Mulch application as the overarching factor explaining increase in soil organic carbon stocks under conservation agriculture in two 8-year-old experiments in Zimbabwe

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Abstract

Conservation agriculture (CA), combining reduced or no tillage, permanent soil cover and improved rotations, is often promoted as a climate-smart practice. However, our understanding about the impact of CA and its respective three principles on top and sub-soil organic carbon (SOC) stocks in low input cropping systems of sub-Saharan Africa is rather limited. The study was conducted at two long-term experimental sites established in 2013 in Zimbabwe. The soil types were abruptic Lixisols at Domboshava Training Centre (DTC) and xanthic Ferralsol at the University of Zimbabwe farm (UZF). Six treatments, replicated four times were investigated: conventional tillage (CT), conventional tillage with rotation (CTR), NT, no-tillage with mulch (NTM), no-tillage with rotation (NTR), no-tillage with mulch and rotation (NTMR). Maize (*Zea mays* L.) was the main crop and treatments with rotation included cowpea (*Vigna unguiculata* L. Walp.). SOC concentration and bulk density were determined for samples taken from the 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-50, 50-75 and 75-100 cm depths. Cumulative organic inputs to the soil were also estimated in all treatments. SOC stocks at equivalent soil mass were significantly ($p < 0.05$) higher under NTM, NTR and NTMR compared to NT and CT in top 5 and 10 cm layers at UZF, while SOC stocks were only significantly higher under NTM and NTMR compared to NT and CT in top 5 cm at DTC. NT alone had a slightly negative impact on top SOC stocks. Cumulative SOC stocks were not significantly different between treatments when considering the whole 100 cm soil profile. Our results showed the overarching role of crop residue mulching in CA cropping systems in enhancing SOC stocks but that this effect was limited to the topsoil. The highest cumulative organic carbon inputs to the soil were observed in NTM treatments at the two sites, and this could probably explain the positive effect on SOC stocks. Our results also showed that the combination of at least two CA principles including mulch is required to increase SOC stocks in these low nitrogen input cropping systems.

Key words: organic inputs, climate change mitigation, climate-smart agriculture, deep soil organic carbon, sustainable intensification

1. Introduction

Soil organic carbon (SOC) is an important determinant of soil fertility, productivity and sustainability, and is a useful indicator of soil quality in tropical agricultural systems where nutrient poor and highly weathered soils are managed with little external inputs (Lal, 1997; Feller and Beare, 1997; Chivenge et al., 2007). Therefore, rebuilding depleted SOC stocks in such soils holds potential to contribute to climate change mitigation (Bossio et al., 2020; Minasny et al., 2017; Swanepoel et al., 2016) through sustainable management of agricultural soils (Paustian et al., 2016; Dignac et al., 2017).

Conservation agriculture (CA), based on minimum soil disturbance, crop residue retention and crop rotation, has been known to improve surface SOC, with beneficial effects on soil functioning such as improved water infiltration (Thierfelder and Wall, 2012, 2009) and better aggregate stability (Six et al., 1999; Thierfelder and Wall, 2012). The potential of CA to increase SOC stocks and thereby mitigate climate change has, however, been much debated (Corbeels et al., 2020a) but the general understanding is that, this potential is relatively low (Du et al., 2017; Powlson et al., 2014, 2016; Cheesman et al., 2016; Corbeels et al., 2020a). In fact, soil C storage has often been over-estimated for CA due to shallow soil sampling. Compared to conventional tillage systems, no-tillage redistributes SOC in the soil profile, with higher concentrations in the topsoil but potentially lower concentrations below, which can result in no differences in whole profile SOC stocks between no-tillage and conventional tillage (Angers and Eriksen-Hamel, 2008). However, this lack of significant differences in many studies assessing whole profile SOC stocks suffer from not enough statistical power to accurately assess the potential significant SOC changes (Kravchenko and Robertson, 2011).

CA can potentially build SOC in deeper soil layers from e.g. the use of cover crops with more extended root systems (Kell, 2011; Thorup-Kristensen et al., 2020; Yang et al., 2023). However, proper soil sampling strategies, to account for both topsoil and subsoil (> 30 cm depth) SOC stocks must, therefore, be prioritized. Soil sampling has often been limited to the top soil plough layer (0-30 cm) in the past two decades (Dube et al., 2012; Powlson et al., 2016; Patra et al., 2019; Yost and Hartemink, 2020), where SOC concentrations, root densities (Chikowo et al., 2003) and microbial activities (Mtambanengwe et al., 2004) are generally largest (Rumpel et al., 2012) and which is the minimum default soil depth recommended by the Intergovernmental Panel for Climate Change (IPCC, 2019). In a meta-analysis of SOC stocks in the top 1 m of soils, Balesdent et al. (2018) found that soils below 0.3 m contain on average 47 % of total SOC stock in the 1 m soil depth and accounts for 19 % of the SOC that has been recently incorporated. Therefore, focusing on topsoil only, could underestimate the potential of agricultural management practices to store SOC (Cardinael et al., 2015). In turn, this can give wrong conclusions on the climate change mitigation potential of agricultural management practices.

There have been many studies on the effects of CA on crop productivity and soil health benefits (Corbeels, Naudin, et al., 2020; Kimaro et al., 2016; Mhlanga et al., 2022a; Swanepoel et al., 2018; Thierfelder et al., 2015, 2017; Thierfelder & Mhlanga, 2022), and other studies have fuelled the debate on CA practicality and adoption in SSA (Giller et al., 2009, 2015; Kassam et al., 2019). However, the effects of CA on SOC dynamics has not been widely investigated in SSA. Thierfelder et al., (2017) have alluded to the fact that, data on climate change mitigation potential of CA in southern Africa is scanty hence the need for more research to better quantify the mitigation effects of CA as a climate-smart technology. It has also been observed that depending on the socio-economic and biophysical conditions, farmers may find it easier to adopt certain CA principles and/or their different combinations (Mbanyele et al., 2021; Baudron et al., 2012), although this also opened up new debates (Thierfelder et al., 2018). Therefore, in this study, the focus was on the individual versus combined effects of CA principles (no-tillage, crop residue retention, crop rotation) on SOC stocks.

As changes in SOC stocks take time to be detected, long-term experiments are crucial, but are rare, especially in Africa (Bationo et al., 2013; Cardinael et al., 2022; Powlson et al., 2016; Thierfelder and Mhlanga, 2022). This study was conducted on two long-term experiments established in 2013 in Zimbabwe. We hypothesized that the full combination of CA components would be associated with higher increases of SOC stocks than adoption of only one component, and that this increase would mainly be due to increased C inputs to the soil and minimum soil disturbance. However, C inputs due to crop rotation might be indirect and we therefore hypothesise that the productivity of the crops is enhanced due to reduction on biotic pressure (pests and diseases), and therefore C inputs to the soil might be increased too. Secondly, cereals in a cereals-legumes rotations tend to benefit from added soil nitrogen through biological nitrogen fixation by the preceding legume crop hence more productivity. The third hypothesis is that crop diversification enhances soil biological processes via different root systems, and enhanced microfauna diversity and/or abundance (e.g. mycorrhizae) that could improve aggregate stability and therefore physical protection of soil carbon. Lastly, high quality residues (from the legume crop) have been shown to be preferentially stabilized in the soil due to a higher carbon use efficiency of soil microbes (Cotrufo et al., 2013; Kopittke et al., 2018).

2. Materials and methods

2.1 Study sites

The study was conducted at two long-term experimental sites established in November 2013 by CIMMYT. The site at the University of Zimbabwe Farm (UZF) is located about 12 km north of Harare city centre (31° 00′ 48″ E; 17° 42′ 24″ S), while the site at the Domboshava Training Centre (DTC) is located about 30 km north-east of Harare (31° 07′ 33″ E; 17° 35′ 17″ S). UZF soils are dolerite-derived xanthic *Ferralsols* (FAO classification) and are medium-textured sandy clay loams (34 % clay) in the top 20 cm with a subsoil (20-40 cm) of slightly higher clay content (38 %). DTC soils are granite-derived abruptic *Lixisols* (FAO classification) and are light-textured sandy loams (15 % clay) in the 0-20 cm layer, overlying abruptly a heavier-textured subsoil (20-40 cm) of 30 % clay (Figure 1).

The two study sites have a sub-tropical climate with cool, dry winters and hot, wet summers with mean annual minimum and maximum temperatures of 12°C and 25°C, respectively (Mapanda et al., 2010). The rainy season starts in November and tails off in March with a mean annual rainfall of 826 and 814 mm at UZF and DTC, respectively (Mhlanga, et al., 2022b). Cumulative seasonal rainfall in 2019/20 (474 mm) was almost half of rainfall received in the 2020/21 season (932 mm) at DTC (Shumba et al., 2023b). At UZF, cumulative seasonal rainfall was 551 mm and 637 mm in the 2019/20 and 2020/21 cropping seasons. On average, minimum and maximum temperatures were 16.9 and 28.1 °C in 2019/20 and 15.5 and 27.2 °C in 2020/21 at DTC and 15.5 and 28.6 °C in 2019/20 and 15.3 and 27.5 °C in 2020/21 cropping season at UZF.

