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ORIGINAL ARTICLE

Effects of planting basins and farmyard manure addition on soil carbon and nitrogen pools under on-farm conditions in Makueni county of Kenya

Edith Kichamu-Wachira[1] | **Zhihong Xu**[1] | **Kathryn Reardon-Smith**[2] | **Leigh Ann Winowiecki**[3] | **Gebiaw Ayele**[4] | **Duan Biggs**[1,5] | **Christine Magaju**[3] | **Sabah Taresh**[1,6] | **Shahla Hosseini-Bai**[1] | **Negar Omidvar**[1]

[1]Centre for Planetary Health and Food Security, School of Environment and Science, Griffith University, Brisbane, Queensland, Australia

[2]Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland, Australia

[3]World Agroforestry (ICRAF), Nairobi, Kenya

[4]Australian Rivers Institute, School of Engineering, Griffith University, Nathan, Queensland, Australia

[5]Northern Arizona University, Flagstaff, Arizona, USA

[6]Date Palm Research Centre, University of Basrah, Basrah, Iraq

Correspondence

Edith Kichamu-Wachira, Centre for Planetary Health and Food Security, School of Environment and Science, Griffith University, Brisbane, Queensland, Australia.
Email: edith.kichamu@griffithuni.edu.au

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Abstract

Climate change, land degradation and inadequate soil nutrients pose significant threats to food security and agricultural sustainability. This study aims to examine the effects of planting basins with farmyard manure on soil total carbon (C), nitrogen (N), isotopic C ($\delta^{13}C$) and N ($\delta^{15}N$) compositions within smallholder-managed farms in Makueni County, Kenya. The study involved two management practices: planting basins with manure (PM) and conventional farming practices (FP) in 12 experimental sites. Soil samples were taken at three depths (0–10, 10–20 and 20–40 cm), with three replicates for each treatment. Significant interactions were observed between land management practices and sites as well as land management practices and soil depth on soil total C and N. At each of the 12 sites, soil total C was higher under PM (ranging from 0.44% to 1.86%, $p<.05$) than FP management (ranging from 0.35% to 1.37%), across all soil depths. Soil total N concentrations ranged from 0.027% to 0.100% under FP and (0.060% to 0.190%, $p<.05$) under PM management. Across soil depths, higher (less negative) soil $\delta^{13}C$ values were observed under conventional farmer practice (range − 22.5‰ to −17.1‰) compared with PM management range (−24.3‰ to −18.1‰). Soil $\delta^{15}N$ was significantly enriched under PM management (range: 7.4‰ to 12.6‰, $p<.05$) compared with the conventional farmer practices (range: 6.1‰ to 9.8‰, $p<.05$). The findings show that planting basins with farmyard manure offers both climate mitigation and adaptation benefits by increasing soil C contents and improving soil fertility. The study provides insights into the real-world implications of these practices, emphasizing the potential of planting basins with manure in enhancing soil quality and climate resilience.

KEYWORDS

climate-smart, manure, planting basins, soil carbon, total N

1 | INTRODUCTION

Climate change, land degradation, and inadequate soil nutrients are significant threats to food security and the sustainability of the agriculture sector (DeLong et al., 2015; Lal, 2015). Soils store around 80% of carbon (C) in terrestrial ecosystems in the form of soil organic C (Ng'ang'a et al., 2019; Powlson et al., 2011). Soil organic C plays a crucial role in climate change mitigation as it regulates carbon dioxide concentration in the atmosphere and is an indicator of soil fertility (Smith et al., 2020). Soil organic C is influenced by agricultural management practices such as tillage, organic amendment, fertilizer addition and inherent soil properties, including texture, mineralogy and biological activity (Kichamu-Wachira et al., 2021; Liu et al., 2020; Mikha et al., 2017). Soil nitrogen (N) availability is critical for plant growth and productivity (Omidvar et al., 2021, 2023). N is a vital component of the proteins required for photosynthesis; thus, soil N limitation can negatively influence the photosynthetic capacity of a plant (Du et al., 2020; Quemada & Gabriel, 2016). Therefore, sustainable management practices that increase N availability in the soil must be applied to ensure optimal plant growth and yield.

Soil C and N isotope compositions ($\delta^{13}C$ and $\delta^{15}N$, respectively) are useful indicators for C and N cycling in terrestrial ecosystems under long-term climate change and local management/disturbance (Fu et al., 2020; Rui et al., 2011; Sun et al., 2010; Xu et al., 2008, 2009). Soil $\delta^{13}C$ and $\delta^{15}N$ are also used to understand the pathways in which C and N leave the ecosystem (Ibell et al., 2010, 2013; Reverchon et al., 2012; Wang, Wang, et al., 2015; Wang, Xu, et al., 2015; McCorkle et al., 2016; Jeong et al., 2022). The ^{15}N of N sources such as manure or fertilizer applied to the soil, N loss, and N cycling processes affects soil $\delta^{15}N$ (Asadyar et al., 2021; Choi et al., 2017, 2020; Succarie et al., 2022; Zhang et al., 2018). The soil $\delta^{15}N$ best indicates N availability or losses since it is enriched with increasing soil N losses because of leaching and denitrification (Ibell et al., 2013; Hosseini-Bai et al., 2015; Wang et al., 2014, Wang, Wang, et al., 2015; Wang, Xu, et al., 2015; Nessa et al., 2021). The discrimination against the heavier ^{15}N isotope by microbial N transformations in the soil predominantly affects soil $\delta^{15}N$ (Asadyar et al., 2021; Hosseini-Bai et al., 2015; Nessa et al., 2021; Succarie et al., 2022; Xu et al., 2008). Thus, higher $\delta^{15}N$ in terrestrial ecosystems indicates active N cycling or N availability because of increased microbial activity (Asadyar et al., 2021; Hosseini-Bai et al., 2015; Succarie et al., 2022; Wang et al., 2020). On the other hand, soil $\delta^{13}C$ is a biological indicator of C cycling and could be used to interpret soil organic matter (SOM) mineralization processes and land uses (Wang et al., 2013; Saiz et al., 2016; Succarie et al., 2020; Sun et al., 2021; Liu et al., 2021; Fu et al., 2023). The C cycle is vital because it affects soil respiration and the process of plant photosynthesis (Farooq et al., 2021; Liu et al., 2021; Succarie et al., 2020; Fu et al., 2023). Soil $\delta^{13}C$ reflects the source of organic matter (C_3 or C_4 vegetation), C turnover and C loss rates from an ecosystem (Han et al., 2020; Jeong et al., 2022). Thus, $\delta^{13}C$ and $\delta^{15}N$ are insightful indicators of land management practices' effect on soil C and N availability and its dynamics.

