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Soil Organic Carbon and Labile Carbon Pools Attributed by Tillage, Crop Residue and Crop Rotation Management in Sweet Sorghum Cropping System

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Abstract: Labile organic carbon (LOC) fractions are considered as sensitive indicators of change in soil quality and can serve as proxies for soil organic carbon (SOC). Although the impact of tillage, crop rotation and crop residue management on soil quality is well known, less is known about LOC and SOC dynamics in the sweet sorghum production systems in South Africa. This short-term study tested two tillage levels: no-till and conventional-tillage, two crop rotations: sweet-sorghum/winter grazing vetch/sweet sorghum and sweet-sorghum/winter fallow/sweet sorghum rotations and three crop residue retention levels: 30%, 15% and 0%. Tillage was the main factor to influence SOC and LOC fractions under the sweet sorghum cropping system in South Africa. NT increased SOC and all LOC fractions compared to CT, which concurs with previous findings. Cold water extractable organic carbon (CWEOC) and hot water extractable organic carbon (HWEOC) were found to be more sensitive to tillage and strongly positively correlated to SOC. An increase in residue retention led to an increase in microbial biomass carbon (MBC). This study concludes that CWEOC and HWEOC can serve as sensitive early indicators of change in soil quality and are an ideal proxy for SOC in the sweet-sorghum cropping system in South Africa.

Keywords: conservation agriculture; soil quality; no-till; land use

1. Introduction

The potential use of bioenergy sweet sorghum in South Africa, like in other countries, offers an opportunity for valuable use of marginal land and hence income to smallholder farmers at low agronomic inputs [1]. Biofuel feedstock production is generally done under intensive agronomic management [2], which has potential to reduce soil quality [3] and intensify soil erosion and its related consequences [4]. Thus, conserving and restoring soils in marginal lands is at the centre of sustainable production of bioenergy crops, and it will also serve as a poverty alleviation strategy [5]. According to Bonin and Lal [6], vegetation and management practices are the main factors influencing soil quality. However, to date, sustainable production systems for bioenergy sweet sorghum in South Africa are not available [7]. Conservation agriculture (CA) is currently promoted as a potential sustainable production for bioenergy sweet sorghum in South Africa [2]. However, research on the effect of CA on soil quality under the production of biofuel feedstock is required in South Africa [2]. Consequently, the potential benefits of CA under sweet-sorghum production systems for vital soil health indicators such as LOCs were not examined in depth.

Soil organic carbon (SOC) is one of the central carbon pools [8], regarded as the centre of soil quality and its functions and a leading indicator of soil health [9,10]. The depletion of SOC leads to poor soil aggregation and stability, loss in water holding capacity, fertility, enzymatic activities and soil biology [11]. Soil erosion and loss in soil productivity are among the visual consequences of SOC depletion [11,12]. Accelerated soil erosion increases carbon dioxide emission [13], which contributes to climate change [12]. Thus, maintaining and improvement of SOC are important for a sustainable production system and reduction in climate change [14,15].

Land use is the chief factor influencing SOC dynamics [8,16,17]. Continuous soil cultivation is known to increase the depletion of SOC by increasing SOC mineralization [18,19]. A less intensive agricultural system, no-till (NT), has been promoted as a system that enhances SOC and helps in climate change mitigation [19–21]. The extent and the rate of SOC increase when NT is adopted varies according to cropping system [20,22,23], soil type [24,25], climate [16,26,27] and other agronomic management practices [28–30]. Thus, SOC dynamics are both site and management specific when NT is adopted. In addition to NT, residue retention plays an important role in enhancing SOC [31–33]; however, residue retention effects may also be controlled by climate, soil type and other management aspects [34]. The change in SOC is also influenced by the crop(s) in rotation, in addition to the main crop [35,36]. Thus, more research on SOC as affected by tillage, crop residue management, crop rotation and nutrient management systems is still needed to advance our understanding of the SOC dynamics [15].

