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Beyond conventional farming: exploring the benefits of planting basins with manure on soil quality as reflected in labile organic carbon and nitrogen indicators in Kenya

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Abstract

Purpose Soil quality is critical for plant growth and ecosystem sustainability. Understanding the indicators that indicate soil quality is, therefore, crucial. Labile organic carbon (C) and nitrogen (N) are important components of soil functions that impact productivity and environmental stability. This study aimed to explore the sensitivity of different labile C and N fractions, including water extractable organic C (WEOC) and total N (WEON) and hot water extractable organic C (HWEOC) and total N (HWEON), to planting basins with manure compared to conventional farming practices.

Methods and methods Soil samples were drawn from 0–10 and 10–20 cm soil depths at 12 sites in Makueni County, Kenya. Samples were analysed for differences in WEOC, HWEOC, WEON, and HWEON between planting basins with manure and conventional farmer practices. We also assessed the correlations of the different labile C and N pools with other soil chemical properties linked to soil quality.

Results and discussions The results showed that planting basins with manure significantly increased mean WEOC (171.53 μg g^{-1}), HWEOC (353.62 μg g^{-1}), WEON (26.60 μg g^{-1}), and HWEON (26.39 μg g^{-1}) compared to those of conventional farming practices ($p < 0.05$). WEOC was positively correlated with WEON and $\delta^{15}N$ ($p < 0.001$) at the 0–10 cm soil layer suggesting that extractable organic matter can be used as an index for soil health and nutrient content.

Conclusion The findings suggest that cold water and hot water extractable C and N are sensitive indicators of the effects of different land management practices on soil quality. The results further demonstrate that planting basins with manure can improve soil quality by increasing labile C and N pools.

Keywords Labile C · WEOC · Planting basins · Labile N

1 Introduction

Soil organic carbon (SOC) is a crucial component in the carbon (C) cycle and is considered an important aspect of soil quality, soil functions, and overall soil health (Chen et al. 2004; Wang et al. 2014, 2022). A decline in SOC results in poor soil structure and decreased water retention, fertility, enzymatic activity, and biological activity (Ghani et al. 2003; Chen et al. 2004). Maintaining and enhancing SOC levels is critical for a sustainable agricultural system and mitigating the impacts of climate change (Lal et al. 2007; Khan et al. 2021; Navarro-Pedreño et al. 2021). SOC comprises several fractions that differ in decomposition, resistance to decay, and turnover rate (Chen et al. 2004; He et al. 2008; Huang et al. 2008; Xu et al. 2008). However, soil organic C levels change slowly, making total SOC an unreliable indicator of

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soil quality changes resulting from land use (Ghani et al. 2003; Abagandura et al. 2023).

Labile C and N are key to studying ecosystem dynamics and nutrient cycling (Ghani et al. 2003; Wang et al. 2019; Yang et al. 2023). Labile C refers to the pool of readily decomposable organic matter in soils. Labile C pools are more accurate and sensitive indicators of early changes in SOC stocks and the impact of changes in soil management practices on soil C sequestration and dynamics (Xu et al. 2011; Wang et al. 2019; Yang et al. 2023). Labile C's rapid turnover rate is a vital energy source for the soil food web. As a result, it plays a crucial role in nutrient cycling, essential for maintaining soil quality and productivity (Ghani et al. 2003; Xu et al. 2011; Wang et al. 2020). The change in labile C pools with different management practices is influenced by site conditions, vegetation, residue management, and land use intensity (Ghani et al. 2003; Francaviglia et al. 2017; Wang et al. 2020; Yang et al. 2023). Changes in the quality and quantity of C input to the soil can immediately affect labile C fractions (Bolinder et al. 1999; Ghani et al. 2003); hence, they are reliable sensors of changes in soil organic C. Soil is a complex system, and measuring just one labile C fraction is insufficient to accurately reflect the changes in soil quality brought about by different management practices. Water extractable organic C (WEOC) and hot water extractable organic C (HWEOC) are some of the components of labile C fractions (Ghani et al. 2003; Liu et al. 2014; Tutua et al. 2019). The WEOC is the dissolved organic C extracted by water using various methods. The WEOC is more sensitive than total organic C in detecting changes in soil C, particularly in response to short-term changes in land management practices such as tillage (Liu et al. 2014; Wang et al. 2014; Martisen et al. 2019). The HWEOC represents the portion of C extractable using hot water, accounting for approximately 3–5% of the total C content (Leinweber et al. 1995). Studies have found that HWEOC is strongly associated with microbial biomass, nitrogen availability, and soil organic C (Ghani et al. 2003). This relationship makes HWEOC a responsive indicator of short-term environmental changes, including variations in temperature, soil moisture, and tillage practices (Weigel et al. 2011; Tutua et al. 2019).

Labile N is the pool of readily available ammonium and nitrate ions in the soil and includes cold and hot water extractable organic total N (WEON and HWEON, respectively). Labile organic N fractions are responsive to management changes and seasonal N availability (Culman et al. 2013; Diederich et al. 2019). Labile organic N pools are easily metabolised and highly correlated with mineralised N in soil (Ghani et al. 2003). Hence, evaluating labile N fractions will contribute to a deeper comprehension of the stability of the soil N pool.

