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Sequestration of Soil Organic Carbon Pools under Diverse Tillage Practices and Cover Crops in Northern Guinea Savanna, Nigeria.

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ABSTRACT

Sequestration of soil organic carbon (SOC) is vital to increase soil quality and carbon stock, decrease soil erosion, and mitigate climate change. This study evaluated effects of tillage and cover crops on the sequestration of different pools of SOC. Three years field trials were conducted at Institute for Agricultural Research farm, Zaria, Nigeria. Three tillage practices [no-till (NT), reduced till (RT), and conventional till (CT)] formed the main treatment while four cover crops [*Glycine max* (GM)*, Centrosema pascuorum* (CP)*, Macrotyloma uniflorum* (MU) *and Cucurbita maxima* (CM)], and a control, without cover crop (NC) formed the sub treatment. After harvesting of test crop each year, soil samples were collected from depths 0-5, 5-10, 10-15, and 15-20 cm. Organic carbon sequestered in soil aggregate fractions [Fine particulate organic carbon (FPOC) intra aggregate particulate organic carbon (IPOC), and silt plus clay associated carbon], bulk soil (total organic carbon, TOC), and dissolved organic carbon (DOC) were determined. Conservation tillage (NT and RT) surpassed CT in Carbon sequestration in both bulk soil and aggregate fractions. No-till soil had 34, 29, and 25 % more TOC than the conventionally tilled soil in the 1st, 2nd, and 3rd years respectively. Similarly, the use of cover crops improved TOC, FPOC, IPOC, silt plus clay associated C and DOC relative to the soil without cover crop, the significance of DOC was in the order of CP > GM > MU > CM > NC. The soil under CP had 50 % more DOC than soil without cover crops. Soil tillage disrupts soil aggregates, increases macroaggregate turnover, and releases C into the atmosphere, resulting in low formation of microaggregates within macroaggregates and low stabilization of SOC. Conservation tillage and cover cropping have great potential for climate change mitigation and, crop and soil productivity improvement by enhancing SOC sequestration.

Keywords: Carbon sequestration; Cover crop; Dissolved organic carbon; Soil organic carbon pools; Tillage

INTRODUCTION

Soil organic carbon (SOC) is a primary indicator of soil health and plays a vital role in food production, greenhouse gas balance, and climate change mitigation and adaptation (Lorenz and Lal, 2016). Carbon (C) sequestration refers to the capturing and secure storing of atmospheric C emitted from the global energy system (USDOE, 1999). It involves the removal of carbon dioxide (CO_2) from the atmosphere and storage of C in soil by biotic (photosynthesis) and abiotic processes (Demessie *et al.*, 2017). The principle helps to offset emissions from fossil fuel combustion and other carbon-emitting activities while enhancing soil quality and long-term agronomic productivity. Furthermore, C sequestration minimizes C loss from a terrestrial ecosystem and reduces the rate of increase in atmospheric CO_2 which is one of the greenhouse gases causing global warming (IPCC, 1990).

The principal global C pools are in the order of oceanic, geologic, pedologic (soil), biotic, and atmospheric pools. Sequestration of C in soil and vegetation is a necessity for improving soil quality and mitigating climate change. Soil is the largest overall reservoir of C and a major source and sink for C exchanges between the atmosphere, terrestrial vegetation, and aquatic environments. Different pools of SOC emanate due to root growth and microbial decomposition; these pools are defined based on relative recalcitrance which governs their residence and turnover times (Eswaran *et al.*, 1995). Soil organic carbon is physically sequestered in soil through the encapsulation of organic fragments by clay particles or soil aggregates, and chemically sequestered through specific bonds of organic matter with other soil constituents (Lal *et al.,* 2003). Different SOC pools such as particulate organic carbon (organic fraction >53 µm diameter, recognizable structure) and a humic fraction (non-identifiable chemical structure such as humic acids and humin) affect different soil functions. Particulate organic carbon is important in providing energy for biological processes while humic fraction is an important source of essential soil nutrients and is the principal pool contributing to the soil's cation exchange capacity (Demessie *et al.*, 2017). Hence, SOC can be sequestered through humification, whereby biomasses are converted into humic substances, which are relatively resistant to microbial attack (Follet, 2001; Follet *et al*., 2001).

One of the major objectives of climate-smart agriculture is to reduce greenhouse gas emissions and enhance soil C sequestration and soil health (Campbell *et al*., 2014; Lipper *et al*., 2014). The key to sequestering more C in soils lies in increasing C inputs and reducing C outputs, which could be achieved through recommended practices such as minimal soil tillage (i.e., conservation tillage) which confers more than 30% residue cover on the soil surface, cover cropping which supplies organic residue, crop rotation, and organic amendment application to soils.

The soils of the West African Savanna biome have a high potential for C sequestration as they are some of the world's oldest and intensively weathered soils with limited water and nutrient holding capacities, low soil organic matter (SOM) due to poor biomass productivity, low soil clay content, rapid decomposition rate due to high temperature and limited depth of root growth caused by physical obstacles, at sub-surface soil layers, like plinthites, laterites and other hardpans (Lahmar *et al*., 2012; Bationo *et al*., 1998). The biogeochemical liabilities of intensive agriculture on these soils are therefore enormous: low fertility, weak aggregation, and aggregate stability, SOM loss, soil C, N and water losses, and atmospheric warming, in addition to little or no C input to compensate for these losses, thereby leading to deplete in soil C stock.

Coupled with these edaphic challenges are the high-intensity rainfall events characteristic of the biome and this high intensity is responsible for soil particle detachment and subsequent soil losses. Aside from drastic soil perturbation resulting in CO_2 emission through disruption of aggregates, rapid mineralization, and loss of SOM; continuous cultivation with conventional tillage system majorly adopted in this ecology predisposes the soil to accelerated erosion and consequently nutrient loss in the Savanna. These Soils are especially, more susceptible to erosion between land preparation operations and the full crop vegetative stage, largely because the soils are unprotected (lack vegetative cover) before the crop reaches full canopy coverage or they are only partially protected. To mitigate the adverse effect of soil loss and CO_2 emission in this biome, a conventional tillage system may not be an appropriate soil management practice for sustainable crop and soil productivity. Development of a soil tillage practice that sequesters atmospheric CO_2 while maintaining and preserving soil resources can be a candidate alternative to the current practice of conventional tillage systems. Furthermore, conservation tillage is being promoted as a practice capable of offsetting greenhouse gas emissions because of its ability to sequester C in soils (Lal, 2004; Six, *et al.*, 2004). However, to protect the soil from being detached (soil loss) due to rain drops impact; cover cropping is being suggested as it can help maintain soil structure.

Therefore, the problem of SOC depletion in the Savanna ecological zone of Nigeria can be tackled through better management aimed at augmenting the normal function of the soils and SOC sequestration. Conservation tillage practices and the use of cover crops may better protect the soil from severe erosion and augment the accrual of SOC. Furthermore, suitable cover crop for conservation tillage for this region is yet to be determined. The ecological interactions that underpin productive, sustainable, crop production under conservation tillage is yet to be understood. This study hypothesizes that a combination of conservation tillage practices and the use of cover crops will minimize the disruption of ecology. Therefore, the objective of this study is to assess the effect of tillage and cover crops on the sequestration of pools of SOC and dissolved organic carbon in a Typic Haplustults of Northern Guinea Savanna, Nigeria.

MATERIALS AND METHODS

Description of Study Site

The trials were conducted at the Institute for Agricultural Research farm (latitude 11.17358°N, longitude 7.63020°E, and altitude of 691 m above sea level) in Samaru, Zaria, Northern Guinea Savanna ecological zone of Nigeria. The study area has a long-term mean annual rainfall of 1101±16.1mm with a uni-modal rainfall pattern annually, beginning in April and ending in October. Mean monthly minimum and maximum temperature ranges from 20 and 12°C in December and to 35 and 28°C in April, respectively. The topography is almost plain (nearly leveled) with a < 2% slope. The soil type is Typic Haplustults derived from pre-Cambrian crystalline basement complex rocks with some quaternary aeolian deposits.