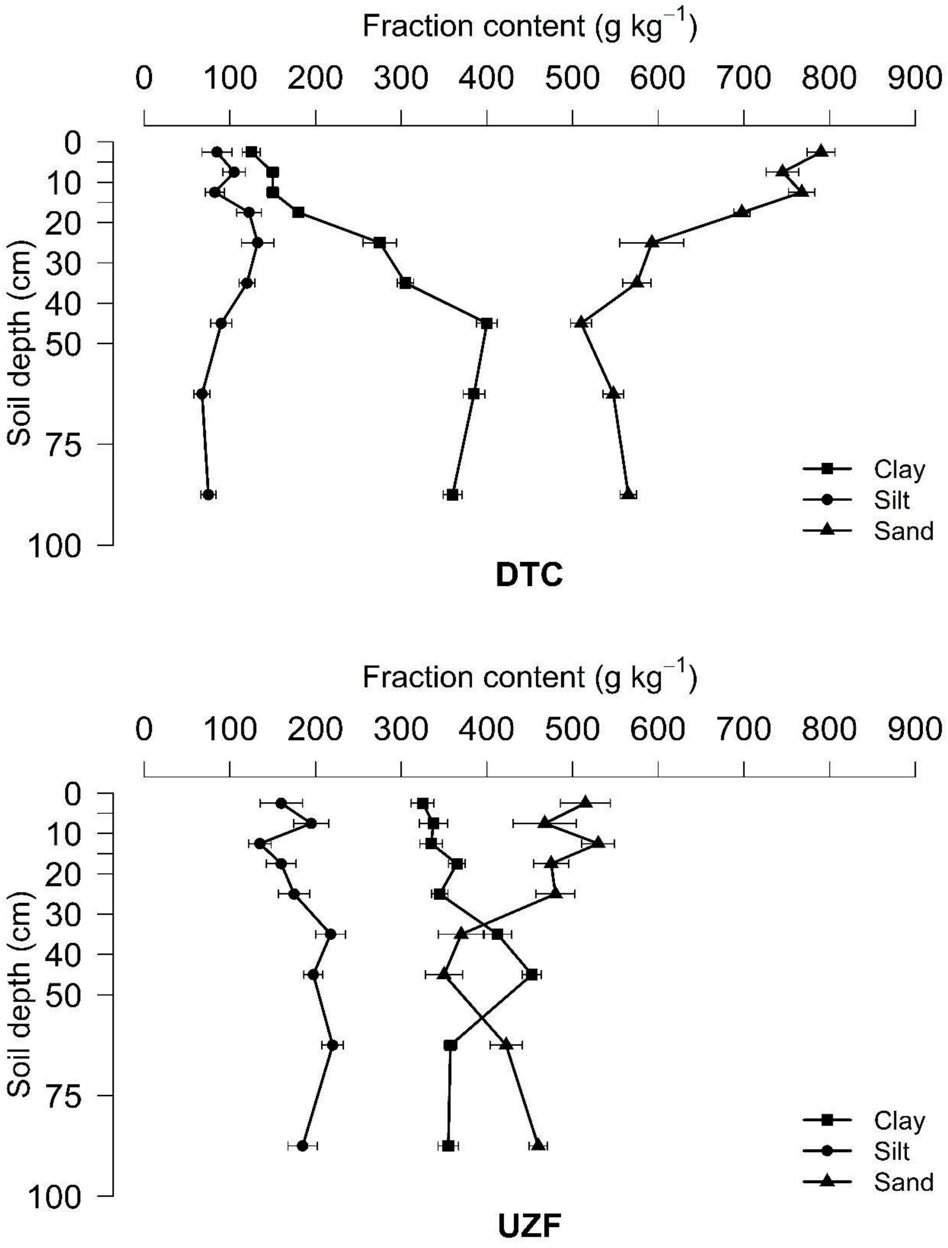

Figure 1. Soil texture to 1 m soil depth at the DTC (top) and UZF (bottom) sites in Zimbabwe. Error bars represent standard errors (N = 4).

2.2 Experimental treatments and crop management

Two identical experiments were set up at the study sites and treatments were maintained every season since November 2013. The experiments were set up in a randomised complete block design (RCBD) with eight treatments replicated in four blocks. However, in this study we investigated only six of these treatments. All crop residues were removed soon after harvesting in all treatments, stored and then applied prior to planting in treatments with mulch. The six treatments in our study were:

1. Conventional tillage (CT) – land preparation was done through digging with a hand hoe and maize (*Zea mays* L.) was sown as a sole crop in rip lines that were created afterwards using an animal-drawn Magoye ripper (a traditional plough with the mouldboard replaced with a ripper tine) at DTC, and in planting basins (approximately 10 cm diameter and 10 cm depth) created using a hand hoe at UZF.
2. Conventional tillage with rotation (CTR) – land preparation was done as in the CT treatment and maize was rotated with cowpea (*Vigna unguiculata* L.).
3. No-tillage (NT) – sole maize was sown in rip lines created using an animal-drawn Magoye ripper (no further soil disturbance was done) at DTC, and in planting basins (approximately 15 cm diameter and 15 cm depth) created using a hand hoe at UZF.
4. No-tillage with mulch (NTM) – maize was sown as in the NT treatment and maize residues from the previous season were applied on the soil surface between maize rows at planting at a rate of 2.5 t DM ha^{-1}.
5. No-tillage with rotation (NTR) – maize was sown in rip lines and rotated with cowpea.
6. No-tillage with mulch and rotation (NTMR) – maize was sown in rip lines and rotated with cowpea and maize residues were applied on the soil surface between maize rows at planting at a rate of 2.5 t DM ha^{-1}.

Crop residues were removed every year after harvest and weighed in again to maintain the exact 2.5 t ha^{-1} residue weight year after year. There was a total of 24 plots at each site which were 6 m wide and 12 m long (72 m^2). Treatments with rotation (CTR, NTR, NTMR) were split into 6 m wide and 6 m long (36 m^2) subplots where maize and cowpea were grown interchangeably every season (maize was sown on one side of the plot while cowpea on the other side).

The inter-row spacing was 90 cm and 45 cm for maize and cowpea, respectively, and the in-row spacing was 25 cm for both crops which translated to 44,444 and 88,888 plants ha^{-1}, respectively. Three seeds were planted per planting station and thinned to one after emergence. Basal dressing of nitrogen (N), phosphorus (P) and potassium (K) was applied within 5 cm of the seeds in the form of compound fertilizer for both maize and cowpea at 11.6 kg N ha^{-1}, 10.6 kg P ha^{-1} and 9.6 kg K ha^{-1}, respectively. Nitrogen top dressing to maize only, was applied at 4 and 8 weeks after emergence (WAE) in two equal splits of 23.1 kg N ha^{-1} each, as ammonium nitrate when soil moisture was adequate. However, in the 2019/20 cropping season at both sites and in the 2020/21 cropping season at UZF, the first N top dressing was delayed by an average of 4.5 and 2.0 weeks, respectively, due to mid-season dry spells. Ammonium nitrate was side dressed within 5 cm of the maize stems. Glyphosate [N-(phosphono-methyl) glycine], a pre-emergent non-selective herbicide was applied at 1.025 L active ingredient ha^{-1} soon after sowing to control weeds. This was followed by manual hoe weeding whenever weeds reached a maximum of 10 cm height or 10 cm in diameter for stoloniferous weeds to achieve a weed clean field. More details about the experiment can be found in Shumba et al., (2023b) and Mhlanga et al., (2022a).

2.3 Soil sampling for bulk density determination and soil organic carbon analysis

Soil sampling was done in May 2021 at both sites. For each treatment and replicate, two sampling points in the maize rows and two sampling points in the middle of the inter-rows were randomly selected. The two samples from the rows were pooled into one sample per depth, similarly to the two samples taken in the inter-rows. The following nine depth increments were considered for both SOC and bulk density (BD) measurements: 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-50, 50-75 and 75-100 cm. Undisturbed soil samples using a metal cylinder (5 cm diameter and 5 cm height) were taken from the following depth ranges 0-5, 5-10, 10-15, 15-20 and 20-30 cm for both SOC and BD measurements. A motorized, hand-held soil corer, with an inside diameter of 10 cm, was used to take samples for the 30-40, 40-50, 50-75 and 75-100 cm depths for SOC analysis from the same positions where undisturbed samples were taken. As no significant differences in BD were found below 20 cm between the different treatments at the two sites (see results section) and to avoid too much destruction of the experimental plots, two soil pits were opened at the edges of the experimental plots (also cropped with maize since 2013) at each site to take BD samples for the 30-40, 40-50, 50-75 and 75-100 cm depths. As a result, BD below 30 cm depth was assumed the same across the treatments.

Soil samples were crumbled and fresh weight was determined using a field scale. Soil moisture was determined on a sub-sample by drying it in an oven at 105°C for 48 hours. All samples were then air-dried and sieved through a 2 mm sieve to determine the mass proportion of coarse soil (> 2 mm) as a fraction of the whole sample. Bulk density (BD) was determined by dividing the dry mass of soil by the volume of the cylinder. Subsamples from the ≤ 2 mm soil fraction were grinded to < 200 µm for SOC analysis. SOC was analysed in the ISO9001:2015-certified IRD LAMA's laboratory in Dakar by dry combustion on 100-mg aliquots of soil (ground to < 200 µm) using a CHN elemental analyser (Thermo Finnigan Flash EA1112, Milan, Italy).

2.4 Soil organic carbon stocks calculation

The mass proportion of the coarse fraction (> 2 mm) was removed to calculate SOC stocks. The equivalent soil mass (ESM) approach was used to determine SOC stocks to avoid systematic bias in SOC calculation when using the fixed depth method (Ellert and Bettany, 1995; Wendt and Hauser, 2013; von Haden et al., 2020). We defined reference soil mass profiles for each site, based on the lowest cumulative soil mass obtained for each replicate. For these references, cumulative soil mass layers were 0-650, 650-1340, 1340-2060, 2060-4160, 4160-5590, 5590-7040, 7040-10550, 10550-13770 Mg soil ha^{-1} at DTC and 0-460, 460-870, 870-1330, 1330-1840, 1840-2760, 2760-4030, 4030-5300, 5300-8190, 8190-11050 Mg soil ha^{-1} at UZF, which roughly corresponded to soil depth layers of 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-50, 50-75, 75-100 cm, respectively. SOC stocks were calculated on the basis of the same soil mass as the reference profile but different soil depth layers which varied by < 1.5 and < 0.6 cm at DTC and UZF, respectively. As mulch was only applied between maize rows, and fertilizer was only applied on maize rows, it was estimated that the row and interrow space represented 22 and 78 % respectively, hence SOC calculations were weighted accordingly (Shumba et al., 2023b). Change in cumulative SOC stock between treatments for a given soil depth was determined using the CT treatment as the reference treatment:

$$\Delta SOC\ stock = SOC\ stock_{treatment(i)} - SOC\ stock_{CT(i)},$$ (Equation 1)

where SOC $\mathrm{stock}_{treatment}$ is the cumulative SOC stock per treatment (CTR, NT, NTM, NRT, NTMR) at a given soil layer and (*i*) representing 0-5, 0-10, 0-15, 0-20, 0-30, 0-40, 0-50, 50-75, 75-100 cm.

SOC accumulation or loss rates (kg C ha^{-1} yr^{-1}) were calculated by dividing the change in stocks by the number of years between the establishment of the experiment and the time of soil sampling (8 years):

$$SOC\ accumulation/loss\ rate = \frac{\Delta SOC\ stocks}{8} \times 1000,\ \text{(Equation 2)}$$

2.5 Estimation of organic carbon inputs to the soil

Maize and cowpea yield and aboveground biomass were measured since the inception of the experiment, except for cowpea during the 2013/14 season. This data gap was filled by using the average cowpea yield and aboveground biomass values across seasons (from 2013/14 to 2020/21). We assumed that 5 % of the maize aboveground vegetative biomass remained in the field because maize stalk slashing at harvesting did not remove the whole stem. A root:shoot ratio of 0.16 and 0.06 for maize and cowpea, respectively (Amos and Walters, 2006; Kahn and Schroeder, 1999; Kimiti, 2011) was used to estimate the contribution of roots to organic C inputs to the soils. Organic C input contribution from weeds was assumed insignificant since there was effective control of weeds through the use of pre-emergence herbicide (glyphosate) and timely manual weeding throughout the cropping season. We also assumed that the relative amounts of organic C transferred through rhizodeposition was the same for maize and cowpea (i.e. 0.45 x root C biomass (Balesdent et al., 2011) and that the organic C content of all plant parts was 430 g kg^{-1} (Ma et al., 2018). Cumulative organic C inputs to the soil were then estimated for each treatment (Cardinael et al., 2022).

2.6 Data analysis

The full dataset is available in the CIRAD repository (Shumba et al., 2023a). Statistical analyses were performed using R software, version 4.0.0 (R Core Team 2020). Normality was tested by the Kolmogorov-Smirnov test. After confirming that data were normally distributed, analyses of variance (ANOVA) was carried out to establish any significant treatment effects on BD, SOC concentration, and SOC stock. Separation of means was done using the post hoc Tukey test at 5 % significance level using the *emmeans* function from the *emmeans* package (Bolker et al., 2009).