The agricultural sector should prioritize enhancing SOC for climate mitigation and improved soil fertility (Gura et al., 2022). This calls for adopting and implementing sustainable farming practices that enhance soil C and N and improve C and N cycling. Climate-smart agriculture (CSA) practices are widely promoted sustainable farming practices to mitigate climate change risks. CSA may offer climate change mitigation and adaptation benefits as it improves productivity and enhances food security while sustaining the environment (Martinsen et al., 2017; Palombi & Sessa, 2013). CSA practices, such as soil nutrient management, tillage management and water-harvesting techniques, enhance C and N pools and agricultural productivity (Hati et al., 2006; Kichamu-Wachira et al., 2021; Kushwa et al., 2016). One such practice is the adoption of planting basins, a technical innovation originating from Burkina Faso in West Africa (Danso-Abbeam et al., 2019). Planting basins - also known as 'Zai pits' or '*Tumbukiza*' in Kenya – is a tillage management practice where holes measuring 60 cm wide by 60 cm long by 60 cm deep are dug into the soil, with or without the addition of organic matter, used for growing crops (Danso-Abbeam et al., 2019; Kathuli & Itabari, 2015; Kimaru-Muchai et al., 2020). This CSA technology has proven effective in semi-arid regions with moisture stress and low soil fertility (Kathuli & Itabari, 2015; Danso-Abbeam et al., 2019). Planting basins have contributed to the restoration of degraded lands and improved soil fertility while cushioning agriculture from the adverse effects of climate change (Marongwe et al., 2012; Marumbi et al., 2020). The planting basins are permanent and can be reused for up to 5 years before major repairs are required. Most farmers add farmyard manure or crop residues in the planting basins before planting crops to enhance productivity. Adding farmyard manure to soil stimulates microbial processes, enhances C and N cycling, and improves soil physical and chemical properties (Du et al., 2020; Li et al., 2019; Ma et al., 2020; Sarker et al., 2018). It has also been reported that planting basins can increase SOC because of minimal soil disturbance (Marumbi et al., 2020; Nyamangara et al., 2014). Therefore, adopting this tillage management practice is promoted as a significant step towards improving soil quality, moisture retention, climate resilience and C sequestration.

Despite a growing body of research on the effects of planting basins with or without amendments on soil C levels (Martinsen et al., 2017; Mupangwa et al., 2013; Nyamangara et al., 2014; Thierfelder & Wall, 2012), a significant gap remains. The majority of these studies have been confined to controlled experimental environments. While invaluable, such controlled conditions could miss capturing smallholder farmers' real-world complexities and challenges. It is particularly noteworthy that there is a dearth of studies investigating the impact of planting basins with manure on soil C and N under genuine on-farm conditions. Baudron et al. (2011) pointed out the inherent limitations of relying solely on controlled tests carried out on research stations. While these tests form the crux of scientific evidence underpinning best practices in agricultural production compared with traditional farming approaches, they frequently do not replicate the exact challenges and limitations of smallholder farmers. In essence, outcomes derived from such controlled environments often assume access to resources or conditions that might be unrealistic or infeasible for smallholder farmers (Baudron et al., 2011). Given these considerations, there is a pressing and unmet need for rigorous studies that assess the impacts of Climate-Smart Agriculture (CSA) and other innovations on soil C and N under real on-farm scenarios. Addressing this gap not only provides more representative findings but could also guide agricultural policy and practice in a direction that is more attuned to the realities of smallholder farming. This study, therefore, aimed to contribute to this underexplored area by examining the effects of planting basins with farmyard manure on soil total C, N, $\delta^{13}C$ and $\delta^{15}N$ compositions within smallholder-managed farms in Makueni county, Kenya. Our guiding hypotheses for this investigation were: (i) the planting basins with manure (PM) practice has no significant influence on soil total C, N, $\delta^{13}C$ and $\delta^{15}N$ and (ii) there is no observed effect on the levels of C, N, $\delta^{13}C$, and $\delta^{15}N$ across varying soil depths.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was conducted on smallholder farms in Makueni County, Kenya (Figure 1). Makueni County is a semi-arid region of Kenya and lies at an altitude of between 600 and 1280 m above sea level (Saiz et al., 2016). The area receives an annual rainfall of between 300 mm