Experimental Layout and Soil Sampling

The experimental field was laid out in a randomized complete block design, split plot arrangement, and replicated three times. The main treatment was three tillage practices namely: conventional tillage; CT, (ploughing, harrowing, and ridging; with crop residue removed at the end of each cropping season as practiced by the local farmers in Northern Nigeria), Reduced tillage; RT, (harrowed once and crop residue incorporated) and No-till; NT, (no soil disturbance except for seed sowing, and crop residue were left on the soil surface). A control i.e., bare land, except for sole maize (no cover crops; NC) and four cover crops namely: *Glycine max* (GM)*, Centrosema pascuorum* (CP)*, Macrotyloma uniflorum* (MU) *and Cucurbita maxima* (CM), were the sub treatment. The experimental field was cropped with maize (Zea mays) as the test crop for three rainy seasons (2011-

2013). Prior to trial establishment, disturbed and undisturbed soil samples were taken from the experimental field at 0-15 cm depth, for routine soil physical and chemical analyses. After trial establishment and the test crop had attained maturity, in each year disturbed auger soil samples were collected in each treatment plot at depths 0-5, 5-10, 10-15, and 15-20 cm for carbon analyses. At each sampling depth, in each replication, soil samples were taken at five different spots per plot and then composited.

Laboratory Analysis

Routine soil physical and chemical analysis

Disturbed soil samples taken at 0-15 cm depth prior to trial establishment, were air-dried and sieved through 2 mm mesh, for determination of particle size distribution by hydrometer method (Gee and Or, 2002), organic carbon by dichromate wet oxidation method (Nelson and Sommers, 1982), soil pH with the aid of a glass electrode pH meter both in water and 0.01M $CaCl_2$ solution, using soil to solution ratio of 1:2.5 (Mcleans, 1982), total nitrogen by micro Kjeldahl digestion method (Bremner and Mulvaney, 1982), Available P by Bray No. 1 acid fluoride method and exchangeable bases as described by Rhodes (1982). The undisturbed soil sample was used for the determination of bulk density by the core method (Grossman and Reinsch, 2002).

Soil aggregate separation

Soil aggregate size separation was achieved by a rapid immersion (slaking) wet sieving method. A 100 g soil sample collected from 0-5, 5-10, 10-15, and 15-20 cm soil depths, was air-dried and passed through a 5 mm mesh. After which, it was placed on top of a nest of 2000, 250, and 53 µm sieves. During the wet sieving, one sieve was used at a time in order of decreasing mesh size, water stable aggregates (i.e., resistant to slaking) were separated by manually moving the sieves up and down 5 cm with 50 repetitions for 2 minutes. The water and soil that went through the sieve were transferred onto the next smaller-sized sieve and the same procedure repeated. Soil retained on each sieve (water-stable aggregates) and the <53 µm fraction (allowed to settle down before its water was decanted) were oven dried at 60°C for more than 24 hours until a constant weight was attained.

Soil Organic Carbon Analyses

Soil aggregate associated organic carbon

Organic carbon content in 2000–250 µm, 250–53 µm, and < 53 µm soil aggregate sizes were determined using the dichromate oxidation method (Nelson and Sommers, 1982) and termed fine particulate, intra aggregate particulate, and silt plus clay associated organic carbon respectively. The sand-free C concentration was thus calculated in aggregate fractions greater than 53 µm (Denef *et al.*, 2004).

$$\text{Sand-free C fraction} = \frac{\text{C fraction}}{1 - [\text{sand proportion}]\ \text{fraction}}$$

Total organic carbon concentrations

Total organic carbon in the bulk soil (< 2.00 mm) was determined by the dichromate wet oxidation method (Nelson and Sommers, 1982).

Table 1 . Physical and chemical properties at soil depth of 0-15cm of the experimental site prior to trial establishment.

Parameters	Values	% CV
Sand (g kg^{-1})	431.11	5.93
Silt (g kg^{-1})	425.77	6.89
Clay (g kg^{-1})	143.11	14.09
Texture	Loam	-
pH (water)	6.3	1.56
pH ($CaCl_2$)	5.4	2.55
Organic carbon (g kg^{-1})	10.17	20.32
Total nitrogen (g kg^{-1})	0.72	19.41
Available P (mg kg^{-1})	2.56	24.33
Exchangeable Calcium (cmol kg^{-1})	1.96	32.05
Exchangeable Magnesium (cmol kg^{-1})	1.03	33.25
Exchangeable Potassium (cmol kg^{-1})	0.24	37.30
Exchangeable Sodium (cmol kg^{-1})	0.1	51.47
Cation exchange capacity (cmol kg^{-1})	4.3	22.34
Bulk density (Mg m^{-3})	1.47	7.68

CV = coefficient of variability

Dissolved organic carbon

Dissolved organic carbon (DOC) was extracted from soil with distilled water in a ratio of 1:4; soil to water, by shaking for one hour, followed by centrifugation and vacuum filtration through 0.45 µm filters (Wright *et al.,* 2005). The extracts were analyzed for DOC by dichromate wet oxidation method (Nelson and Sommers, 1982).

Data Analysis

Data collected for the three years of study were subjected to statistical analysis of variance for randomized complete block design, using the generalized linear model (GLM) procedure of statistical analytical software, SAS package (SAS, 2008) Significant differences among treatment means were separated using the Duncan multiple range test.

RESULTS AND DISCUSSION

Characterization of Soil of Study Area

The physical and chemical properties of soil of the study area before the trial establishment are presented in Table 1. The soil is generally loam (L) in texture with 43% sand, 43% silt, and 14% clay and moderately acidic in soil reaction (pH 5.4 in $CaCl_2$), with moderate OC (10.17 g kg^{-1}) and bulk density (1.4 Mg m^{-3}); but poor in total nitrogen (0.72 g kg^{-1}). The soil has very low available phosphorus (2.56 mg kg^{-1}), exchangeable calcium, and cation exchange capacity (4.3 cmol kg^{-1}). While exchangeable magnesium, potassium, and sodium are generally low.

Table 2. Tillage, cover crop, and sampling depth effects on total organic carbon concentrations, during the first, second, and third-year cropping seasons, and the mean across the three years at Samaru, northern Nigeria.

	Total organic carbon concentrations (g kg^{-1})			
Treatments	First-year	Second year	Third year	Combined
Tillage (T)				
No-till (NT)	12.09a	11.03a	11.71a	11.61a
Reduced (RT)	11.92a	10.13a	8.43c	10.47a
Conventional (CT)	9.05b	8.57b	9.40b	8.86b
SE ±	0.332	0.260	0.017	0.300
Significance	**	**	**	*
Cover Crops (C.)				
No Cover	9.01c	7.49b	8.57d	8.43c
Macrotyloma uniflorum	9.49c	9.76a	9.53b	9.67b
Centrosema pascorum	12.36a	11.31a	9.78a	10.81a
Glycine max	10.25bc	8.51ab	9.28c	9.11b
Cucurbita maxima	11.74ab	8.66ab	8.58d	9.14b
SE ±	0.299	0.335	0.022	0.258
Significance	**	*	**	**
Depth (cm) D				
0-5	10.82 a	11.75a	12.86a	11.14a
5-10	9.72 a	9.65b	9.92b	9.93a
10-15	8.24 ab	6.54c	8.17c	7.93b
15-20	5.51 c	5.19d	5.65d	5.41c
SE ±	0.019	0.300	0.020	0.019
Significance	**	**	**	*
Interactions				
T x C	NS	NS	NS	NS
T x D	NS	*	NS	NS
D x C	NS	*	NS	NS
T x D x C	NS	NS	NS	NS

Means followed by the same letter (s) within a treatment group are not significantly different at a 5% level of significance using Duncan Multiple Range Test. SE = standard error, * = Significant at p = 0.05, ** = Significant at p = 0.01 and NS = not significant

Effect of Tillage and Cover Crop on Carbon Sequestration in Soil

Effect of tillage, cover crop, and sampling depth on total organic carbon concentrations

Tillage, cover crop, and sampling depth effects on total organic carbon (TOC) are presented in Table 2. No-till and RT had significant advantages concerning TOC in the 3 years of study and the means across the years, except in the third year where RT recorded lower TOC relative to NT. The combined results across the three years showed that NT soil had 33.59, 28.71, and 24.47 % more TOC than the conventionally tilled soil in the 1st, 2nd, and 3rd years respectively. However, consistently low TOC was observed on the CT plots throughout the years of experimentations.