3. Results

3.1 Soil bulk density

The different cropping systems (CT, CTR, NT, NTM, NTR, NTMR) had no significant ($p > 0.05$) effect on BD across all soil depths except in the 5-10 cm depth in the inter-row at DTC (Figure 2) where BD was on average 5 % lower in the conventional tillage treatments (CT, CTR) than in the no-tillage treatments (NT, NTR). However, soil depth and location (row or inter-row), and the soil depth x location interaction had significant ($p < 0.001$) effects on BD. In the tillage layer (0-15 cm), BD was at least 2 % higher in the inter-rows than in the rows at both sites. In the deeper soil layer (15 – 30 cm), there were no significant ($p > 0.05$) differences. BD for depths below 30 cm were the same across treatments since it was determined from pits outside the experiment. It ranged between 1.47 – 1.51 and 1.47 – 1.49 g cm^{-3} (Table S1) in the subsoil (30 – 100 cm layers) at DTC and UZF, respectively.

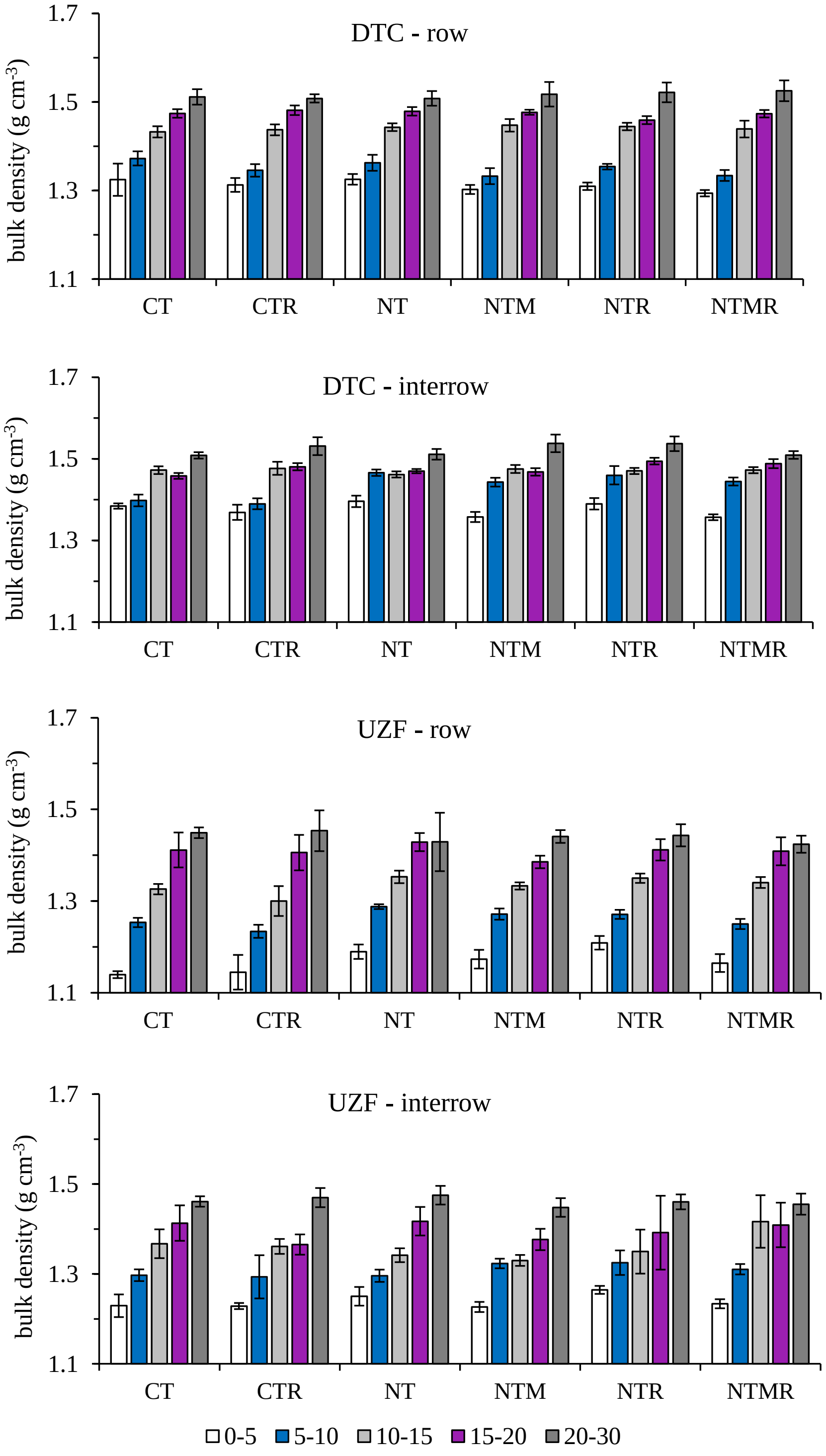

Figure 2. Top soil bulk density (0-30 cm) at the Domboshava Training Centre (DTC) and University of Zimbabwe Farm (UZF) experimental sites in Zimbabwe. CT: conventional tillage, CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation. Error bars represent standard errors (N = 4).

3.2 SOC concentration

SOC concentration decreased significantly ($p < 0.001$) with soil depth (Figure 3, Table S2) and was highest in the surface soil (0-5 cm) for all treatments (Table S2). There were significant treatment effects in the 0-5 cm ($p = 0.001$) and 5-10 cm ($p = 0.005$) soil layers at DTC and in the 0-5 cm layer ($p < 0.001$) only, at UZF. NTM had significantly ($p < 0.05$) higher SOC concentration compared to conventional tillage treatments (CT, CTR) and NT in the 0-5 cm soil layer at both sites (Figure 3); the increase in SOC concentration ranged between 31 to 46 % and 14 to 22 % at DTC and UZF, respectively. However, SOC concentration in NTM was equal ($p > 0.05$) to NTR and NTMR treatments at both sites.

In the 5-10 cm soil layer of DTC, SOC concentrations in NTM and NTR were at least 19 % higher ($p = 0.005$) than in NT and CT (Table S2). There were no significant ($p > 0.05$) treatment effects on SOC concentration below 10 cm soil depth at DTC and below 5 cm depth at UZF.

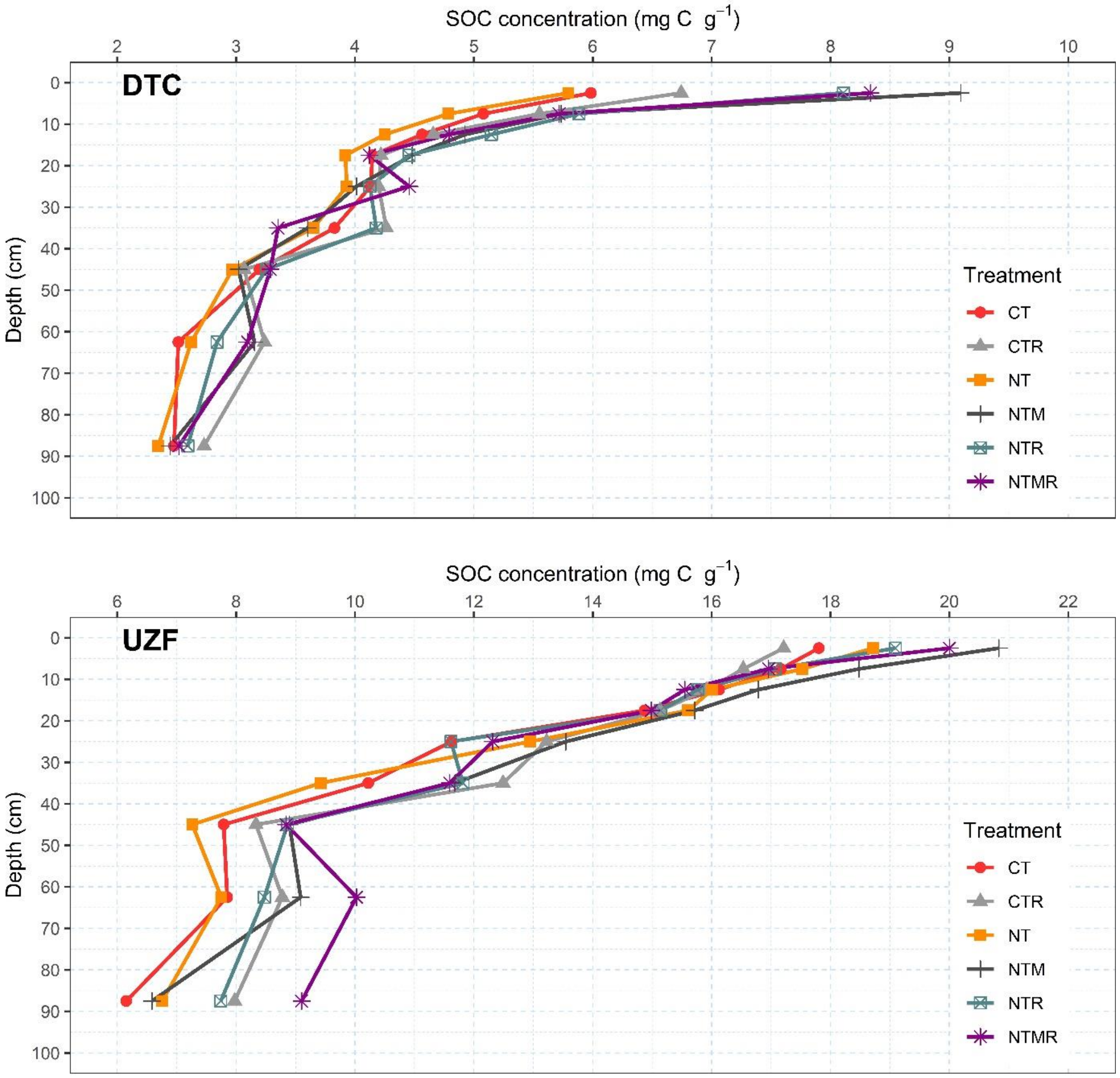

Figure 3. Soil depth distribution of organic carbon concentration for the different experimental treatments at the Domboshava Training Centre (DTC) and University of Zimbabwe Farm (UZF) experimental sites in Zimbabwe. Error bars represent standard errors (N = 4). CT: conventional tillage, CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation.

3.3 SOC stock

There were significant ($p < 0.05$) treatment effects on SOC stocks per soil layer in the top 5 at UZF and 10 cm at DTC (Table S3). Compared to CT, CTR and NT, NTM had at least 1.1 and 1.3 times more SOC stocks in the top 5 and 10 cm layers at UZF and DTC, respectively. In terms of cumulative SOC stocks, significant ($p < 0.05$) treatment effects were limited to the top 30 cm at DTC and the 20 cm at UZF, where no tillage with mulching (NTM) increased SOC stocks (Table 1). There were no significant ($p > 0.05$) tillage effects on SOC stocks (CT vs NT) for both sites. The rotation component had no significant ($p > 0.05$) effects on SOC stocks when comparing CTR and NTR at DTC. However, the maize-cowpea rotation under NT (NTR) had at least 16 % higher SOC stocks in the top 30 cm compared to NT. In contrast, NTR had at least 7 % more SOC stocks than CTR in the top 10 cm at UZF. Compared to NT and CT, the mulching component significantly ($p < 0.05$) increased SOC stocks by at least 8 % at UZF and 13 % at DTC in the top 20 and 30 cm soil layers, respectively. SOC stocks in the full CA treatment (NTMR) were not significantly ($p > 0.05$) different with the other combinations of CA principles (NTM, NTR) and CTR at DTC. At UZF, the full CA treatment had similar SOC stocks as all the other NT treatments (NT, NTM, NTR).