Several studies have investigated the impact of various land management strategies on labile C and N pools. For example, Chen et al. 2018 found that manure or crop residue application increased WEOC. Similarly, Xu et al. (2011) discovered that manure application enhanced WEOC, total organic carbon (TOC), and microbial biomass carbon (MBC). Applying organic amendments increases labile C pools, indicating that these management practices can help preserve and improve soil quality (Chantigny 2003; Benbi et al. 2015; Chen et al. 2018; Abagandura et al. 2023). Studies have also shown the positive effect of minimum tillage on labile C and N pools compared to conventional farming practices (Ghani et al. 2003; Chen et al. 2007, 2009; Liu et al. 2014; Wang et al. 2014). Controlled studies have also shown a significant increase in HWEOC under planting basins with manure management (Martinsen et al. 2019, Munera-Echeverri et al. 2020). This method minimises soil disturbance to only 10% of the total land area, in contrast to conventional ploughing, which involves turning over entire fields (Ghani et al. 2003). Reducing soil disturbance can help to minimise physical soil degradation, such as erosion and water runoff, enhance soil properties, and manage resources (Chen et al. 2009; Liu et al. 2014). Besides, localising inputs such as manure within planting basins enhances nutrient use efficiency and significantly reduces costs.

The sensitivity of different labile C and N pools to different land management practices is still an active research area. There is a limited body of knowledge on the impact of planting basins with manure amendments on labile N and C pools under on-farm conditions. This study aimed to explore the sensitivity of different labile C and N pools, including WEOC and WEON and HWEOC and HWEON, to planting basins with manure compared to conventional farming practices. We also assessed the correlation of the different labile C and N pools with other soil chemical properties linked to soil quality. Our study is based on research conducted in Makueni County, Kenya, under on-farm conditions. The results of our study have important implications for farmers and policymakers, as they provide insights into the effects of different land management practices on soil quality and productivity.

2 Methods

2.1 Study design and sample collection

The study was conducted on smallholder farms in Makueni County, Kenya. Makueni County is a semiarid region in Kenya located between 600 and 1280 m above sea level (Saiz et al. 2016). The area receives between 300 and 800 mm of precipitation annually, with mean annual minimum temperatures of 20.2 ℃ and mean annual maximum temperatures of 35.8 ℃. The area of Makueni County is approximately 8000 km^2, and its population in 2018 was over 900,000 (Muema et al. 2018). The region is characterised by small-scale farmers engaging in crop and animal production. Maize, pigeon peas, sorghum, cowpeas, millet, beans, green grammes (mung bean), and mangoes are the most important crops (Muema et al. 2018).

Soil samples were taken from twelve farmer fields located in various villages within Makueni County. The sample sites were farmer-managed fields, and the treatments were conducted under farm-specific conditions. The treatment comprised (i) planting basins with annual additions of farmyard manure and (ii) conventional farmer practices involving extensive excavation of flatlands by hand hoe or oxen plough every season with no manure addition. Except for site F10, which was sandy, and sites F3 and F8, which were clay loams, the soils were classed as loams (clay loam and sandy loam). In the treatment sites, maize was cultivated within the planting basins, while legumes (pigeon peas, sorghum, cowpeas, millet, beans, and green grammes) were grown outside. The conventional farmer practices plots contained both maize and legumes.

We collected soil samples at two depths (0–10 cm and 10–20 cm) from 5 m × 5 m plots within the two treatments at each of the 12 sites, with three replicates per treatment. The plots were chosen to ensure that the soil types of the control and treatment plots were comparable. Eleven of the studied farms had permanent planting basins of 60 cm × 60 cm × 60 cm, with the exception of farm F10, which had planting basins measuring 300 cm × 100 cm × 60 cm. The manure was either composted on the farms or purchased from neighbours. Around 4–6 kg of manure are added annually per planting basin.

2.2 Hot water and cold-water extraction

Labile C and N pools were assessed using cold water extractable organic C (WEOC), hot water extractable organic C (HWEOC), cold water extractable total N (WEON), and hot water extractable total N (HWEON). We adopted the methods used in previous studies (Wang et al. 2020) (see Fig. 1). To extract WEOC and WEON, we added 7 g of air-dried and sieved soil to a falcon tube and added 30 ml of water. This was then shaken in an end-to-end shaker for 5 min and centrifuged at 10,000 rpm for 10 min. The resulting suspension was filtered through a Whatman 42 paper and a 0.45 µm filter membrane and then sent to a TOC/TN analyser for WEOC and WEON analysis.

To extract hot water extractable carbon and nitrogen, 7 g of air-dried and sieved soil was added to a falcon tube. We then added 30 ml of water, placed it in an end-to-end shaker for 5 min, and incubated it for 18 h at 70 ℃. The solution was centrifuged for 10 min at 10,000 rpm and filtered through a Whatman 42 paper. Finally, the solution was sent to a Shidmazu TOC/TN analyser for HWEOC and HWEON analysis.

2.3 Statistical analysis

Two-way analysis of variance (ANOVA) was used to assess the interaction of location, treatment, and soil depth (Table 1). Where interaction between location and treatment or soil depth were found significant, a series of one-way ANOVA were performed to explore differences among

