.*, 2011) who also reported high amount of available nutrient in vegetable and fruit-based cropping systems compared to cereal crop while working in China.

Similarly, the results showed that the interaction between cropping systems and locations had a positive significance on available soil phosphorus. Available phosphorus in Zombe ward was highest in vegetable-based cropping system followed by orchard and agroforestry. Again, cereal-based and uncultivated land exhibited the lowest amount of available phosphorus respectively. This trend can be attributed to the high application of agro-chemicals on vegetable and orchard-based cropping system under intensive agricultural practices. The observed relatively higher amounts of phosphorus under agroforestry compared to cereal-based can be attributed to litter fall under agroforestry based systems that aid in nutrient cycling. The results agree with the findings by (Bal & Toky, 1993) who reported soil surface enrichment with nutrients from the fall from trees of litter, twigs, branches, and fruits in agroforestry systems.

Moreover, the results revealed that orchard-based cropping system had the highest amount of phosphorus in Kauwi ward. This was followed by uncultivated land and cereal-based cropping system. Further, the results showed the lowest amount of phosphorus under agroforestry-based and vegetable-based cropping systems. The highest amount of available phosphorus observed under orchard based cropping system in Kauwi ward can be attributed to the higher application of organic manures under such cropping system under traditional agricultural practices with the aim of better yields.

Conversely, the results also revealed higher amounts of available phosphorus in Zombe ward compared to Kauwi ward. Again, this can be attributed to the intensive agriculture practiced in Zombe ward along Thua river basin as compared to Kauwi ward where farmers practice traditional agriculture.

The results revealed that, the interaction between cropping systems and locations had a positive significance on available soil potassium. Further, the results depicted the highest amount of available potassium on vegetable-based and orchard cropping systems in Zombe ward. Like in the other parameters, this can be attributed to the application of agrochemicals especially inorganic fertilizers under intensive agriculture practiced in Thua river valley of Zombe ward.

Moreover, higher amounts of potassium was observed under agroforestry based as compared to cereal-based cropping system. The possible explanation for this is the higher nutrient cycling for agroforestry cropping system due to litter fall. The return of crop residues, manure and urine, green manure, and transfer of nutrients from trees to crops in agroforestry through pruning, leaf drop and root decomposition were other significant processes in aid of soil nutrient recycling. In Kauwi ward, available potassium was highest in agroforestry and cereal-based cropping systems. Vegetable, orchard and uncultivated land based cropping systems had the lowest amount of available potassium. The highest amount of potassium observed in agroforestry can be attributed to litter fall leading to nutrient cycling. More accessible nutrients in a system relying on agroforestry are likely the result of more efficient nutrient recycling than in a cereal cropping system. By "nutrient cycling," we mean the process by which nutrients within the soil-plant system are transferred from one component to another; for instance, when nitrogen is released from soil organic matter as ammonium or nitrate and then taken up by plants. Nutrient cycling also includes the incorporation of leguminous green manures into the soil, the transfer of nutrients from trees to crops in agroforestry systems via pruning, leaf drop, or root decomposition, and the return of crop residues like stover to the soil.

Moreover, the results show that available potassium was higher in Zombe ward compared to Kauwi ward. Field visits revealed that chemical-based fertilizers like DAP and NPK were highly used in Zombe ward while farmers in Kauwi ward used organic manure like crop residues, compost, and animal droppings to improve soil nutrients in their farms. These results agree with findings by (Das *et al.*, 2022) who found out that application of adequate K input through either commercial fertilizer or alternative sources like crop residues, manures, and K-rich minerals, or their suitable combination, must be made to meet the crop demand under intensive cultivation to boost up crop yields, maintain soil health, and fetch more farm income in the long run.