SOC stocks for the whole soil profile for this study (0-100 cm) were at least 8.1, 3.5 and 2.1 times higher at DTC and 11.6, 4.4 and 2.4 times higher at UZF than the SOC stocks in the 0-5 cm (surface soil), 0-15 cm (tillage depth) and 0-30 cm (IPCC standard depth) layers. SOC stocks for the subsoil (30-100 cm) ranged from 18.4 to 51.4 Mg C ha^{-1} at DTC and 41.9 to 124.9 Mg C ha^{-1} at UZF. Therefore, subsoil represented more than half (at least 53 % at DTC and 58 % at UZF) of SOC stocks for the whole 100 cm soil profile.

Site	Cumulative ESM (Mg ha^{-1})	Approximate soil depth (cm)	Cumulative SOC stocks (Mg C ha^{-1})						LSD	Significance
			CT	CTR	NT	NTM	NTR	NTMR		
DTC	650	0-5	3.9 ± 0.8c	4.4 ± 0.4bc	3.8 ± 0.7c	5.9 ± 1.2a	5.3 ± 1.1ab	5.4 ± 0.7ab	0.9	$p < 0.001$
	1340	0-10	7.4 ± 1.3c	8.2 ± 0.6bc	7.1 ± 1.1c	9.9 ± 1.8a	9.4 ± 1.5ab	9.4 ± 1.1ab	1.2	$p < 0.001$
	2060	0-15	10.7 ± 1.6c	11.6 ± 0.8bc	10.1 ± 1.3c	13.5 ± 2.0a	13.1 ± 1.7ab	12.9 ± 1.2ab	1.7	$p < 0.05$
	2760	0-20	13.6 ± 1.7b	14.6 ± 1.0ab	12.9 ± 1.4b	16.7 ± 2.1a	16.2 ± 1.9a	15.8 ± 1.4a	2.1	$p < 0.05$
	4160	0-30	19.4 ± 1.9ab	20.5 ± 1.2ab	18.4 ± 1.6b	22.3 ± 2.2a	22.0 ± 1.9a	22.0 ± 1.5a	2.7	$p < 0.05$
	5590	0-40	24.9 ± 2.0a	26.6 ± 1.3a	23.7 ± 1.7a	27.5 ± 2.3a	27.9 ± 2.0a	26.9 ± 1.6a	3.1	ns
	7040	0-50	29.6 ± 1.9a	31.2 ± 1.3a	28.0 ± 1.8a	32.0 ± 2.4a	32.7 ± 2.1a	31.7 ± 1.7a	3.4	ns
	10550	0-75	38.5 ± 2.0a	42.6 ± 1.3a	37.3 ± 2.0a	39.5 ± 2.4a	42.7 ± 2.1a	42.6 ± 1.9a	5.2	ns
	13770	0-100	46.5 ± 2.0a	51.4 ± 1.3a	44.8 ± 2.0a	47.5 ± 2.4a	51.1 ± 2.2a	50.7 ± 2.0a	6.3	ns
UZF	460	0-5	8.2 ± 0.9cd	7.9 ± 0.5d	8.6 ± 0.6bc	9.6 ± 1.0a	8.8 ± 0.9bc	9.2 ± 0.9ab	0.7	$p < 0.001$
	870	0-10	15.4 ± 1.5bc	14.8 ± 1.0c	15.9 ± 1.3b	17.3 ± 1.7a	15.9 ± 1.6b	16.3 ± 1.4ab	1.1	$p < 0.05$
	1330	0-15	22.9 ± 1.9b	22.1 ± 1.6b	23.4 ± 1.8b	25.1 ± 2.1a	23.2 ± 1.9b	23.6 ± 1.7ab	1.7	$p < 0.05$
	1840	0-20	30.8 ± 2.2b	29.9 ± 2.1b	31.3 ± 2.0ab	33.3 ± 2.4a	30.9 ± 2.2b	31.0 ± 2.1b	2	$p < 0.05$
	2760	0-30	42.3 ± 2.4a	42.8 ± 2.2a	44.1 ± 2.1a	46.4 ± 2.8a	41.9 ± 2.7a	43.3 ± 2.7a	3.3	ns
	4030	0-40	55.2 ± 2.6a	58.1 ± 2.6a	57.2 ± 2.2a	61.0 ± 3.3a	56.7 ± 3.0a	57.5 ± 3.2a	4.8	ns
	5300	0-50	66.3 ± 2.7a	70.4 ± 3.0a	67.5 ± 2.3a	73.1 ± 3.9a	68.8 ± 3.1a	69.7 ± 3.3a	6.6	ns
	8190	0-75	89.3 ± 3.1a	95.9 ± 3.3a	90.0 ± 2.7a	89.9 ± 4.6a	93.7 ± 3.9a	98.4 ± 4.3a	17	ns
	11050	0-100	107.8 ± 3.5a	119.1 ± 3.7a	109.8 ± 3.3a	110.9 ± 5.2a	116.1 ± 4.9a	124.9 ± 5.6a	19	ns

Table 1. Cumulative SOC stocks at the Domboshava Training Centre (DTC) and University of Zimbabwe Farm (UZF) after 8 years of different tillage, residue and crop management systems. Means in the same row followed by different superscript letters are significantly

different and associated errors are standard errors (N = 4). CT: conventional tillage, CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation.

3.4 SOC accumulation and loss rates

SOC accumulation rates at UZF differed significantly ($p < 0.05$) with soil depth where top soil layers (0-5, 0-10, 0-15, 0-20 and 0-30 cm) had SOC accumulation rates that were at least 6.9 times less than when considering the 0-100 cm soil profile (Table 2). In contrast, there were no significant ($p > 0.05$) differences, at DTC in SOC accumulation rates with depth. On average, SOC accumulation rates ranged between 0.13 and 0.08 Mg C ha^{-1} yr^{-1} in the top soil (0-5 cm) to 0.33 and 1.16 Mg C ha^{-1} yr^{-1} for the whole 1 m soil profile at DTC and UZF, respectively. The depth and treatment interaction had no significant ($p > 0.05$) effects at both sites.

On the other hand, the different treatments in this study had significant ($p < 0.05$) effects in SOC accumulation / loss rates in the top 20 cm soil layer at both sites (Table 2). At DTC, NT had significant ($p < 0.05$) net loss of SOC in the 0-20 cm layer, ranging between -0.09 and -0.02 Mg C ha^{-1} yr^{-1}, whereas NT treatments (NTM, NTR, NTMR) had SOC accumulation rates ranging from 0.17 to 0.38 Mg C ha^{-1} yr^{-1}. However, maize stover mulching (NTM) had significantly ($p < 0.05$) higher SOC accumulation rates than CTR (2.9 – 4.2 times) and NT (5.2 – 13.5 times) in the top 15 cm and 20 cm layers, respectively. The different combinations of mulching and rotation under NT (NTM, NTR and NTMR) had no significant ($p > 0.05$) differences in SOC accumulation rates. Similarly, rotation treatments (CTR, NTR, NTMR) showed no significant ($p > 0.05$) differences in SOC accumulation rates. Thus, the full CA treatment had similar SOC accumulations rates to treatments with at least 2 combinations of CA principles (NTM and NTR) and to CTR.

In contrast, at UZF, CTR had significant ($p < 0.05$) net loss of SOC in the top 20 cm (Table 2). The no-tillage treatments (NT, NTM, NTR, NTMR) showed significantly ($p < 0.05$) higher SOC accumulation rates (0.05 – 0.25 Mg C ha^{-1} yr^{-1}) than CTR which ranged between -0.07 to -0.03 Mg C ha^{-1} yr^{-1} in top 10 cm soil layer. NTM had the highest SOC accumulations rates (0.28 to 0.32 Mg C ha^{-1} yr^{-1}) when considering the 0-15 and 0-20 cm soil layers. SOC accumulation rates in NTM were at least 3.8, 3.5 and 2.4 times higher than CTR, NT and NTR in the top 20 cm. The full CA treatment (NTMR) had significantly ($p < 0.05$) higher SOC accumulation rates compared to CTR (2.5 – 5.3 times) in the top 10 cm and lower SOC accumulation rate to NTM in the 0-10 cm (2.3 times) and 0-20 cm (10.6 times) soil layer. However, there were no significant ($p > 0.05$) differences in SOC accumulation rates between treatments beyond 20 cm soil layer at both sites.

Site	Approximate soil depth (cm)	SOC accumulation or loss rate (Mg C ha^{-1} yr^{-1})					LSD	Sig
		CTR	NT	NTM	NTR	NTMR		
DTC	0-5	0.06 ± 0.05bc	-0.02 ± 0.02c	0.25 ± 0.05a	0.17 ± 0.02ab	0.19 ± 0.04ab	0.13	***
	0-10	0.10 ± 0.09bc	-0.04 ± 0.04c	0.31 ± 0.09a	0.24 ± 0.01ab	0.25 ± 0.08ab	0.16	***
	0-15	0.12 ± 0.13bc	-0.07 ± 0.05c	0.35 ± 0.13a	0.30 ± 0.01ab	0.27 ± 0.12ab	0.23	**
	0-20	0.12 ± 0.17ab	-0.09 ± 0.05b	0.38 ± 0.17a	0.32 ± 0.01a	0.27 ± 0.16a	0.29	**
	0-30	0.13 ± 0.25a	-0.13 ± 0.07a	0.36 ± 0.25a	0.32 ± 0.08a	0.33 ± 0.20a	0.35	ns
	0-40	0.22 ± 0.25a	-0.15 ± 0.07a	0.33 ± 0.25a	0.38 ± 0.07a	0.25 ± 0.23a	0.41	ns
	0-50	0.20 ± 0.27a	-0.20 ± 0.14a	0.30 ± 0.27a	0.40 ± 0.09a	0.26 ± 0.22a	0.46	ns
	0-75	0.51 ± 0.28a	-0.15 ± 0.28a	0.13 ± 0.28a	0.53 ± 0.13a	0.51 ± 0.20a	0.73	ns
	0-100	0.62 ± 0.32a	-0.20 ± 0.37a	0.13 ± 0.32a	0.58 ± 0.29a	0.53 ± 0.20a	0.86	ns
UZF	0-5	-0.03 ± 0.03c	0.05 ± 0.04b	0.17 ± 0.05a	0.07 ± 0.04b	0.13 ± 0.06ab	0.08	***
	0-10	-0.07 ± 0.04c	0.07 ± 0.08b	0.25 ± 0.09a	0.07 ± 0.07b	0.11 ± 0.08b	0.13	**
	0-15	-0.10 ± 0.03b	0.06 ± 0.11b	0.28 ± 0.13a	0.04 ± 0.07b	0.09 ± 0.11ab	0.22	**
	0-20	-0.11 ± 0.07b	0.06 ± 0.14b	0.32 ± 0.17a	0.02 ± 0.11b	0.03 ± 0.12b	0.25	**
	0-30	0.06 ± 0.15a	0.22 ± 0.25a	0.51 ± 0.25a	-0.05 ± 0.18a	0.12 ± 0.16a	0.44	ns
	0-40	0.37 ± 0.11a	0.25 ± 0.27a	0.72 ± 0.25a	0.19 ± 0.28a	0.29 ± 0.14a	0.65	ns
	0-50	0.51 ± 0.20a	0.15 ± 0.34a	0.85 ± 0.27a	0.31 ± 0.41a	0.43 ± 0.10a	0.88	ns
	0-75	0.83 ± 0.56a	0.08 ± 0.55a	0.08 ± 0.28a	0.55 ± 0.76a	1.14 ± 0.44a	1.17	ns
	0-100	1.41 ± 0.86a	0.25 ± 0.75a	0.98 ± 0.32a	1.03 ± 1.26a	2.14 ± 0.99a	2.31	ns

Table 2. SOC change rates (± standard error, N = 4) of the different treatments compared to CT (conventional tillage) at Domboshava Training Centre (DTC) and University of Zimbabwe

farm (UZF). Means in the same row followed by different superscripts are significantly different. CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation, LSD = least significance difference, ns = not significant, Sig = significance, ** = $p < 0.05$, *** = $p < 0.001$.

