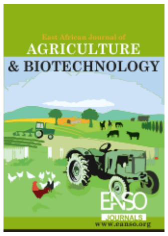

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Original Article

Temporal variation in soil quality and carbon sequestration potential of different cropping systems in Arid and Semi-Arid parts of South Eastern Kenya

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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. To meet the requirements of growing inhabitants, farmers have turned to unsustainable methods including monoculture, excessive use of pesticides and fertilizers, and increased agricultural intensification. A study to determine the seasonal variation of soil quality under different cropping systems and carbon sequestration potential was done during the years 2018 and 2019 in Kauwi and Zombe Wards of South Eastern Kenya. Five cropping systems namely, vegetable, cereal, fruit, and agroforestry were selected, whereas uncultivated land was considered as control. During the typical long (MAM) and short (OND) rainfall seasons, composite soil samples were taken from the cropping systems at random, making the treatment combinations ten. Each farming system had surface soil samples obtained from a depth of 0 to 15 centimetres. Two-way ANOVA was used to analyze the results. The results revealed that the influence of cropping systems on seasonal variation of soil quality parameters varied significantly ($p<0.05$). Further, the interaction between cropping systems and seasons significantly influenced soil pH and soil organic carbon. The short rain season registered lower soil pH values across all cropping systems. Soil Organic Carbon was found to be highest in vegetable-based cropping systems during short and long rain seasons. Electrical Conductivity was highest during the long rain season across all cropping systems. Soil bulk density was lowest during the short rains and under uncultivated land. NPK varied significantly across the cropping systems in the different rain seasons. Higher carbon stock was found in the Zombe ward as compared to the Kauwi ward. Carbon density values were noticed to be highest under Vegetable-based cropping systems in both study locations. This can be ascribed to the heavy application of organic and artificial fertilizers by farmers to increase yields and profits. Based on the results, Vegetable and agroforestry cropping systems were found to contain the highest amounts of soil carbon, and therefore, with the potential to sequester the highest amount of soil carbon. Both tiers of government should promote vegetable and agroforestry cropping systems to minimize the effects of climate change.

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INTRODUCTION

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.*, 2002). 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's average annual growth rate was 1.1% between 2015 and 2020 (Gu *et al.*, 2021). According to the United Nations, the global population will grow from the current 7 billion people to 9.3 billion in 2050 and 10.1 billion in 2100 (Lee, 2011). To meet the requirements of growing inhabitants, farmers have turned to unsustainable methods including monoculture, excessive use of pesticides and fertilizers, and increased agricultural intensification (Tillman *et al.*, 2012).

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 requires 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 (Sanchez *et al.*, 2002, Otsuka *et al.*, 2016). 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 *et al.*, 2005). This trend has repercussions for the pervasive rural poverty in SSA (FAO 2015, Chamberlin *et al.*, 2016), 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).

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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 *et al.*, 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 the breakdown of soil structure, deposition of organic materials in the soil, and decrease in the fungal community due to the rise in bacterial population (Rousk *et al.*, 2010).

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 objective of this study was to assess the temporal variation in soil quality under different cropping systems and carbon sequestration potential in Kauwi and Zombe wards of Kitui County.

MATERIALS AND METHODS

Study Area

The research was conducted in two areas of Kitui County, South Eastern Kenya: the Kauwi ward (Kauwi village) and the Zombe/Mwitika ward (Thua River basin). 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. On the other hand, farmers in the Zombe/Mwitika ward in the Thua River valley practice intensive agriculture, a strategy that involves a great deal of labour and capital in order to maximize crop production.

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 millimetres (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 *et al.*, 2014). 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

