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Carbon sequestration and selected hydraulic characteristics under conservation agriculture and traditional tillage practices in Malawi

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Abstract. Conservation agriculture (CA) is increasingly promoted among smallholder farmers of sub-Saharan Africa in a quest to improve food security while sustaining the natural resource base of the agro-ecosystems where agriculture is based. The aim of this study was to investigate the effects of CA and traditional tillage on soil organic carbon (SOC) and selected hydraulic properties in two contrasting agro-ecological zones of Malawi. Six farmers hosted on-farm trials in each location, with each farmer having the following treatments: CA with continuous sole maize (CA-SM), CA with maize–legume intercrops (CA-ML), and traditional tillage with continuous sole maize (CT-SM). Soil samples were randomly collected in October 2015, from farmers' fields located in Chipeni, Chinguluwe, Lemu, and Zidyana where CA had been implemented for 10 years (2005–2015) at six depth intervals: 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. Bulk density, soil water characteristics, and pore size distribution were determined using undisturbed core samples. At all sites, CA improved total SOC, carbon stocks, and the stable fraction of particulate organic carbon. Maize–legume intercropping under CA had 35%, 33%, and 73% more total SOC than CT-SM in Chipeni, Lemu, and Zidyana respectively. In Chinguluwe and Lemu, CA-ML had 0.54 and 0.50 g kg^{-1} respectively more stable fraction of particulate organic carbon (POMP) than CT-SM; whereas in Chipeni, CA-SM had 0.73 g kg^{-1} higher POMP compared with CT-SM. CA also improved soil porosity, pore size distribution, and water retention capacity by increasing the proportion of mesopores and micropores compared with CT-SM. Thus, changing management practices from CT-SM to CA has the potential to improve the soil organic matter and soil hydraulic properties across agro-ecological zones in Malawi, which is important for sustainable agriculture. Farmers should be encouraged to minimise tillage, retain residues as mulch on the soil surface, and practice crop rotation.

Keywords: agro-ecological zones, carbon sequestration, conservation agriculture, hydraulic characteristics, smallholder farmers, traditional tillage.

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Introduction

At an expert meeting organised by the Food and Agriculture Organization (FAO) of the United Nations in Rome in 2009, it was agreed that agricultural production will have to increase by 70% (on average) to feed the forecasted 9.6 billion people by 2050 (Montemurro and Diacono 2016). Despite enormous efforts by different stakeholders to increase food production, the challenges in sub-Saharan Africa (SSA) are multifaceted: land degradation, declining land availability, and low rainfall as well as the impact of climate change and variability. With this in mind, the UN adopted the Sustainable Development Goals (SDGs), which aim to address 17 sustainable development goals by 2030 of which Goal 2 is Zero Hunger (UN 2015). Conservation agriculture (CA) practices are increasingly seen as a potentially effective strategy to address low agricultural productivity in SSA (Ngwira *et al*. 2012; Thierfelder *et al*. 2015) thus addressing SDG Goal 2. Conservation agriculture is characterised by three principles: continuous minimum mechanical soil disturbance, permanent organic soil cover, and diversification of crop species grown in sequence or associations (FAO 2015).

Conservation agriculture enhances smallholders' capacity to mitigate and adapt to the effects of climate change (Thierfelder *et al*. 2015) through increased organic matter sequestration (Thierfelder *et al*. 2013) (SDG Goal 13), and restoring degraded lands (Sithole *et al*. 2016; Holden *et al*. 2018). This in turn, among other properties, improves soil structure, soil water retention (TerAvest *et al*. 2015), and infiltration (Thierfelder *et al*. 2013) and reduces soil erosion (Thierfelder *et al*. 2012) (SDG Goal 15). Although several studies have generated enough evidence on the impacts of CA on crop productivity and adapting agriculture to climate change, there is limited evidence documented on the mitigation effects of CA to climate change in Malawi and SSA generally. This study was undertaken to generate evidence on the effects of CA on mitigating the negative effects of climate change, especially given that the environmental effects differ from other parts of the world such as the Americas and Europe where CA has been promoted for decades. It is envisaged that the evidence generated will inform policy recommendations of the best CA practices to be practiced by farmers in the region and will lead to sustainability of smallholder agriculture.

According to Thierfelder *et al*. (2015), the effect of CA in increasing crop yields is more evident in soils with high clay and silt content. Conservation agriculture is reported to be more resilient to climate variability than conventional tillage (CT) (Aryal *et al*. 2016; Sithole *et al*. 2016). The resilience of CA systems to climate variability are likely due to the increased soil water content emanating from enhanced soil water infiltration (Thierfelder and Wall 2009; Thierfelder *et al*. 2013) as a result of the increase in soil organic matter (Thierfelder *et al*. 2012). However, there is limited research evidence elucidating the mechanisms and processes behind improved soil water relations under CA disaggregated by agro-ecological zones in order to clearly document the impacts of CA on ecosystem services delivery (Palm *et al*. 2014). Several SSA countries are promoting CA, including Malawi (Ngwira *et al*. 2013); however, the adoption rate is low (Tittonell *et al*. 2012; Brown *et al*. 2018). Many of these countries that adopted CA are practicing intercropping of cereal crops with legumes under CA in order to restore degraded lands through improved fertility and soil organic matter for maximal crop production (Thierfelder and Wall 2009). In SSA, where water is a major limiting factor for crop production, the rate of land restoration, however, depends on the rate at which organic matter is replenished (Thierfelder and Wall 2009).

The objective of the study was to investigate the effects of CA and CT on soil organic carbon (SOC) and selected hydraulic properties in two contrasting agro-ecological zones of Malawi. It was hypothesised that CA (a) improves the soil water holding capacity of the soil by increasing total porosity and the percentage (fraction) of mesopores, (b) increases the total organic carbon and the easily decomposable organic carbon fraction of the soil regardless of the soil type, agro-ecology, and cropping system (mono-crop vs legume–maize intercrop), and (c) can extend soil carbon sequestration below the top 30 cm of the soil profile compared with CT. The study was conducted in mid- and low-altitude agro-ecological zones of Malawi that represent major maize-growing areas in the country on farmers' fields that had implemented CA for 10 years on the same sites.