3.5 Organic carbon inputs via crops residues, root mortality and rhizodeposition to the soil

There were significant ($p < 0.001$) differences in cumulative OC inputs between treatments (Figure 4). Cumulative OC inputs were at least 1.5 times higher in mulch treatments (NTM, NTMR) than in treatments without mulch. However, the mulch plus rotation treatment (NTMR) had significantly ($p < 0.001$) lower cumulative OC inputs than continuous mulching (NTM). Cumulative OC input after 8 seasons was as high as 16.0 and 10.5 Mg C ha^{-1} at DTC and 16.2 and 12.4 Mg C ha^{-1} at UZF in NTM and NTMR, respectively (Figure 4), resulting in mean annual OC input rates of about 1.3 to 1.6 Mg C ha^{-1} yr^{-1} for NTMR and 2.0 Mg C ha^{-1} yr^{-1} for NTM. The other treatments had mean annual OC input rates ≤ 1.0 Mg C ha^{-1} yr^{-1}.

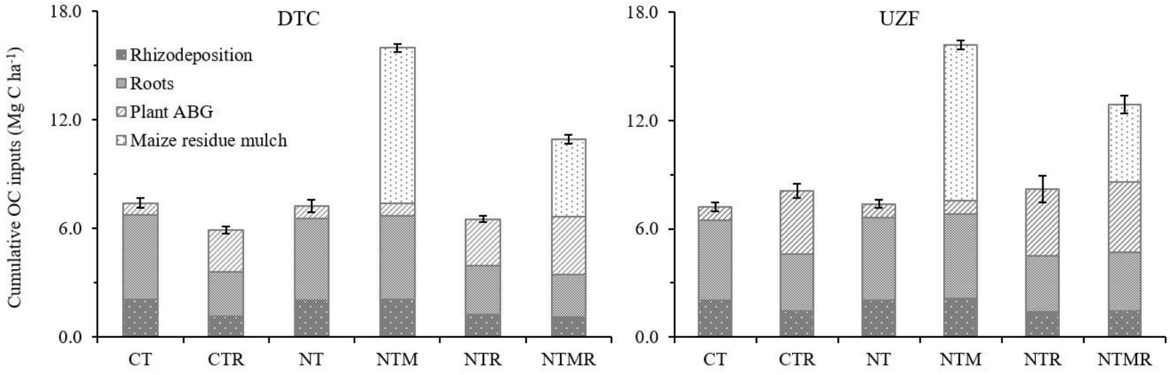

Figure 4. Estimated cumulative organic carbon (OC) inputs to the soil from the 2013/14 to the 2020/21 cropping season for the different treatments at the Domboshava Training Centre

(DTC) and the University of Zimbabwe Farm (UZF) experimental sites. Error bars represent standard errors (n = 4) for the cumulative OC. CT: conventional tillage, CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation, ABG: aboveground biomass.

4. Discussion

4.1 Role of soil texture in SOC accumulation

Soil texture is widely recognized to influence SOC stocks (Sun et al., 2020) through physical and chemical protection of SOC against microbially mediated decomposition (Chivenge et al., 2007; Mtambanengwe et al., 2004). In our study, the main difference between the two study sites is soil texture in the top soil (0-30 cm), where DTC had light textured (sandy loams) soils and UZF had medium to heavy textured (sandy-clay-loams) soils (Figure 1). These soil textural differences explain why there were no differences in SOC stocks, changes and accumulation rates between NTM, NTR and NTMR at DTC regardless of higher cumulative OC inputs in NTM and NTMR (Figure 4). The direct SOC inputs in the top soil at DTC, where SOC was more concentrated (Table S2, Figure 3) was subject to mineralization because of low clay content and thus low protection by soil micro-aggregates (Chivenge et al., 2007; Mtambanengwe et al., 2004; Sun et al., 2020), such that the differences in OC inputs had little effect. Light textured soils have large pores which cannot protect SOC against microbial decomposition (Mtambanengwe et al., 2004; Christensen, 1987; Sun et al., 2020; Kravchenko and Guber, 2017). Additionally, the low clay content meant less surface area for SOC adsorption (Han et al., 2016; Churchman et al., 2020) which is another mechanism for SOC protection from mineralization. In contrast, there were differences between NTM and NTR at UZF in the top soil layers and intermediate between NTM and NTMR. Cumulative OC inputs in NTMR (12.4 Mg C ha^{-1}) were about 75 % of cumulative OC inputs in NTM (16.2 Mg C ha^{-1}) (Figure 4) after 8 seasons. The added C, especially from maize stover mulch, most likely was protected by clay particles as well as formation of organo-mineral complexes (Malepfane et al., 2022; Chivenge et al., 2007; Jephita et al., 2023) which protects SOC from mineralization (Dunjana et al., 2012; Shumba et al., 2020; Button et al., 2022; Rumpel et al., 2012; Sanaullah et al., 2016).

4.2 SOC distribution across soil depth

Cumulative SOC stocks for the whole soil profile (0-100 cm) for this study were at least 8.0, 4.0 and 2.0 times higher than the 0-5 (surface soil), 0-15 (tillage depth for the study) and 0-30 (IPCC standard depth for SOC studies), for the two sites, respectively. This means that, over half of SOC stocks for this study were in the sub-soil (30-100 cm) which reflects on the importance of sub-soil SOC stocks. Significant SOC stocks in the sub-soil have also been reported by other authors (Yost and Hartemink, 2020; Balesdent et al., 2018; Cardinael et al., 2015; Harrison et al., 2011; Lal, 2018). Significant effects of mulch and/or rotation under NT were restricted to the top 30 cm in our study as well as other studies in SSA (Dube et al., 2012; Powlson et al., 2016) and the world at large (Balesdent et al., 2018; Yost and Hartemink, 2020), which is most likely why the default soil depth for IPCC for SOC studies is 0-30 cm (IPCC, 2019). However, this underestimates whole soil profile C storage (Harrison et al., 2011; Singh et al., 2018; Lorenz and Lal, 2005). Therefore, it is crucial to consider whole soil profile sampling when monitoring SOC storage in agricultural ecosystems to determine their C sequestration potential in the pursuit of climate change mitigation (Malepfane et al., 2022). SOC mineralization is relatively low in the sub-soil due to lack of oxygen and physical protection of SOC (aggregate protected C) (Rumpel et al., 2012; Sanaullah et al., 2016; Shumba et al., 2020; Button et al., 2022). Therefore, in the pursuit to improve subsoil (> 30 cm) SOC stocks through root mortality and exudates, crop varieties with higher root-length densities (Chikowo et al., 2003) in the subsoil are recommended.

In this study, there is a conspicuous rotation effect at UZF in the subsoil (60 – 100 cm) on SOC concentration which is however, not significant. However, there is a block effect at UZF on SOC concentration in the subsoil as shown in Figure S2 (see Figure S1 for DTC where no block effect was observed) where there seems to be "outliers" in blocks 3 and 4. We decided not to exclude the "outliers" since we thought it was a block effect rather than a treatment effect. As a result, there are no significant differences in SOC concentration between treatments in deep soils. If we exclude the "outliers" in deep soils the graph for SOC concentration is as shown in Figure S3 where the rotation effects tend to diminish. Nonetheless, all raw data of this paper can be freely accessed on the CIRAD data repository and linked to this paper (Shumba et al., 2023a).

4.3 Cumulative SOC stocks and accumulation rates

Overall, the insignificant differences in cumulative SOC stocks and SOC accumulation / loss rates between the different cropping systems in this and other studies (Laura et al., 2022; Leal et al., 2020) when considering whole soil profile (0-100 cm) is alluded to the dilution effect due to low OC inputs beyond 30 cm. Organic C inputs in the subsoil (> 30 cm) through crop root mortality and root exudates are highly reduced due to low root biomass (Button et al., 2022; Chikowo et al., 2003). Several authors have also reported similar cumulative SOC stocks for soil profile depth > 30 cm between different tillage and residue management practices (Angers et al., 1997; Doran et al., 1998; Lal, 2015; Powlson et al., 2014). This can be alluded to an accumulation of uncertainty when cumulating SOC stocks in several soil layers with their respective error of measurement. This weakens the power of detecting statistically significant differences even where such differences exist (Kravchenko and Robertson, 2011). Kravchenko and Robertson, (2011) bemoaned the lack of enough replication when sampling deep soil horizons to reduce variability and the importance of post hoc power analysis to reduce Type II error. This study was limited to four replicates which might not have enough statistical power to detect significant differences between treatments when considering the whole soil profile.

4.3.1 Mulching

The overarching role of mulching in cumulative SOC stocks and accumulation / loss rates at both sites (Tables 1 and 2), albeit, in the top soil (< 30 cm) has been shown in this study. Cumulative SOC stocks (Table 1) and SOC accumulation / loss rates (Table 2) did not differ with residue management under NT systems (NTM, NTMR) in the top soil at DTC regardless of high external OC inputs through maize residue application in mulch treatments (Figure 4, Table S4). This was attributed to low clay content (< 15 % clay) in the top 20 cm hence low physical SOC protection (Chivenge et al., 2007; Mtambanengwe et al., 2004; Sun et al., 2020), such that the differences in OC inputs had little effect. Alternatively, SOC can be protected from mineralization through adsorption to clay particles (Han et al., 2016; Churchman et al., 2020). However, there was low surface area for SOC adsorption due to low clay content in the top soil at DTC. Conversely, maize residue mulching effects were significant at UZF though NTMR was indifferent when compared to the rest of the NT treatments. Cumulative OC inputs in NTMR (12.4 Mg C ha^{-1}) were about 77 % of cumulative OC inputs in NTM (16.2 Mg C ha^{-1}) but at least 57 % higher OC inputs than NT and NTR after 8 seasons (Figure 4). This was alluded to SOC adsorption and physical protection due to higher clay content at UZF. Nonetheless, several studies have shown that aboveground biomass is less effective in sustaining SOC stocks compared to belowground biomass (Hirte et al., 2018, 2021; Jones et al., 2009; Villarino et al., 2021) and we attribute that to the insignificant cumulative SOC stocks and accumulation rates between the NT treatments other than NTM regardless of higher aboveground biomass in NTR and NMTR than NT (Figure 4).