Soil organic carbon change is relatively slow; hence, total SOC only does not reflect sensitive changes in soil quality due to land use [11,37]. Labile organic carbon (LOC), a component of SOC, was found to be a good and sensitive early indicator of minor changes in soil after a change in land use [11,37,38]. LOC is the smallest part of SOC yet important in controlling nutrient availability to crops and microbes [39,40]. The change in LOC in given land use is controlled by site-specific conditions, vegetation, residue management and land-use intensity [41]. For that reason, inconsistency in the change in LOC resulting from land uses exists in literature [8]. Moreover, a lack of organic carbon, nitrogen, sulphur and other elements in the soil significantly influences sorghum and other cereal composition [1,42]. Thus, the aim of this study was to determine the effect of tillage, crop rotation and crop residue management on SOC and LOC pool dynamics in a sweet-sorghum production.

Although the goal in biofuel and food crops production is to maximize the harvested aboveground biomass, such management practices may have negative impacts on soil quality by decreasing SOC [43]. Therefore, it is important to determine the most suitable residue return levels that maintain or enhance SOC and its LOC pools.

2. Materials and Methods

2.1. Site Description and Experimental Design

The experiment was carried out at the University of Fort Hare experimental farm which is located at latitude 32°46′ S and longitude 26°50′ E. Study site descriptions, treatments, experimental design and agronomic practices were as described by Malobane et al. [5]. Briefly, the experimental site climatic conditions are classified as semi-arid and it receives an annual mean rainfall of about 575 mm during the summer months. The dominant soil form at the experimental site is of alluvial origin, also known as Haplic Cambisol. The soil at the site has 60% sand, 18% silt, 22% clay, pH (H_2O) 6.98 and SOC 11.5 g kg^{-1}.

The experiment was conducted between October 2016 and March 2019. A randomised complete block designed with a 2 × 2 × 3 split-split-plot arrangement, replicated three times, was used in this study. The main plot measured 12.8 × 17 m and was assigned to tillage treatments (NT and CT). A sub-plot (5.4 × 17 m) was assigned to crop rotations (S-V-S and S-F-S). Sub-sub-plots (5.4 × 5 m) were assigned to crop residue management, 0%, 15% and 30% residue retentions of total fresh harvested biomass.

Sweet sorghum was planted in all the plots at 55,000 plants ha^{-1} in summer. An amount of 300 kg ha^{-1} of 2:3:4(30) basal fertiliser was applied at sweet sorghum during sowing and 400 kg ha^{-1} of limestone ammonium nitrate fertiliser as a top dressing at 6 weeks after sowing. Grazing vetch cover crop (*Vicia dasycarpa* cv. Max) was inoculated with *Rhizobium leguminosarum* biovar viciae and sown during winter in the allocated plots at recommended seed rates of 35 kg ha^{-1}. Glyphosate (N-(phosphono-methyl) glycine, 360 g L^{-1}) was applied at 5 L ha^{-1} to terminate the cover crop before seed development. Cylam 50EC (Lambda-cyhalothrin (pyrethroid), 50 g L^{-1}) was used to control pests in the sweet sorghum crop. Weeds were controlled by hand hoeing in all plots whenever it was necessary.

2.2. Sampling

Soil samples for SOC and LOC were collected at the end of March 2019, after harvesting sweet-sorghum. The experimental treatments were carried out for a duration of 3 years before samples were collected. A composite sample made up of three random samples taken at 0.1 m depth in each plot was used for analysis. Noticeable crop residues were removed from the composite sample before analysis. The composite sample was divided into two portions: one for microbial mass carbon (MBC) and the other portion for SOC and LOC fractions. The determination of MBC was carried out on the same day the soils were collected. Composite samples for SOC and LOC analysis were air-dried and passed through a 2 mm sieve before analysis.