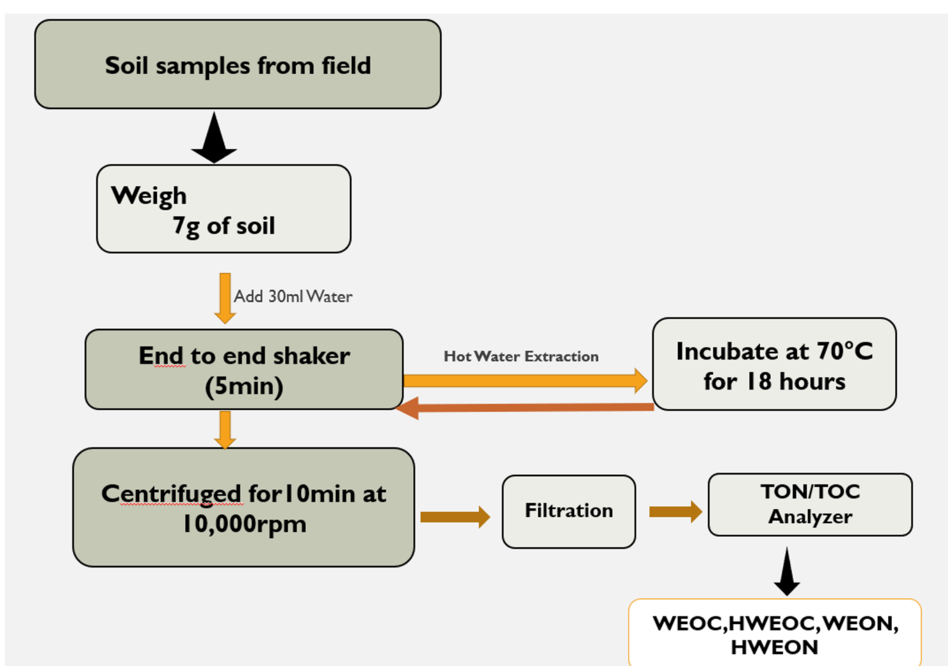

Fig. 1 Schematic diagram for water extraction of labile carbon and nitrogen

Table 1 Two-way ANOVA on the effect of planting basins with manure addition on water extractable organic C (WEOC), hot water extractable organic C (HWEOC), water extractable total N (WEON), and hot water extractable total N (HWEON)

		WEOC (μg g^{-1})		HWEOC (ug/g^{-1})		WEON (μg g^{-1})		HWEON (μg g^{-1})	
	df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Treatment	1	41.45	**	91.20	**	341.79	**	125.99	**
Site	11	13.60	**	3.80	**	7.10	**	5.61	**
Depth	2	34.29	**	231.39	**	49.60	**	33.10	**
Treatment × site	11	3.17	**	3.17	**	8.86	**	4.76	**
Treatment × depth	2	41.82	**	0.04	ns	60.25	**	8.06	*

ns not significant ($p > 0.05$)
*$p < 0.05$; **$p < 0.001$

treatments. All statistical tests were performed using Statistix version 8 software.

3 Results

3.1 Effect of land management practices on water extractable organic carbon (WEOC)

Our study showed a significant increase in WEOC in planting basins with manure (171.53 μg g^{-1}) compared to conventional farming practices (126.88 μg g^{-1}) (Table 2). The WEOC was higher in the 10–20 cm (169.51 μg g^{-1}) than in the 0–10 cm soil depth (128.89 μg g^{-1}). WEOC values varied across the sites, with the highest WEOC under planting basins with manure observed at location F1, followed by F4 at soil depth 0–10 cm. Location F6 observed the least WEOC accumulation under PM at 0–10 cm soil depth. At 0–10 cm soil depths, WEOC was significantly increased under PM management in eight sites. Four sites (F2, F5, F6, and F10) showed no significant difference in WEOC between PM and FP at depths 0–10 cm. Accumulation of WEOC in soils at 10–20 cm depth, though greater in planting basin with manure than FP, was not significantly different, except at site F9 (Fig. 2).

3.2 Effect of land management practices on hot water extractable organic carbon (HWEOC)

HWEOC was significantly higher in planting basins with manure (325.72 μg g^{-1}) compared to conventional farming (231.57 μg g^{-1}) practices (Table 2). HWEOC decreased with depth, with higher HWEOC observed in the upper soil layer (0–10 cm). The HWEOC in the top 0–10 cm soil depth significantly differed from the deeper soil layers (Table 3). Sites F1, F2, F3, F7, F8, and F9 observed significantly high HWEOC values in PM at the 0–10 cm soil depth compared to FP management (Fig. 3a). However, only three sites (F3, F8, and F9) observed significantly higher HWEOC under PM management compared to FP at the 10–20 cm soil layer (Fig. 3b).

3.3 Effect of land management practices on water extractable organic nitrogen (WEON)

Our study showed that WEON was significantly increased under planting basin with manure management (26.60 μg g^{-1}) compared to conventional (14.13 μg g^{-1}) practices (Table 2). Higher WEON was observed at soil depth of 0–10 cm than the 10–20 cm soil layer. There were slight variations in WEON across sites, with sites F1, F3, F4, F5, F7, F8, and F9 not significantly different (Appendix 1). The highest WEON values were observed at location F1, while the lowest was in site F6. In all 12 sites, WEON was increased in planting basins with manure than in FP management at 0–10 cm and 10–20 cm soil depths. At 0–10 cm soil depth, no significant difference in WEON was observed at sites F2, F10, and F11, with the rest showing significant differences between PM and FP. On the other hand, at the 10–20 cm soil layer, no significant difference was evident between PM and FP except at sites F4 and F9 (Fig. 4).