4.3.2 Tillage

Significant changes in SOC stocks and accumulation rates were restricted to the top 20 cm at both sites below which there were no differences between treatments (Table 2). The consistently low SOC stocks under NT, CT and CTR and SOC accumulation rates (CTR and NT) at both sites was attributed to low OC inputs (Table S4, Figure 4). NT and CT had generally low yields in terms of grain and vegetative aboveground biomass (Mhlanga et al., 2021; Shumba et al., 2023b) since the establishment of the experiment in the 2013/14 season and hence low OC inputs through stubble, root mortality and root exudates. Our results dovetails with studies done elsewhere (Du et al., 2017; Koga and Tsuji, 2009) and meta-analyses and reviews (Corbeels et al., 2020a; Lal, 2018, 2015) where the authors found that NT alone does not significantly improve SOC. However, higher SOC stocks were observed when NT was combined with at least two CA principles (mulching and rotation) at DTC in the top 20 cm (Table 1). It has been reported that NT cropping systems enhance SOC accumulation through increasing C inputs in the top layers and reducing erosion through minimum soil disturbance (Six et al., 2000; Lal, 2015, 2018; Bai et al., 2019; Cai et al., 2022). Minimum soil disturbance through NT also physically protects SOC in microaggregates from exposure to oxidative losses (Shumba et al., 2020; Six et al., 2002; Dolan et al., 2006; Liang et al., 2020). However, NT without mulch is a nonentity compared to other combinations of CA principles for long-term sustainability in cropping systems (Nyamangara et al., 2013; Kodzwa et al., 2020; Mhlanga et al., 2021; Li et al., 2020; Bohoussou et al., 2022) and NT is only effective in increasing SOC stocks when it is associated with other CA principles, especially mulch. On the other hand, our study suggest that NT can achieve the same results of SOC storage as NTR and NTMR since they had similar SOC stocks at UZF. This can be explained by the low aboveground OC inputs in rotation treatments during the season when cowpeas were grown.

4.3.3 Maize-cowpea rotation

Legume rotations have been found to improve SOC accumulation rates and subsequent soil structural improvement (aggregation) induced by the addition of organic residues with favourable C/N ratio (Virk et al., 2022; Laub et al., 2023; Jephita et al., 2023). However, in our study, cowpea rotation benefits on SOC accumulation rates were not significant at DTC. Maize-cowpea rotation had no significant effects on maize yield (Shumba et al., 2023b; Mhlanga et al., 2021) which corresponded to low belowground biomass as well. Instead, maize stover mulching improved maize yields at DTC. Nevertheless, benefits from cowpea rotation under NT cropping systems (NTR, NTMR) compared to CT cropping systems (CTR) were significant, albeit only in the top 10 cm, at UZF; CTR had a net loss of SOC (-0.07 ± 0.04 to 0.03 ± 0.03 Mg C ha^{-1} yr^{-1}). Significantly higher maize yields in rotation treatments were observed at UZF (Shumba et al., 2023b; Mhlanga et al., 2021) and were attributed to more soil mineral N due to biological nitrogen fixation from the preceding cowpeas. Higher aboveground biomass is positively related to below ground biomass resulting in significant belowground OC inputs, of higher quality in the rotation treatments in the season when maize is grown. However, the net SOC loss in CTR at UZF was due to seasonal exposure to oxidative losses (SOC mineralization) through disruption of soil macroaggregates by tillage as alluded by Bai et al., (2019); Cambardella and Elliott, (1993) and Lal, (2018). We underscore that maize-cowpea rotation under NT improved SOC accumulation in the top soil due to reduced soil disturbance and alternate OC inputs of high (cowpeas) and low quality (maize). High quality OC inputs have a positive priming effect (Chen et al., 2014) which have been shown to be preferentially stabilized in the soil due to a higher carbon use efficiency of soil microbes (Cotrufo et al., 2013; Kopittke et al., 2018). This explains significant improvement in SOC stocks under the combination of NT and alternate high- and low-quality OC inputs (maize-cowpea rotation) to the soil in medium to heavy textured soils at UZF and vice versa at DTC.

5. Conclusions

Our study has shown the overarching importance of mulching and of combining at least two CA principles to improve top SOC stocks. No tillage (NT) alone could not increase SOC stocks, and even led to a slight decrease compared to CT, due to lower crop productivity in NT and therefore reduced OC inputs to the soil. Nevertheless, whole profile (0-100 cm) SOC stocks were the same between all the treatment. Our study also showed that sampling the entire soil profile is necessary for a more accurate view of SOC accumulation potential among different cropping systems.

6. Data availability

All data are freely available on the CIRAD data repository https://doi.org/10.18167/DVN1/VPOCHN (Shumba et al., 2023a).

7. Author contributions

CT designed, established and maintained the experiments since 2013; RCa, RCh were involved in soil sampling campaigns; AS, RCa performed the statistical analyses, graphics and drafting the manuscript; AS, RCa, RCh, MC, JS, CT reviewed and edited the manuscript.

8. Competing interests

One of the co-authors is a member of the editorial board of the SOIL journal. The other authors have no competing interests to declare.

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10. References

Amos, B. and Walters, D. T.: Maize Root Biomass and Net Rhizodeposited Carbon, Soil Sci. Soc. Am. J., 70, 1489–1503, https://doi.org/10.2136/sssaj2005.0216, 2006.

Angers, D. A. and Eriksen-Hamel, N. S.: Full-inversion tillage and organic carbon distribution in soil profiles: A meta-analysis, Soil Sci. Soc. Am. J., 72, 1370–1374, https://doi.org/10.2136/sssaj2007.0342, 2008.

Angers, D. A., Bolinder, M. A., Carter, M. R., Gregorich, E. G., Drury, C. F., Liang, B. C., Voroney, R. P., Simard, R. R., Donald, R. G., Bevaert, R. P., and Martel, J.: Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada, Soil Tillage Res., 41, 191–201, https://doi.org/10.4141/S96-111, 1997.

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Bo, T., Hui, D., Yang, J., and Matocha, C.: Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis, 25, 2591–2606, https://doi.org/10.1111/gcb.14658, 2019.

Balesdent, J., Derrien, D., Fontaine, S., Kirman, S., Klumpp, K., Loiseau, P., Marol, C., Nguyen, C., Pean, M., Personeni, E., and Robin, C.: Contribution de la rhizodéposition aux matières organiques du sol, quelques implications pour la modélisation de la dynamique du carbone, Etude Gest. des sols, 18 (3), 201–216, 2011.

Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Cornu, S., Derrien, D., Fekiacova, Z., and Hatté, C.: Atmosphere–soil carbon transfer as a function of soil depth, Nature, 559, 599–602, https://doi.org/10.1038/s41586-018-0328-3, 2018.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Adolwa, I., and Saidou, K.: Overview of Long Term Experiments in Africa, in: Lessons Learned from Long-Term Soil Fertility Management Experiments in Africa., Springer Science+Business Media Dordrecht, 1–26, https://doi.org/10.1007/978-94-007-2938-4, 2013.

Baudron, F., Andersson, J. A., Corbeels, M., and Giller, K. E.: Failing to Yield? Ploughs, Conservation Agriculture and the Problem of Agricultural Intensification: An Example from the Zambezi Valley, Zimbabwe, J. Dev. Stud., 48, 393–412, https://doi.org/10.1080/00220388.2011.587509, 2012.

Bohoussou, Y. N. D., Kou, Y. H., Yu, W. B., Lin, B. jian, Virk, A. L., Zhao, X., Dang, Y. P., and Zhang, H. L.: Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: A global meta-analysis, Sci. Total Environ., 842, 156822, https://doi.org/10.1016/J.SCITOTENV.2022.156822, 2022.

Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., and White, J. S. S.: Generalized linear mixed models: a practical guide for ecology and evolution, Trends Ecol. Evol., 24, 127–135, https://doi.org/10.1016/j.tree.2008.10.008, 2009.

Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R. J., von Unger, M., Emmer, I. M., and Griscom, B. W.: The role of soil carbon in natural climate solutions, Nat. Sustain., 3, 391–398, https://doi.org/10.1038/s41893-020-0491-z, 2020.

Button, E. S., Pett-Ridge, J., Murphy, D. V., Kuzyakov, Y., Chadwick, D. R., and Jones, D. L.: Deep-C storage: Biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils, Soil Biol. Biochem., 170, 108697, https://doi.org/10.1016/j.soilbio.2022.108697, 2022.

Cai, A., Han, T., Ren, T., Sanderman, J., Rui, Y., Wang, B., Smith, P., Xu, M., and Yu'e Li: Declines in soil carbon storage under no tillage can be alleviated in the long run, 425, 1–3, https://doi.org/10.1016/j.geoderma.2022.116028, 2022.

Cambardella, C. A. and Elliott, E. T.: Carbon and Nitrogen Distribution in Aggregates from Cultivated and Native Grassland Soils, Soil Sci. Soc. Am. J., 57, 1071–1076, https://doi.org/10.2136/SSSAJ1993.03615995005700040032X, 1993.

Cardinael, R., Chevallier, T., Barthès, B. G., Saby, N. P. A., Parent, T., Dupraz, C., Bernoux, M., and Chenu, C.: Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - A case study in a Mediterranean context, Geoderma, 259–

260, 288–299, https://doi.org/10.1016/j.geoderma.2015.06.015, 2015.

Cardinael, R., Guibert, H., Kouassi Brédoumy, S. T., Gigou, J., N'Goran, K. E., and Corbeels, M.: Sustaining maize yields and soil carbon following land clearing in the forest–savannah transition zone of West Africa: Results from a 20-year experiment, F. Crop. Res., 275, https://doi.org/10.1016/j.fcr.2021.108335, 2022.

Cheesman, S., Thierfelder, C., Eash, N. S., Kassie, G. T., and Frossard, E.: Soil carbon stocks in conservation agriculture systems of Southern Africa, Soil Tillage Res., 156, 99–109, https://doi.org/10.1016/j.still.2015.09.018, 2016.

Chen, R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X., Blagodatskaya, E., and Kuzyakov, Y.: Soil C and N availability determine the priming effect: Microbial N mining and stoichiometric decomposition theories, Glob. Chang. Biol., 20, 2356–2367, https://doi.org/10.1111/gcb.12475, 2014.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Nyamadzawo, G., and Giller, K. E.: Nitrate-N dynamics following improved fallows and maize root development in a Zimbabwean sandy clay loam, Agrofor. Syst., 59, 187–195, https://doi.org/10.1023/B:AGFO.0000005219.07409.a0, 2003.