5.1.3 Location-wise variation in status of Soil Bulk Density under different cropping systems in the study area

The results of this study revealed that soil bulk density was highest under vegetable and cereal-based cropping systems in Zombe ward. Similarly, it was higher under agroforestry based than orchard-based cropping systems. The highest bulk density under vegetable-based cropping system in Zombe ward can be attributed to the high level of input and output per unit of agricultural land area which characterizes intensive agriculture. Field visits revealed that different types of vegetables e.g. kales, tomatoes e.t.c. are planted annually on the same small piece of land along the Thua river valley, hence the high soil bulk density on vegetable-based cropping system. Similarly, the results reported highest amount of soil bulk density under vegetable based cropping system in Kauwi ward. The trend observed was similar to that in Zombe ward in all the cropping systems under study. Again, the highest soil bulk density recorded under vegetable based cropping system can be attributed to high soil compaction during intensive cultivation.

The results also revealed that soil bulk density was higher in Zombe ward compared to Kauwi ward under all cropping systems. This is due to intensive agriculture practiced in Zombe ward whereas farmers in Kauwi ward practice traditional farming. Intensive agriculture entails high manipulation on soils that leads to excess compaction. Excess compaction restricts soil aeration and crop root development, restricting water uptake, nutrient availability and overall crop growth. The findings agree with those of (Bal & Toky, 1993), who found that agroforestry systems had a low bulk density. The results are consistent with these findings. When compared to cereal crops and the control group, the comparatively low soil bulk density that is found in cropping systems that are based on fruits and vegetables may be attributed to the large amounts of organic manure that are applied in such systems. Generally, there was low soil bulk density observed in uncultivated land, orchard, and agroforestry cropping systems due to less soil disturbance under minimum tillage practices. This allowed increased soil aeration, water uptake, and overall nutrient availability for optimum crop growth under intense application of organic manure. Also, the other possible explanation for the high soil bulk density in Zombe ward compared to Kauwi ward is that intensive agriculture in Zombe is practiced along Thua river valley where soils are sandy compared to soils in Kauwi.

5.2 Seasonal Variation of Soil Quality under Different Cropping Systems in Kauwi and Zombe Wards of Kitui County

5.2.1 Seasonal variation of Soil pH, Electrical Conductivity, and Soil Organic Carbon under different cropping systems in the study area

The study established that soil pH was observed to be low (acidic) under vegetable and cereal-based cropping systems as compared to the other cropping systems and control during both short and long rains. Moreover, acidity was higher during the short rain season compared to the long rain season. The slight increase in acidity across the different cropping systems during the short rains could be attributed to leaching which is associated with runoff caused by high rains. This is so because, in the region, short rains are more than long rains. Studies have shown that rainfall contributes to soil acidity when water combines with carbon dioxide to form weak acid i.e. carbonic acid. The weak acid ionizes, releasing hydrogen and bicarbonate. The released hydrogen ions replace the calcium ions held by soil colloids, causing the soil to become acidic. The displaced calcium ions combine with the bicarbonate ions to form calcium bicarbonate, which being soluble is leached from the soil. The net effect is increased soil acidity.

The results showed that Electrical Conductivity (EC) was lowest under uncultivated land, followed by cereal and agroforestry cropping systems in both short and long rain seasons. The highest EC was observed under vegetable-based and orchard-based cropping systems. The possible explanation for this trend is the use of chemical fertilizers on vegetable and orchard-based cropping systems across the seasons which leads to excess nitrification that accelerates soil salinization under such systems. The low EC observed under uncultivated land and agroforestry systems can be attributed to the low soil disturbance under such systems across the seasons. It was also observed that the EC did not fluctuate very much from season to season regardless of the cropping strategy that was used. Even while the electrical conductivity is somewhat lower during the short rain season, it was still within the usual range under all of the systems, which suggests that the prevalent farming methods of the area have not had an effect on the salt content of the soils. The study also revealed that EC was higher during the long rain season compared to the short rain season across all the cropping systems. The lower EC observed in the short rain season compared to the long rain season can be attributed to leaching.