Lower TOC in CT soil relative to NT and RT soils is an indication of loss of C as a result of soil tillage. When soil is tilled, soil aggregates are disrupted and a large amount of CO_2 is released within days (Duiker and Myers, 2002). Furthermore, the depth (20cm) of soil inversion by the disc plough gives room for greater loss of CO_2 from the soil to the atmosphere as a result of the fast oxidation of organic matter buried in the plough depth and release of massive quantities of CO_2 (Awale *et al*., 2017). During tillage operation, crop residues are incorporated, aeration is increased and mineralization of OC is enhanced therefore the reduction in C levels in CT soil. Moreover, the High number of earthworms in soils of NT and RT treatments relative to CT of this study site as published in Lawal (2019), might have induced increased earthworm fecal pellets in NT and RT. These fecal pellets are stores/traps for C (Schrader *et al*., 1997) thereby protecting this C against water and microbial decomposition, by protecting the C in silicon-rich coating or polysaccharides (Barois *et al*., 1998; Fujimaki *et al*., 2010). In addition, since the soil of the study area is loamy in texture, it could also contribute to the slow C mineralization (Koutika *et al*., 2001) especially in NT and RT systems due to minimal soil disturbance.

Effect due to the different cover crops evaluated revealed significantly higher TOC on soil covered with CP, relative to all other cover crops and the control/no cover crop (11 and 28 % respectively) in all the years of trial and the combined. Except in the first year where CP was statistically at par with CM and the second year, where all cover crops evaluated performed statistically the same. Significantly low TOC was however observed on the plots without cover crops in the 3 years of study and combined.

Generally, the use of cover crops influenced higher TOC and some aggregate associated C content relative to the bare soil where there are no cover crops, the order of sequestration being *Centrosema pascuorum* > *Glycine max* > *Macrotyloma uniflorum* > *Cucurbita maxima.* Higher biomass production by *Centrosema pascuorum* may have influenced higher root density as well as root exudates production thus higher OC content in its underlying soil. Furthermore, cover crops directly provide C inputs to soils, through their root development and rhizodeposition which also benefit soil structure (Awale *et al*., 2017). The large volume of residues deposition; therefore, organic matter (OM) engendered in cover crop plots relative to no cover crop plot, may have influenced C sequestration through the formation of soil macroaggregates, which are the basis for promoting SOC preservation and accumulation (Six *et al*., 2002). In addition, crop residues provide organic substrates to soil microorganisms which in turn produce binding agents and promote soil aggregation (Guggenberger *et al*., 1999) by reducing soil erosion which is the major cause of C emission from the soil, thereby offering stability for aggregate-associated C. Conversely, residue removal reduces C input to the soil system and ultimately decreases SOC storage. Furthermore, cover crop covers the soil thereby reducing the impact of high soil temperature in the tropics and consequently OM decomposition rate, in addition to promoting fungal and earthworm biomasses (Briones and Schmidt, 2017), hence improving SOC stabilization. The surface soils of 0-5 cm had consistently higher TOC than the sub-surface soils of 10-15 cm and 15-20 cm depth in all the years of experimentation by 41 and 106 % respectively. This was however comparable to TOC in 5-10 cm in the first year and the means across the years.

Furthermore, there was a significant interaction of tillage versus depth (Figure 1) indicating that TOC decreases with increasing soil depth irrespective of the tillage practice. A significant interaction of soil depth versus cover crops (Figure 2) indicates that at all depths, soil with cover crops had significantly higher TOC than soil with no cover crop except at 5-10 cm and 15-20 cm soil depths where soil covered with CP and CM respectively had statistically similar TOC with the bare soil, and at 10-15 cm where only soil covered with MU had higher TOC than the bare soil.

Higher TOC and aggregate associated C at the topsoil could be ascribed to higher deposition of crop residues at the soil surface most especially in the NT system where crop residues are not incorporated. In addition, much of the maize and cover crop root growth occurs in the surface soil, and roots are generally known to contribute more greatly to SOC than aboveground biomass (Allmaras *et al*., 2004; Balesdent and Balabane, 1996). However, in the CT system, OC content increased with depth, with the lowest sampling depth having higher C content, this could be ascribed to the redistribution of crop residues from the soil surface to the lower depths as a result of soil inversion during ploughing operation. Furthermore, the Inversion of the soil mixes surface crop residues and creates a flush of microbial activity that leads to the rapid decomposition of SOM (Novak *et al*., 2009) at lower depths. Many researchers (Awale *et al*., 2017; Denef *et al*., 2004; Six *et al.,* 2003) reported the loss of soil organic matter due to the

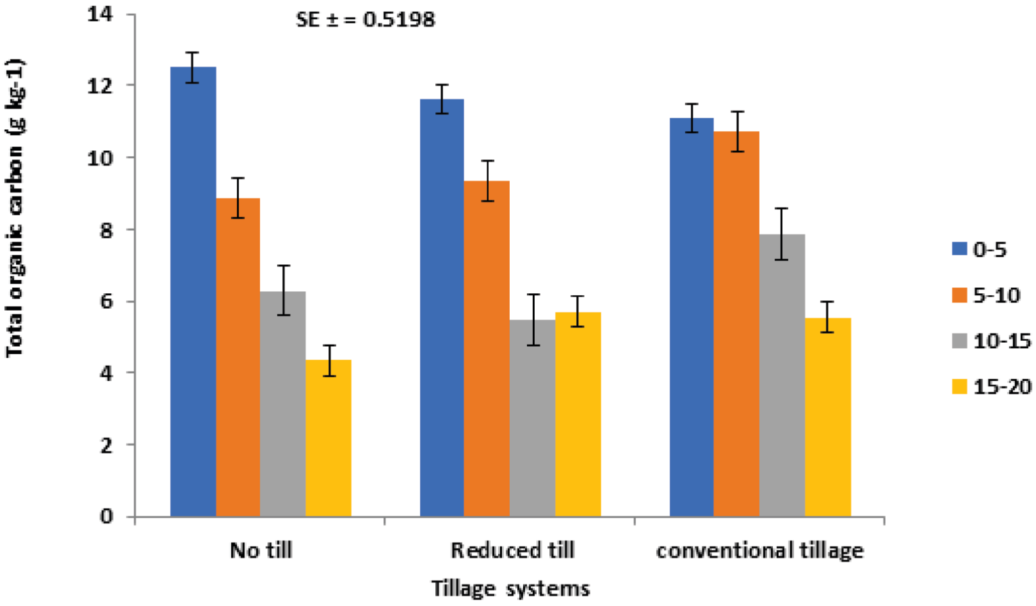

Figure 1. Interaction of tillage and depth (cm) on total organic carbon content (g kg^{-1}) during the second year cropping season.