Chivenge, P. P., Murwira, H. K., Giller, K. E., Mapfumo, P., and Six, J.: Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils, Soil Tillage Res., 94, 328–337, https://doi.org/10.1016/j.still.2006.08.006, 2007.

Christensen, B. T.: Decomposability of organic matter in particle size fractions from field soils with straw incorporation, Soil Biol. Biochem., 19, 429–435, https://doi.org/10.1016/0038-0717(87)90034-4, 1987.

Churchman, G. J., Singh, M., Schapel, A., Sarkar, B., and Bolan, N.: Clay Minerals As the Key To the Sequestration of Carbon in Soils, Clays Clay Miner., 68, 135–143, https://doi.org/10.1007/s42860-020-00071-z, 2020.

Corbeels, M., Cardinael, R., Powlson, D., Chikowo, R., and Gerard, B.: Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated: Comment on: "Meta-analysis on carbon sequestration through conservation agriculture in Africa," Soil Tillage Res., 196, 104300, https://doi.org/10.1016/j.still.2019.104300, 2020a.

Corbeels, M., Naudin, K., Whitbread, A. M., Kühne, R., and Letourmy, P.: Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa, Nat. Food, 1, 447–454, https://doi.org/10.1038/s43016-020-0114-x, 2020b.

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., and Paul, E.: The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter?, Glob. Chang. Biol., 19, 988–995, https://doi.org/10.1111/gcb.12113, 2013.

Dignac, M. F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G. T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P. A., Nunan, N., Roumet, C., and Basile-Doelsch, I.: Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review, Agron. Sustain. Dev., 37, https://doi.org/10.1007/s13593-017-0421-2, 2017.

Dolan, M. S., Clapp, C. E., Allmaras, R. R., Baker, J. M., and Molina, J. A. E.: Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management, Soil Tillage Res., 89, 221–231, https://doi.org/10.1016/j.still.2005.07.015, 2006.

Doran, J. W., Elliott, E. T., and Paustian, K.: Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management, Soil Tillage Res., 49, 3–18, https://doi.org/10.1016/S0167-1987(98)00150-0, 1998.

Du, Z., Angers, D. A., Ren, T., Zhang, Q., and Li, G.: The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis, Agric. Ecosyst. Environ., 236, 1–11, https://doi.org/10.1016/j.agee.2016.11.007, 2017.

Dube, E., Chiduza, C., and Muchaonyerwa, P.: Conservation agriculture effects on soil organic matter on a Haplic Cambisol after four years of maize-oat and maize-grazing vetch rotations in South Africa, Soil Tillage Res., 123, 21–28, https://doi.org/10.1016/j.still.2012.02.008, 2012.

Dunjana, N., Nyamugafata, P., Shumba, A., Nyamangara, J., and Zingore, S.: Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe, Soil Use Manag., 28, https://doi.org/10.1111/j.1475-2743.2012.00394.x, 2012.

Ellert, B. H. and Bettany, J. R.: Calculation of organic matter and nutrients stored in soils under contrasting management regimes, Can. J. Soil Sci., 75, 529–538, https://doi.org/10.4141/cjss95-075, 1995.

Feller, C. and Beare, M. H.: Physical control of soil organic matter dynamics in the tropics, Geoderma, 79, 69–116, https://doi.org/10.1016/S0016-7061(97)00039-6, 1997.

Giller, K. E., Witter, E., Corbeels, M., and Tittonell, P.: Conservation agriculture and smallholder farming in Africa: The heretics' view, F. Crop. Res., 114, 23–34, https://doi.org/10.1016/j.fcr.2009.06.017, 2009.

Giller, K. E., Andersson, J. A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., and Vanlauwe, B.: Beyond conservation agriculture, Front. Plant Sci., 6, 1–14, https://doi.org/10.3389/fpls.2015.00870, 2015.

von Haden, A. C., Yang, W. H., and DeLucia, E. H.: Soils' dirty little secret: Depth-based comparisons can be inadequate for quantifying changes in soil organic carbon and other mineral soil properties, Glob. Chang. Biol., 26, 3759–3770, https://doi.org/10.1111/gcb.15124, 2020.

Han, L., Sun, K., Jin, J., and Xing, B.: Some concepts of soil organic carbon characteristics and mineral interaction from a review of literature, Soil Biol. Biochem., 94, 107–121, https://doi.org/10.1016/j.soilbio.2015.11.023, 2016.

Harrison, R. B., Footen, P. W., Harrison, R. B., Footen, P. W., and Strahm, B. D.: Deep Soil Horizons: Contribution and Importance to Soil Carbon Pools and in Assessing Whole-Ecosystem Response to Management and Global Change, For. Sci., 57, 67–76, 2011.

Hirte, J., Leifeld, J., Abiven, S., Oberholzer, H. R., and Mayer, J.: Below ground carbon inputs to soil via root biomass and rhizodeposition of field-grown maize and wheat at harvest are independent of net primary productivity, Agric. Ecosyst. Environ., 265, 556–566, https://doi.org/10.1016/j.agee.2018.07.010, 2018.

Hirte, J., Walder, F., Hess, J., Büchi, L., Colombi, T., van der Heijden, M. G., and Mayer, J.: Enhanced root carbon allocation through organic farming is restricted to topsoils, Sci. Total Environ., 755, 143551, https://doi.org/10.1016/j.scitotenv.2020.143551, 2021.

IPCC: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories., 1–19 pp., 2019.

Jephita, G., Jefline, K., Willis, G., and Justice, N.: Carbon stock, aggregate stability and hydraulic properties of soils under tillage, crop rotation and mineral fertiliser application in sub-humid Zimbabwe, Heliyon, 9, https://doi.org/10.1016/j.heliyon.2023.e15846, 2023.

Jones, D. L., Nguyen, C., and Finlay, R. D.: Carbon flow in the rhizosphere : carbon trading at the soil – root interface, Plant Soil, 321, 5–33, https://doi.org/10.1007/s11104-009-9925-0, 2009.

Kahn, B. A. and Schroeder, J. L.: Root Characteristics and Seed Yields of Cowpeas Grown with and without Added Nitrogen Fertilizer, Hortscience A Publ. Am. Soc. Hortcultural Sci., 34, 1238–1239, https://doi.org/10.21273/hortsci.34.7.1238, 1999.

Kassam, A., Friedrich, T., and Derpsch, R.: Global spread of Conservation Agriculture, Int. J. Environ. Stud., 76, 29–51, https://doi.org/10.1080/00207233.2018.1494927, 2019.

Kell, D. B.: Breeding crop plants with deep roots: their role in sustainable carbon , nutrient and water sequestration, Ann. Bot., 108, 407–418, https://doi.org/10.1093/aob/mcr175, 2011.

Kimaro, A. A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., Mutuo, P., Abwanda, S., Shepherd, K., Neufeldt, H., and Rosenstock, T. S.: Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania?, Nutr. Cycl. Agroecosystems, 105, 217–228, https://doi.org/10.1007/s10705-015-9711-8, 2016.

Kimiti, J. M.: Influence of integrated soil nutrient management on cowpea root growth in the semi-arid Eastern Kenya, African J. Agric. Res., 6, 3084–3091, https://doi.org/10.5897/AJAR10.1023, 2011.

Kodzwa, J. J., Gotosa, J., and Nyamangara, J.: Mulching is the most important of the three conservation agriculture principles in increasing crop yield in the short term, under sub humid tropical conditions in Zimbabwe, Soil Tillage Res., 197, 104515, https://doi.org/10.1016/j.still.2019.104515, 2020.

Koga, N. and Tsuji, H.: Effects of reduced tillage, crop residue management and manure application practices on crop yields and soil carbon sequestration on an Andisol in northern Japan, Soil Sci. Plant Nutr., 55, 546–557, https://doi.org/10.1111/j.1747-0765.2009.00385.x, 2009.

Kopittke, P. M., Hernandez-Soriano, M. C., Dalal, R. C., Finn, D., Menzies, N. W., Hoeschen, C., and Mueller, C. W.: Nitrogen-rich microbial products provide new organo-mineral associations for the stabilization of soil organic matter, Glob. Chang. Biol., 24, 1762–1770, https://doi.org/10.1111/gcb.14009, 2018.

Kravchenko, A. N. and Guber, A. K.: Soil pores and their contributions to soil carbon processes, Geoderma, 287, 31–39, https://doi.org/10.1016/j.geoderma.2016.06.027, 2017.

Kravchenko, A. N. and Robertson, G. P.: Whole-Profile Soil Carbon Stocks: The Danger of Assuming Too Much from Analyses of Too Little, Soil Sci. Soc. Am. J., 75, 235–240, https://doi.org/10.2136/sssaj2010.0076, 2011.

Lal, R.: Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2-enrichment, Soil Tillage Res., 43, 81–107, 1997.

Lal, R.: Sequestering carbon and increasing productivity by conservation agriculture, J. Soil Water Conserv., 70, 55A-62A, https://doi.org/10.2489/jswc.70.3.55A, 2015.

Lal, R.: Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems, Glob. Chang. Biol., 24, 3285–3301, https://doi.org/10.1111/gcb.14054, 2018.

Laub, M., Corbeels, M., Couëdel, A., Ndungu, S. M., Mucheru-muna, M. W., Mugendi, D., Necpalova, M., Waswa, W., Van de Broek, M., Vanlauwe, B., and Six, J.: Managing soil organic carbon in tropical agroecosystems: evidence from four long-term experiments in Kenya, SOIL, 9, 301–323, https://doi.org/10.5194/soil-9-301-2023, 2023.

Laura, van der P. K., Andy, R., Meagan, S., Francisco, C. J., Wallenstein, M. D., and Cotrufo, M. F.: Addressing the soil carbon dilemma: Legumes in intensified rotations regenerate soil carbon while maintaining yields in semi-arid dryland wheat farms., Agric. Ecosyst. Environ., 330, https://doi.org/10.1016/j.agee.2022.107906, 2022.

Leal, O. A., Amado, T. J. C., Fiorin, J. E., Keller, C., Reimche, G. B., Rice, C. W., Nicoloso, R. S., Bortolotto, R. P., and Schwalbert, R.: Linking cover crop residue quality and tillage system to CO_2-C emission, soil c and n stocks and crop yield based on a long-term experiment, Agronomy, 10, https://doi.org/10.3390/agronomy10121848, 2020.

Li, Y., Li, Z., Chang, S. X., Cui, S., Jagadamma, S., Zhang, Q., and Cai, Y.: Residue retention promotes soil carbon accumulation in minimum tillage systems: Implications for conservation agriculture, Sci. Total Environ., https://doi.org/10.1016/ j.scitotenv.2020.140147, 2020.

Liang, B. C., VandenBygaart, A. J., MacDonald, J. D., Cerkowniak, D., McConkey, B. G., Desjardins, R. L., and Angers, D. A.: Revisiting no-till's impact on soil organic carbon storage in Canada, Soil Tillage Res., 198, 104529, https://doi.org/10.1016/j.still.2019.104529, 2020.

Lorenz, K. and Lal, R.: The Depth Distribution of Soil Organic Carbon in Relation to Land Use and Management and the Potential of Carbon Sequestration in Subsoil Horizons, Adv. Agron., 88, 35–66, https://doi.org/10.1016/S0065-2113(05)88002-2, 2005.