Materials and methods

Site description and climatic dynamics

The study was conducted on farmers' fields that had been implementing CA trials since 2005 in Chinguluwe, Mvera, Bazale, and Zidyana Extension Planning Areas (EPAs) in Salima, Dowa, Balaka and Nkhotakota districts of Malawi respectively. Agro-ecological zones, location, rainfall, and soil texture of the study sites are provided in Table 1. Chinguluwe, Chipeni, and Lemu are located in the dry subhumid zone and Zidyana is in the humid region of the country (Table 1). The textural class of soils in the study sites showed little variation, ranging from sandy clay loam to sandy clay and had a pH (H_2O) ranging between 5.3 and 5.7, suggesting that measures of soil amelioration to arrest soil acidity are required. The dominant soil types found in Chinguluwe, Chipeni, Lemu, and Zidyana include Eutric Cambisols, Chromic Luvisols, Chromic Luvisols, and Haplic Luvisols respectively (WRB 1998). Rainfall (precipitation) data were collected using a rain gauge mounted in 2004 at the centre of community hosting the trials. The Department of Climate Change and Meteorological Services in Malawi collected temperature and potential evapotranspiration (PET) data from the EPAs where the study sites are located. Aridity indices were used as a proxy of the degree of water deficiency present in the four study areas. Aridity index was calculated by dividing the average annual precipitation by the average annual potential evapotranspiration.

Experimental design and treatments

Ten-year field plots of 1000 m^2 (50 m × 20 m) were arranged in a randomised complete block design comprising three replications (farmers) of three tillage practices. The tillage treatments were:

(1) Traditional tillage practice (CT-SM) – Traditional land preparation using a hand hoe, maize planted as sole crop on ridges, and residues removed as practiced by farmers.

(2) Conservation agriculture (CA-SM) – Minimum soil disturbance, maize directly seeded into undisturbed soil

Table 1. Description of the study sites based on geographical location, weather information, aridity zone class, and soil classification

masl, metres above sea level; PET, potential evapotranspiration

District	Site	Soil pH (H_2O)	Agro-eco zone	Altitude (masl)	Latitude	Longitude	Temperature (°C)	Rainfall (mm)	PET (mm)	Aridity zone class	Soil textural class
Balaka	Lemu	5.3	Low altitude	720	–14.79	35.00	22	841	1388	Dry subhumid	Sandy clay
Dowa	Chipeni	5.5	Mid altitude	1160	–13.76	34.05	20	733	1530	Dry subhumid	Sandy clay loam
Nkhotakota	Zidyana	5.6	Low altitude	535	–13.23	34.23	25	1360	1546	Humid	Sandy clay
Salima	Chinguluwe	5.7	Low altitude	657	–13.69	34.23	24	853	1538	Dry subhumid	Sandy clay

and stover residues retained at the rate of 2.5 t ha^{-1} as surface mulch every year after crop harvest.

(3) Conservation agriculture with legume (pigeon pea) intercrop (CA-ML) – Minimum soil disturbance, maize intercropped with grain legumes directly seeded into undisturbed soil. Maize stover and legume residues retained as surface mulch aiming at 2.5 t ha^{-1} every year after each crop harvest.

All trials were managed by farmers in target communities with support from extension officers and research technicians providing recommendations on management of the plots. All plots were seeded on the same day after the first effective rains in each year, defined as a rainfall greater than 30 mm after 15 November. Ridges in the CT practice were prepared by a hand hoe around October and planting was done using a hand hoe. Ridge spacing was kept constant in all treatments: 75 cm between maize rows, 25 cm between plant stations within each row, and one seed per station. All treatments received uniform fertiliser rate of 69 kg N ha^{-1} that was supplied as 100 kg of N : P : K ha^{-1} (23 : 21 : 0 + 4S) at seeding and 100 kg urea ha^{-1} (46% N) approximately three weeks after planting. Weed control in all the three plots was done by manual weeding as necessary.

Soil sampling and analysis

Soil samples were collected in October 2015, before the onset of the rainy season, from each plot of the 10 years (2005–2015) on-farm trials located at different regions of Malawi. Soil samples were collected from randomly selected five sampling points per plot using a 4.5-cm diameter auger. The samples from each sampling point were collected at six depth intervals: 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. The five samples for each plot were mixed thoroughly to make a composite sample per plot per depth. The soil samples were oven-dried at 40°C, from which a 100-g subsample was used for the determination of fractionate carbon. The rest of the composite sample was ground to pass through a 2-mm sieve and homogenised. Bulk density (ρ_b) was determined from a core sample taken by driving a metal core of 4.5 cm diameter and 5 cm height into the side of a 50 cm dug pit at a depth of 20 cm. The soil was oven-dried at 105°C for 24 h to obtain the oven-dry weight of the soil. The ρ_b was calculated by dry mass of the soil divided by the core volume.

A subsample of the ground and sieved sample was used for pH, total SOC, and soil texture determination. Soil pH (H_2O) was determined using a digital pH meter (Fisher Scientific™ accumet™ AB15+ Basic and Bio Basic™ pH/mV/°C Meters) in 1 : 2.5 soil : water suspension (Jackson 1973). Total SOC was determined using the Walkley–Black method (Walkley and Black 1934). This method is mostly used in quantifying SOC and stocks of soils in most developing countries while acknowledging its limitations for scientific studies. The SOC stock was calculated on a per hectare basis using Eqn 1 after Gonçalves *et al*. (2019).

$$\mathrm{SOC}_{\mathrm{stock}} = \mathrm{TOC} \times \rho_b \times h \times 10000 \tag{1}$$

where SOC stock is the stock of organic carbon in Mg ha^{-1}, TOC is the total organic carbon in g kg^{-1}, ρ_b is the soil bulk density in Mg m^{-3}, and h is the thickness (depth) in cm.