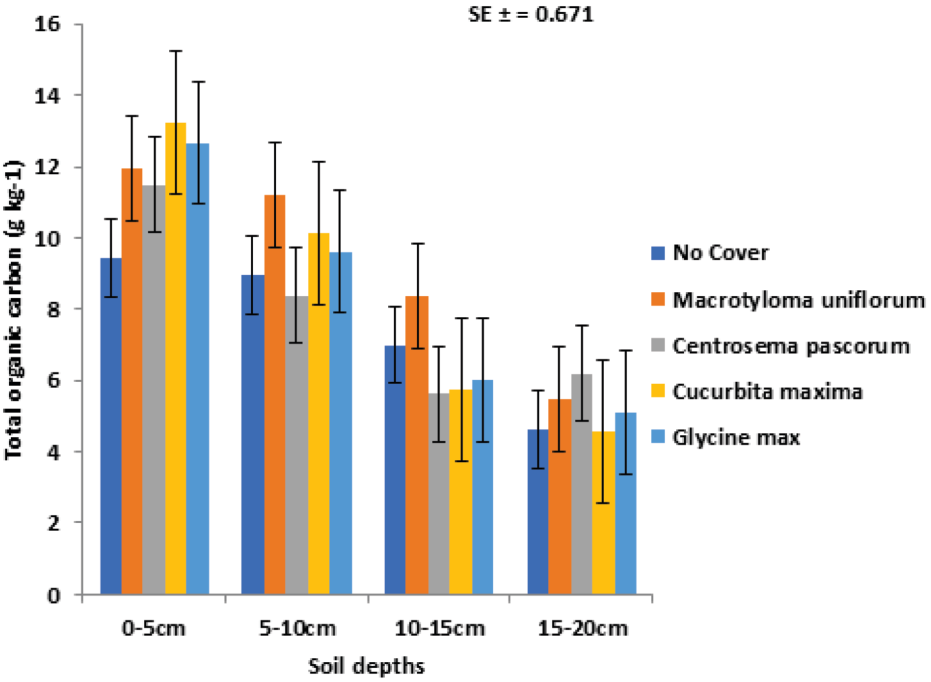

Figure 2. Interaction of cover crops and depth on total organic carbon content (gkg^{-1}) during the second year cropping season

ploughing of soil.

Effect of tillage, cover crop, and sampling depth on Fine particulate organic carbon

Effect due to the different tillage practices adopted in this study revealed that, in the first year, CT had the highest fine particulate organic carbon (FPOC) followed by RT and NT in that order (Table 3), while in subsequent years of study (second and third) and the combined across the 3 years, highest FPOC was observed on RT plots whereas least FPOC was recorded in NT plot. The effect due to cover crop was not significant for FPOC throughout the years of study. Consistently high FPOC was observed in the topsoil (0-5cm) throughout the years of study and combined. This was comparable to FPOC in 5-10 and 10-15cm in the second year and 5-10cm in the third year and the combined. The lowest FPOC was observed in the sub-surface soil (15-20cm).

Higher FPOC in CT soil in the first year could be ascribed to the quick breakdown of fresh crop residues during tillage operation thereby promoting higher FPOC due to the quick mineralization of fresh detritus. The FPOC is, however, not sustainable in soil because FPOC is the labile C fraction that is readily accessible to microbes and their residence time in soil is very short (a few weeks to a few years) (Weil and Brady, 2017). Harrowing activity in reduced tillage allowed for faster decomposition of fresh organic residues, therefore higher FPOC in RT in the 2nd and 3rd years relative to the first year. Furthermore, lower FPOC in CT soil in the other years but the first year indicates that higher oxidation of FPOC due to intensive tillage resulted in the loss of FPOC in CT practice. The lowest FPOC in NT soil relative to other tillage treatments signifies slow decomposition of FPOC when soil is not

Table 3 . Tillage, cover crop , and sampling depth effects on Fine particulate organic carbon during the first, second, and third-year cropping seasons, and the mean across the three years at Samaru, northern Nigeria .

	Fine particulate organic carbon (g kg^{-1})			
Treatments	First-year	Second year	Third year	Combined
Tillage (T)				
No-till (NT)	8.13 b	30.76c	19.45c	19.43c
Reduced (RT)	6.71 c	46.56a	26.63a	25.97a
Conventional (CT)	9.28 a	36.96b	23.12b	24.11b
SE ±	0.247	1.878	0.999	0.999
Significance	**	**	**	**
Cover Crops (C.)				
No Cover	7.71	44.48	26.09	26.00
Macrotyloma uniflorum	8.25	41.66	24.95	25.03
Centrosema pascuorum	8.41	31.95	20.18	21.12
Glycine max	8.30	37.87	23.04	23.33
Cucurbita maxima	7.51	34.52	21.01	22.33
SE ±	0.319	2.424	1.290	1.290
Significance	NS	NS	NS	NS
Depth (cm) D				
0-5	12.19 a	42.86a	27.53a	26.01a
5-10	9.27 b	39.49a	24.38ab	23.96ab
10-15	5.79 c	37.01ab	21.40bc	21.38bc
15-20	4.89 d	33.00c	18.94c	19.01c
SE ±	0.284	2.168	1.154	1.154
Significance	**	**	**	*
Interactions				
T x C	NS	NS	NS	NS
T x D	NS	**	NS	NS
D x C	**	NS	NS	NS
T x D x C	**	*	NS	NS

Means followed by the same letter (s) within a treatment group are not significantly different at 5% level of significance using Duncan Multiple Range Test. SE = standard error, * = Significant at p = 0.05, ** = Significant at p = 0.01 and NS = not significant tilled and therefore slow release of this C fraction of OM for crop use; this further confirms the pronounced effect of tillage on this C fraction. Long-term tillage with frequent ploughing accelerates the turnover rate of macroaggregates and limits the physical protection of labile SOM associated with soil aggregates (Beare *et al*., 1994; Grandy and Robertson, 2006). Similarly, reduced plant inputs due to the harvesting of agricultural products and crop residue removal as in CT practice reduces macroaggregate formation (Oades, 1984) and consequently FPOC sequestration. Since macro-aggregates are good predictors of potential SOC responses to tillage or land use change because of their importance for storing more labile SOM (Angers and Giroux, 1996; Jastrow *et al*., 1996) and their beneficial effects on structural stability that lead to enhanced infiltration of water, resistance to erosion, and ultimately C sequestration.

Second-order interaction of tillage x cover crops x depth on FPOC content during the first-year cropping season (Figure 3), revealed that the plot under RT with CP as a cover crop at 0-5 cm depth had the highest FPOC relative to all other treatment combinations. Interaction of tillage and depth on FPOC content (Figure 4) during the second-year cropping season showed that FPOC reduced with increasing soil depth, except at the CT practice where FPOC increased with soil depth.