Table 2 Summarised results for the 12 sites on the effect of planting basins with manure addition on water extractable organic C (WEOC), hot water extractable organic C (HWEOC), water extractable total N (WEON), and hot water extractable total N (HWEON)

		WEOC (μg g^{-1})	HWEOC (μg g^{-1})	WEON (μg g^{-1})	HWEON (μg g^{-1})
Treatment	FP	126.88b	231.57b	14.13b	16.34b
	PM	171.53a	325.72a	26.60a	26.39a

Lowercase letters indicate significant differences among different treatments at $p < 0.05$

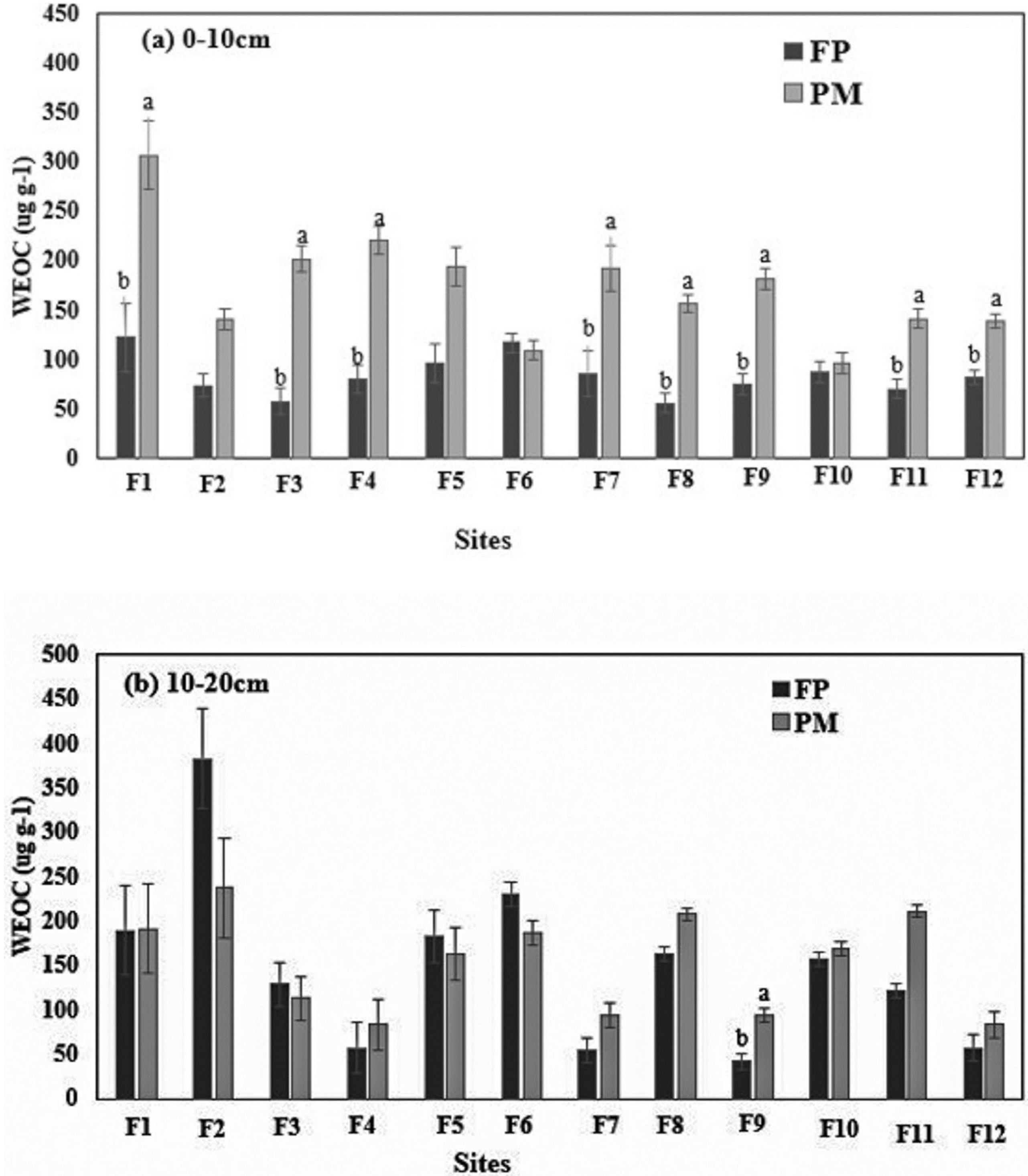

Fig. 2 Effects of conventional farmer practice (FP) and planting basin with manure (PM) on water extractable organic carbon (WEOC) at depths of **a** 0–10 cm and **b** 10–20 cm across 12 sites (F1 to F12) in Makueni. Values are means; error bars are SE. Lowercase letters indicate significant differences ($P < 0.05$) between treatments

Table 3 Effects of different soil depths on water extractable organic C (WEOC), hot water extractable organic C (HWEOC), water extractable total N (WEON), and hot water extractable total N (HWEON) at the 12 sites in Makueni

Soil depths	WEOC (μg g^{-1})	HWEOC (μg g^{-1})	WEON (μg g^{-1})	HWEON (μg g^{-1})
0–10 cm	128.89b	353.62a	22.83a	23.95a
10–20 cm	169.51a	203.66b	18.19b	18.79b

Values are means. Lowercase letters indicate significant differences among different soil depths at $p<0.05$. No letter means no statistically significant difference

3.4 Effect of land management practices on hot water extractable organic nitrogen (HWEON)

Hot water extractable organic N was significantly increased in planting basins with manure (PM) compared to FP (Table 2). Our results showed that the effect of planting basins with manure on HWEON decreased with soil depth, with the highest values observed in the topsoil layer. At the 0–10 cm soil layer, HWEON was significantly increased under PM management in seven sites (Fig. 5a), with the highest values observed at F3 and F4. No significant difference was observed between PM and FP in sites F5, F6, F10, F11, and F12 (Fig. 5a). HWEON was not significantly different in PM compared to FP at the 10–20 cm soil across the 12 sites.