Analysis of SOC stock was done only for the top 20-cm soil layer because ρ_b was measured only for the top 20 cm due to limited number of core samplers.

Fractions of particulate organic carbon (POC) were determined by the wet sieving method adapted from FAO/IAEA organic carbon fractions analytical manual (FAO 2005). Soil subsamples of 50 g from the collected composite samples were dispersed with 10% sodium hexametaphosphate solution and wet sieved through 2-mm and 250-, 50-, and <50-µm sieves. The same procedure was repeated with the dry 50 g (dry weight, DW) of a fresh nondispersed soil sample. Sand was dispersed with 2 g L^{-1} of NaOH and oven-dried at 550°C for 2.5 h (Wang *et al*. 2011) and weighed. The weight of the sand was then subtracted from the weight of the initial sieving of each fraction.

The fractions that were determined included the following: total POC of dispersed soil (POMT), the unprotected POC of nondispersed soil (POMU), the POC that is physically protected by the soil aggregates (POMP), and the easily decomposable proportion of POC (POMR). This study only presented the results for POMR and POMP because POMT and POMU were used to calculate the important former two. The difference between dispersed and nondispersed samples at second sieve (250 µm) gives the POMP by the soil aggregates and is the stable fraction.

Soil textural class analyses were conducted on composite soil samples using the Bouyoucos hydrometer (manufactured by Gallenkamp) method (Bouyoucos 1962). Textural classes were classified using the textural triangle (Thien 1979).

Soil-water characteristic curves and pore size distribution (PSD)

Triplicate undisturbed soil cores were randomly collected per plot per replicate to a depth of 20 cm with a 4.5-cm diameter core sampler of 5-cm height. The core samples were allowed to be saturated by allowing de-aired water to move from bottom through capillary action in a tray filled with water to 3/4 of the height of the core sampler. The samples were left until they reached saturation. The saturated core samples were exposed to five matric potentials in a 15-bar pressure plate (1500 model, Soil moisture Equipment, USA): 15, 30, 100, 300, and 500 kPa. These five points were selected on the basis that beyond 500 kPa, it takes long time to achieve equilibrium due to the height of the sample. Soil cores were allowed to drain at each pressure level until there was no change in weight; and the last equilibrium in the current study was reached at 500 kPa. After the last equilibrium was achieved (500 kPa), the core samples were removed from the pressure plates, weighed, and dried in an oven for 24 h at 105°C for soil water content and ρ_b determination. The empirical parameters α, n, θ_s, and θ_r needed for equation (Eqn 2) (van Genuchten 1980) were generated using the RETC program from the water potential and corresponding volumetric water content data collected earlier:

$$\theta = \theta_s + \theta_s - \theta_r/(1 + \mathrm{h}\alpha)^n))^m \tag{2}$$

where θ is effective soil water saturation, θ_s and θ_r are saturated and residual moisture contents respectively, h is matric potential (kPa), α is the inverse of the air entry potential (cm^{-1}) parameter responsible for PSD, and n and m

are dimensionless fitting parameters that depend on pore sizes. Where m is calculated using Eqn 3 as follows;

$$m = 1 - 1/\mathrm{n} \qquad (3)$$

The 'Solver' function in Microsoft Office Excel (2016 version) was used to estimate the best fit parameter values for θ_r, α, and n, based on values that produced the smallest residual error between measured and calculated values for θ (Eze *et al*. 2020).

In order to determine the effect of management practices on the soil PSD, a graph of the hydraulic capacity function was drawn as a function of the pore radii (Ogunwole *et al*. 2015). The five pressure points described above were used to interpolate hydraulic potential heads from the initial five to more potential heads above 500 kPa. The accuracy of the five experimental points was assessed using generated confidence limits of the RETC program which were above 95% in all the cases. The hydraulic capacity function (c_w) at each suction head was determined using Eqn 4 (Ogunwole *et al*. 2015).

$$c_w = \alpha^{\mathrm{n}}(\theta_s - \theta_r)mn(-h)^{\mathrm{n}-1}/[1 + (-h\alpha)^n]^{m+1} \qquad (4)$$

The pore radii (r, μm) at each suction head (h, cm) were determined using Eqn 5 (Ogunwole *et al*. 2015).

$$r = 1490/h \qquad (5)$$

In this study, PSD classification followed the methods of Ogunwole *et al*. (2015) and Cameron and Buchan (2006), which are also used by the United States Department of Agriculture. Ogunwole *et al*. (2015) classified soil pore sizes into five classes: <0.1 μm (cryptopores), 0.2–15 μm (ultra-micropores), 15–30 μm (micropores), 30–75 μm (mesopores), and >75 μm (macropores). These classes are further categorised according to their storage use into three bigger categories: cryptopores (up to 0.2 μm) are residual pores, ultra-micropores and micropores are storage pores (0.2–30 μm), and >30 μm are the mesopores and macropores regarded as drainable pores.

Statistical analysis

Total carbon, carbon stocks and fractions, and pore volumes were subjected to multivariate data analysis (MANOVA) using randomised complete block design of the linear model of GENSTAT statistical package 18th edition (Payne *et al*. 2015). MANOVA was chosen based on the assumption that a multivariate test decreases the probability of type one error as well as taking proper account of the correlation between variables. MANOVA was used to test individual and interactive effects of site and treatment on total SOC, SOC stock, POMP, and POMR at $P < 0.05$. Stability test showed uniformity of the sites because the proportion of largest and smallest mean square error for treatments was less than 4. Differences between treatment means were separated using the Tukey HSD *post hoc* test. All the nonlinear least-squares analyses for water characteristic curves such as saturated moisture content (θ_s), residual moisture content (θ_r), α, m, and n were performed using RETC 2008 model at confidence limits of 95%. There was no interaction between sites and treatments for drainable, storage and residual pores (m^3 m^{-3}), hence ANOVA was only performed for the main effect of treatments for such factors.