Vegetable-based cropping system registered the lowest SOC under short rainfall while cereal based registered the highest SOC. On the other hand, uncultivated land registered the lowest amount of SOC during the long rainfall season. Vegetable-based registered the highest amount of SOC under long rains. This trend can be attributed to the accumulation of soil nutrients under vegetable-based system because of low rainfall hence low wash-off. It was also found that cereal-based cropping system had the highest soil organic carbon while vegetable based recorded the lowest during the short rain season. This trend can be attributed to fact that short rains are more intense than long rains in the region causing high nutrient leaching hence the lower percentage of soil organic carbon during the short rains. For water to be transported below the plant's root region, the water balance must be favorable, meaning that the amount of water added to the soil from rainfall and irrigation is more than the amount of water lost through evaporation. Leaching causes more nutrient loss in wetter environments than drier ones (Schroth & Sinclair, 2003). Low rainfall surface runoff and consistent fertilizer application over the long season likely explain the higher levels of soil organic carbon found in vegetable-based cropping systems.

Moreover, the slight acidity in short rains could be attributed to leaching which is associated with runoff caused by high rains. The case study shows that leaching losses of nutrients are more common in wetter environments than in drier ones. The reverse is true during the long rain season vegetable-based cropping system recorded the highest soil organic carbon due to regular application of fertilizer and low rainfall surface runoff during the season. Significant effects on soil organic carbon were seen as a result of the interaction between cropping systems and seasons.

5.2.2 Seasonal variation in status of Nitrogen, Phosphorus and Potassium in Soils under different cropping systems in the study area

The results of the study showed that total nitrogen was highest under cereal-based cropping system compared to the other cropping systems under study during short rains. Vegetable-based cropping system exhibited the highest amount of total nitrogen during the long rains. Uncultivated land showed the lowest amount of total nitrogen compared to the other cropping systems across the seasons. The research also found that during the long rain season compared to the short rain season, soil nitrogen was considerably greater across all cropping systems. Since cropping systems and seasons were shown to have no significant effect on soil total nitrogen in the research region, it is likely that less leaching occurs during the season of low run off. Similarly, (Hollister *et al.*, 2013) showed that nitrate is readily leached because it has a weak interaction with the negatively charged matrix of most top soils, making it a highly mobile element in the soil.

The findings showed that soil available phosphorus was also significantly impacted by the interactions between cropping systems and seasons. Uncultivated land followed by orchard cropping system registered the highest amount of available phosphorus over the short rain season. Vegetable and agroforestry-based cropping systems exhibited the lowest amount of available phosphorus over the short rain season. This trend can be attributed to high saturation of soils under such systems due to intensive cultivation. These results align with findings by (Tibbett *et al.*, 2022) who found out that Phosphorus is released faster when soil is well aerated (higher oxygen levels) than when it is saturated. Additionally, research has shown that at lower pH levels, phosphate tends to bind with aluminum or iron compounds in the soil, making phosphorus less available for plant uptake (Jensen *et al.*, 2010). Orchard-based cropping system exhibited the highest amount of soil phosphorus followed by vegetable-based cropping system over the long rain season. Cereal, uncultivated land, and agroforestry-based cropping systems exhibited the lowest available phosphorus over the long rains season. The results showed that available phosphorus was higher after the long rains season across all the cropping systems compared to the short rains season.

Further scrutiny of the data revealed that the highest amount of potassium was observed under cereal-based cropping system after the short rains season. Orchard-based cropping system had the lowest available potassium during the short rains season. Under the long rains season, vegetable-based cropping system had the highest available soil potassium, while uncultivated land had the lowest available soil potassium. This trend can be attributed to the use of NPK based fertilizers under such cropping systems as compared to uncultivated land which was used as control. Lower amounts of available soil potassium were observed under the long rains compared to short rains. This flux can be attributed to the different rate of exchangeable potassium ions uptake by plants during the different rain seasons. The results agree with research findings by (Firmano *et al.*, 2017) who observed the same while working on long-term potassium administration/deprivation cycles on tropical Oxisol.