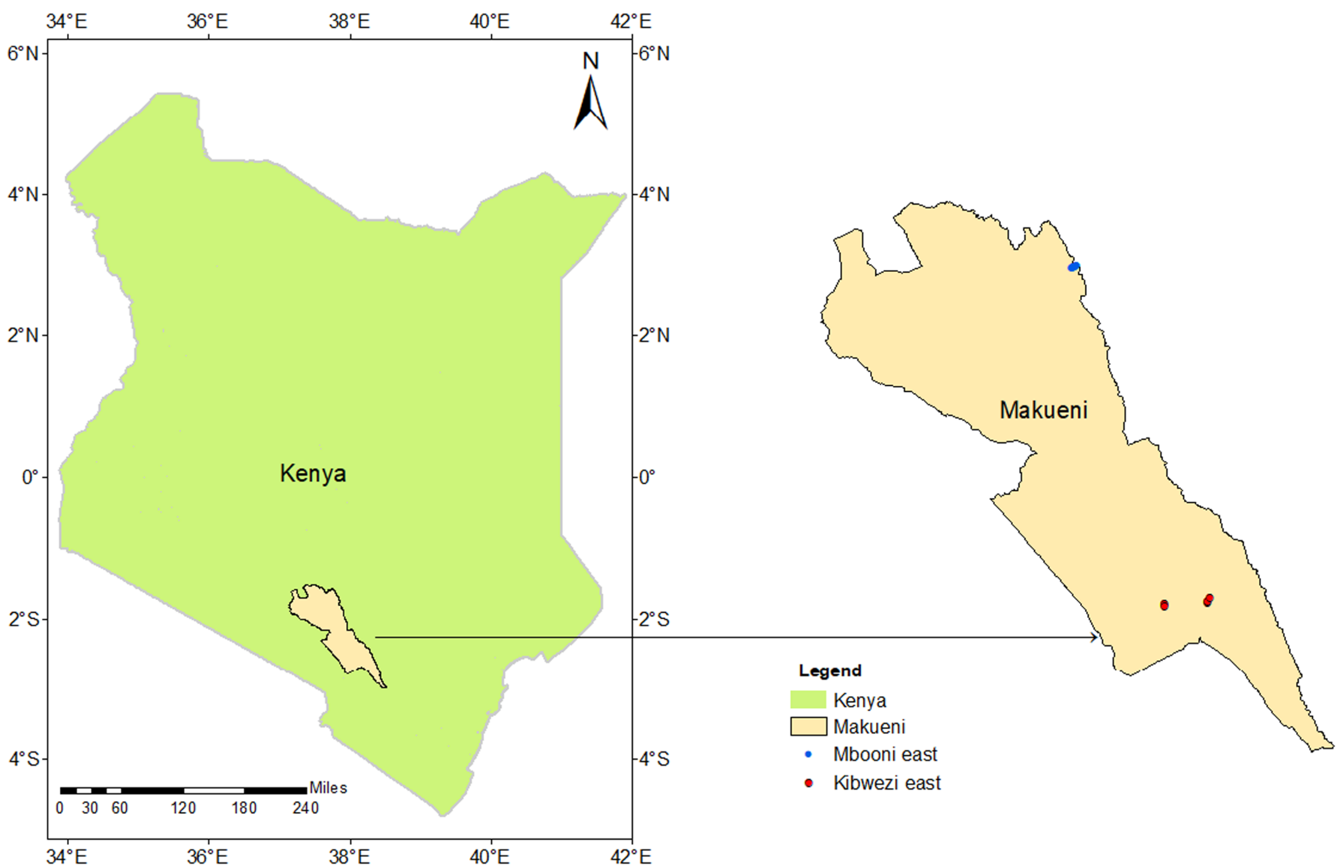

FIGURE 1 Map of Kenya showing the study.

TABLE 1 Distribution and sites of farmers' plots across two sub-counties in Makueni County.

Subcounty	Site	Gps co-ordinates		Altitude	Average rainfall (mm)	Soil type	Other management in treatment plots
		Latitude	Longitude				
Kibwezi East (Mtito Andei)	F1	−2.5764	38.1862	693.5	590.8	Clay loam	Charcoal dust added
	F2	−2.5892	38.1792	715.6	590.8	Clay loam	
	F3	−2.5852	38.1802	595.6	590.8	Clay	
	F4	−2.5985	38.0641	833.6	628.8	Clay loam	
	F5	−2.5918	38.0634	860.0	628.8	Clay loam	
	F6	−2.5959	38.0642	844.7	628.8	Sandy loam	
Mbooni East (Kalawa)	F7	−1.6902	37.8182	939.5	765.3	Clay loam	300 cm × 100 cm × 45 cm basins, irrigation
	F8	−1.6926	37.8176	964.9	765.3	Clay	
	F9	−1.6881	37.8287	964.2	765.3	Sandy loam	
	F10	−1.6886	37.8288	936.1	765.3	Sandy	
	F11	−1.6957	37.8145	970.6	765.3	Clay loam	
	F12	−1.6902	37.8247	955.0	765.3	Sandy loam	

and 800 mm with annual mean minimum temperatures of 20.2 degrees Celsius and annual mean maximum temperatures of 35.80 degrees Celsius. Makueni County covers 8034.7 km^2, with a population of 922,183 (Muema et al., 2018). The poverty index is ca. 64%, higher than the national index, which is 47%. The major livelihood source is agriculture, which employs ca. 78% of the rural population directly and indirectly. The area is characterized by smallholder mixed farming, with the farmers engaging in livestock and crop farming. The major crops cultivated include maize, pigeon peas, sorghum, cowpeas, millet, beans, green grams (mung bean) and mangoes (Muema et al., 2018).

Soil sampling was conducted in Makueni County, across 12 farmer fields — six from Mbooni East and six from Kibwezi East sub-county. These fields are hereafter referred to as 'sites'. These sites were farmer-managed, and treatments were under on-farm conditions. The sampled farms had implemented the CSA practices (i.e. planting basins with annual addition of farmyard manure) from 2018–2021. Prior to adopting these CSA practices, land use on these farms primarily involved crop farming, with maize as the principal crop grown in the plots. Crop rotation was also a part of the farming system, and the sequence included maize followed by pigeon peas or green grams in some of the plots. Additionally, other crops grown in these plots included cowpeas and green grams, further diversifying the agricultural activities. On all sampled sites, farmers used both planting basins with farmyard manure (treatment) and conventional farmer practices (control); thus, we sampled treatments and control sites from each farm. Eleven of the sampled farms had permanent basins measuring 60 cm × 60 cm × 45 cm, except for farm F10, where planting basins were 300 cm × 100 cm × 45 cm. The inter-basin spacing was 60 cm. The farmyard manure used was composted on the farms or bought from neighbours. Ca. 4–6 kg of manure per planting basin is added yearly. Conventional farmer practices comprised the overall digging of flatlands using oxen or hand hoes. No manure was added to the FP plots (all sites). Soils were classified according to the USDA[1] soil textural triangle with most sites being clay loam and sandy loam except for site F10 which was sandy, and sites F3 and F8 were clay (Moreno-Maroto & Alonso-Azcarate, 2022; Soil Survey Division, 2017). Details of the selected farms are provided in Table 1. In the treatment plots, maize was grown inside the planting basins, while legumes (pigeon peas, sorghum, cowpeas, millet, beans and green grams) were outside. The control plots had a mixture of both maize and legumes.

[1]United States Department of Agriculture

The study employed a randomized complete block design (RCBD) at each of the 12 sites. Within each site, we established two treatments: (i) planting basins with farmyard manure (PM) and (ii) conventional farmer practice (FP). Each treatment was replicated three times, resulting in a total of six plots per site. The plots, 5 m × 5 m each, were carefully selected to ensure that the soil types in the control (FP) plots closely matched with those in the treatment (PM) plots. For the PM treatment, soil samples were collected explicitly from inside the planting basins.