Results

SOC sequestration

At all sites, there were no significant differences in SOC between the baseline line values and the values recorded after 10 years in the CT system. There were significant ($P < 0.001$) site × treatment and site × depth interaction effects for total SOC concentration (Table 2). Treatments did not show any significant effects in Chinguluwe; however, CA-SM and CA-ML gave significantly higher total SOC in Chipeni, Lemu, and Zidyana compared with the initial values. Intercropping maize with legumes under CA gave 40%, 25%, and 141% more total SOC than initial values analysed for Chipeni, Lemu, and Zidyana respectively (Table 3). Similarly, CA-SM had 44%, 27%, and 66% more SOC than initial values for Chipeni, Lemu, and Zidyana respectively. Total SOC showed no significant differences in the first 40-cm soil layer at Chinguluwe; however, at Chipeni, Lemu, and Zidyana changes were observed for the 20-cm soil layer downwards. The SOC contents in the top 0–20 cm layers of the four sites (Chinguluwe, Chipeni, Lemu, and Zidyana) were 21%, 29%, 25%, and 43% higher than the middle 20–60 cm layers, and 50%, 83%, 52%, and 168% higher than the bottom 60–100 cm layers respectively. Similarly, the SOC content of the middle 20–60 cm soil

Table 2. Multivariate analysis (MANOVA) for soil organic carbon (g kg^{-1}), soil organic carbon stock (Mg ha^{-1}, 20 cm), and POMP and POMR (g kg^{-1}, 100 cm) across sites, treatments, and depth

POMP, the stable fraction of particulate organic carbon; POMR, the easily degradable fraction of particulate organic carbon; v.r., variance ratio; *F* pr., *F* probability

Source of variation	Soil organic carbon			Soil organic carbon stock			POMP			POMR	
	d.f.	v.r.	*F* pr.	d.f.	v.r.	*F* pr.	d.f.	v.r.	*F* pr.	v.r.	*F* pr.
Rep stratum	2	0.38		2			2	6.05		4.24	
Site	3	133.33	<0.001	3	1676.38	<0.001	3	24.52	<0.001	13.11	<0.001
Treatment	3	25.93	<0.001	2	466.43	<0.001	2	98.08	<0.001	268.83	<0.001
Depth	5	46.35	<0.001				5	50.03	<0.001	65.68	<0.001
Site × Treatment	9	4.76	<0.001	6	47.13	<0.001	6	4.73	<0.001	3.67	0.002
Site × Depth	15	1.99	0.018				15	2.25	0.007	0.23	0.999
Treatment × Depth	15	1.15	0.314				10	3.36	<0.001	0.84	0.587
Site × Treatment × Depth	45	0.58	0.983				30	0.58	0.959	0.35	0.999

Table 3. Mean total soil organic carbon (SOC), POMP, and POMR (g kg^{-1}) as influenced by interactions between site and treatment and between site and depth

Means within same row followed by the same letter do not significantly differ from each other ($P < 0.05$). CA-ML, conservation agriculture maize–legume intercrop; CA-SM, conservation agriculture continuous sole maize; CT-SM, traditional tillage practice continuous sole maize; POMP, the stable fraction of particulate organic carbon; POMR, the easily degradable fraction of particulate organic carbon

	Treatment				Depth (cm)					
Site	Initial	CA-ML	CA-SM	CT-SM	0–10	10–20	20–40	40–60	60–80	80–100
					Total SOC					
Chinguluwe	8.52 bc	8.73 bc	8.42 bc	8.49 bc	10.43 cdef	10.13 cdefg	9.05 defghi	7.91 efghij	6.88 ghij	6.82 ghijk
Chipeni	10.48 b	14.75 a	15.18 a	10.88 b	17.28 a	15.9 ab	13.52 bc	12.13 cd	10.22 cdefg	7.89 fghij
Lemu	7.70 cd	9.66 bc	9.81 bc	7.32 cd	11.34 cde	9.72 defgh	8.82 defghi	7.98 efghij	7.2 fghij	6.67 hijk
Zidyana	3.24e	7.83 cd	5.39 de	4.49 e	8.24 efghi	6.93 ghij	5.93 ijk	4.67 jkl	3.4 kl	2.26 l
					POMP					
Chinguluwe	N/A	1.00 bc	0.756 cde	0.461 ef	1.1 bcd	1.022 bcd	0.8 cdef	0.656 defg	0.456 efg	0.4f g
Chipeni	N/A	1.578 a	1.156 b	0.428 ef	1.933 a	1.478 ab	1.111 bcd	0.822 cdef	0.622 defg	0.356 fg
Lemu	N/A	1.144 b	0.917 bcd	0.644 de	1.333 bc	1.022 bcd	0.956 bcde	0.789 def	0.722 defg	0.589 defg
Zidyana	N/A	0.928 bcd	0.539 ef	0.256 f	1.067 bcd	0.822 cdef	0.589 defg	0.433 efg	0.344 fg	0.189 g
					POMR					
Chinguluwe	N/A	3.4 a	3.033 bc	2.239 ef	3.444	3.2	3	2.767	2.533	2.4
Chipeni	N/A	3.089 abc	2.806 cd	2.1 f	3.178	2.889	2.733	2.533	2.411	2.244
Lemu	N/A	3.35 ab	3.128 ab	2.544 de	3.622	3.3	3.078	2.8	2.7	2.544
Zidyana	N/A	3.394 a	3.1 abc	2.033 f	3.478	3.144	2.878	2.7	2.533	2.322

layer was 24%, 42%, 21%, and 87% higher than the bottom 60–100 cm layers at Chinguluwe, Chipeni, Lemu, and Zidyana respectively.