3.5 Relationship between labile C and N pools and other soil properties

The WEOC was highly correlated with WEON ($r^2=0.79$, $p<0.001$) and soil $\delta^{15}N$ ($r^2=0.32$, $p<0.001$) at the 0–10 cm soil depth (Fig. 6a, b). However, there was no relationship between WEOC and WEON in the 0–20 cm soil layer (results not presented). Regression analysis showed that soil WEON and soil $\delta^{15}N$ explained 79% and 32% of the change in total WEOC. Similarly, WEON was significantly linearly related to HWEON ($r^2=0.66$, $p<0.001$), with HWEON explaining a total of 66% change in WEON (Fig. 6c). Soil HWEON explained 61% of the change in soil TC ($p<0.001$).

4 Discussion

4.1 Sensitivity of labile C and N pools to planting basins with manure

The results of this study indicate that planting basins with manure significantly increased WEOC, WEON, HWEOC, and HWEON compared to conventional farming practices. Nonetheless, the labile C and N components showed varying degrees of alteration. Labile C is an important component of soil functions that impact productivity and environmental stability, as it serves as an energy source for the soil food web and influences nutrient cycling (Liu et al. 2014). The higher WEOC under planting basins with manure suggests that this land management practice can improve soil quality by increasing labile C pools. Previous studies have separately reported increases in labile C with organic amendments (Liang et al. 2011; Xu et al. 2011; Benbi et al. 2015) and minimum tillage (Chen et al. 2009; Liu et al. 2014; Wang et al. 2014; Martinsen et al. 2019) practices. For instance, studies have found considerable increases in the WEOC upon manure amendment, mostly due to soluble elements (Liang et al. 2011; Xu et al. 2011). The presence of these soluble elements helps to provide energy for microbial growth and activity, leading to the breakdown of SOC into simpler WEOC forms. Manure amendments are known to increase the availability of plant nutrients in the soil and improve soil physical properties (Benbi et al. 2015). Although WEOC is a minor component of SOC, it serves as a buffer in replenishment mechanisms such as desorption from soil colloids, dissolution from litter, and exudation from plant roots (Chantigny 2003; Chen et al. 2018). The WEOC seems to offer a direct substrate for soil microbes. The significantly higher HWEOC in planting basins with manure compared to farming practice collaborates with previous research findings. For instance, studies under controlled experimental conditions reported significant increases in HWEOC under planting basins compared to conventional practices (Martinsen et al. 2019; Munera-Echeverri et al. 2020).

Tillage practices have also been found to affect labile C pools. For instance, studies have shown that conservation tillage (minimum and no-tillage) led to a greater accumulation of labile C pools than conventional tillage practice (Chantigny 2003; Chen et al. 2007, 2009; Liu et al.2014; Wang et al. 2014; Martinsen et al. 2019). In our study, planting basins (a minimum tillage practice) and manure addition (an organic amendment) likely explain increased accumulation in the labile C and N pools. In the FP practices, the loss of labile C is accelerated due to the increased tillage frequency, which exposes organic matter content to microbial degradation. The combined effects of minimum tillage and manure addition may benefit the soil's physical structure and the quantity and quality of soil C and N pools, which are important for enhanced C cycling and soil fertility. Furthermore, the improved soil physical structure may increase the exchange rate of nutrients, water, oxygen, and