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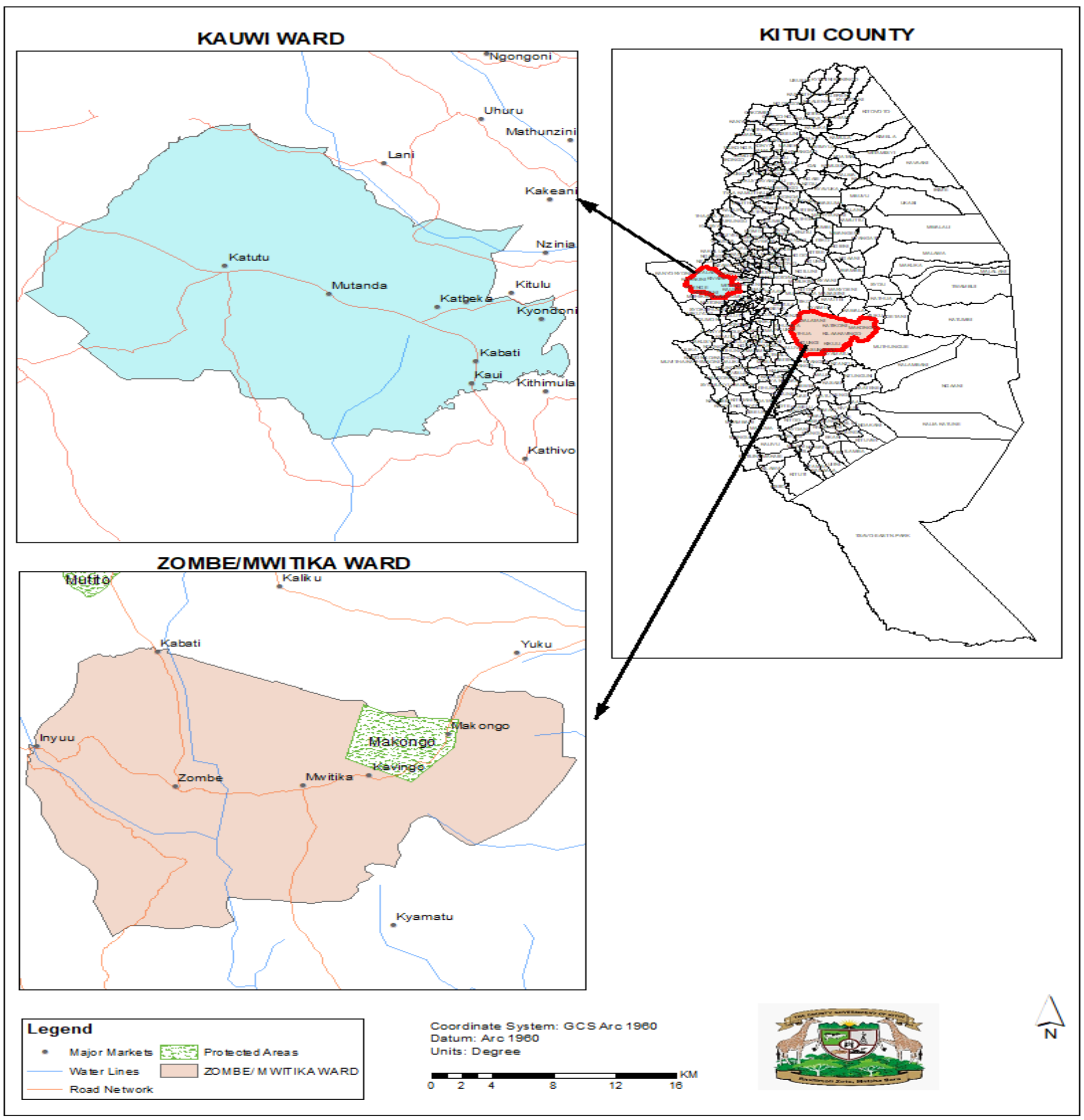
annual low is around 14 degrees Celsius, with a wide range in between.

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.

The population density of Kitui County is anticipated to rise to 39 people per square kilometre from its 2009 level of 33 people per square kilometre, 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. The study areas are shown in Figure 1 below.

Figure 1 Map of Kitui showing the location of study areas



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Cropping systems and experimental details

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 were purposefully selected in both Kauwi and Zombe wards of Kitui County. Uncultivated land was used as control. Composite soil samples were randomly collected from the cropping systems during conventionally long (MAM) and short (OND) rain seasons. The selected systems were replicated five times in the farmers' fields.

Treatment Combination

5*2= 10

Replications= 5

Soil Samples and sampling procedure

Each farming system had surface soil samples obtained from a depth of 0 to 15 centimetres throughout the long and short rain seasons for laboratory examination. Surface soil was considered because agricultural soils are among the planet's largest reservoirs of carbon and hold the potential for expanded carbon sequestration and thus provide a prospective way of mitigating the increasing atmospheric concentration of carbon dioxide. Six composite soil samples were selected from each farming method to ensure their inclusion. For the various cropping systems, soil samples were taken, packaged and labelled during the long rain season (March to May) and the short rain season (October–December) and transported to the laboratory for analysis of selected soil indicators following standard methods. Soil samples were air-dried, ground and sieved (2mm) before laboratory examination. The indicators included soil bulk density which was estimated by the standard core method (Singh, 1980), and soil organic carbon was determined by the rapid titration method (Walkey & Black, 1934). Total nitrogen was determined by the alkaline potassium permanganate method (Subbaiah & Asija 1949), available phosphorus was determined by Olsen's method (Olsen 1954), available potassium was determined by ammonium acetate (Merwin & Peech, 1951), electrical conductivity was determined by 1:2.5 soil: water suspension method (Sims & Jackson, 1971), and pH (pH meter). The soil organic carbon stock Qi ($Mgha^{-1}$) was computed by multiplying soil carbon content (%) with bulk density Di (gm^3), volume fraction of coarse fragments Gi and depth Ei (m) and expressed as Mg C ha^1 as per the following formula given by Batjes (1996).

