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Research

Potential of perennial forages on soil carbon sequestration across agroecological zones with varying management practices in Meru County, Kenya

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Abstract
The decline in soil organic carbon (SOC) due to continuous cultivation practices threatens soil productivity and compromises climate change mitigation efforts. This study investigates the effect of agro-ecological zones (AZ), management practices (MP), and specific forages on SOC and its related fractions: particulate organic carbon (POC) and mineral-associated organic carbon (MAOC), in Meru County, Eastern Kenya. Thirty-five predetermined perennial forage fields with Brachiaria (B), Panicum (*Panicum maximum*) (P), Napier grass (*P.P. Schumach*) (N), paired with maize (*Zea mays*) (M) growers, and with two MP [farmyard manure (FYM) and inorganic fertilizer application] were selected per agro-ecological zone. A factorial plot design was employed, with zones as the main plots, the MP as split plots, and the forages as split-split plots. Soil samples were collected from 1 m-by-1 m plots across 35 farms at depths of 0–50 cm, and analyzed for pH, bulk density, SOC content, POC, MAOC, and other micronutrients. Soil samples were statistically analyzed using two-way ANOVA. From the survey, 70% of the respondents had perennial forages of more than 3 years except for panicum which majority had planted for <3 years. Most of the farmers interviewed applies organic manure. Bulk density ranged from 1.07 to 1.19 g cm^{-3}, with the highest values under inorganic fertilizers and the lowest under FYM, showing significant differences between paired plots ($p = 0.0011$). Soil pH ranged from 5.13 to 5.36, and MP significantly affected all micronutrients, with FYM combined with Panicum having the highest cation exchange capacity (19.45 cmol/kg) and manganese (96.30 ppm), and FYM combined with maize showing the highest available phosphorus (54.08 cmol/kg). Results showed no significant differences in mean values of POC and MAOC across zones, though the Lower Zone (LZ) had higher POC (6.63 g C kg^{-1}) and MAOC (7.24 g C kg^{-1}) compared to the Mid Zone (MZ) and Upper Zone (UZ). Different forages exhibited varying levels of MAOC, POC, and SOCs, with Brachiaria showing the highest SOC (15.69 g C kg^{-1}) and Panicum the lowest (14.84 g C kg^{-1}). Particulate organic carbon and MAOC content were significantly different across forages and maize ($p < 0.05$), with Brachiaria having higher MAOC (5.37 g C kg^{-1}) and POC (5.97 g C kg^{-1}). FYM combined with Brachiaria resulted in the highest POC (6.09 g C kg^{-1}) and MAOC (5.44 g C kg^{-1}). POC and MAOC concentrations varied significantly with soil depth, showing higher values in the top 10 cm. The Mid Zone recorded significantly higher SOC, POC, and MAOC than the UZ and LZ. This study concludes that AZ and MP substantially influence SOC sequestration, with FYM and Brachiaria being most effective in LZ.

Keywords Agro ecological zones · Brachiaria · Forages · Panicum · Soil organic carbon fractions

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1 Introduction

In many developing countries, agriculture serves as the cornerstone of the economy, supporting livelihoods and food security for millions of people [1]. Smallholder farming systems, which integrate crops and livestock and rely largely on rain-fed agriculture, are particularly prevalent in Sub-Saharan Africa [24]. These systems are essential, contributing up to 80% of total food consumption in the region [1]. However, they face numerous challenges exacerbated by climate change, including soil degradation, nutrient depletion, and reduced agricultural productivity [24]. Forage-based livestock production dominates over 70% of agricultural land in tropical regions, playing a critical role in food production and income generation [24]. Yet, the resilience of these systems is increasingly tested by climate change-related factors such as altered rainfall patterns, increased incidence of pests and diseases, and more frequent extreme weather events [24]. These challenges not only threaten agricultural productivity but also exacerbate land degradation, which in turn impacts ecosystem services crucial for maintaining soil fertility and productivity [3].

In Kenya, for instance, significant portions of land—more than 20%—are severely degraded due to a combination of factors like weak soil structure, overgrazing, compaction from heavy machinery, and inadequate land management practices [10]. These practices contribute to the loss of soil organic carbon (SOC), a vital component for soil health and agricultural sustainability [10]. SOC plays a crucial role in soil structure, water retention, nutrient cycling, and carbon sequestration, thereby influencing both agricultural productivity and climate change mitigation efforts [14]. Effective management strategies to preserve SOC in tropical cropping systems include reduced tillage, application of organic inputs like manure and crop residues, and erosion control measures [29]. These practices help slow the rate of SOC loss and maintain soil fertility over time [29]. Understanding the dynamics of SOC, including its fractions such as particulate organic matter (POM), mineral-associated organic carbon (MAOC), and particulate organic carbon (POC), is essential for developing targeted soil management practices that enhance carbon sequestration and agricultural sustainability [27]. MAOC, which is more stable and resistant to decomposition, plays a significant role in long-term soil carbon storage, while POC is more labile and is influenced by recent organic inputs, making both fractions critical to understanding soil carbon dynamics.