There was a significant ($P < 0.001$) site × treatment interaction on SOC stocks in the first 20-cm soil layer (Table 4). The SOC stocks (Mg ha^{-1}) were significantly higher ($P < 0.05$) under the two CA systems than CT-SM at all study sites. Although there was no significant effect on SOC stocks between the two CA systems at Chinguluwe, there was a significant difference between CA-SM and CA-ML at Chipeni, Lemu, and Zidyana. In the humid region of Zidyana, CA-ML gave 0.05 Mg ha^{-1} more SOC stock than CA-SM, and CA-SM gave 0.02 and 0.03 Mg ha^{-1} more SOC stock than CA-ML in Chipeni and Lemu respectively. The CA-ML gave 0.05 and 0.07 Mg ha^{-1} more SOC stock than CT-SM at Chinguluwe and Zidyana respectively; and CA-SM gave 0.10 and 0.13 Mg ha^{-1} more than CT-SM at Chipeni and Lemu respectively. In general, SOC stocks in the top 20-cm soil layer were higher in the dry subhumid regions than the humid region of Zidyana.

Table 4. Soil organic carbon stocks (Mg ha^{-1}) in the top 20 cm as influenced by conservation agriculture (CA) and traditional tillage (CT) practices in Chinguluwe, Chipeni, Lemu, and Zidyana following 10 years of CA implementation

Means within a column followed by the same letter do not significantly differ from each other ($P < 0.05$). CA-ML, conservation agriculture maize–legume intercrop; CA-SM, conservation agriculture continuous sole maize; CT-SM, traditional tillage practice continuous sole maize

	Soil carbon stocks			
Treatment	Chinguluwe	Chipeni	Lemu	Zidyana
CA-ML	0.29 a	0.44 b	0.31 b	0.25 a
CA-SM	0.28 a	0.47 a	0.33 a	0.20 b
CT-SM	0.24 b	0.37 c	0.20 c	0.18 c

POC fraction

There were significant ($P < 0.001$) site × treatment interaction effects for both POMP and POMR (Tables 2). The two CA systems did not significantly differ in POMP and POMR at Chinguluwe and Lemu, but CA-LM had 0.42 and 0.41 g kg^{-1} higher POMP than CA-SM at Chipeni and Zidyana respectively. At Chinguluwe and Lemu, CA-ML had 0.54 and 0.50 g kg^{-1} respectively more POMP than CT-SM (Table 2). Only at Chipeni did CA-SM have 0.73 g kg^{-1} higher POMP compared with CT-SM. The two CA systems only significantly differed at Chinguluwe compared with the rest of the sites for POMR (Table 5). The CA-ML had 0.37 g kg^{-1} higher POMR than CA-SM. The CA-ML had 1.16, 0.99, 0.81, and 1.36 g kg^{-1} higher POMR compared to CT-SM at Chinguluwe, Chipeni, Lemu, and Zidyana respectively. At Chinguluwe, Chipeni, Lemu, and Zidyana, CA-SM had 0.79, 0.71, 0.58 and 1.07 g kg^{-1} respectively higher POMR than CT-SM.

There was a significant interaction ($P < 0.01$) between sites and depth on POMP. There were no significant differences ($P > 0.05$) in POMP in the first 40-cm layer at Chinguluwe, Lemu, and Zidyana, POMP was significantly higher in the 0–10 compared with 20–40 cm soil layer at Chipeni (Table 2). The POMP was 74% higher in the 0–10 compared with the 20–40 cm soil layer at Chipeni. There were no significant differences in POMP from 40 cm downwards at all sites. At Chinguluwe, Chipeni, Lemu, and Zidyana the 0–20 cm soil layer had 0.56, 1.11, 0.48, and 0.62 g kg^{-1} respectively higher POMP compared with the 40–100 cm layer. There was also a significant interaction ($P < 0.001$)

Table 5. Mean total soil organic carbon (SOC), POMP, and POMR (g kg^{-1}) as influenced by interaction between treatment and depth

Means within same row followed by the same letter do not significantly differ from each other ($P < 0.05$). CA-ML, conservation agriculture maize–legume intercrop; CA-SM, conservation agriculture continuous sole maize; CT-SM, traditional tillage practice continuous sole maize; POMP, the stable fraction of particulate organic carbon; POMR, the easily degradable fraction of particulate organic carbon

Treatment	Depth (cm) 0–10	10–20	20–40	40–60	60–80	80–100
			Total SOC			
Initial	10.38	8.91	7.87	7.03	5.7	5.02
CA-ML	14.55	12.34	10.33	9.48	8.3	6.48
CA-SM	12.91	12.23	10.62	8.38	7.5	6.59
CT-SM	9.45	9.19	8.52	7.82	6.3	5.55
			POMP			
CA-ML	1.95 a	1.492 b	1.208 bcd	1.017cdef	0.767 defgh	0.542 ghi
CA-SM	1.392 bc	1.175 bcde	0.9 defg	0.642 fghi	0.558 ghi	0.383 hi
CT-SM	0.733 efgh	0.592 fghi	0.483 ghi	0.367 hi	0.283 i	0.225 i
			POMR			
CA-ML	3.95	3.633	3.425	3.158	2.917	2.767
CA-SM	3.633	3.308	3.067	2.867	2.742	2.483
CT-SM	2.708	2.458	2.275	2.075	1.975	1.883

Table 6. Mean values for saturated moisture content (θ_s), residual moisture content (θ_r), α, and n for CT-SM, CA-SM, and CA-ML treatments across the sites

CA-ML, conservation agriculture maize–legume intercrop; CA-SM, conservation agriculture continuous sole maize; CT-SM, traditional tillage practice continuous sole maize