QI=CiDiEi(1-Gi)

Statistical analysis

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. The statistical tests were conducted with the aid of OPSTAT statistical software and the mean was compared at a critical difference of $p<0.05$

RESULTS AND DISCUSSION

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

Scrutiny of the 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 as compared to the long rainy season under different farming systems. The study area's soil pH was also

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significantly affected by the interaction between cropping systems and seasons. The present study established that soil pH was observed to be high (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. These findings concur with findings by (Tabatabai *et al.,* 1985) who found that sources of acidity in soils include carbonic acid (H2CO3) formed from high carbon dioxide (CO2) concentrations in the soil atmosphere produced from the root and microbial respiration, acidity produced in mineralization of organic Nitrogen and sulphate and from ammonium cation forming fertilizers, organic acids produced from litter decomposition, and addition in precipitation.

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 a vegetable-based cropping system to (206.68dSm^{-1}) in uncultivated land during the short rains. It followed the descending 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. Scrutiny of 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.

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 (0.70%). Vegetable-based was lowest at (0.40%) during the short rain season.

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The study area's soil organic carbon levels were shown to be significantly impacted by the interactions between agricultural practices and seasons. (Table 1). Vegetable-based cropping system registered the lowest SOC under short rainfall while the cereal based registered the highest SOC. On the other hand, uncultivated land registered the lowest amount of SOC during the long rainfall season. The 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 the cereal-based cropping system had the highest soil organic carbon while the vegetable-based recorded the lowest during the short rain season. This trend can be attributed to the 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 favourable, meaning that the amount of water added to the soil from rainfall and irrigation is more than the amount of water lost through evaporation. Low rainfall and consistent fertilizer application over the long season are likely to 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 interplay between cropping systems and seasons.

Table 1: 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	

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

Scrutiny of the results presented in Table 2 indicated 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}).

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}, which was greater across all cropping systems. On soil nitrogen content in general, it was found that the interaction between cropping systems and seasons was not significant. The results of the study showed that total nitrogen was highest under the 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. Scrutiny of the results revealed 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 region, it is likely that less leaching occurs during the season of low runoff. Similarly, Lehmann 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.

Available phosphorus ranged from 217 kg ha^{-1} to 114.22 kg ha^{-1} across the seasons which was rated as medium. 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. 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). The findings showed that soil-accessible phosphorus was also significantly impacted by the interactions between cropping systems and seasons. Uncultivated land followed by an orchard cropping system registered the highest amount of available phosphorus over the short rainy season. Vegetable and agroforestry-based cropping systems exhibited the lowest amount of available phosphorus over the short rainy season. This trend can be attributed to the 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 aluminium 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 rainy season. Cereal, uncultivated land, and agroforestry-based cropping systems exhibited the lowest available phosphorus over the long rainy 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.

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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 registered 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. Further scrutiny of the data revealed that the highest amount of potassium was observed under the cereal-based cropping system after the short rain season. Orchard-based cropping system had the lowest available potassium during the short rains season. Under the long rainy 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 rates 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. Similar research by (Rengel *et al.*, 2008) explains that large areas of agricultural land in the world are deficient in Potassium with export in agricultural produce and leaching (especially in sandy soils) contributing to the lowering of potassium content in the soil. The capacity of a genotype to grow and yield well in soils low in available potassium is potassium efficiency.

Table 2: Seasonal variation in the 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 $^{0.05}$									
Cropping systems	0.044			0.01			NS		
Seasons	0.028			0.00			0.00		
Cropping systems X Seasons	NS			0.02			0.001		

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

The study 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 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 3). Examination of 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.

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 *et al.*, 2008), 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 rain seasons. The most plausible reason for this is that 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. Similar findings were reported by (Franzluebbers *et al.*, 1996).

Table 3: 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

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 and 5).

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Table 4: 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 5: 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 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 seasons. All the cropping systems under study had higher 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 6).

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Table 6: 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**

According to the results of the study, vegetable-based cropping systems had a greater carbon density than any other kind of cropping system in both the 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. 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. 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 the Kauwi ward.

Further, season-wise the results depict that carbon density was higher during long rain seasons as compared to the 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. The results are in consonance with the findings of (Brar *et al.*, 2015, Du *et al.*, 2023) who found that cropping systems defined by lengthy periods of organic manure application had greater amounts of carbon reserves. Further, the study shows that the orchard-based cropping system exhibited the lowest total carbon stock across the rainy seasons. This can be ascribed to the low area of land allocated to orchard farming in the study area.

CONCLUSION

Soil 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 the short rain season. Although it was slightly higher during the long rainy season, it was not significantly influenced by the interaction between cropping systems and seasons. 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. Soil bulk density was lowest during the short rains and under uncultivated land. The NPK varied significantly across the cropping systems in the different rain seasons. Therefore, 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-

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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 have the potential to sequester the highest amount of carbon. Vegetable and agroforestry cropping systems were found to have the potential to sequester the highest amounts of carbon, therefore, both the national and county governments should develop and implement policies that promote the adoption of vegetable and agroforestry cropping systems to improve soil quality, crop production and environmental quality hence mitigate the effects of climate change. Likewise, such measures will positively impact soil organic carbon and soil quality.

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