2.2 | Soil sample collection and analysis

Soil samples were collected mid-season during the October–November–December 2020 rain season. The soil samples were taken from adjacent treatment (planting basins with farmyard manure) and control (conventional farming) plots. Soil samples were collected at three depths: 0–10 cm, 10–20 cm and 20–40 cm. This was done by collecting 5 soil cores from each plot for each depth interval, which were combined to form a single composite sample for that specific depth. This process was repeated for each of the depth intervals. Compositing samples within each depth stratum ensures a representative sample by averaging out small-scale spatial variability, a standard approach in soil science to capture average plot conditions for the specified depth (Hofman & Brus, 2021). For the PM plots, soil samples were collected inside the planting basins. The soil samples were kept in separate labelled bags and transferred to the CIFOR-ICRAF Soil–Plant Spectral Diagnostics Laboratory in Nairobi, Kenya. All the collected soil samples ($n = 216$) were air-dried at 60°C, passed through a 2 mm sieve, and shipped to Griffith University, Australia, for further analysis. The samples were then ground to a fine powder using a Rocklabs™ ring grinder, then weighed and transferred into tin capsules for soil total C, total N, $\delta^{15}N$ and $\delta^{13}C$ analyses. These analyses were conducted to offer insights into how different practices impact soil health and quality. All the analyses, soil total C, total N, δ 1^{5}N and $\delta^{13}C$, were conducted using an Isotopic Ratio Mass Spectrometer connected to a CN Eurovector Elemental Analyser at Griffith University's Australia Isotopes Laboratory (Ibell et al., 2013; Xu et al., 2008).

2.3 | Statistical analysis

The data were checked for normality using the Shapiro–Wilk test in SPSS v. 27.0 and log-transformed where necessary to satisfy the normality condition. Three-way analysis of variance (ANOVA) tests were conducted to explore the interactions between the treatments, sites and soil depths. This was followed by a series of one-way ANOVAs for each of the 12 sites. The Tukey HSD post hoc test was then conducted at a 5% probability level ($p < .05$).

3 | RESULTS

3.1 | Soil total C and total N

Significant interactions were observed between land management practices and sites as well as land management practices and soil depth (three-way ANOVA, $p < .001$) on soil total C and N (Table 2). Generally, at each of the 12 sites, soil total C was higher under planting basins with manure (PM) (range 0.44% to 1.86%) than conventional farmer practice (FP) management (0.35% to 1.37%) across all soil depth categories (Figure 2). The highest soil total C concentrations were observed in soils collected at the 0–10 cm depth and the lowest at the 20–40 cm depth. Soil

TABLE 2 Three-way analysis of variation (ANOVA) on the impacts of site, treatment (land management practice) and soil depth on TC, TN, $\delta^{13}C$ and $\delta^{15}N$ in all 12 sites combined.

	TC			TN			$\delta^{13}C$			$\delta^{15}N$		
Treatments	*Df*	*F*	*p*	*Df*	*F*	*p*	*Df*	*F*	*p*	*Df*	*F*	*p*
Treatment	1	311.35	**	1	359.76	**	1	187.69	**	1	322.32	**
Site	11	29.05	**	11	26.32	**	11	39.75	**	11	34.99	**
Soil depth	2	69.11	**	2	54.26	**	2	102.88	**	2	3.844	*
Treatment × Site	11	9.77	**	11	8.77	**	11	9.63	**	11	6.50	**
Treatment × Soil depth	2	20.59	**	2	24.73	**	2	2.19	ns	2	4.53	*
Site × Soil depth	22	1.01	ns	22	1.13	ns	22	1.57	ns	22	1.15	ns
Treatment × Site × Soil depth	22	1.39	ns	22	1.16	ns	22	1.03	ns	22	1.01	ns

Note: Not significant ($p > .05$), *$p < .05$; **$p < .001$.

Abbreviation: ns, not significant.