5.2.3 Seasonal variation of Soil Bulk Density under different cropping systems in the study area

Results revealed that soil bulk density was highest under vegetable and cereal-based cropping systems under the short rain season. Orchard-based and uncultivated land exhibited the lowest soil bulk density. The cropping system wise trend was the same under the long rain season whereby vegetable and cereal cropping systems exhibited the highest soil bulk density.

This scenario can be attributed to the compaction of soil due to continuous and seasonal cultivation of crops under such cropping systems. Under both short and long rains uncultivated land showed the lowest soil bulk density. This can be attributed to minimum soil disturbance under uncultivated land. These findings align with those of (Grant & Lafond, 1993), who found that no-till soils had a lower bulk density than either conventional or minimum-tilled soils. Soil bulk density was also found to be lower during the short rain season across all cropping systems and greater during the long rains seasons. The most plausible reason for this is because farmers in the study region anticipate additional rainfall throughout the typically brief rain season, which leads to appropriate and improved farm management with little soil disturbance and increased soil organic matter.(Arshad *et al.*, 1997) research on soil quality assessment methodologies finds this to be the case.

5.2.4 Evaluation of Carbon Sequestration Potential of different cropping systems in the study area

Results revealed that, vegetable-based cropping systems had a greater carbon density than any other kind of cropping system in both Zombe and Kauwi wards. Uncultivated land has the lowest carbon density of all the terrain types studied. This pattern may be explained by the practice of applying farm yard waste and fertilizers in order to raise output levels and, as a result, the economic rewards that come from using this technique. The findings are consistent with those of (Seremesic *et al.*, 2017), who found that there was a large increase in carbon stores in wheat-based cropping systems and untilled grass at the 4-yr rotation with manure and mineral fertilization while working on changes in Soil Carbon Stock under the Wheat-based Cropping Systems at Vojvodina Province of Serbia. The study revealed that the carbon density in Zombe was higher compared to that in Kauwi ward. This can be attributed to the high use of mineral fertilizers as compared to Kauwi ward.

Further, season wise the results depict that carbon density was higher during long rain seasons than short rain season in all the cropping systems. The low carbon density observed during short rains can be attributed to more runoff in the study area leading to leaching. Conversely, the results show that cereal-based exhibited the highest carbon density during the short rains while vegetable-based cropping system exhibited the highest carbon density during the long rains season. This coincides with the results of (Shi *et al.*, 2012; R. Singh *et al.*, 2015), found that cropping systems defined by lengthy period of organic manure application had greater amounts of carbon reserves. Further, the study shows that orchard-based cropping system exhibited the lowest total carbon stock across the rain seasons. This can be ascribed to the low area of land allocated to orchard farming in the study area.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The current study confirmed that soil pH was lower in Zombe than in Kauwi ward, although it was within the normal range in both sites. The slight acidity in Zombe was attributed to high intensive form of agriculture in the area. Generally, the Electrical Conductivity was significantly higher in Zombe than in Kauwi ward. Vegetable-based cropping system exhibited higher EC than all the other cropping systems. This was attributed to the higher use of inorganic fertilizers under vegetable farming. From the results that depict that NPK was higher in Zombe ward than in Kauwi ward across the cropping systems, it is important to conclude that soils in Zombe ward have been influenced by intensive agriculture through application of inorganic fertilizers. Vegetable based cropping system also had the highest influence on NPK specifically in Zombe ward. The interaction between the cropping systems and locations significantly differed between the two sites owing to the different practices in agricultural activities. Likewise, soil bulk density was higher in vegetable-based cropping systems and relatively higher in Zombe than in Kauwi wards. In conclusion, there was statistically significant spatial variation in soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County. The significant difference in the soil parameters was influenced by the different locations.