Introducing and promoting the cultivation of forage species like *Brachiaria* spp. represents a promising strategy for enhancing SOC levels in SSA [4, 20]. *Brachiaria* spp., known for its deep rooting system, high biomass production, and adaptation to low fertility and drought-prone conditions, has shown significant potential in improving soil organic carbon stocks and enhancing livestock productivity [4, 20]. These forages not only contribute organic matter to the soil but also improve soil structure, reduce erosion, and increase soil water holding capacity, thereby enhancing overall soil health and resilience to climate variability. In contrast, traditional annual crops like maize (*Zea mays*) typically have shorter growing periods and lower biomass production compared to perennial forages [6]. Moreover, maize cultivation often involves intensive tillage practices that can accelerate SOC decomposition and reduce soil carbon stocks, particularly in fragile and erosion-prone soils [6].

Future research should focus on conducting long-term field studies to monitor SOC dynamics under different cropping systems and management practices [29]. Evaluating the impacts of *Brachiaria* spp. and maize cultivation on SOC dynamics, including POC and MAOC fractions, will provide valuable insights into sustainable agricultural practices that enhance soil health and resilience to climate change impacts [27]. Incorporating socio-economic factors and farmer perceptions into research and development help in ensuring the adoption and scalability of the practices among smallholder farmers in Sub-Saharan Africa.

Effective management of soil organic carbon is critical for achieving sustainable agricultural development, enhancing food security, and mitigating climate change impacts in tropical farming systems [14]. By promoting practices that preserve and enhance SOC levels, such as integrating forage species like *Brachiaria* spp., countries in Sub-Saharan Africa can improve soil fertility, increase agricultural productivity, and contribute to global efforts toward climate change adaptation and mitigation. These strategies are particularly relevant in regions like Meru County, Kenya, where smallholder farming dominates and faces challenges from climate variability and land degradation, highlighting the urgent need for sustainable soil management practices.

To address this need, the aim of this study is to evaluate the influence of agro-ecological zones and management practices on the soil carbon sequestration capacities of selected perennial forages, specifically *Brachiaria* spp., panicum (*Panicum maximum*), Napier grass (*P.P. Schumach*), and maize (*Zea mays*) control. The study seeks to identify sustainable land management strategies that enhance soil organic carbon levels and improve soil health

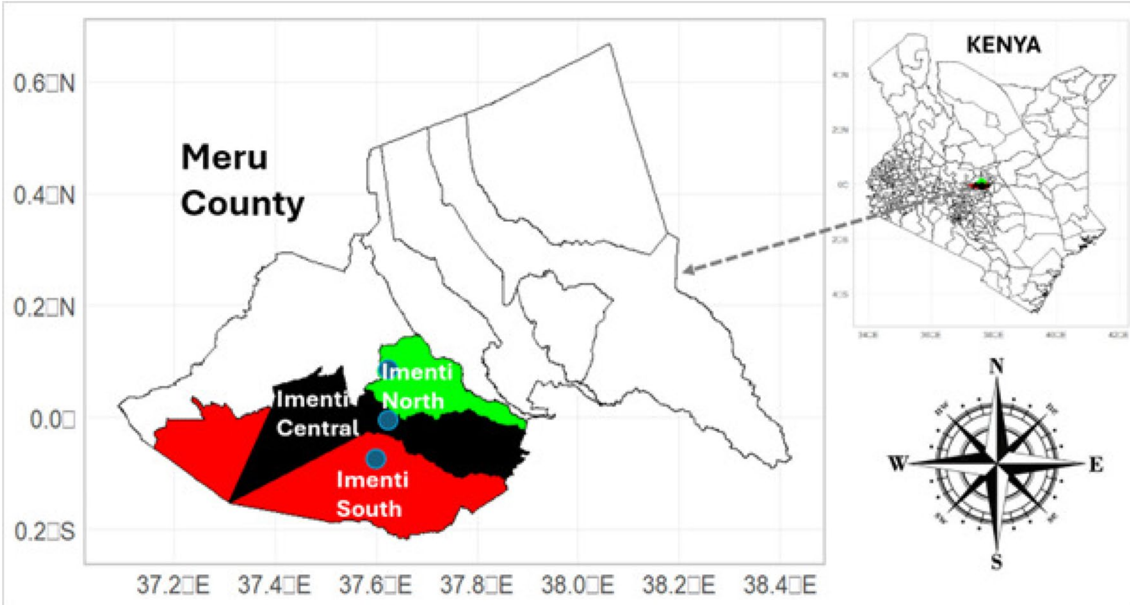

Fig. 1 Map of the study sites

Table 1 Weather data for Meru County, Kenya, from March to June 2021

Month	Average high temperature (°C)	Average low temperature (°C)	Total precipitation (mm)
March	27.0	21.0	146
April	25.0	20.0	235
May	24.0	19.0	150
June	22.0	18.0	57

in forage-based livestock production. We hypothesize that integrating farmyard manure (FYM) with *Brachiaria* spp. will significantly enhance soil organic carbon levels when compared to the use of conventional inorganic fertilizers.