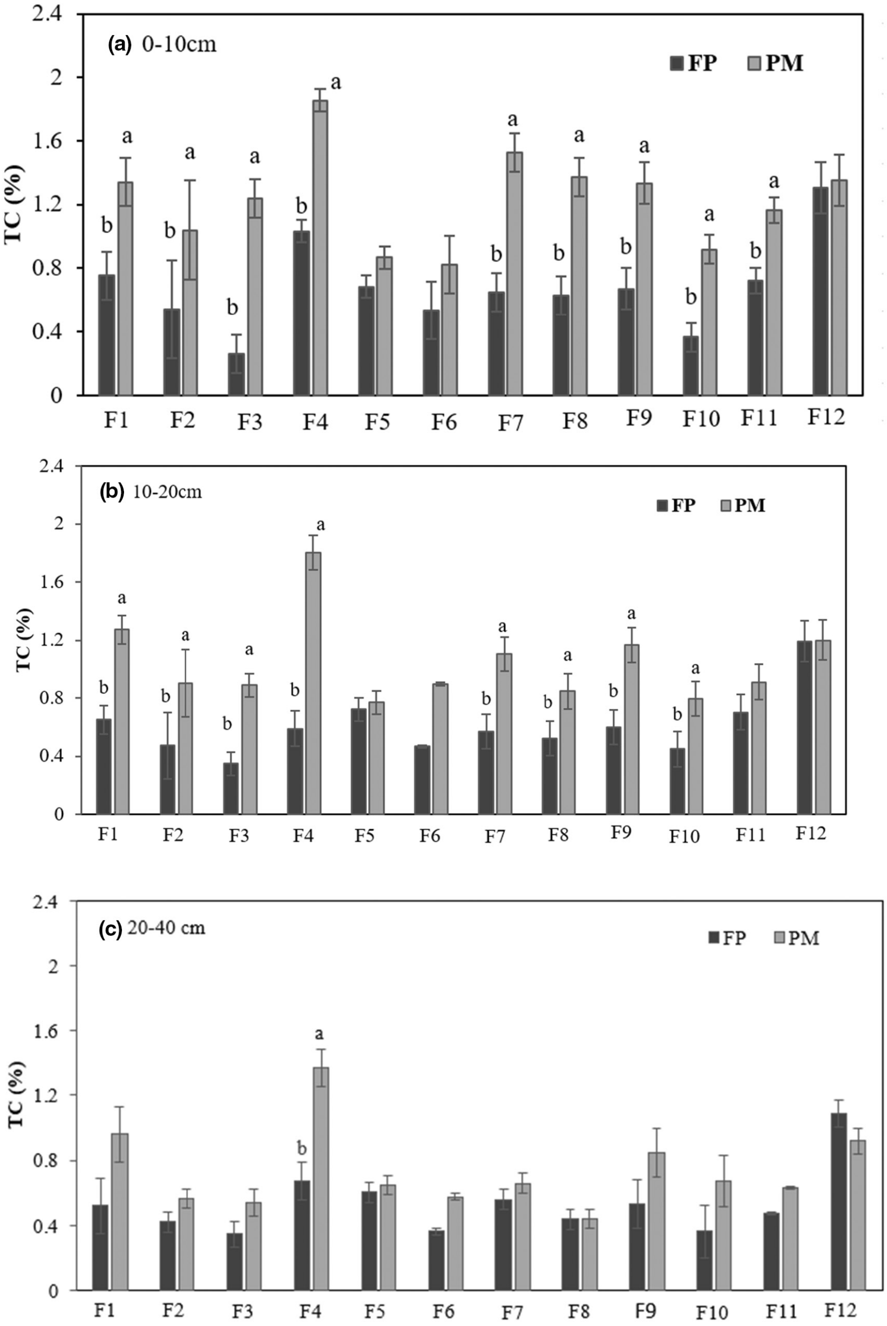

FIGURE 2 Effects of conventional farmer practice (FP) and planting basins with manure (PM) on soil total carbon (TC) at depths (A) 0–10 cm (B) 10–20 cm and (C) 20–40 cm at sites F1 to F12 in Makueni ($p < .05$). Lowercase letters indicate significant differences among different treatments. No letters = not significant (ns). Errors bars indicate Standard Error (SE).

total C was significantly higher under PM than FP at nine sites at the 0–10 cm soil layer (Figure 2A). In the subsoil layer (10–20 cm), eight of the 12 sites showed significantly higher mean soil TC under PM (Figure 2B). This significant increase in total C concentrations could be attributed to the addition of organic matter from manure in the planting basins and the minimum tillage promoted by these basins. However, there was no significant difference in total C under PM at depths of 20–40 cm (Figure 2C) in 11 sites, with sites F4 the exception. F4 also had the highest values of total C across the three depths under PM compared with the other 11 sites. This relatively high total C concentration in site F4 could be attributed to adding charcoal dust to the planting basins alongside farmyard manure.

Similarly, soil total N was higher under PM than FP at the three soil depths across the 12 sites (Figure 3). Soil total N values ranged from 0.027% to 0.10% under FP and (0.06% to 0.19%) under PM management across the 12 sites and the three soil depths. The highest total N under PM was observed at site F4, possibly due again to the addition of charcoal dust in the planting basins. Soil total C and total N across the sites decreased with increasing soil depth (Figures 2 and 3). Soil total N was significantly higher under PM than FP in the 0–10 cm soil layer (Figure 2A) at all the sites except F5. In the 10–20 cm soil

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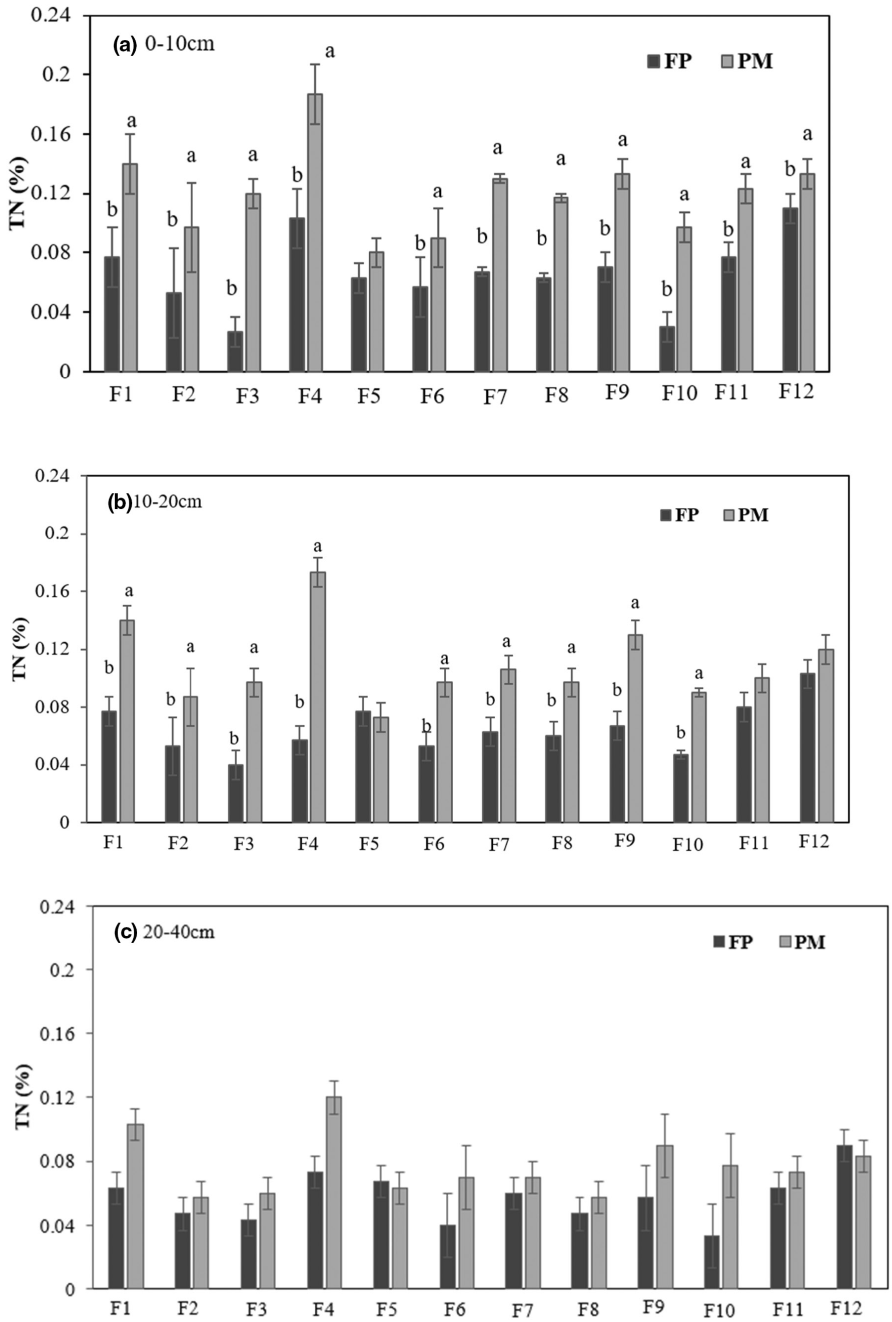