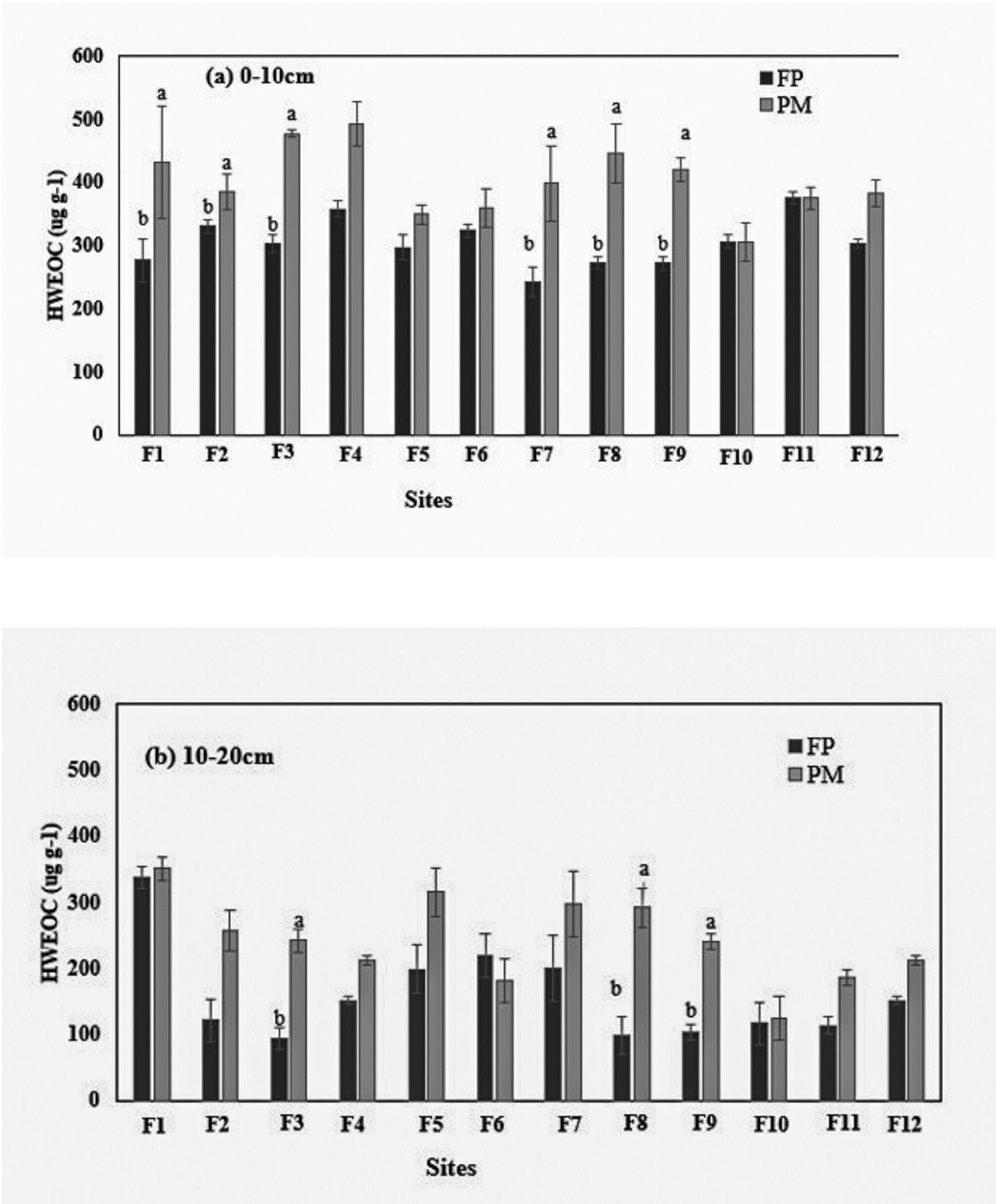

Fig. 3 Effects of conventional farmer practice (FP) and planting basin with manure (PM) on hot water extractable organic carbon (HWEOC) at depths of **a** 0–10 cm and **b** 10–20 cm across 12 sites (F1 to F12) in Makueni. Values are means; error bars are SE. Lowercase letters indicate significant differences ($P < 0.05$) between treatments

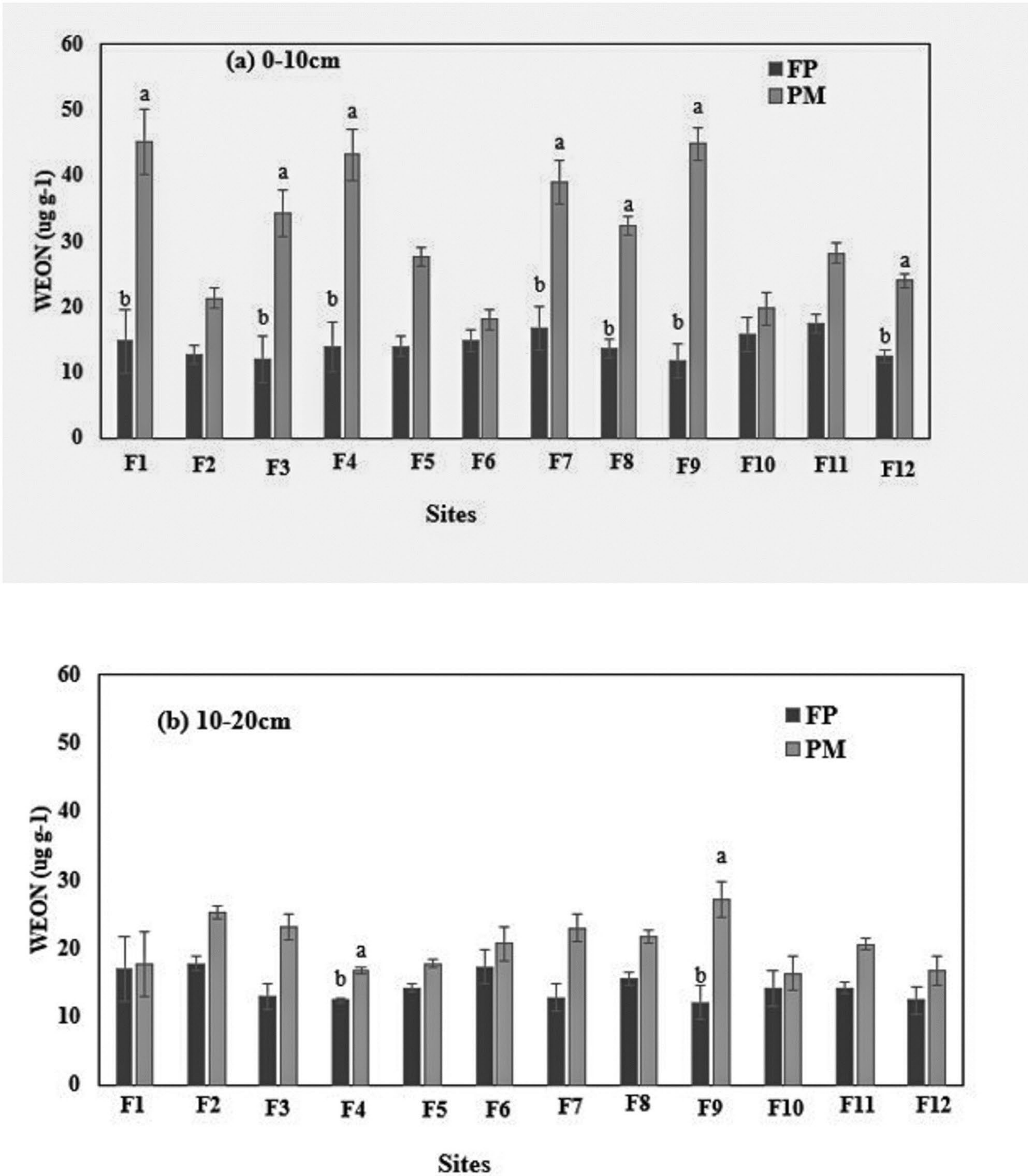

Fig. 4 Effects of conventional farmer practice (FP) and planting basin with manure (PM) on water extractable organic nitrogen (WEON) at depths of **a** 0–10 cm and **b** 10–20 cm across 12 sites (F1 to F12) in Makueni. Values are means; error bars are SE. Lowercase letters indicate significant differences ($P < 0.05$) between treatments

other resources for microbial growth and activity. Thus, our findings suggest that planting basins with manure management effectively enhances labile C pools.