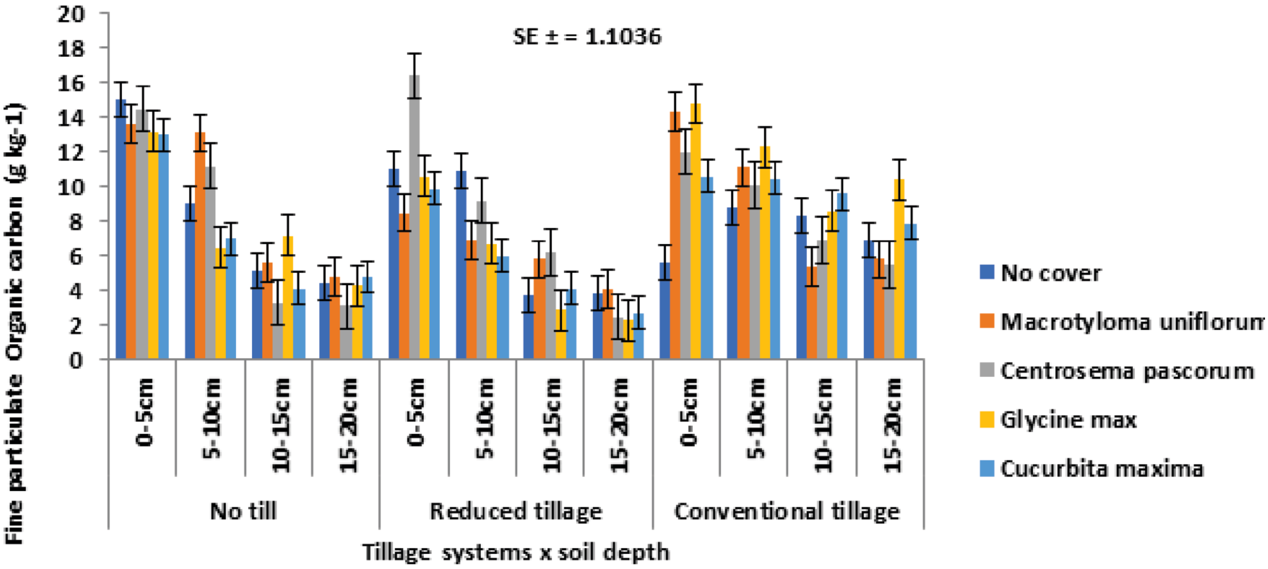

Figure 3. Second order interaction of tillage x cover crops x depth on fine particulate organic carbon content (g kg^{-1}) during the first year cropping season.

The relationship between FPOC and small macro aggregate proportion is presented in figure 5. A linear equation with an r-squared value of 0.597 described the association, indicating a dependency of almost 60% of the proportion of small macro aggregate on FPOC. The strong positive relationship between FPOC and small macroaggregate proportion suggests that FPOC influences macroaggregate stability, despite their being labile in soil with very short residence time. Fine particulate organic carbon increases with the increasing proportion of macroaggregates (Figure 5); therefore, their abundance in soil might influence macro aggregation because FPOC primarily serves as a nucleation site for micro and macroaggregate formation (Denef *et al*., 2004). Whereas, long-term C sequestration within micro and macroaggregate is mainly as mineral-associated C (silt plus clay associated C). The mineral-associated C is formed during the decomposition of FPOC and stabilized through SOM binding with clay minerals.

Effect of tillage, cover crops, and sampling depth on intra-aggregate particulate organic carbon

Effects due to soil tillage, cover crops, and sampling depth on Intra aggregate particulate organic carbon (IPOC) in the first, second, and third-year cropping seasons, and means across the years are presented in Table 4. Intra aggregate particulate organic carbon in NT and RT was significantly higher than that in the CT by 33 and 20% respectively. Variation due to cover crop had no significant effect on IPOC throughout the years of study, however, on average CP, MU, GM, and CM had 10, 3, 10, and 8 % respectively more IPOC than the NC soil. Effect due to sampling depth revealed IPOC in the topsoil (0-5cm) was consistently higher than other sampling layers throughout the years of study and the combined years. Significantly lower IPOC was observed in the 15-20cm layer in all years of study and the means across the 3 years

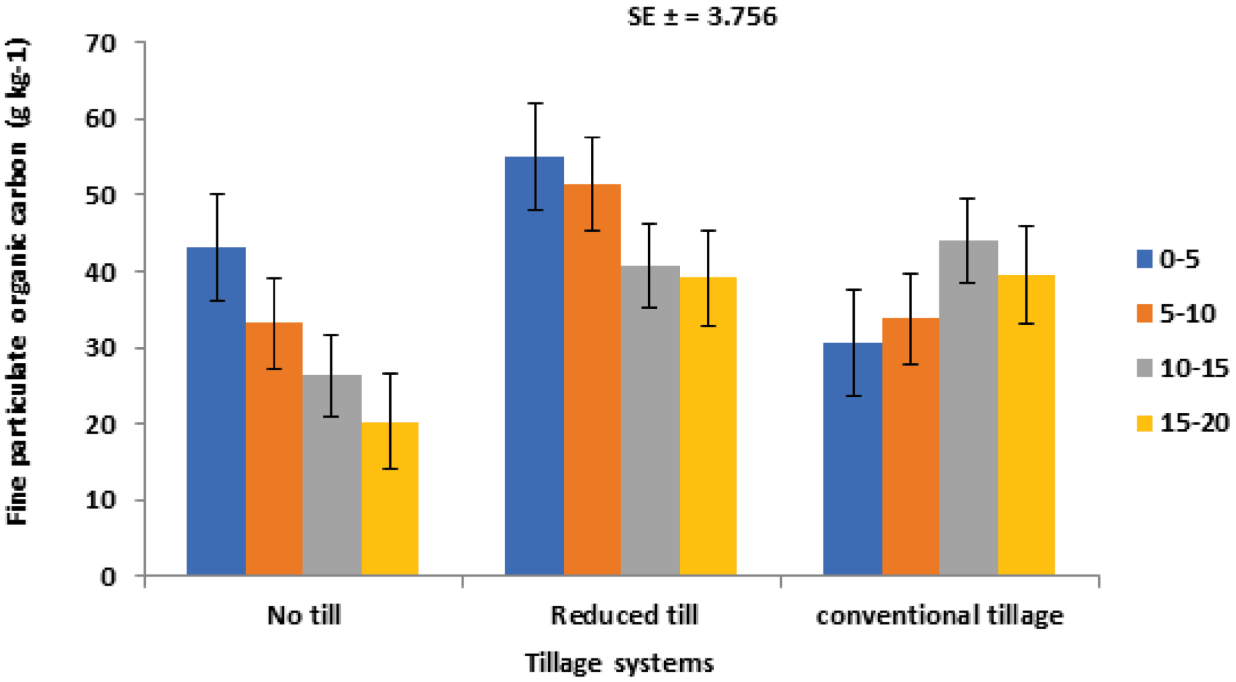

Figure 4: Interaction of tillage and depth on fine particulate organic carbon content (g kg-^{1}) during the second-year cropping season.