2 Materials and methods

2.1 Study area

The study was conducted between March and June 2021 in Imenti Central, Imenti North and Imenti South, Meru County. The study sites are located at Latitude 0.0463°N, Longitude 37.6559°E (Imenti Central), Latitude 0.0833°N, Longitude 37.6167°E (Imenti North), and Latitude −0.0833°S, Longitude 37.6167°E (Imenti South) (Fig. 1).

The county has a bi-modal rainfall pattern, with the long rains running from March to June, and the short rains start in October and end in December. The weather data for the data collection period (March–June) is presented in Table 1

The soil type at the experimental field is humic Nitisol (IUSS WG WRB, 2015). It is well weathered with moderate to high inherent fertility, clay textured [22], and highly acidic with high iron oxide content favoring P-sorption with moderately low cation exchange capacity (CEC). Detailed soil fertility analysis values are provided in (Table 2) based on the study by [22].

Table 2 Soil fertility analysis values

Parameter	Value	Unit
Soil organic carbon (SOC)	2.5	%
Total nitrogen (TN)	0.15	%
Phosphorus (P)	10	mg/kg
Potassium (K)	0.25	cmol/kg
Calcium (Ca)	15	cmol/kg
Magnesium (Mg)	5	cmol/kg
pH (H_2O)	5.0–5.5	
Cation exchange capacity (CEC)	20	cmol/kg

2.2 Sample selection for survey

A total of thirty-five perennial forage grass growers were surveyed, selected through a stratified random sampling method to ensure representation across the three agro-ecological zones. This was done by generating a checklist of all farmers from three zones (upper, Mid and lower zone) who grow brachiaria (*Brachiaria* spp), Panicum (*Panicum maximum*), Napier grass (*P.P. Schumach*) paired with maize (*Zea mays*) field with help of a frontline extension staff. The Upper Zone (UZ), Imenti Central, is characterized by higher altitudes and greater rainfall, while the Mid Zone (MZ) Imenti North, has moderate altitude and rainfall, and the Lower Zone (LZ) Imenti South is at a lower altitude with less rainfall. A semi-structured questionnaire was used to determine the forage years of production with a target of <3 years, 3 years and >3 years for the selected perennial forages Panicum (*Panicum maximum*) (P), (Bracharia (B) and Nappier (N) in addition data on soil management practices.

2.3 Research design and soil sampling

An in-situ experiment was conducted in the 35 selected farms with a factorial plot design was employed in this study, where the agro-ecological zones served as the main plots (upper zone (UZ), mid zone (MZ), and lower zone (LZ), management practices were designated as split plots, and forage types were arranged as split-split plots. Specifically, the in-situ study was conducted across three distinct agro-ecological zones:

Within each zone, two management practices were considered the application of FYM and the use of inorganic fertilizers (IF). These management practices aimed to evaluate their effects on soil carbon dynamics and overall soil health. The forage treatments included three types: Brachiaria (*Brachiaria* spp.), Guinea grass (*Panicum maximum*), Napier grass (*Pennisetum purpureum*), and maize (*Zea mays*) which were chosen for their varying contributions to soil organic matter and nutrient cycling.

2.3.1 Soil sampling and analysis

Soil samples were collected from 1 m × 1 m plots at depths of 0–50 cm. The soil samples were analyzed for several parameters, including pH, bulk density, soil organic carbon (SOC) content, particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and various micronutrients.

2.4 Bulk density determination

Coring rings of known volume were used to collect the samples. Sampling was done carefully by driving the coring ring into the soil using hand sledge and a block of wood. Analysis of soil bulk density was done using the methodology described by Cresswell and Hamilton (2002). Oven proof containers were weighed first before the soil is transferred. The soil and the container were oven dried at 105 °C for 24 h. The soil and container were then removed from the oven and left to cool in a desiccator then weighed and recorded.

Soil bulk density (g cm^{-3}) was then be calculated as shown (Eq. 1)

$$BD = \frac{W}{V} \tag{1}$$

where BD is the bulk Density (g cm^{-3}), W is the weight of oven dried soil (g) and V is the volume of core sample (cm^3).

2.5 Soil pH determination

The pH was measured with a glass electrode pH meter on 1: 2.5 (w/v) suspension of soil in water, in all cases after shaking for 30 min.

2.6 Soil organic carbon and total nitrogen (%) determination

Soil organic carbon (SOC) was determined using the Walkley black method. This method involves the oxidation of organic carbon in the soil by a strong oxidizing agent, potassium dichromate ($K_2Cr_2O_7$), in the presence of concentrated sulfuric acid (H_2SO_4). First, a representative soil sample is air-dried and sieved to remove any large particles. The fine soil sample is then treated with a mixture of potassium dichromate solution and concentrated sulfuric acid, which facilitates the oxidation of organic carbon into carbon dioxide (CO_2). After the oxidation reaction, the excess potassium dichromate is titrated using a standard ferrous ammonium sulfate (FAS) solution. The FAS solution reacts with any remaining dichromate, and the amount required to reach the endpoint, usually indicated by a color change, is measured. The SOC content is then calculated based on the volume of FAS used, which correlates to the amount of dichromate consumed in the oxidation process. The formula for calculating SOC (Eq. 2).

$$\text{SOC}\ (\%) = \frac{\text{Volume of FAS used} \times \text{FAS concentration equivalent factor}}{\text{Weight of the soil sample}} \times 100 \tag{2}$$

While the Walkley–Black method is known for its reliability, it can slightly overestimate SOC because it also oxidizes non-organic carbon fractions. Despite this, the method is widely used due to its simplicity, cost-effectiveness, and reasonable accuracy.