The study also found that WEOC was higher in the 10–20 cm soil depth than in the 0–10 cm depth. Previous studies have reported a deeper accumulation of labile C

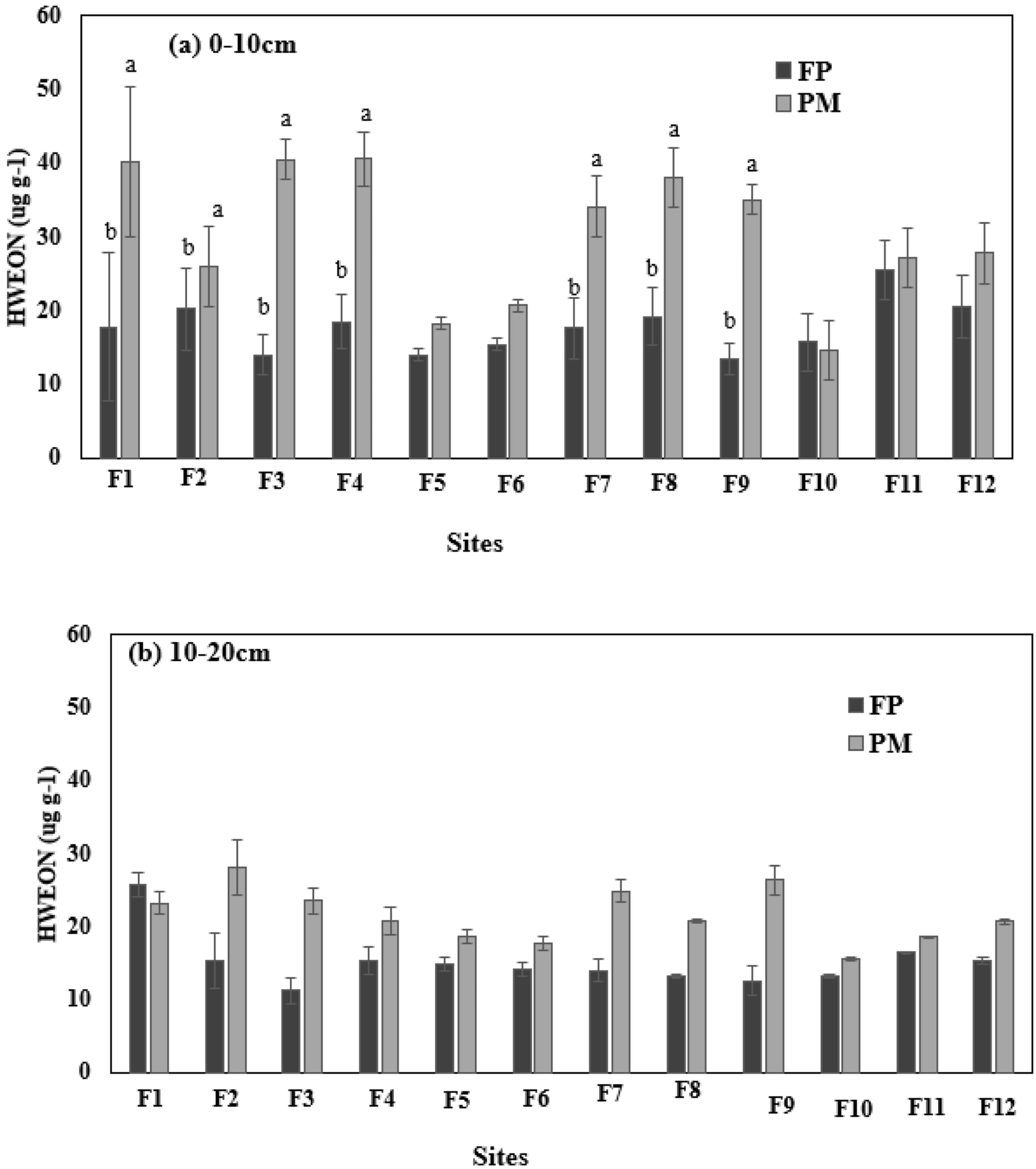

Fig. 5 Effects of conventional farmer practice (FP) and planting basin with manure (PM) on hot water extractable organic nitrogen (HWEON) at depths of **a** 0–10 cm and **b** 10–20 cm across 12 sites (F1 to F12) in Makueni. Values are means; error bars are SE. Lowercase letters indicate significant differences ($P < 0.05$) between treatments

fractions due to organic amendments (Chen et al. 2018; Wang et al. 2020). The higher WEOC in the deeper soil layer may be due to the slow decomposition rate of organic matter in these layers and the increased microbial activity or leaching (Chen et al. 2018; Wang et al. 2020). On the contrary, our results show that concentrations of HWEOC and HWEON decreased with soil depth, aligning with similar findings (Chen et al. 2009; Liang et al. 2011).