Treatment	Site	θ_s	θ_r	α	n	R^2
CT-SM	Chinguluwe	0.480	0.000	0.039	1.154	0.993
	Chipeni	0.510	0.191	0.010	1.496	0.994
	Lemu	0.470	0.000	0.011	1.196	0.990
	Zidyana	0.503	0.000	0.009	1.129	0.970
	Mean	0.490	0.048	0.017	1.244	0.987
CA-SM	Chinguluwe	0.500	0.000	0.021	1.207	0.997
	Chipeni	0.540	0.000	0.018	1.116	0.990
	Lemu	0.501	0.000	0.012	1.425	0.980
	Zidyana	0.520	0.000	0.014	1.123	0.970
	Mean	0.515	0.000	0.016	1.218	0.984
CA-ML	Chinguluwe	0.528	0.000	0.017	1.324	0.970
	Chipeni	0.580	0.000	0.011	1.074	0.993
	Lemu	0.523	0.000	0.015	1.337	0.980
	Zidyana	0.569	0.000	0.006	1.115	0.970
	Mean	0.550	0.000	0.012	1.212	0.978

between treatment and soil depth for POMP (Table 5). Although CT-SM did not show any significant changes in POMP within the 0–60 cm soil layer, both CA-SM and CA-ML showed an increase in POMP in the top 0–10 cm compared with deeper soil from 40 cm downwards. For example, CA-ML had 0.46 and 0.74 g kg^{-1} higher POMP in the 0–10 compared with 10–20 and 20–40 cm layers respectively. Similarly, CA-SM had 0.49 higher POM in the 0–10 than the 20–40 cm soil layer. In general, although both CA systems increased the amount of POMP in the first 20-cm soil layer compared with CT-SM, at lower soil depths the amount of POMP was similar for all three treatments. The CA-ML and CA-SM had 1.06 and 0.62 g kg^{-1} higher POMP in the 0–20 cm soil layer than CT-SM respectively.

Soil-water characteristics curves

The mean saturated volumetric water content (θ_s), which indicates total porosity, was highest for CA-ML compared with CA-SM and CT-SM (Table 6), representing an increase of 6% and 10% respectively. Conversely, the air entry value decreased under the two CA systems compared with CT-SM. The introduction of legumes under CA lowered air entry potential by 31% and 40% compared with CA-SM and

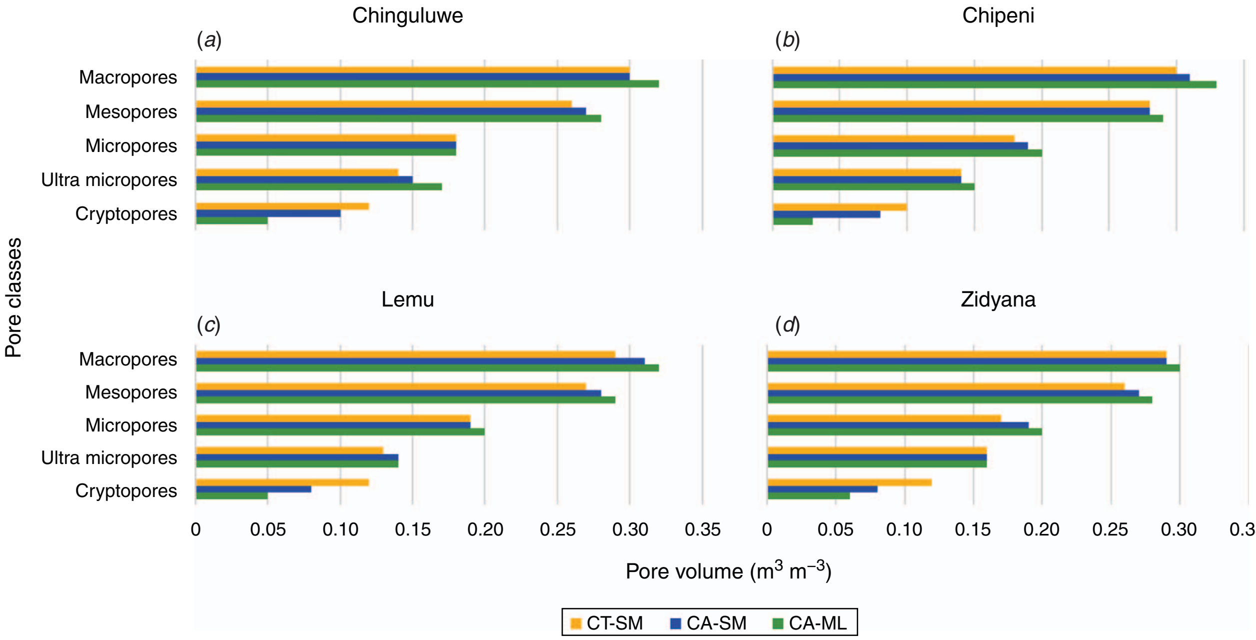

Fig. 1. Pore size distribution for traditional tillage sole maize (CT-SM), conservation agriculture sole maize (CA-SM) and conservation agriculture maize–legume intercrop (CA-ML) across the sites (*a*–*d*).

CT-SM respectively. The air entry value for CA-SM was 7% lower than for CT-SM practice.

PSD

The CA treatments enhanced the formation of micropores, mesopores, and macropores across sites (Fig. 1). In contrast, CT-SM practice had a higher fraction of cryptopores than CA treatments. Between CA treatments, CA-ML had higher fractions of micropores, mesopores, and macropores than CA-SM in most cases. However, CA-SM had a higher fraction of cryptopores than the CA-ML.

In general, the drainable pores constituted a higher proportion of the total soil porosity compared with the storage and residual pores at all sites (Fig. 1). Soil pore volume for macropores in the dry subhumid zones of Chinguluwe, Chipeni, and Lemu sites ranged within 0.3–0.33 m^3 m^{-3}, and those of the humid zone of Zidyana ranged within 0.29–0.3 m^3 m^{-3}. Across site analysis showed no significant effect on drainable pore volume fraction of treatments, sites, and the associated interactions. However, there was a significant ($P < 0.05$) difference in the volume fractions of the storage and residual pores among treatments (Table 7). The CT practice increased pore volume fraction of residual pores by 57% compared with CA-ML; however, CA-SM and CA-ML increased the volume fraction of storage pores by 17% and 24% compared with CT-SM respectively (Table 8).