Determination of Total Nitrogen (%) was done using Kjeldahl method.

The process involved several steps: First, a sample was digested with concentrated sulfuric acid and a catalyst to break down organic matter and convert nitrogen into ammonium. The sample was then neutralized with sodium hydroxide, which released ammonia gas. This ammonia was distilled and absorbed in boric acid, and the amount of ammonia was quantified through titration with a standard acid. The total nitrogen content was calculated Using the formula in (Eq. 3)

$$\text{T.N}\ (\%) = \frac{\text{Volume of titrant(mL)} \times \text{Concentrationoftitrant(mol/L)} \times \text{Equivalencyfactor}}{\text{Weight of the soil sample}} \times 100 \tag{3}$$

Weight of the sample (g) $\times$ 100.

This method is known for its sensitivity and reliability.

2.6.1 Soil organic carbon and soil organic nitrogen stock calculations

SOC and TN stocks were calculated using Eqs. 4 and 5 respectively.

$$\text{SOC stock (Mg ha}^{-1}) = \text{SOC} \times \text{BD} \times \text{D} \times \text{cf} \tag{4}$$

$$\text{SON stock (Mg ha}^{-1}) = \text{SON} \times \text{BD} \times \text{D} \times \text{cf} \tag{5}$$

where, SOC: concentration of soil organic carbon (%); SON: concentration of soil organic Nitrogen (%); BD: bulk density (g/cm^3); D is the total depth at which the sample was taken(cm). *cf* is the conversion factor = ($kg\ cm^{-3}$) × (10,000 $cm^2\ m^{-2}$) × (10,000 $m^2\ ha^{-1}$) [14].

2.7 Mineral-associated organic carbon (MAOC) and particulate organic carbon (POC) determination

SOM were separated into mineral-associated organic carbon (MAOC) and particulate organic matter (POC) using size fractionation procedure as modified by [2]. 10 g of air-dried soil were extracted with 30 mL Sodium hexametaphosphate solution (5 g L^{-1}) in 100 mL sampling bottles and shaken horizontally for 18 h. After 18 h, the sample were then be passed through a 0.053 mm sieve. The fraction retained on the sieve as POC while the finer, clay and silt fraction that were pass through the sieve as MAOM.

2.8 Statistical analysis

Effects of planted forages and maize (*Zea mays*) plantations on total SOC, SOC fractions, and the interactions were analyzed by two-way analysis of variance (ANOVA) using Genstat 15th edition. Means were separated using Tukey's HSD test and least significant difference (LSD) test at $p \leq 0.05$. Tukey's HSD was applied for multi-way comparisons, while LSD was used for pairwise mean separations, ensuring accurate distinctions. A simple linear regression analysis was used to reveal the relationship between SOC and its fractions and Perennial forages and maize (*Zea mays*) plots.

3 Results

3.1 Survey

From the survey data, 70% of the respondents had perennial forages of more than 3 years except for panicum which majority had planted for <3 years. Most of the farmers interviewed applies organic manure.

3.2 Interactive effects of zone and forages on soil BD, pH and soil micronutrients

The interaction of management practices (Mgt) and forage/crop types (F/C) had a significant effect on bulk density, with the highest mean observed under IF*N (Table 3). Conversely, the FYM plots exhibited lower bulk densities compared to the inorganic fertilizer treatments, though these differences were not statistically significant.

Table 3 Interactive effects of zone and forages on soil pH and soil micronutrients

Mgt	F/c	BD (g/cm^3)	pH (H_2O)	Mn (ppm)	Zn (ppm)	CEC (cmol/kg)	Cu (ppm)	Fe (ppm)	P (ppm)
IF	N	1.19^{a}	5.13^{a}	88.65^{b}	9.47^{bc}	21.39^{b}	2.698^{ab}	55.84^{a}	39.15^{b}
	BR	1.12^{a}	5.25^{a}	86.54^{a}	7.82^{a}	19.37^{a}	2.411^{ab}	63.51^{c}	34.41^{a}
	M	1.18^{a}	5.27^{a}	94.93^{c}	11.21^{e}	22.50^{b}	2.311^{a}	55.47^{a}	53.73^{d}
	P	1.14^{a}	5.19^{a}	95.93^{cd}	11.10^{de}	19.10^{a}	2.502^{ab}	60.48^{b}	41.84^{c}
FYM	N	1.12^{a}	5.23^{a}	89.02^{b}	9.84^{cd}	21.74^{b}	2.747^{b}	56.21^{a}	39.50^{b}
	BR	1.13^{a}	5.33^{a}	86.91^{a}	8.19^{ab}	19.72^{a}	2.460^{ab}	63.88^{c}	34.76^{a}
	M	1.07^{a}	5.36^{a}	95.30^{cd}	11.58^{e}	22.84^{b}	2.360^{ab}	55.84^{a}	54.08^{d}
	P	1.07^{a}	5.32^{a}	96.30^{d}	11.47^{e}	19.45^{a}	2.551^{ab}	60.85^{b}	42.19^{c}