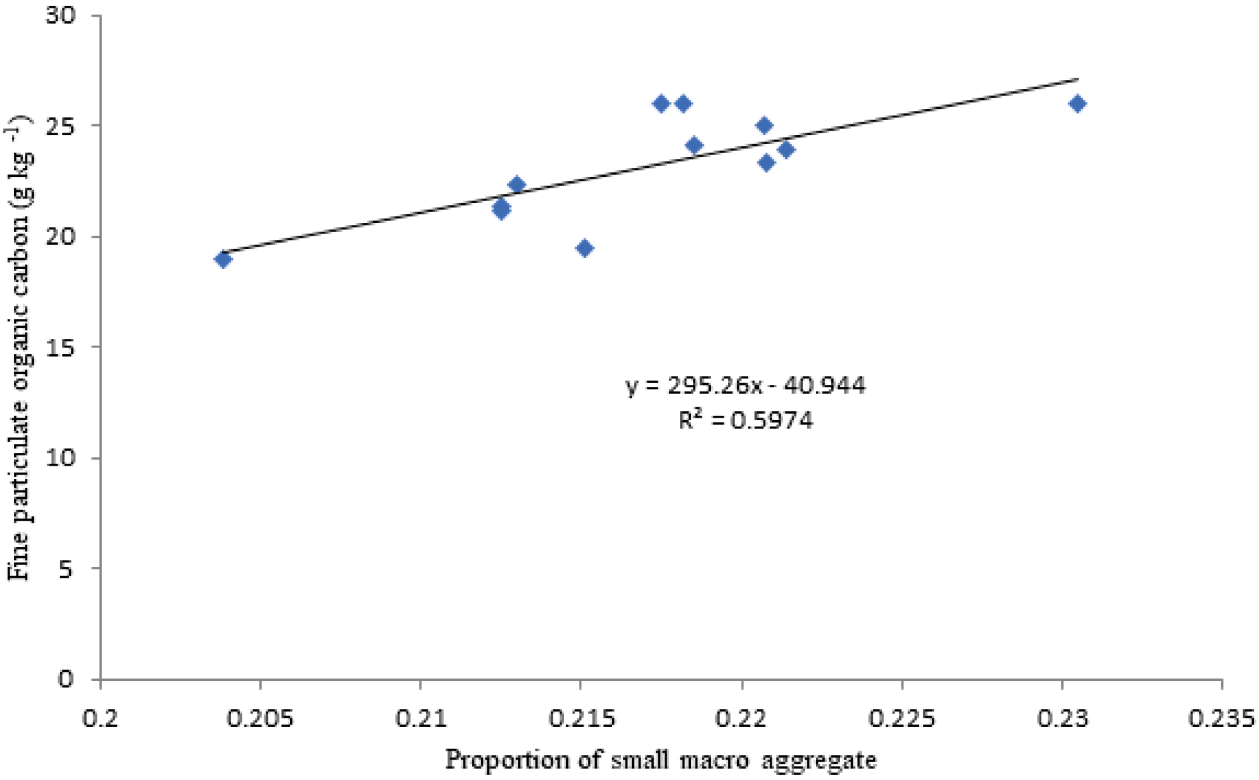

Figure 5. Relationship between macro aggregate proportion versus fine particulate organic carbon

of study except in the second year where IPOC in 5-10 cm was statistically at par with that in the 15-20 cm depth.

Intra aggregate particulate organic carbon is the C physically protected in soil microaggregates as a site for physical protection from decomposition (Weil and Brady, 2017). Higher IPOC content in NT and RT soils relative to CT could be due to little or no disturbance in these treatments which allowed for better protection of this OC fraction. The microaggregate fraction and micro-aggregates-within-macroaggregates were additionally proposed as diagnostic fractions for the SOC sequestration potential in sustainable agroecosystems (Kong *et al*., 2005). Different studies have shown that the IPOC is sensitive to management-induced changes in a wide range of soil types and under different climates (Denef *et al*., 2004; Kong *et al*., 2005; Six and Paustian, 2014). These findings suggested that microaggregates-within-macroaggregates may be indicative of changes in total SOC in response to changes in tillage and other management practices (Denef *et al*., 2004; Six *et al*., 2000).

Table 4. Tillage, cover crop, and sampling depth effects on intra aggregate particulate organic carbon (g kg^{-1}), during the first, second, and third-year cropping seasons, and the mean across the three years at Samaru, northern Nigeria.

	Intra aggregate particulate organic carbon (g kg^{-1})			
Treatments	First-year	Second year	Third year	Combined
Tillage (T)				
No-till (NT)	10.39a	11.33a	11.36a	11.06a
Reduced (RT)	10.40a	10.32b	9.65b	9.97b
Conventional (CT)	7.98b	8.68c	8.24c	8.29c
SE ±	0.2941	0.2908	0.2932	0.2929
Significance	**	**	**	**
Cover Crops (C.)				
No Cover	9.17	9.90	9.54	9.51
Macrotyloma uniflorum	9.34	10.28	9.81	9.79
Centrosema pascorum	10.44	10.45	10.45	10.50
Glycine max	9.35	11.43	10.39	10.45
Cucurbita maxima	9.64	10.79	10.51	10.31
SE ±	0.3796	0.5988	0.3786	0.3782
Significance	NS	NS	NS	NS
Depth (cm) D				
0-5	13.61 a	13.14a	13.37a	13.20a
5-10	10.38 b	9.81bc	10.09b	10.06b
10-15	8.37 c	10.69b	9.53b	9.08b
15-20	6.00 d	8.65c	7.33c	7.26c
SE ±	0.39396	0.5356	0.3386	0.3385
Significance	**	**	**	**
Interactions				
T x C	NS	NS	NS	NS
T x D	NS	NS	NS	NS
D x C	NS	NS	NS	NS
T x D x C	NS	NS	NS	NS

Means followed by the same letter (s) within a treatment group are not significantly different at 5% level of significance using Duncan Multiple Range Test. SE = standard error, * = Significant at p = 0.05, ** = Significant at p = 0.01 and NS = not significant

The lowest IPOC in the CT system confirms the pronounced effect of tillage on this fraction of C; as tillage disrupts soil aggregate and therefore allows loss of C stored in this aggregate fraction by exposing SOM physically protected in soil aggregates to degradation. Since CT results in the breakdown of macroaggregates and the release of aggregate protected SOC.

Effect of tillage, cover crops, and depth of sampling on silt plus clay-associated carbon

Table 5 shows the effect of tillage, cover crops, and depth of sampling on silt plus clay-associated carbon during the 3 years of study and combined. In the first year, significantly higher silt + clay carbon was recorded on the

Table 5. Tillage, cover crop, and sampling depth effects on Silt plus clay-associated carbon, during the first, second-, and third-year cropping seasons, and the mean across the three years at Samaru, northern Nigeria.

	Silt plus clay-associated carbon (g kg^{-1})			
Treatments	First-year	Second year	Third year	Combined
Tillage (T)				
No till (NT)	11.41 b	12.01a	12.11a	11.34a
Reduced (RT)	9.45 c	9.21b	9.53b	9.38b
Conventional (CT)	12.53 a	7.68b	9.33b	9.97b
SE ±	0.249	0.2675	0.2076	0.2075
Significance	**	**	*	*
Cover Crops (C)				
No Cover	10.62 c	6.93b	8.77b	9.00b
Macrotyloma uniflorum	11.64 ab	8.06a	9.85a	9.98a
Centrosema pascorum	11.99 a	8.32a	10.15a	10.11a
Glycine max	10.62 c	8.86a	9.74a	9.89a
Cucurbita maxima	10.79 bc	8.72a	9.75a	9.77a
SE ±	0.3225	0.3453	0.2679	0.2680
Significance	**	**	**	**
Depth (cm) D				
0-5	14.49 a	11.92a	13.21a	12.98a
5-10	12.75 b	8.42b	10.58b	10.59b
10-15	9.60 c	6.49c	8.05c	8.05c
15-20	7.69 d	5.88c	6.78d	6.80d
SE ±	0.2885	0.3089	0.2397	0.2400
Significance	**	**	**	**
Interactions				
T x C	**	**	NS	NS
T x D	NS	NS	NS	NS
D x C	**	**	NS	NS
T x D x C	NS	NS	NS	NS

Means followed by the same letter (s) within a treatment group are not significantly different at a 5% level of significance using Duncan Multiple Range Test. SE = standard error, * = Significant at $p = 0.05$, ** = Significant at $p = 0.01$ and NS = not significant

CT plots while in other years and combined, the NT plot surpassed RT and CT concerning this C.

Conventional tillage increased silt plus clay C in the first year, albeit not sustainable, as this C pool was lost in the CT practices in subsequent years while the NT enhanced accumulation of silt plus clay C fraction. The return of all crop residues to soil and non-soil disturbance in the NT practices resulted in higher chemically protected C due to better stable soil aggregates in NT, induced by high OM content thus rendering good stabilization for this C fraction. Silt + clay C fraction is a useful indicator for the SOC storage capacity in many soils (Lawal *et al*., 2012). Clay minerals can stabilize SOC against microbial attack through the absorption of organic molecules (Ladd *et al.*, 1996) by binding organic matter. Clay particles help form and stabilize soil aggregates, imposing a physical barrier between decomposer microflora and organic substrates, and limiting water and oxygen available for decomposition (Dominy *et* al., 2002)

This silt + clay fraction of C is also known as the chemically protected SOM associated with micro-aggregates (Weil and Brady, 2017); it is little affected by agronomic practices, as micro aggregates are less disrupted in the course of cultivation. Furthermore, this pool of SOM is shielded from microbial decomposition by being chemically protected in silt and clay-size particles, through their adsorption to clay minerals (Ladd *et al.,* 1985) and by isolation in micropores (Adu and Oades, 1978; Foster, 1981). In addition, chemically protected SOM can resist decomposition due to the stability of fulvic and humic acid contained in it (Solomon *et al.*, 2002).