FIGURE 3 Effects of conventional farmer practice (FP) and planting basin with farmyard manure (PM) on total nitrogen (TN) across at depths (A) 0–10 cm (B) 10–20 cm and (C) 20–40 cm at sites F1 to F12 in Makueni ($p < .05$). Lowercase letters indicate significant differences among different treatments. No letters = ns. Errors bars indicate SE.

layer, there was no significant difference between PM and FP at F5,11 and 12; however, the rest of the sites showed a significant difference in total N under PM compared with FP (Figure 2B). There was no significant difference (Figure 3C) in total N between FP and PM at the deep soil layer (20–40 cm) for all 12 sites.

3.2 | Soil $\delta^{13}C$ and $\delta^{15}N$

Generally, across the three soil depths, less negative soil $\delta^{13}C$ values were observed under the conventional farmer practice compared with the PM management (Table 3). Soil $\delta^{13}C$ was significantly higher (less negative) under FP (range −22.5‰ to −17.1‰) across the three depths (0–10, 10–20 and 20–40 cm) at sites F1, F4, F7, F9 and F10 compared with PM (range −24.3‰ to −18.1‰). The less negative $\delta^{13}C$ values under conventional farmer practice (FP) across several sites (F1, F4, F7, F9, and F10) hint at a mixed history of C3 and C4 plant residues, or potentially a more significant influence of C4 residues like maize. This could imply that conventional farming practices at these sites historically leaned towards the cultivation of C4 crops or a mix of C3 and C4 crops. No significant difference was observed in soil $\delta^{13}C$ between PM and FP at sites F5, F6, F8, F11 and F12 across the three depths. The lack of significant differences in $\delta^{13}C$ values between PM and FP at sites F5, F6, F8, F11, and F12 may indicate

TABLE 3 Effects of conventional farmer practice (FP) and planting basins with farmyard manure (PM) on soil δ^{13}C and δ^{15}N at 12 sites across the three different depths in Makueni.

		δ^{13}C		δ^{15}N	
Site	Soil depth	PM	FP	PM	FP
F1	0–10 cm	−23.4(0.3)	**−22.5(0.3)**	**11.9(0.7)**	9.1(0.7)
	10–20 cm	−23.7(0.4)	**−21.9(0.4)**	**12.1(0.5)**	9.3(0.5)
	20–40 cm	−22.9(0.9)	**−20.3(0.9)**	**12.6(0.6)**	9.8(0.6)
F2	0–10 cm	−22.2(0.4)	−22.1(0.4)	**11.3(0.8)**	7.9(0.8)
	10–20 cm	−22.3(0.3)	**−21.1(0.3)**	**11.5(0.9)**	7.6(0.9)
	20–40 cm	−21.4(0.4)	−19.4(0.4)	**10.7(0.5)**	7.9(0.5)
F3	0–10 cm	−23.7(0.5)	−22.4(0.5)	**10.4(1.8)**	6.4(1.8)
	10–20 cm	−23.2(0.2)	**−20.4(0.2)**	**10.5(0.6)**	8.3(0.6)
	20–40 cm	−21.7(0.6)	**−18.3(0.6)**	**10.0(0.4)**	8.7(0.4)
F4	0–10 cm	−24.3(0.6)	**−21.4(0.6)**	**8.7(0.9)**	7.7(0.9)
	10–20 cm	−23.9(0.5)	**−20.3(0.5)**	**9.0(0.7)**	8.0(0.7)
	20–40 cm	−22.6(0.7)	**−19.3(0.7)**	**9.0(0.5)**	8.3(0.5)
F5	0–10 cm	−19.2(0.9)	−18.9(0.9)	**8.1(0.5)**	6.3(0.5)
	10–20 cm	−18.8(0.6)	−17.6(0.6)	7.9(0.5)	7.1(0.5)
	20–40 cm	−18.1(0.7)	−16.8(0.7)	7.7(0.4)	7.6(0.4)
F6	0–10 cm	−20.5(0.6)	−21.6(0.6)	**8.9(0.5)**	7.3(0.5)
	10–20 cm	−20.1(0.7)	−21.1(0.7)	**8.6(0.5)**	7.2(0.5)
	20–40 cm	−19.0(0.8)	−21.0(0.8)	**8.2(0.9)**	6.9(0.9)
F7	0–10 cm	−21.7(0.6)	**−19.4(0.6)**	**7.4(0.5)**	6.4(0.5)
	10–20 cm	−21.2(0.6)	**−17.6(0.6)**	**7.6(0.5)**	7.7(0.5)
	20–40 cm	−18.2(0.8)	**−17.0(0.8)**	8.2(0.4)	8.1(0.4)
F8	0–10 cm	−22.6(0.6)	−21.2(0.6)	**8.8(0.5)**	7.0(0.5)
	10–20 cm	−21.7(0.6)	−19.1(0.6)	8.3(0.5)	7.1(0.5)
	20–40 cm	−19.0(0.8)	−17.9(0.8)	7.4(0.2)	7.3(0.2)
F9	0–10 cm	−22.5(0.3)	**−19.54(0.3)**	**9.0(0.6)**	7.4(0.6)
	10–20 cm	−21.8(0.3)	**−19.0(0.3)**	**9.3(0.6)**	6.3(0.6)
	20–40 cm	−20.8(0.5)	**−18.1(0.5)**	**9.2(0.7)**	7.4(0.7)
F10	0–10 cm	−22.1(0.3)	**−19.5(0.3)**	**8.9(0.6)**	6.9(0.6)
	10–20 cm	−21.3(0.3)	**−19.1(0.3)**	**8.8(0.6)**	6.7(0.6)
	20–40 cm	−21.4(0.5)	**−18.5(0.3)**	**9.4(0.7)**	7.2(0.7)
F11	0–10 cm	−21.1(0.3)	−21.8(0.3)	**8.5(0.6)**	6.1(0.6)
	10–20 cm	−20.6(0.3)	−20.4(0.3)	**8.3(0.6)**	6.5(0.6)
	20–40 cm	−19.0(0.5)	−17.6(0.3)	**8.1(0.7)**	7.2(0.7)
F12	0–10 cm	−20.9(0.3)	−18.2(0.3)	**8.7(0.6)**	6.5(0.6)
	10–20 cm	−20.1(0.3)	−18.0(0.3)	**9.2(0.6)**	6.5(0.6)
	20–40 cm	−18.4(0.5)	−17.1(0.7)	**8.1(0.7)**	6.9(0.7)