F/c Forage/crop, *MGT* management, *BR* Brachiaria spp, *M* Maize (*Zea mays*), *N* Napier, *P* Panicum (*Panicum maximum*)

Means followed by the same superscript letter (within a column of each parameter) are not significantly ($p < 0.05$) different

Table 4 Effects of forages and maize (*Zea mays*) and depth on particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

Forage	Panicum	Napier	Maize	Brachiaria
MAOC (g C kg^{-1})	4.45^{a}	4.63^{b}	4.39^{a}	5.37^{c}
POC (g C kg^{-1})	5.86^{b}	5.42^{a}	5.38^{a}	5.97^{b}
Depth	0–10	11–20	21–50	
MAOC (g C kg^{-1})	4.84^{b}	4.77^{b}	4.53^{a}	
POC (g C kg^{-1})	5.71^{a}	5.65^{a}	5.61^{a}	

Means followed by the same superscript letter (within a row of each parameter) are not significantly ($p < 0.05$) different by Tukey's HSD test

Table 5 Interactive effects of management and forage/crop on particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

Management	Forage/crop	POC (g C kg^{-1})	MAOC (g C kg^{-1})
Inorganic fertilizer (IF)	Napier	5.304^{ab}	4.557^{ab}
	Brachiaria	5.859^{de}	5.293^{c}
	Panicum	5.746^{cd}	4.379^{a}
	Maize	5.264^{a}	4.318^{a}
Farmyard manure (FYM)	Napier	5.534^{bc}	4.704^{b}
	Brachiaria	6.089^{e}	5.439^{c}
	panicum	5.976^{de}	4.526^{ab}
	Maize	5.494^{abc}	4.465^{ab}

Means followed by the same superscript letter (within a column of each parameter) are not significantly ($p < 0.05$) different by Tukey's HSD test

Soil pH across the study sites displayed variability, indicating the influence of different management practices. The management strategies employed significantly affected all measured micronutrients. For instance, the FYMP treatment exhibited the highest cation exchange capacity and manganese levels, while FYMM demonstrated enhanced phosphorus availability (Table 3).

3.3 Effects of forages and maize (*Zea mays*) and depth on particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

The content of particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) varied significantly among the three forages and maize (*Zea mays*), with notable differences observed across treatments. Specifically, *Brachiaria* spp. exhibited higher Mnera, Associated Organic carbon levels compared to *Zea mays*, Napier grass (*Pennisetum purpureum*), and *Panicum maximum* (Table 4). A similar trend was observed for particulate organic carbon, which was significantly higher under *Brachiaria* spp. in comparison to *Panicum maximum*, *Zea mays*, and Napier grass. The results also indicated that while mean values of POC at different soil depths did not show significant differences, 0–10 cm had higher POC compared to 21–50 cm (Table 4). In contrast, MAOC levels displayed significant differences across all soil depths, with the highest concentrations found in the 0–10 cm, followed by the 11–20 cm.