Analysis of data on the effect of cover crops showed that NC consistently had lower silt + clay-associated C throughout the years of study and combined. However, in the 1st year, the silt + clay C for the NC plots was comparable with that on GM and CM-covered plots. Effect due to sampling depth showed that topsoil (0-5cm) consistently had higher silt + clay C relative to other sampling depths, while 15-20 cm had the least throughout the years of study and combined across the three years. The interaction of tillage x cover crop and cover crop x depth was significant in the 1st and 2nd years of study. All other interactions were not significant.

Interaction of Tillage and Cover crops on Silt plus clay-associated C during the 2nd year of cropping season showed that in all the tillage systems implored, plots with cover crops enhanced Silt plus clay-associated C relative to plots with no cover crop (Figure 6). Interaction of cover crops and depth on silt plus clay-associated C during the 2nd year of cropping season (Figure 7) revealed that all cover crops used in this study significantly enhanced silt plus clay-associated C in 0-5 and 5-10 cm soil depths relative to soil with no cover crop. Whereas, no significant difference was observed in the silt plus clay associated C in soil with cover crops relative to those with no cover crops in 10-15 and 15-20 cm depths.

The higher silt plus clay-associated C in soils under cover crops relative to the bare is an indication that a greater amount of living roots in soils with cover crops could have influenced the production of more root exudates and consequently C content. In addition, the generation of more crop residues in the cover crop plots will consequently improve SOM content. Higher silt plus clay-associated C at the surface soil is also attributable to higher crop residue deposition at the soil surface relative to subsurface soil.

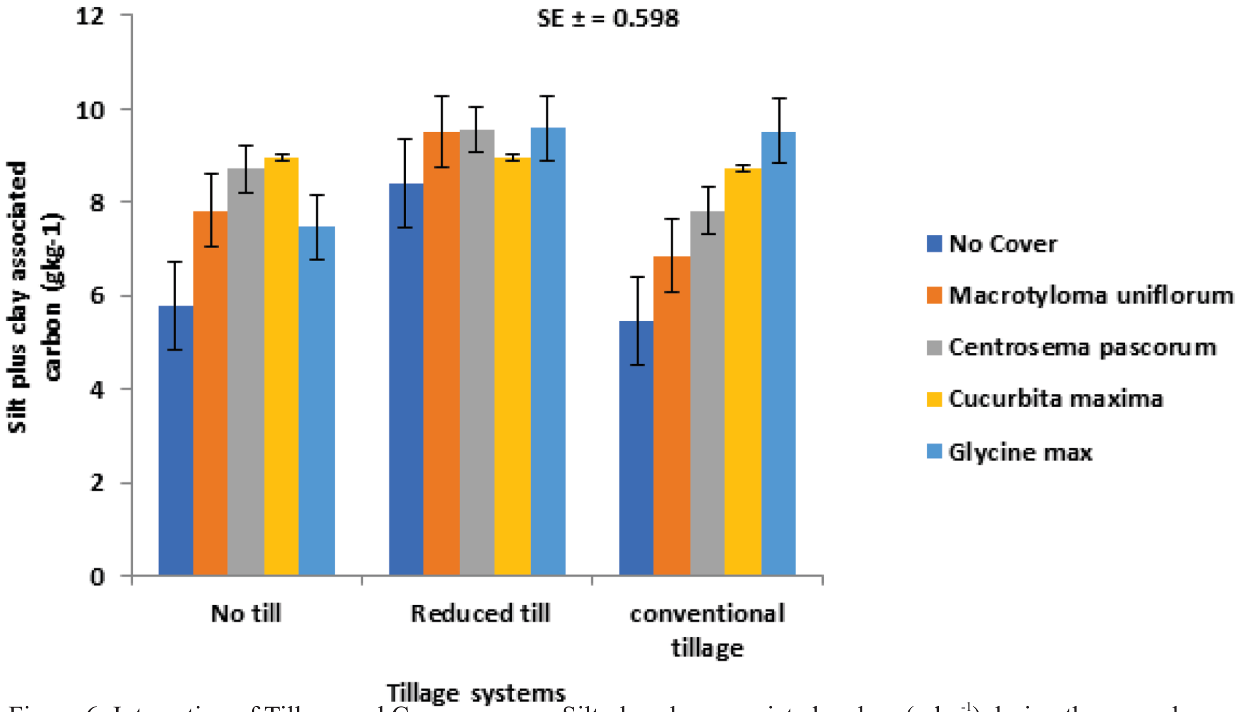

Figure 6: Interaction of Tillage and Cover crops on Silt plus clay associated carbon (g kg^{-1}) during the second year cropping season

Effect of tillage, cover crops, and sampling on Dissolved organic carbon concentrations

Table 6 shows the effect of tillage, cover crop, and soil depth on Dissolved Organic Carbon (DOC) during the three years of cropping seasons and the means across the years. No-till treatment consistently had significantly higher DOC than the other tillage practices evaluated in all years of study and the means across the three years. Dissolve organic carbon is that C in soil solution readily available for plant uptake. Higher DOC in soils of NT may indicate slow release of soil nutrients in this practice due to physical protection for C in stable soil aggregates in less disturbed soil, thereby curtailing its losses. Tillage enhances the quick mineralization of OM, due to the abrasion effect of tillage implements on crop residue and soil macroaggregate thereby increasing the surface area of plant residues for microbial attack. Furthermore, some of the C stored in macroaggregates may be lost to the atmosphere when soil is tilled and oxidation takes place, while those that are water-soluble may be leached out of the root zone of cultivated crops therefore, this may likely explain lower DOC in CT and RT relative to NT practice. This is following earlier findings of Carrillo-Gonzalez *et al*. (2013); Dou *et al*. (2008), and Six *et al*. (2000) where intensive tillage broke down soil macroaggregates and exposed microaggregate protected DOC to microbial decomposition

The effect due to cover crop was not significant, except in

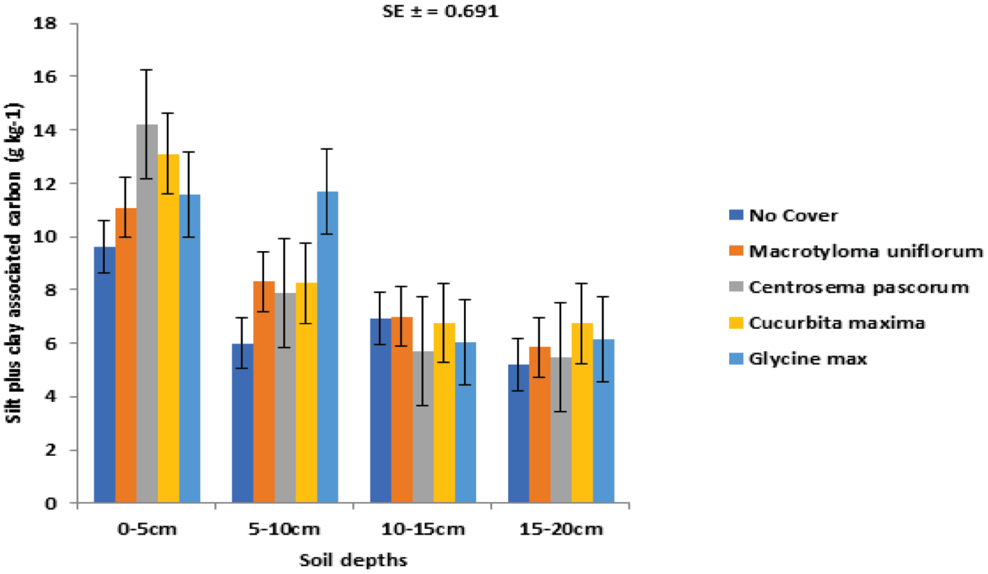

Figure 7. Interaction of cover crops and depth on silt plus clay associated carbon (g kg^{-1}) during the second year cropping season