PSD via hydraulic capacity function and pore radii

All treatments were characterised as unimodal, expressed by the existence of one inflection point on the retention curve within the range of 0–500 kPa matric potentials, which coincides with the peak on the derivative curve of the PSD to the retention curve (Fig. 2). Using the function of the pore radius, the inflection points of the graphs coincide with the

Table 7. ANOVAs for the main effect of treatments on drainable, storage, and residual pores

s.s., sum of squares; m.s., mean square; *F* pr., *F* probability

Source of variation	d.f.	s.s.	m.s.	*F* pr.
		Drainable pores		
Treatment	2	0.000021	0.000011	0.992
Residual	6	0.008403	0.001401	
Total	11	0.009118		
		Storage pores		
Treatment	2	0.011868	0.005934	0.003
Residual	6	0.001982	0.00033	
Total	11	0.017771		
		Residual pores		
Treatment	2	0.012833	0.006416	0.014
Residual	6	0.00413	0.000688	
Total	11	0.019568		

Table 8. Mean soil pore volumes for residual, storage and drainable pores

Means within same column followed by same letter are not significantly different ($P < 0.05$) (the first letter denotes the statistically highest performing)

Treatment	Mean pore volumes (m^3 m^{-3})		
	Residual pores	Storage pores	Drainable pores
CA-ML	0.1345 b	0.3925 a	0.4725 a
CA-SM	0.1549 ab	0.3700 a	0.4745 a
CT-SM	0.21180 a	0.3175 b	0.4713 a

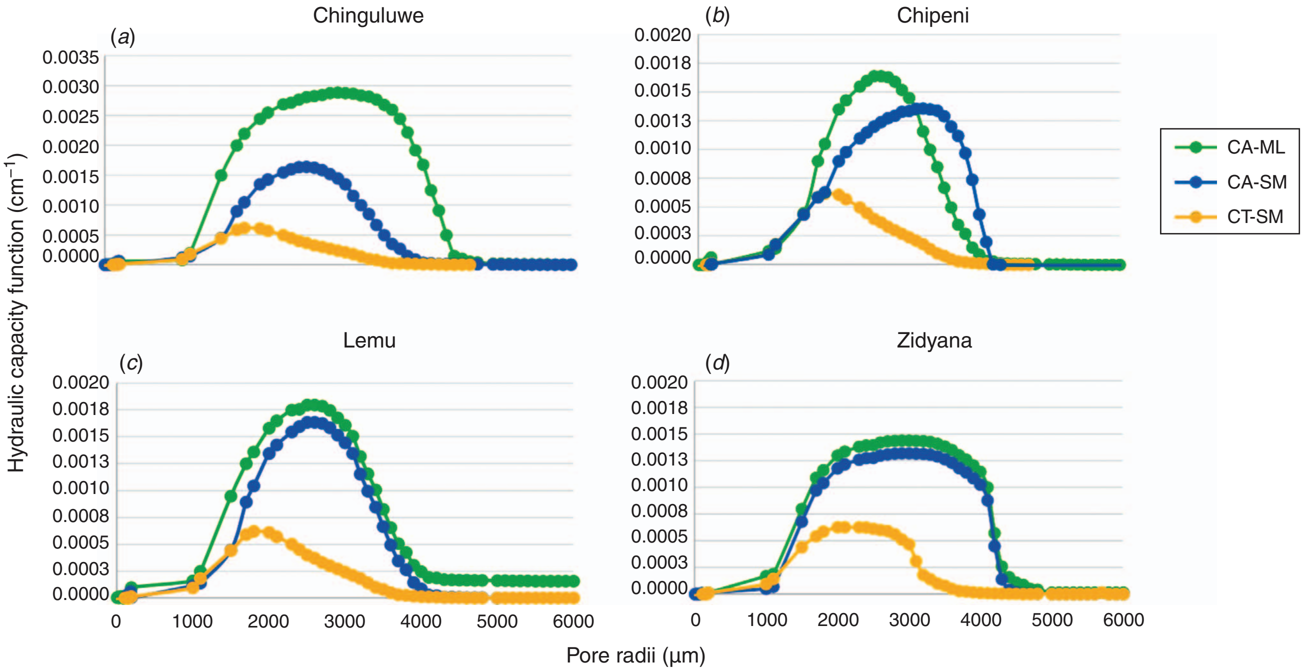

Fig. 2. Pore size distribution obtained using hydraulic capacity function (cw) for traditional tillage practice (CT-SM), conservation agriculture sole maize (CA-SM) and conservation agriculture maize–legume (CA-ML) across the sites

peaks in the capillary region and are separated by minimum with lowest value at the air entry point (h_A). Generally, at all the sites, CA contributed more to higher peaks in the capillary region of the graphs of pore distribution frequency than CT-SM practice. In addition, the inflection points of the graphs for the treatments were located slightly higher in the capillary region for CA compared with CT-SM practice. The CA, especially CA-ML, resulted in higher peaks compared with CA-SM and CT-SM practices.

In comparison with the graph peaks and inflection points across treatments in the capillary region, CA had on average lower air-entry parameter values and the inflection points were located at relatively higher inflection points than CT-SM practice. The slopes of the graphs for Chinguluwe and Zidyana were slightly lower compared with Lemu and Chipeni.

Discussion

Carbon sequestration

Total SOC, SOC stocks, and carbon fractions were influenced by environmental factors and management practices. The current study showed that the two CA systems sequestered more carbon than the CT system. The relative improvement in SOC sequestration under CA is mainly attributed to the plant residues left behind during harvest and minimal physical disturbance of residues and rhizosphere (Zachmann *et al.* 1987). A significant amount of the total carbon in the soil profile was located in the top 20 cm of soil in the majority of the study sites. The impact of CA on carbon distribution within the soil profile, however, extended down to a depth of 40 cm compared with the CT-SM. This concurs with previous findings by Thierfelder and Wall (2012), who reported a significant increase in SOC in the top 30 cm under CA compared to CT-SM. The two CA systems did not increase SOC beyond 40 cm depth and this corroborates with results of Luo *et al.* (2010) that indicated that studies on soil organic matter need to extend beyond the top 40 cm.