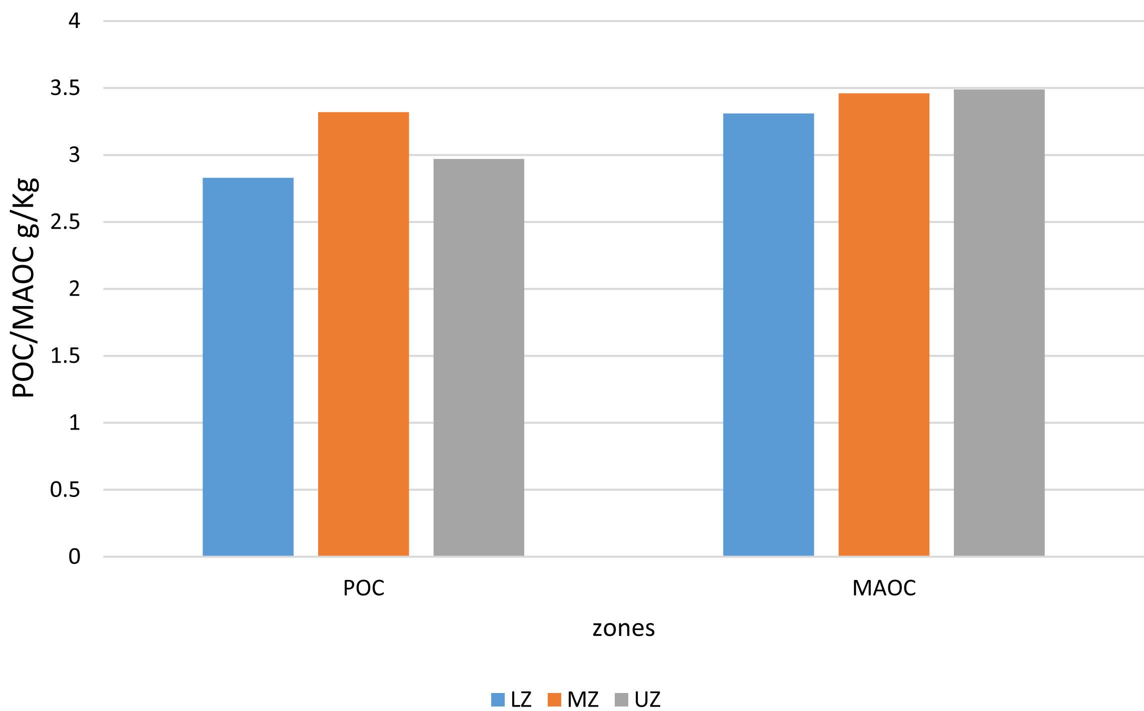

Fig. 2 Effects of zone on particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

Table 6 Soil organic carbon stocks, soil organic nitrogen stocks and CN ratio under different forages

Forage/crop	SOCs (Mg/ha)	SONS (Mg/ha)	CN ratio
BR	18.28^{c}	3.34^{a}	5.5
M	15.61^{b}	3.39^{a}	4.6
N	11.10^{a}	3.40^{a}	3.3
P	20.50^{d}	3.85^{ab}	5.3

Means followed by the same superscript letter (within a column of each parameter) are not significantly ($p < 0.05$) different by Tukey's HSD test

3.4 Interactive effects of management and forage/crop on particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

The results from this study showed that the interactive (Mgt*F/C) mean values of POC and MAOC were significantly different. Thus, brachiaria with Farmyard manure had higher POC than panicum with Farmyard manure and Napier with Farmyard manure, but not significantly different from FYM*M. There was also a significant difference for MAOC among the different interactions of Mgt*F/C (Table 5), with the highest values observed in FYM*Br compared to other interactions, although it was not significantly different from IF*Br.

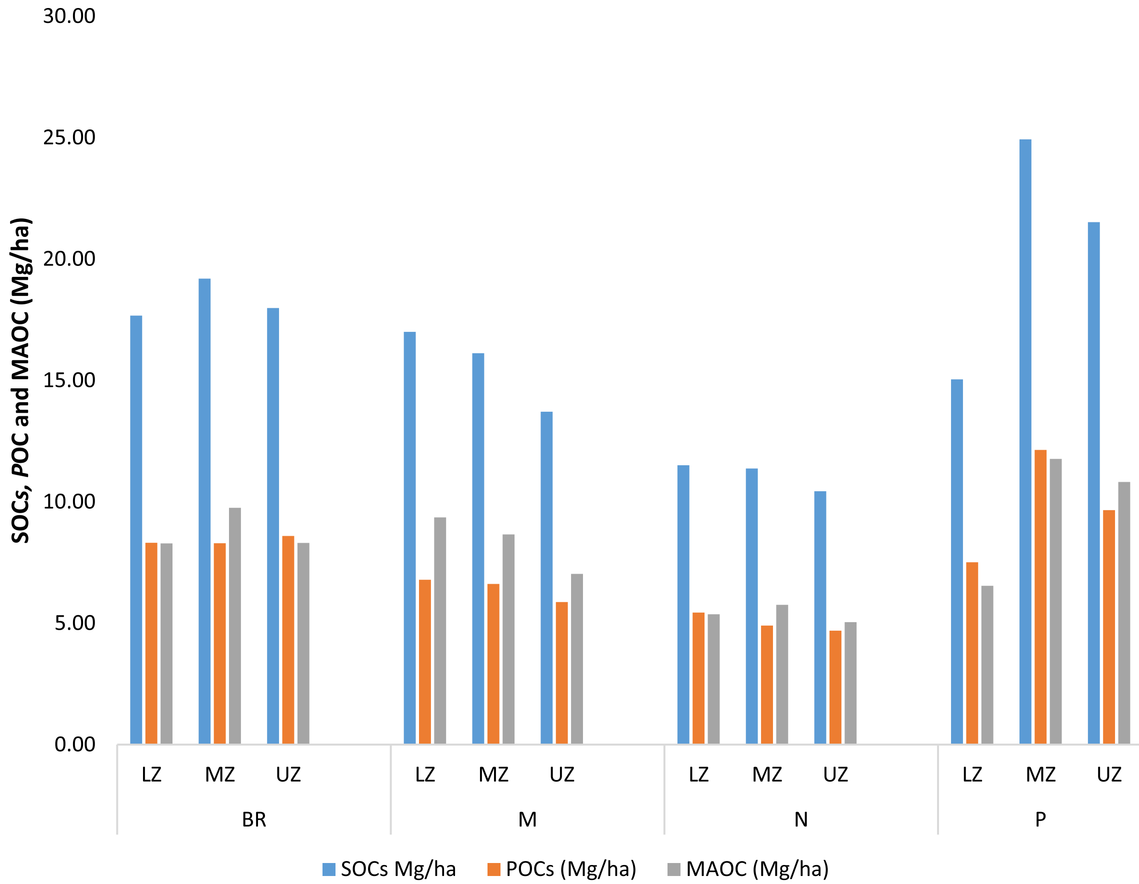

Fig. 3 Interactive effects of zone and forage/maize on soil organic carbon stocks (SOCs), particulate organic carbon (POC) and mineral associated organic carbon (MAOC)