Note: Values in bold indicate significant differences among the different treatments at each depth ($p < .05$). Values in brackets indicate ±SE.

similar historical management practices or vegetation cover across these sites, or the influence of other factors that have homogenized the isotopic signatures, such as similar residue return or mineralization rates.

Soil δ^{15}N was significantly higher under PM management (range: 7.4‰ to 12.6‰) compared with the conventional farmer practices (range: 6.1‰ to 9.8‰). The lowest values in soil δ^{15}N were observed at the 0–10 cm depth, with the highest values recorded at the 20–40 cm soil depth (Table 2). The observed depth variations in δ^{15}N values could be because of the stratification of nitrogen in the soil profile, as organic matter, and consequently nitrogen, predominantly accumulates on the surface, causing increased isotopic fractionation in the upper layers. Over time, with the downward movement of nitrogen through the soil, such as through leaching, deeper layers may exhibit elevated $\delta^{15}N$ values. Soil $\delta^{15}N$ was significantly higher at sites F5, F7 and F8 at the 0–10 cm soil layer only under PM (8.1‰, 7.4‰, 8.8‰, respectively) than FP (6.3‰, 6.4‰, 7.0‰, respectively) management (Table 3). The significantly higher $\delta^{15}N$ values at sites F5, F7 and F8 at the 0–10 cm depth under PM could be influenced by site-specific conditions, such as microclimate, soil type, or historical management practices. For instance, differences in soil type across sites might impact nitrogen dynamics and the resultant isotopic composition. Sites with clayey soils (e.g. F3, F8) might have different microbial activities and nitrogen transformations than those with loamy or sandy soils. For the other nine sites (F1, F2, F3, F4, F6, F9, F10, F11 and F12), mean soil $\delta^{15}N$ was significantly higher under PM than FP across all three soil depths (0–10, 10–20 and 20–40 cm).

3.3 | Impact of geographical location and other environmental factors

Soil total C, N and $\delta^{15}N$ varied across the sites. These variations in observed soil C, N and $\delta^{15}N$ could be because of various factors, including elevation, soil type or rainfall. The two sub-counties, Kibwezi East (Mtito Andei) and Mbooni East (Kalawa), have different average rainfalls, with Mbooni East receiving more rainfall (Table 1; Table S2). Soil TC and TN in site F4 were significantly different from all other sites (Table S1). This could be attributed to the rainfall amount and the addition of charcoal dust in the planting basins. Soil total C and N in sites F6, F7, F9 and F12 were not significantly different from each other but were different from the rest of the sites. Soil total C values at Sites F2 and F3, which are at relatively low altitudes and receive the lowest amount of rainfall compared with other sites, had low total C values. Site F10 observed the lowest total C and N values, which could be attributed to the soil texture, as this is the only site with sandy soils (Table S2; Table 1). High soil $\delta^{15}N$ values were observed in low rainfall sites F1, F2 and F3 (590 mm mean annual rainfall) than in sites with higher rainfall (765 mm mean annual rainfall) such as sites F11 and F12 (Table 3; Table S2). The high $\delta^{15}N$ values observed in the drier areas could be attributed to elevated N volatilization during pronounced temperatures in these areas.

4 | DISCUSSION

4.1 | Soil total C and total N

This study indicates that planting basins with farmyard manure significantly enhances soil total C and total N concentrations, underscoring the potential climate mitigation and adaptation benefits of this practice. It is of paramount importance to acknowledge that the legacy of previous crops—particularly the C4 plant maize and associated crop residues—coupled with manure, could have set a foundational stage for the soil's response to different management practices. The role of mineralization, especially from the decomposition of C4 residues like maize, has a profound impact on the soil C:N ratio, driving its fertility and productivity (Kan et al., 2022; Wang, Wang, et al., 2015; Wang, Xu, et al., 2015). The addition of manure, a rich source of organic matter, amplifies this effect by introducing additional C and N into the soil, further modifying its mineralization dynamics.

The variability in soil C, N and isotopic compositions across sites, as highlighted in this study, underscores the importance of real-world conditions where farmers may not follow all the recommended guidelines. This implies that results on planting basins with manure on farmer-managed farms may differ for different sites, farmer management, soil types and climatic conditions. Several studies that have conducted controlled experiments have reported significantly higher soil C under planting basins with manure management (Mupangwa et al., 2013; Thierfelder & Wall, 2012). While some studies suggest that planting basins under on-farm conditions may not significantly increase soil C (Martinsen et al., 2017; Nyamangara et al., 2014), this study presents divergent findings. The key distinction between this study and previous research is the choice of amendments; in the study conducted by Martinsen et al. (2017), only fertilizers were incorporated into the planting basins, whereas Nyamangara et al. (2014) solely incorporated crop residues. The findings from this study therefore suggest that the addition of manure in planting basins has a more profound influence on soil C and N than the use of fertilizer or crop residues. Comparable to the observation in our study, Marumbi et al. (2020) found that planting basins with organic amendments significantly increase soil C under on-farm conditions in Zimbabwe because of the localized manure application and minimized soil disturbance in the planting basins. Planting basins are considered a no-tillage management practice; hence, the minimal soil disturbance ensures minimal disruption of soil C and protection from microbial mineralization (Marumbi et al., 2020; Nyamangara et al., 2014). Tillage in conventional farmer practices causes soil disturbance and exposes organic material to microbial mineralization leading to soil organic matter loss (Mikha & Rice, 2004). Therefore, the differences in total soil C and N between planting basins with farmyard manure and conventional farmer practices likely resulted from minimal soil disturbance, reduced microbial mineralization, reduced water loss and organic (manure) amendments. Given this, our study indicates that farmers' adoption and continuing use of PM can be expected to build up C and N content in soils gradually.