2.3. Analysis

Soil organic carbon (SOC) was determined using the Walkley black method. Particulate organic matter (POM) was determined using a method by Camberdella et al. [44]. Briefly, 10 g of air-dried soil was 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 was then passed through a 0.053 mm sieve, and material remaining on the 0.053 mm sieve was then dried at 55 °C. The soil sample dried at 55 °C was then placed in a crucible and heated at 450 °C for 4 h using a muffle furnace. POM was calculated using the formula below

$$\text{POM mg g}^{-1} = \left(\frac{\text{Weight at 55°C} - \text{Weight at 450 °C}}{\text{Weight at 55°C}}\right) \times 1000$$

Water extractable organic carbon was separated into two fractions, namely CWEOC and HWEOC [11]. The soil sample of 3 g air-dried sample was weighted in 30 mL polypropylene centrifuge tubes and extracted with 30 mL of distilled water at 30 rpm for 30 min. After extraction, the suspension was centrifuged at 3500 rpm for 30 min. To extract HWEC, 30 mL of distilled water was added into the sediments from CWEC extraction and vigorously shaken for 10 s, capped and placed in a water bath at 80 °C for 16h. At the end of extraction, the tubes were vigorously shaken for 10 s and then centrifuged at 3500 rpm for 30 min. The organic C in the supernatant was determined using the Walkley Black method [35].

The chloroform fumigation–extraction procedure was used for the determination of MBC following the methods of Anderson and Ingram [45]. K_c of 0.38 was used in the experimental trials [46].

Statistical Analysis

The JMP 14 was used to perform three-way analysis of variance (ANOVA). The least significant difference method at $p \leq 0.05$ was used for mean separations.

3. Results

In this short-term study, SOC and LOC—i.e., MBC, CWEOC, HWEOC and POM—were mainly influenced by tillage (Table 1). SOC and HWEOC were highly significantly ($p < 0.01$) influenced by tillage, while MBC, CWEOC and POM were only significantly ($p < 0.05$) influenced by tillage (Table 1). No significant interaction among the three factors was found on SOC, CWEOC, HWEOC and POM, while MBC was influenced ($p < 0.05$) by tillage × rotation × residue management interaction (Table 1). In addition, MBC was strongly influenced ($p < 0.001$) by crop residue management (Table 1).

Table 1. Analysis of variance (ANOVA) results of soil organic carbon (SOC), microbial biomass carbon (MBC), cold water extractable organic carbon (CWEOC), hot water extractable organic carbon (HWEOC) and particulate organic matter (POM) as influenced by tillage, crop rotation, crop residue management and their interaction.

	SOC	MBC	CWEOC	HWEOC	POM
Till.	0.0012 **	0.0367 *	0.0143 *	0.0050 **	0.0371 *
Rot.	0.8407	0.1454	0.5942	0.1108	0.1166
Res. man.	0.9285	<0.0001 ***	0.2311	0.3485	0.3979
Till. × Rot.	0.7428	0.8268	0.2198	0.2349	0.2966
Till. × Res. man.	0.9380	0.9700	0.6570	0.4578	0.6612
Rot. × Res. man.	0.8506	0.4363	0.1894	0.4832	0.9620
Till. × Rot. × Res. Man	0.1528	0.0497	0.8582	0.7748	0.6014

Till: tillage, Rot.: Rotation, Res. man: Residue management, *, **, *** significant difference at 0.05, 0.01 and 0.001, probability level, respectively.

The application of NT resulted in significantly higher SOC, MBC, CWEOC, HWEOC and POM compared to CT treatment (Table 2). SOC was 15.83% higher under NT compared to CT treatment (Table 2). MBC, CWEOC, HWEOC and POM, which form part of LOC, were 9.58%, 70.89%, 35.42% and 18.30% higher in NT compared to CT treatment, respectively. The measured LOC fractions constituted less than 35% of the total SOC.

Table 2. Effects of tillage on soil organic carbon (SOC), microbial biomass carbon (MBC), cold water extractable organic carbon (CWEOC), hot water extractable organic carbon (HWEOC) and particulate organic matter (POM).

Measured Variables	Tillage Treatments	
	NT	CT
SOC (mg kg^{-1})	10868.78 a	9382.72 b
MBC (mg kg^{-1})	83.83 a	76.50 b
CWEOC (mg kg^{-1})	38.28 a	22.40 b
HWEOC (mg kg^{-1})	88.47 a	65.33 b
POM (mg kg^{-1})	3492.93 a	2952.57 b

NB: NT: no-till, CT: conventional tillage, numbers followed by different letters within the same row show difference among the tillage systems.