3.5 Effects of zone on particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

The results from this study show that the mean values of POC and MAOC were not significantly different across the three zones. However, the mid zone exhibited higher POC compared to both the upper zone and the lower zone. In contrast, there were no significant differences in MAOC levels among the three zones, although the upper zone had the highest MAOC values, followed closely by the mid and lower zones (Fig. 2).

3.6 Soil organic carbon stocks, soil organic nitrogen stocks CN ratio under different forages

Soil organic carbon fractions, SOC, and SON stocks varied with different forages and crops. The highest mean SOC stock was observed in *Panicum* compared to *Brachiaria spp.* and maize. In contrast, SON stocks did not show significant differences across all forages and maize, although *Panicum* recorded the highest SON levels (Table 6).

3.7 Interactive effects of zone and forage/maize on soil organic carbon stocks (SOC), particulate organic carbon (POC) and mineral associated organic carbon (MAOC) content

The results from this study indicate that the mean values of SOCs, POC, and MAOC were significantly different across the three zones. Specifically, the MZ exhibited higher SOCs and POC compared to both the UZ and the LZ when considering *Panicum* forage. In contrast, there were no significant differences in MAOC among the three zones, although the mid zone had the highest MAOC values, followed by the UZ and LZ (Fig. 3).

4 Discussion

The study revealed significant variations in soil organic carbon (SOC) and soil organic nitrogen (SON) stocks among different forages and crops, underscoring the influence of different forages on soil carbon and nitrogen dynamics. *Panicum maximum* exhibited the highest mean SOC stock, followed by *Brachiaria* spp. and maize (*Zea mays*). This variation can be attributed to several factors related to plant characteristics and litter quality. Research supports the idea that perennial grasses like *Panicum maximum*, with their extensive root systems and high biomass production, contribute significantly to SOC sequestration. These plants enhance organic matter input into the soil, promoting SOC accumulation through root turnover and litter decomposition processes [20, 33]. In contrast, maize, being an annual crop with different growth patterns and litter quality, may contribute less to SOC formation due to lower quality residues and less extensive root systems compared to perennial grasses [18].

Although SOC varied significantly among the forages, SON stocks showed no significant differences. This suggests that while different plants may affect SOC accumulation differently, they may have similar impacts on SON stocks, possibly due to comparable nitrogen inputs from root exudates and decomposition residues across the forages [31]. The C ratio indicates variations in the decomposition rates of organic matter and nitrogen mineralization potential. Lower C ratios generally imply faster decomposition and potentially higher nitrogen mineralization rates, influencing soil fertility and nutrient availability [26, 30].

Application of farmyard manure (FYM) was found to increase SOC content due to its carbon content and improved soil water holding capacity, which is essential for soil nutrient enhancement [15]. FYM stimulates microbial populations and enhances soil conditions, accelerating organic matter decomposition and carbon release [11, 27]. This enhancement in microbial activity contributes significantly to the buildup of soil organic carbon, which is crucial for soil fertility and ecosystem health. FYM serves as a valuable source of soil nutrients and contributes to the improvement of soil physical structure [15]. The application of FYM is a widely adopted method to enhance soil fertility by increasing the availability of nutrients. Recent studies indicate that forage crops exhibit luxury consumption of nutrients when supplemented with inorganic fertilizers, depleting soil reserves due to the immediate availability of nutrients [12, 21]. This phenomenon underscores the importance of sustainable nutrient management practices in agriculture.

Forage crops like *Panicum* and *Brachiaria* exhibit substantial carbon sequestration potential, attributed to their robust root systems and efficient nutrient uptake [28, 30]. These findings underscore the importance of selecting appropriate forages in agricultural systems to enhance SOC levels and overall ecosystem resilience. Root-derived carbon inputs, rapidly absorbed and preserved within soil aggregates, further contribute to particulate organic matter and humus fractions, supporting long-term soil organic matter dynamics and carbon sequestration [9, 15].