Significant effects of planting basins with manure on soil C were limited to the top and subsoil layers (i.e. 0–20 cm depths). The decrease in soil total C and total N with increasing soil depth could be attributed to the reduced effect of organic (manure) inputs with increasing soil depth (Marumbi et al., 2020). This could be as a result of the increased organic matter in the topsoil brought about by the localized manure application and the poor mixing of the manure with soil in these minimum-till systems. The significantly higher soil total C and N at site F4, where charcoal dust was also used in the planting basins, indicates that the combined use of planting basins, farmyard manure and biochar could result in even greater soil C content. This is supported by controlled field experiments that have documented the ability of biochar in combination with poultry manure to improve soil chemical properties (Adekiya et al., 2019; Farrar et al., 2019, 2021; Hosseini-Bai et al., 2015; Sandhu et al., 2019). However, there is a need for further research to investigate the effects of the combined use of planting basins, biochar and manure on soil carbon and nitrogen pools.

4.2 | Soil $\delta^{13}C$ and $\delta^{15}N$

Soil $\delta^{15}N$ provides insights into differences in the contribution of various land management practices to soil C and N stocks. The $\delta^{15}N$ value is a measure of the ratio of stable isotopes of N (^{15}N and ^{14}N) and can provide insights into various processes, including microbial N transformations. Our results showed that soil $\delta^{15}N$ was enriched by planting basins with farmyard manure management. The soil $\delta^{15}N$ enrichment may result from leaching, nitrification, denitrification or volatilization (Busari et al., 2016; Hosseini-Bai et al., 2015). The higher soil $\delta^{15}N$ in PM management could be explained by the addition of manure, which has been found in previous studies (Busari et al., 2016; Chalk et al., 2014) to lead to higher $\delta^{15}N$ than the control (without manure). Increased N availability and N mineralization processes from organic amendments lead to the enriched $\delta^{15}N$ in the soils (Mani, 2021). Improved $\delta^{15}N$ values in PM indicate that planting basins with farmyard manure enhances N-cycling. The high $\delta^{15}N$ values observed under PM also indicate high N availability for plant uptake, which means higher crop production in PM than in FP practices. Studies have also observed higher $\delta^{15}N$ values in water-limited soils, consistent with our study, where sites with less rainfall exhibited higher soil $\delta^{15}N$ values indicating a more open N cycling than high rainfall areas (Shan et al., 2019; Wu et al., 2019).

Our study indicated that soil $\delta^{13}C$ was significantly lower (more negative) under PM management than in conventional farmer practices. This implies that soil organic matter turnover and C-cycling vary with management practice. The difference in $\delta^{13}C$ values between FP and PM could be attributed to organic matter inputs and the different rates of C mineralization, as reported by Bayer et al. (2001) and Fuentes et al. (2010). Previous studies also show that adding organic amendments such as manure leads to more negative $\delta^{13}C$ values (Busari et al., 2016; Li et al., 2010; Sainju et al., 2008). Our study further showed that the deeper soil layers had higher $\delta^{13}C$ values (less negative) than the topsoil (0–10 cm), which could be explained by the long exposures to decomposition in the deeper soils (Fuentes et al., 2010). The most pronounced $\delta^{13}C$ values at the 20–40 cm depth suggest prolonged organic matter inputs, potentially indicating historical shifts in crop types or land management practices (Kan et al., 2022). In essence, the observed $\delta^{13}C$ values, varying with soil depth and management practice, underscore the intricate interplay of historical vegetation, land-use decisions, and carbon cycling dynamics in these soils.

5 | CONCLUSION

This study, conducted under on-farm conditions in Makueni County, Kenya, reinforces the potential of planting basins with farmyard manure (PM) in enhancing soil C and N levels, offering a promising pathway for climate change mitigation and improved soil fertility. The study's findings resonate beyond the boundaries of our experimental site, carrying implications for global challenges related to climate change mitigation and sustainable agriculture. Specifically, this real world study confirms previously reported results from controlled trials of significant enhancements in total soil C and N concentrations, with the most pronounced effects observed within the top 20 cm of soil. These findings signal a viable pathway towards climate change mitigation and improved soil fertility on a global scale. Notably, the study findings unveil a noteworthy increase in $\delta^{15}N$ levels in soils under PM management, indicating heightened N-cycling. This dual benefit—carbon sequestration and increased nutrient availability—carries significant implications for global food security and agricultural sustainability. These findings underscore the potential of the study to inform and shape international strategies for addressing the challenges posed by a changing climate. Furthermore, the observed variations in soil C, N, and isotopic values across different sites emphasize the role of site-specific factors, such as rainfall, altitude, and soil type. This understanding highlights the necessity for context-specific agricultural practices, thereby enhancing the relevance of our findings for diverse global agricultural landscapes. Interestingly, our study has also highlighted the potential synergistic benefits of combining biochar with farmyard manure in planting basins, as seen in site F4, suggesting avenues for further research. In conclusion, this study not only extends the current understanding of the efficacy of planting basins combined with manure in real-world settings but also positions these findings within the broader historical and scientific narrative of soil carbon and nitrogen dynamics. Therefore, this research contributes to the global discourse on sustainable agriculture and soil health, providing practical solutions for a more sustainable and resilient agricultural future worldwide.

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CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial interests to disclose.

DATA AVAILABILITY STATEMENT

Data and materials used from this study are available by request to the corresponding author Edith Kichamu-Wachira through the email edith.kichamu@griffithuni.edu.au/edith.kichamu@uq.net.au.

CONSENT TO PARTICIPATE

Not applicable.

CONSENT TO PUBLISH

All authors of this manuscript give consent for this manuscript to be published.

ORCID

Edith Kichamu-Wachira https://orcid.org/0000-0002-7534-3695

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SUPPORTING INFORMATION

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