Table 6. Tillage, cover crop, and sampling depth effects on dissolved organic carbon concentrations (mg kg^{-1}), during the first, second, and third-year cropping seasons, and the mean across the three years at Samaru, northern Nigeria

Treatments	First-year	Second year	Third year	Combined
Tillage (T)		**Dissolved Organic Carbon (mg kg^{-1})**		
No-till (NT)	390.72 a	196.75	206.98a	293.73a
Reduced (RT)	178.68 b	165.69	181.76b	172.19b
Conventional (CT)	180.34 b	153.52	127.43c	166.93c
SE ±	21.230	19.082	1.830	11.527
Significance	**	NS	*	**
Cover Crops (C.)				
No Cover	236.5	173.3	113.95e	199.88
Macrotyloma uniflorum	276.1	164.82	183.03c	207.89
Centrosema pascorum	215.84	217.35	228.42a	220.54
Glycine max	268.68	161.08	189.83b	181.23
Cucurbita maxima	252.45	143.38	144.98d	180.26
SE ±	27.408	24.634	2.362	14.881
Significance	NS	NS	*	NS
Depth (cm) D				
0-5	268.18	169.85	205.12a	219.01
5-10	248.58	167.59	209.18a	208.08
10-15	237.16	175.22	129.29c	206.19
15-20	245.74	175.3	144.64b	210.52
SE ±	24.514	22.041	2.112	13.310
Significance	NS	NS	*	NS
Interactions				
T x C	NS	NS	NS	NS
T x D	NS	NS	NS	NS
D x C	NS	NS	NS	NS
T x D x C	**	NS	NS	NS

Means followed by the same letter (s) within a treatment group are not significantly different at 5% level of significance using Duncan Multiple Range Test. SE = standard error , * = Significant at p = 0.05 , ** = Significant at p = 0.01 and NS = not significant

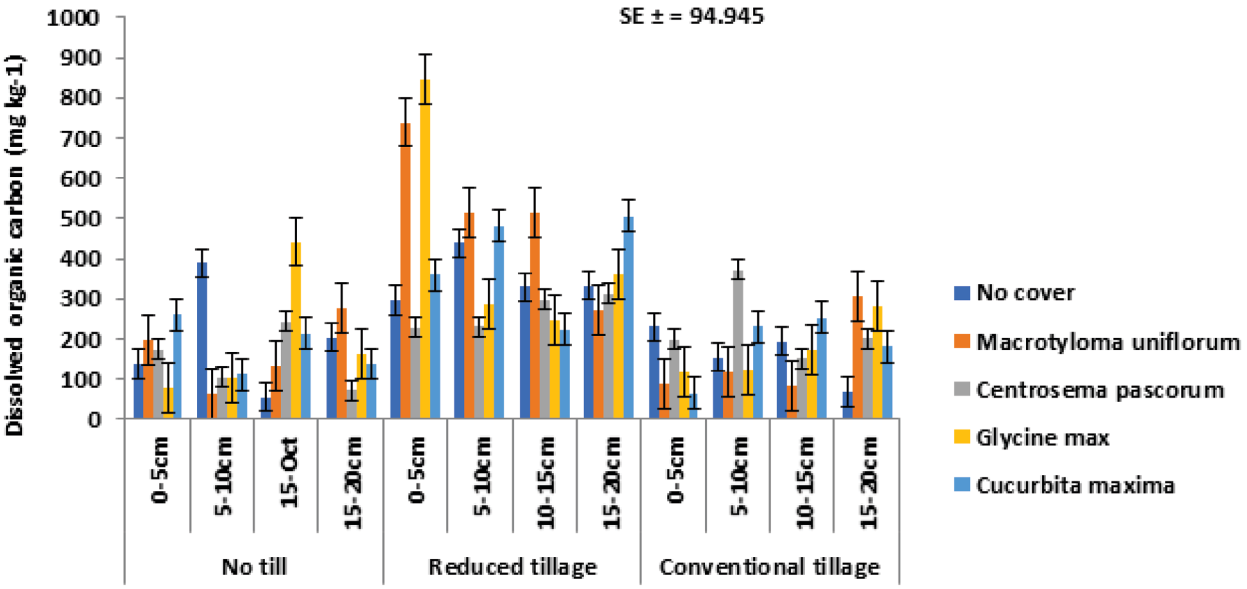

Figure 8. Second order interaction of tillage x cover crops x depth on dissolved organic carbon (mg kg^{-1}) during the first year cropping season

the third year where the use of *Centrosema pascuorum* cover crop resulted in significantly higher (50 % more) DOC than no cover crop plots (NC). Similarly, all other cover crops tested had significantly higher DOC than NC soil, their significance was in the order of *Centrosema pascuorum* > *Glycine max* > *Macrotyloma uniflorum* > *Cucurbita maxima* > no cover crop. Though there was no significant difference in DOC in the first two years of study concerning cover crops and depth. There was a decrease in DOC concentration in the second year relative to the first except for *Centrosema pascuorum.* The ability of *Centrosema pascuorum* to induce higher DOC in the third year, which was higher than what was obtained in the first and second year, may be an indication of slower decomposition of *Centrosema pascuorum* biomass as well as the higher return of SOM relative to bare soil and other cover crops evaluated. Higher biomass production in cover-cropped soil relative to the bare soil with no cover may be attributed to higher DOC in the soils with the cover cop. Nonetheless, the higher biomass production by *Centrosema pascuorum*, than all other cover crops evaluated, might have imparted its high OM content in soil; consequently, the highest DOC content in soil under *Centrosema pascuorum*. Wright *et al*., (2005) reported that compost mineralization increased SOM and contributed to DOC dynamics in soil, and improved the growth of Bermuda grass [*Cynodon dactylon* (L.) Pers.]; with the highest rate of 160 Mg compost/ha contributing 179% greater DOC in 29 months after application than before application.

The top 0-5 and 5-10 cm soil depths had significantly higher DOC than the lower depths (15-20 and 10-15 cm) in that order. Only the 2nd order interaction of tillage x cover crop x depth was significant in the first year. Second-order interaction of tillage x cover crops x depth on DOC during the first-year cropping season reveals that soils under MU and GM at 0-5 cm depth in RT practice had significantly higher DOC relative to all other treatment combinations (Figure 8).

Higher DOC at the topsoil (0-5 and 5-10 cm) in the third year portrays a high concentration of this nutrient at these depths. The soil surface is the immediate recipient of plant residues, especially in the conservation tillage practice where there is minimal/reduced soil disturbance. These residues are therefore higher on the soil surface consequently generating higher OM which may release DOC better. In addition, since the distribution of plant roots is most concentrated in these soil depths there may be a higher release of root exudates and consequently higher DOC.

CONCLUSION

Conservation agriculture has great potential for climate change mitigation. The combination of conservation tillage (NT and RT) practices and the use of cover crops enhanced the sequestration of different pools of SOC and DOC relative to the conventional tillage practice without a cover crop. *Centrosema pascuorum* could be selected as the best cover crop among the evaluated in this study because it was consistently a better cover crop among others in sequestering all the different pools of SOC and releasing DOC. It is therefore vital to discourage crop residue removal from farmlands as practiced by local farmers in northern Nigeria. but encourage the adoption of conservation tillage and the use of cover crops to attain healthier soils.

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