The above-ground dry matter contributes to an increase in MAOC in the top layer of soil depth. This finding aligns with the research by [25], which indicates that the highest carbon stocks are found in the soil surface due to the deposition of residues from the forage and the concentration of root systems in the top layers of soil. The results obtained in this research indicate that *Brachiaria* spp. and *Panicum* showed an increase in POC content. This is attributable to the high quantity of above-ground residues and the direct influence of roots as the primary source of soil carbon, particularly in the plots of *Panicum* and *Brachiaria spp.* Thus, the greater below-ground root biomass of these forages led to increased microbial activity and subsequently higher POC and MAOC compared to Napier grass and maize. This concurs with findings from [18, 19], which indicate that the voluminous root systems of *Panicum maximum* and *Brachiaria* spp. significantly contribute to soil organic matter (SOM) accumulation. Recent studies continue to support this observation, underscoring the role of extensive root systems in enhancing SOM content and carbon sequestration [13, 30]. Additionally, the higher canopy in *Panicum* and *Brachiaria* results in increased soil moisture content, encouraging high litter turnover and thus contributing to SOC from the surface. Protective cover over the soil surface has been shown to reduce the impacts of wind and water erosion on surface horizons [7]. Higher levels of mineral-associated organic carbon (MAOC) are associated with the decomposition of plant residues and nutrient mineralization [15, 27]. Previous studies have reported that *Brachiaria* spp. positively affects POC due to increased organic residue inputs into the soil [5]. Moreover, Lopes et al. [17] associated the higher MAOC content in *Brachiaria* spp. with greater shoot dry matter production and exudate release compared to other species.

From this research, it is evident that POC was higher in the mid zone than in the other zones. This indicates that forage/crop biomass changes with the zones, significantly impacting SOC input, hydrological processes, and, consequently, the effects on POC and mineral-associated organic carbon. The mid zone, as characterized by [8], experiences distinct climatic conditions that affect vegetation biomass and productivity, thereby influencing the quantity of organic carbon input into the soil. Recent studies continue to highlight the variability in climate conditions across different zones and its impact on soil organic carbon dynamics [28, 30].

Research supports that different agro-ecological zones can significantly influence soil carbon fractions due to varying environmental conditions and management practices. For instance, studies by [28, 32] highlight how soil carbon levels can vary across different geographical zones, influenced by factors such as climate, soil type, and vegetation cover. The mid zone's higher SOC and POC levels align with findings by [23], who emphasize the role of favorable environmental conditions and plant species in promoting carbon sequestration through increased root biomass and organic matter inputs. Regarding MAOC, although no significant differences were observed among the three zones in this study, previous research by [16, 30] underscores the stability of mineral-associated organic carbon across diverse environmental gradients. This stability suggests that while particulate organic carbon may vary with management practices and environmental conditions, mineral-associated organic carbon remains relatively consistent due to its bonding with soil minerals.

5 Conclusion

The study revealed significant variations in soil organic carbon (SOC) and its fractions, particularly particulate organic carbon (POC) and mineral-associated organic carbon (MAOC), across different agroecological zones. Notably, the Mid Zone demonstrated the highest SOC levels, highlighting its potential for enhanced carbon sequestration under suitable management practices. Among the forages assessed, *Brachiaria* spp. outperformed *Panicum maximum* and maize (*Zea mays*) in sequestering SOC. This indicates that the selection of forage species is crucial for maximizing SOC benefits in tropical farming systems, underscoring the importance of incorporating effective forage species to improve soil health.

The application of farmyard manure (FYM) significantly enhanced soil health indicators, leading to higher SOC and nutrient retention compared to inorganic fertilizers. This reinforces the recommendation for integrating organic amendments into farming practices as a sustainable strategy to enhance soil fertility and mitigate land degradation. The results suggest that promoting the cultivation of perennial forages, particularly *Brachiaria* spp., combined with organic amendments like FYM, could substantially improve soil health and agricultural productivity. Such practices not only contribute to enhanced soil fertility but also support climate change mitigation efforts by increasing carbon storage in soils.

Finally, the study recommends further investigation into the long-term effects of perennial forages on SOC dynamics. It is essential to explore the socio-economic factors that may influence farmers' adoption of sustainable agricultural practices. Understanding these factors will be crucial for effectively scaling successful interventions across diverse agro-ecological contexts in Kenya and other regions.

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Author contributions Janeth Chepkemoi- has contributed to conception or design of the work, data collection, data analysis and interpretation, drafting the article and critical revision of the article. She oversaw the data collection process, ensuring accurate soil sampling techniques across the thirty-five farms. A.G also analyzed key soil properties, such as pH and bulk density, and provided insights on the implications of the findings for sustainable agricultural practices. Her expertise was instrumental in framing the research within the context of soil health and productivity. Prof. Richard Onwonga-has contributed to critical revision of the article and final approval of the version to be published. Angela Gitau contributed to the conceptualization and design of the study, focusing on the selection of agro-ecological zones and management practices. Bitange Naphis was responsible for the statistical analysis of the data, utilizing two-way ANOVA to assess the impacts of management practices and forage types on soil organic carbon dynamics.

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Data availability Data is provided within the manuscript.

Declarations

Ethics approval and consent to participate All authors have reviewed the manuscript and agree to its submission to this journal.

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Informed consent The sampling was conducted on farmers field and permission was obtained from the farmers to sample at their field.

Compliance with ethical standards The protocols for this research were approved by NACOSTI Committee in accordance with the NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY AND INNOVATION (NACOSTI).

Competing interests The authors declare no competing interests.

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