Implementation of 30% residue retention treatment favoured MBC regardless of tillage or crop rotation (Figure 1). NT + S-V-S + 30% had 83.91% higher MBC compared to CT + S-F-S + 0% treatment combination, which is considered as common practice among smallholder farmers.

Residue retention of 30% had significantly higher MBC compared to both 15% and 0% residue retention (Table 3). The 30% residue retention had 35.85% and 51.50% higher MBC compared to 15% and 0% residue retentions, respectively.

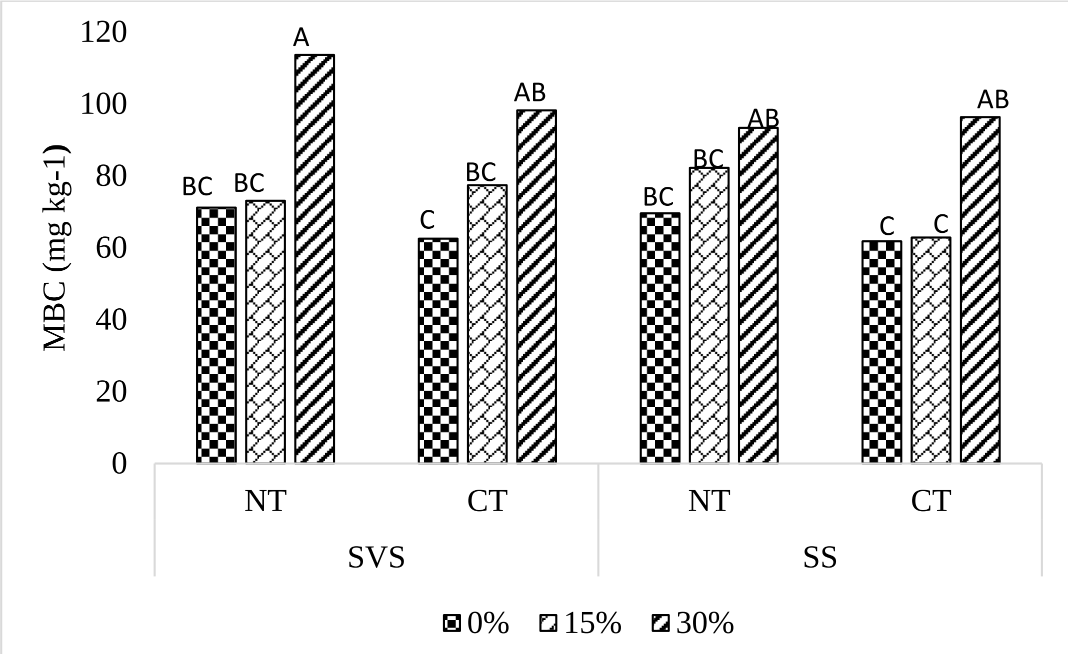

Figure 1. Tillage × rotation × residue management interaction effects on MBC (mg kg^{-1}). NT: no-till, CT: conventional tillage, SVS: sweet-sorghum/winter grazing vetch/sweet sorghum, SS: sweet sorghum/winter fallow/sweet sorghum. Different letter on the bars indicate differences among the treatment combinations.

Table 3. MBC (mg kg^{-1}) as influenced by crop residue management.

Residue Management	MBC (mg kg^{-1})
0%	66.25 b
15%	73.88 b
30%	100.37 a
p value < 0.001	

Numbers followed by different letters within the same row indicate differences among the treatments.

Soil organic carbon was positively correlated to all the selected LOC fractions: MBC, CWEOC, HWEOC and POM (Table 4). SOC was strongly correlated to HWEOC, and the lowest correlation was with MBC (Table 4). Selected LOC fractions were also positively correlated to each other (Table 4).

Table 4. Correlations between soil organic carbon (SOC), microbial biomass carbon (MBC), cold water extractable organic carbon (CWEOC), hot water extractable organic carbon (HWEOC) and particulate organic matter (POM).