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H., and Fang, J.: Variations and determinants of carbon content in plants: A global synthesis, Biogeosciences, 15, 693–702, https://doi.org/10.5194/bg-15-693-2018, 2018.

Malepfane, N. M., Muchaonyerwa, P., Hughes, J. C., and Zengeni, R.: Land use and site effects on the distribution of carbon in some humic soil profiles of KwaZulu-Natal, South Africa, Heliyon, 8, https://doi.org/10.1016/j.heliyon.2021.e08709, 2022.

Mapanda, F., Mupini, J., Wuta, M., Nyamangara, J., and Rees, R. M.: A cross-ecosystem assessment of the effects of land cover and land use on soil emission of selected greenhouse gases and related soil properties in Zimbabwe, Eur. J. Soil Sci., 61, 721–733, https://doi.org/10.1111/j.1365-2389.2010.01266.x, 2010.

Mbanyele, V., Mtambanengwe, F., Nezomba, H., Groot, J. C. J., and Mapfumo, P.: Comparative short-term performance of soil water management options for increased productivity of maize-cowpea intercropping in semi-arid Zimbabwe, J. Agric. Food Res., 5, 100189, https://doi.org/10.1016/j.jafr.2021.100189, 2021.

Mhlanga, B., Ercoli, L., Pellegrino, E., Onofri, A., and Thierfelder, C.: The crucial role of mulch to enhance the stability and resilience of cropping systems in southern Africa, Agron. Sustain. Dev., 41, https://doi.org/10.1007/s13593-021-00687-y, 2021.

Mhlanga, B., Pellegrino, E., Thierfelder, C., and Ercoli, L.: Conservation agriculture practices drive maize yield by regulating soil nutrient availability, arbuscular mycorrhizas, and plant nutrient uptake, F. Crop. Res., 277, 108403, https://doi.org/10.1016/j.fcr.2021.108403, 2022a.

Mhlanga, B., Ercoli, L., Thierfelder, C., and Pellegrino, E.: Conservation agriculture practices lead to diverse weed communities and higher maize grain yield in Southern Africa, F. Crop. Res., 289, 108724, https://doi.org/10.1016/j.fcr.2022.108724, 2022b.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z. S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., O'Rourke, S., Richer-de-Forges, A. C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C. C., Vågen, T. G., van Wesemael, B., and Winowiecki, L.: Soil carbon 4 per mille, Geoderma, 292, 59–86, https://doi.org/10.1016/j.geoderma.2017.01.002, 2017.

Mtambanengwe, F., Mapfumo, P., and Kirchmann, H.: Decomposition of organic matter in soil as influenced by texture and pore size distribution, in: Managing Nutrient Cycles to Sustain Soil Fertility in Sub-Saharan Africa, edited by: Bationo, A., Academy Science Publishers and TSBF CIAT, Nairobi, 261–276, 2004.

Nyamangara, J., Masvaya, E. N., Tirivavi, R., and Nyengerai, K.: Effect of hand-hoe based conservation agriculture on soil fertility and maize yield in selected smallholder areas in Zimbabwe, Soil Tillage Res., 126, 19–25, https://doi.org/10.1016/j.still.2012.07.018, 2013.

Patra, S., Julich, S., Feger, K. H., Jat, M. L., Sharma, P. C., and Schwärzel, K.: Effect of conservation agriculture on stratification of soil organic matter under cereal-based cropping systems, Arch. Agron. Soil Sci., 65, 2013–2028, https://doi.org/10.1080/03650340.2019.1588462, 2019.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., and Smith, P.: Climate-smart soils, Nature, 532, 49–57, https://doi.org/10.1038/nature17174, 2016.

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., and Cassman, K. G.: Limited potential of no-till agriculture for climate change mitigation, Nat. Clim. Chang., 4, 678–683, https://doi.org/10.1038/nclimate2292, 2014.

Powlson, D. S., Stirling, C. M., Thierfelder, C., White, R. P., and Jat, M. L.: Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems ?, Agriculture, Ecosyst. Environ., 220, 164–174, https://doi.org/10.1016/j.agee.2016.01.005, 2016.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rumpel, C., Chabbi, A., and Marschner, B.: Carbon Storage and Sequestration in Subsoil

Horizons: Knowledge, Gaps and Potentials, in: Recarbonization of the Biosphere: Ecosystems and the Global Carbon Cycle, edited by: Lal, R., Lorenz, K., Hüttl, R. F., Schneider, B. U., and Von Braun, J., Springer Science+Business Media B.V, 445–464, https://doi.org/10.1007/978-94-007-4159-1, 2012.

Sanaullah, M., Chabbi, A., Maron, P. A., Baumann, K., Tardy, V., Blagodatskaya, E., Kuzyakov, Y., and Rumpel, C.: How do microbial communities in top- and subsoil respond to root litter addition under field conditions?, Soil Biol. Biochem., 103, 28–38, https://doi.org/10.1016/j.soilbio.2016.07.017, 2016.

Shumba, A., Dunjana, N., Nyamasoka, B., Nyamugafata, P., Madyiwa, S., and Nyamangara, J.: Maize (*Zea mays*) yield and its relationship to soil properties under integrated fertility, mulch and tillage management in urban agriculture, South African J. Plant Soil, 1–10, https://doi.org/10.1080/02571862.2019.1678686, 2020.

Shumba, A., Chikowo, R., Thierfelder, C., Corbeels, M., Six, J., and Cardinael, R.: Data for "Mulch application as the overarching factor explaining increase in soil organic carbon stocks under conservation agriculture in two 8-year-old experiments in Zimbabwe", https://doi.org/10.18167/DVN1/VPOCHN, CIRAD Dataverse, V2, 2023a.

Shumba, A., Chikowo, R., Corbeels, M., Six, J., Thierfelder, C., and Cardinael, R.: Long-term tillage, residue management and crop rotation impacts on N_2O and CH_4 emissions on two contrasting soils in sub-humid Zimbabwe, Agric. Ecosyst. Environ., 341, https://doi.org/10.1016/j.agee.2022.108207, 2023b.

Singh, G., Schoonover, J. E., Williard, K. W. J., Kaur, G., and Crim, J.: Carbon and Nitrogen Pools in Deep Soil Horizons at Different Landscape Positions, Soil Sci. Soc. Am. J., 82, 1512–1525, https://doi.org/10.2136/sssaj2018.03.0092, 2018.

Six, J., Paustian, K., and Elliott, E.: Aggregate and soil organic matter dynamics under conventional and no-tillage systems, Soil Sci. Soc. Am. J., 63, 1350–1358, 1999.

Six, J., Elliott, E. T., and Paustian, K.: Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture, Soil Biol. Biochem., 32, 2099–2103, https://doi.org/10.1016/S0038-0717(00)00179-6, 2000.

Six, J., Conant, R. T., Paul, E. A., and Paustian, K.: Stabilization mechanisms of soil organic matter : Implications for C-saturation of soils, 155–176, 2002.

Sun, W., Canadell, J. G., Yu, L. L., Yu, L. L., Zhang, W., Smith, P., Fischer, T., and Huang, Y.: Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture, Glob. Chang. Biol., 26, 3325–3335, https://doi.org/10.1111/gcb.15001, 2020.

Swanepoel, C. M., van der Laan, M., Weepener, H. L., du Preez, C. C., and Annandale, J. G.: Review and meta-analysis of organic matter in cultivated soils in southern Africa, Nutr. Cycl. Agroecosystems, 104, 107–123, https://doi.org/10.1007/s10705-016-9763-4, 2016.

Swanepoel, C. M., Rötter, R. P., van der Laan, M., Annandale, J. G., Beukes, D. J., du Preez, C. C., Swanepoel, L. H., van der Merwe, A., and Hoffmann, M. P.: The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific, Soil Tillage Res., 183, 72–82, https://doi.org/10.1016/j.still.2018.05.016, 2018.

Thierfelder, C. and Mhlanga, B.: Short-term yield gains or long-term sustainability? – a synthesis of Conservation Agriculture long-term experiments in Southern Africa, Agric. Ecosyst. Environ., 326, 107812, https://doi.org/10.1016/j.agee.2021.107812, 2022.

Thierfelder, C. and Wall, P. C.: Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe, Soil Tillage Res., 105, 217–227, https://doi.org/10.1016/j.still.2009.07.007, 2009.

Thierfelder, C. and Wall, P. C.: Effects of conservation agriculture on soil quality and productivity in contrasting agro-ecological environments of Zimbabwe, Soil Use Manag., 28, 209–220, https://doi.org/10.1111/j.1475-2743.2012.00406.x, 2012.

Thierfelder, C., Matemba-Mutasa, R., and Rusinamhodzi, L.: Yield response of maize (*Zea mays* L.) to conservation agriculture cropping system in Southern Africa, Soil Tillage Res., 146, 230–242, https://doi.org/10.1016/j.still.2014.10.015, 2015.

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T. S., Lamanna, C., and Eyre, J. X.: How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa, Food Secur., 9, 537–560, https://doi.org/10.1007/s12571-017-0665-3, 2017.

Thierfelder, C., Baudron, F., Setimela, P., Nyagumbo, I., Mupangwa, W., Mhlanga, B., Lee, N., and Gérard, B.: Complementary practices supporting conservation agriculture in southern Africa. A review, Agron. Sustain. Dev., 38, https://doi.org/10.1007/s13593-018-0492-8, 2018.

Thorup-Kristensen, K., Halberg, N., Nicolaisen, M., Olesen, J. E., Crews, T. E., Hinsinger, P., Kirkegaard, J., Pierret, A., and Dresbøll, D. B.: Digging Deeper for Agricultural Resources, the Value of Deep Rooting, Trends Plant Sci., 25, 406–417, https://doi.org/10.1016/j.tplants.2019.12.007, 2020.

Villarino, S. H., Pinto, P., Jackson, R. B., and Piñeiro, G.: Plant rhizodeposition : A key factor for soil organic matter formation in stable fractions, Sci. Adv., 7, 1–14, https://doi.org/10.1126/sciadv.abd3176, 2021.

Virk, A. L., Lin, B. J., Kan, Z. R., Qi, J. Y., Dang, Y. P., Lal, R., Zhao, X., and Zhang, H. L.: Simultaneous effects of legume cultivation on carbon and nitrogen accumulation in soil, Adv. Agron., 171, 75–110, https://doi.org/10.1016/bs.agron.2021.08.002, 2022.

Wendt, J. W. and Hauser, S.: An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers, Eur. J. Soil Sci., 64, 58–65, https://doi.org/10.1111/ejss.12002, 2013.

Yang, L., Luo, Y., Lu, B., Zhou, G., Chang, D., Gao, S., Zhang, J., Che, Z., and Cao, W.: Long-term maize and pea intercropping improved subsoil carbon storage while reduced greenhouse gas emissions, Agric. Ecosyst. Environ., 349, 108444, https://doi.org/10.1016/J.AGEE.2023.108444, 2023.

Yost, J. L. and Hartemink, A. E.: How deep is the soil studied – an analysis of four soil science journals, Plant Soil, 452, 5–18, https://doi.org/10.1007/s11104-020-04550-z, 2020.