Season-wise, the pH was found to be lower during the short rain season than during the long rain season across all the cropping systems. The slight acidity during the short rains was attributed to leaching which is associated with runoff caused by high rains. Generally, the electrical conductivity was higher during the long rain season as compared to short rain season. Similarly, soil organic carbon was highest in vegetable-based cropping systems during short and long rains season although, it was higher in long rains seasons than in short rains seasons. In conclusion, it is evident that intensive cultivation leads to high soil organic carbon and also high during short rains than long rains. Soil bulk density was lowest during the short rains and under uncultivated land. This can be attributed to minimum soil disturbance under uncultivated land. The NPK varied significantly across the cropping systems in the different rain seasons. In conclusion, there was statistically significant seasonal variation in soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County. The significant difference in the soil parameters was influenced by the different rain seasons.

High carbon stock was found in the Zombe ward, which corresponded to greater carbon densities under vegetable-based agricultural systems. Vegetable-based cropping systems in both study locations had a greater carbon density than any other cropping system because they used farm yard waste and fertilizers to boost yields and profits. The low carbon density observed during short rains can be attributed to more runoff in the study area leading to leaching. In conclusion, vegetable cropping systems had the potential to sequester the highest amount of carbon.

From the above results it is imperative to conclude that farmers in the study area generally used more inorganic manure, which points to challenges in their crop yield increase and long term replenishment of soil nutrients. Continued use of soils with such minimal organic fertilizer application by farmers indicates there exists unsustainable soil nutrient management practices in the area. Farmers, however, need more sensitization on the use of both organic and inorganic fertilizers in both study areas.

6.2 Recommendations

The analysis of these results depicted high soil pH, EC, soil organic carbon, NPK and bulk density levels in Zombe ward due to high application of inorganic fertilizers, hence the need for the county and national government to intensify their efforts in farmer education to moderate fertilizer use for optimum production. Farmers in the study area should be sensitized on the right cropping systems and soil nutrient management practices to use in their farms. On the other hand, farmers in Kauwi should be encouraged to embrace use of fertilizers for optimum production for food security and adaptation to climate change. The high cost of inorganic fertilizers could be mitigated through subsided farm input supplies and intensive agricultural extension services brought closer to the farmers. The low use of inorganic fertilizers in Kauwi ward resulting to low levels of soil parameters like NPK, could be addressed through farmer sensitization and government subsidies in agricultural inputs for sustainable soil nutrient management. Field farmer schools and benchmarking farm field trips should be explored to increase farmer knowledge and food production.

The findings also showed that there was statistically significant seasonal variation in soil quality under different cropping systems in Kauwi and Zombe wards of Kitui County. Therefore, both levels of governments should sensitize farmers to embrace diversified cropping systems that promote optimum levels of soil parameters under the various rain seasons in the region. Such measures will positively impact on soil organic carbon and soil quality. Further studies to assess the right amount of fertilizers under the current rainfall regimes in the county will be appropriate to help farmers attain optimal harvests and adapt appropriately to climate change.

The current deemed profitable vegetable farming which attracts considerable soil nutrient management and carbon storage could be replicated in the other crops if sound agricultural policies and enhanced agricultural extension services are adopted. The county government should also formulate policies on integrated farming practices, promoting pasture development in the area to address the competing needs for crop residue as livestock feed. The increased manure production will ensure the sustainable utilization of more organic manure in the farms. Moreover, organizations in the agricultural and environmental sectors will make informed choices on suitable cropping systems and nutrient management methods to promote and enhance soil quality. The findings will lead to food security and economic gains in Kauwi and Zombe wards.

Agroforestry systems have higher soil organic carbon due to litter fall. The county government should educate farmers to explore and adopt practices that promote agroforestry systems, which is a cheaper option to increase soil organic carbon and increase crop production in the area. Minimum tillage practices should also be encouraged under intense manure application to enhance low soil bulk density to increase soil aeration, water uptake, and nutrient availability for crop growth.

Vegetable and agroforestry cropping systems were found to contain the highest amounts of carbon, therefore, both the national and county governments should develop and implement policies that trigger farmers to adopt such cropping systems to minimize the effects of climate change.

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