	SOC	MBC	HWEOC	CWEOC	POM
SOC	1				
MBC	0.17	1			
HWEOC	0.72	0.52	1		
CWEOC	0.53	0.61	0.19	1	
POM	0.49	0.62	0.72	0.26	1

4. Discussion

After 3 years of the sweet-sorghum production system in Eastern Cape, South Africa, SOC and selected LOC fractions significantly responded mainly to tillage. Tillage seems to able to alter the soil environment for microorganisms and SOC by increasing exposure of physically protected soil organic matter to microbial decomposition leading to a decline in SOC and biological activities [18,19,47]. Previous studies have demonstrated that some LOC fractions respond to changes in management faster and to a greater extent than SOC [38,48]. In this study, differences in LOC fractions between the tillage practices ranging between 9.58% and 70.89%, while SOC was at 15.83%, demonstrating that LOC fractions respond more to tillage than SOC.

The application of NT resulted in higher SOC and LOC fractions compared to CT treatment (Table 2). This is similar to previous findings [49–51]. Soil cultivation increases the influence of freezing-thawing and drying-rewetting cycles on soil properties, which increases aggregate disruption and accelerates the LOC mineralization and decline in SOC [18,47,52]. Our findings are in contrast with Zhao et al., who did not find a significant difference in SOC under NT and CT. The authors argued that their findings might mainly be due to environmental conditions on their site.

This study generally concurs with previous studies that reported LOC fractions to be sensitive to tillage [51,53,54] apart from MBC for which percentage differences between NT and CT were less than that of SOC. Alvarez and Alvarez [55] also found that NT and CT had no influence on MBC. In this study, CWEOC was more sensitive to tillage than other LOC fractions. HWEOC was found to be higher than CWEOC, supporting previous studies [48,56]. The increase in LOC under NT is mainly due to the re-aggregation which protects the newly added carbon from residues [57]. Under the NT environment, biological activities are favoured, enhancing enzymes production which enhances LOC fractions [58,59]. The increase in LOC with NT application suggests that NT contributes to the improvement of soil functions as LOC is a vital energy source for soil micro-organisms which stimulate nutrient cycling, conserving soil quality and productivity [39].

The increase in MBC with residue retention (Table 3) is mainly due to residues offering nutrients for microbial growth and activity [60]. This supports previous studies that found an increase in MBC after residue retention management [61,62]. The increase in MBC is an indication of enhancement in soil health and gives an insight into the living SOC fraction [63]. In addition, the increase in MBC is a good indicator of overall biological activity which is crucial for nutrient cycling and availability [62]. The application of NT + S-V-S + 30% which covers all the main principles of CA increased MBC more than the other treatment combinations, proving to be a potential management practice to exploit the benefits of CA in the sweet-sorghum production system in South Africa. The increase in MBC after implementation of NT, rotation and residue retention was previously reported [64]. Crop in rotation offers extra substrate for microbial growth and activity, which leads to an increase in MBC [65,66].

The LOC fractions were positively correlated to SOC. This is in line with previous findings [48,51,52,67]. This suggests that the dynamics of LOC fractions can serve as an alternative to SOC changes in soils under agricultural and SOC is their major determinant in soil [51,52]. LOC is regarded as an important starting point for the establishment of stable SOC [68]. In this study, SOC was strongly correlated to HWEOC than other LOC fractions (Table 4), suggesting that HWEOC is a better proxy for SOC in the sweet-sorghum production system in South Africa and its monitoring will be crucial during restoration of marginal lands. Positive correlations among LOC fractions were also previously reported [48,51,52,67]. This is because LOC fractions are closely associated with each other [67].

5. Conclusions

Results from this study show that, in the short-term, SOC and LOC fractions studied under the sweet-sorghum production system in South Africa are more sensitive to tillage than to both residue retention and rotation management. The application of NT increased both SOC and all LOC fractions. The results also suggest that the various LOC fractions represent different SOC pools, with CWEOC and HWEOC representing pools that seem to be more sensitive to tillage. This makes them more suitable early indicators of soil quality than MBC, POM and SOC under a sweet-sorghum production system in South Africa. The fact that measured LOCs and SOC were not influenced by crop rotation and the interaction between tillage, crop rotation and residue retention warrants further studies. Therefore, studies evaluating treatments for a medium- to long-term period are recommended. In addition, inclusion of summer crop diversity/intercropping/crop rotation treatments is recommended for future studies in order to maximise biomass yield during the rainy season.

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