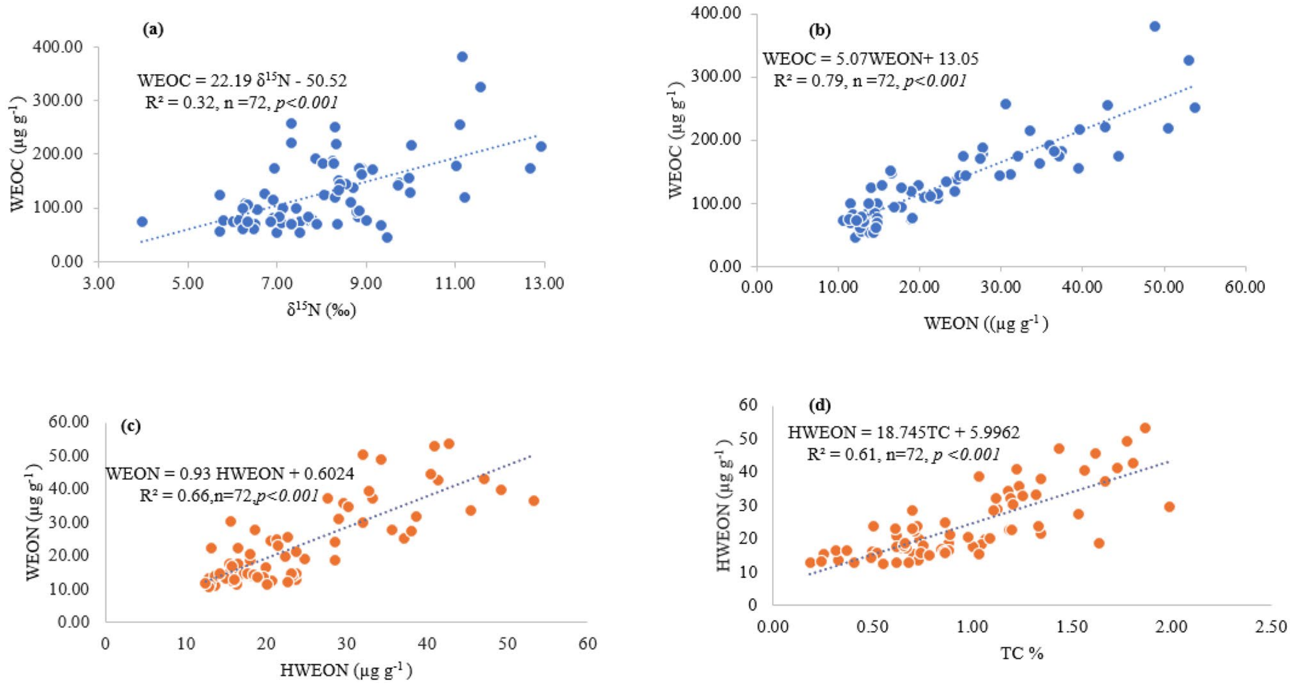

Fig. 6 Relationship among different soil properties at 0–10 cm soil depth

Additionally, our study found enhanced WEON in planting basins with manure compared to conventional farming practices a trend observed in other studies with manure amendment (Haney et al. 2012; Chen et al. 2018).

In our study, labile C and N pools varied across the sites, with some sites observing significant differences while others did not. The variability in the accumulation of labile C and N pools across the sites suggests that other factors, such as soil type and climate, may also play a role in determining the effectiveness of this management practice in different contexts. Besides, this study was under on-farm conditions, and farmers vary in their utilisation of land management practices such as planting basins, fertiliser use, as well as the application rates of manure. This variability results in differing degrees of soil disturbance and inputs of organic carbon and nutrients (Martinsen et al. 2017; Marumbi et al. 2020). When coupled with intrinsic site/farm heterogeneity including soil qualities and microclimate, which can also impact crop productivity, such land management factors may account for the significant variation in the labile C and N pools observed among sites in our study.

4.2 Relationship between labile C and N and other soil chemical properties

The study results indicate a strong correlation among WEOC, WEON, and $\delta^{15}N$ at the 0–10 cm soil depth. Specifically, there was a strong positive correlation between WEOC and WEON, similar to the trend reported by Liu et al. (2014). These findings suggest that using manure management in planting basins may positively impact the accumulation of organic carbon and nitrogen in the soil, potentially improving soil fertility and productivity. However, the lack of a relationship between WEOC and WEON at the 10–20 cm soil layer suggests that the impact of manure management on soil health may be limited to the uppermost layer of the soil. It is also important to note that while the study shows a correlation between these variables, it does not provide evidence of a causal relationship.

5 Conclusion

This study has highlighted that there were significant increases in both water and hot-water extractable C and N pools under planting basins with manure compared to conventional farmer practices. This finding substantiates the usefulness and sensitivity of using such labile C and N pools as soil quality and health indicators, especially in the topsoil layer (0–10 cm depth), in response to the best management practices of planting basins with manure addition. We recommend further research into the long-term effects of planting basins with manure on soil quality and health, potential trade-offs, and their integrative role in the broader agroecosystem context.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11368-023-03651-3.

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Data availability Data and materials used from this study are stored at Griffith university research repository and available by request to the corresponding author edith.kichamu@griffithuni.edu.au.

Declarations

Competing interests Prof Zhihong Xu, a co-author of this manuscript, is an Editor in the Journal of Soils and Sediments. Prof Zhihong Xu would like to exclude his participation and the responsibility of this manuscript, and this is to be assigned to an alternative Editor.

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