Soil carbon sequestration was higher under CA-ML in areas characterised by relatively higher rainfall or higher temperature such as Zidyana and Chinguluwe. In contrast, SOC sequestration in areas characterised by relatively lower rainfall and temperature, such as Chipeni and Lemu, was higher for CA-SM than CA-ML. This is probably due to the amount of rainfall received in the different study locations, which influences the amount of biomass produced and directly impacts SOC stocks (Yan *et al.* 2015). It can be assumed that the higher rainfall received in Zidyana and Chinguluwe influenced high biomass production because of less competition for water resources between maize and legumes under intercropping. The low amount of rainfall in Chipeni and Lemu might have caused high competition for water between maize and legumes in intercrops thus leading to low biomass production and, therefore, the low organic matter deposition into the soil. It has been reported that under moisture scarcity conditions, growth of intercropped legumes may be hampered, leading to reduced productivity and impaired quality (Layek *et al.* 2014).

Dry subhumid areas of Chipeni and Lemu sequestered more soil carbon compared with the humid area of Zidyana and the dry subhumid area of Chinguluwe. These differences could be explained by the environmental conditions among the study locations. For example, Zidyana is located in a high rainfall area and receives on average 500 mm more rainfall than the other three locations. In addition, the mean monthly temperature during the rainy season in Zidyana (>25°C) was on average 5°C higher than Chipeni and 3°C higher than Lemu. Such higher rainfall combined with higher temperature creates a conducive environment for rapid microbial proliferation thus speeding up organic matter decomposition (Cameron and Buchan 2006).

Similarly, SOC in Chinguluwe was lower than Lemu and Chipeni. This is most probably attributed to the relatively even distribution of the mean monthly rainfall in Chinguluwe (193–290 mm) compared with Lemu (110–281 mm), despite a similar total annual rainfall. According to recent model simulation studies by Ogbazghi *et al*. (2016), rainfall distribution significantly affects SOC decomposition in areas receiving mean annual rainfall of 600 mm and higher. Additionally, the relatively lower SOC sequestration in Lemu compared with Chipeni, which are both located in the dry subhumid zone, is most probably due to the relatively higher mean annual rainfall in Lemu (840 mm) compared with Chipeni (733 mm). Also, mean annual temperature was 2°C higher for Lemu than Chipeni. Thus, Lemu had relatively conducive environmental conditions for microbial activity to break down organic matter.

The current study showed that SOC was embedded in the micro-aggregates (250–500 µm diameter). A higher proportion of the POC was in the easily decomposable form (POMR) compared with the more stable form (POMP) both under CA and CT practices. This was most probably due to the short time span of the study sites, a decade, as per the soil organic matter categorisation based on the residence time (Bell and Lawrence 2009). These authors classified SOC based on the residence time in the soil as follows: crop residue on the soil surface (weeks–months), buried crop residue and roots (months–years), POC (years–decades), humus (decades–centuries), and resistant SOC (centuries–millennia). In the current study, CA increased POMP compared to CT systems. In similar studies, Six *et al*. (1999) and Huang *et al*. (2010) found increased particulate organic accumulation in fractions occluded within micro-aggregates (POMP) under minimal tillage systems. This fraction had 1.6 times higher carbon concentration for no tillage compared with CT. The results in the current study and those of Huang *et al*. (2010) correspond well with the conceptual model proposed by Six *et al*. (2000), which stated that 'tillage enhances the turnover rate of macro-aggregates and prevents the formation of micro-aggregates'. The difference between the decomposable fraction and the more stable fraction of the POC was more distinct in the dry subhumid zone of Chinguluwe, Chipeni, and Lemu with an aridity index of 0.5–0.6 than in the humid zone of Zidyana with aridity index of 0.9.

Soil water retention, total porosity, and PSD

Soil water retention, total porosity, and PSD varied due to SOC which was influenced by the cropping systems. The CA increased PSD and water retention capacity compared with CT-SM. Similar results were reported by Bhattacharyya *et al*. (2005), with a significant improvement in soil water retention under zero tillage (ZT) compared with CT-SM and mouldboard ploughing in the 0–7.5 and 7.5–15.0 cm soil depths. Similarly, Azooz *et al*. (1996), reported greater water retention in the top 7.5 cm soil layer under CA than CT in a sandy clay loam and silt loam soils. In the current study, soil water retention under CA was much higher in the presence of legume intercrop than sole maize across the sites. This is probably due to the presence of higher OM, which resulted in improvements in total porosity and PSD. The CA increased the proportion of ultra-micropores and micropores in the capillary region of the soil retention curve compared with CT-SM practices, thus improving the water retention capacity of soils. The current findings corroborate with those of Shukla *et al*. (2006), who reported that soil under ZT had a larger proportion of mesopores and micropores than CT soil. Rainfall simulation studies of Ngwira *et al*. (2013) showed high water infiltration in CA systems compared with CT-SM, suggesting an improved network of pores created by CA systems.

Of the four study sites, Chipeni, which was characterised by highest SOC (Table 3), had the highest total porosity as indicated by the mean saturated moisture content values (Table 8). This concurs with previous findings by Eusufzai and Fujii (2012) of an increase in total porosity and water retention capacity as the SOC increased. In the present study, variation in water retention capacity among sites was further demonstrated by the proportion of storage pores and the steepness of slope for PSD frequencies. The inflection points for graphs of PSD frequency were located slightly higher for Chipeni and Zidyana compared with Lemu and Chinguluwe sites, suggesting that Chipeni and Zidyana had higher proportions of storage pores than Lemu and Chinguluwe. In addition, among the sites located in the dry subhumid zone, the flatter slopes in the capillary region for Chipeni also indicated increased PSD compared with Lemu and Chinguluwe, which had steeper slopes. Although not quantified in the current study, these improvements in PSD at Chipeni may be due to the enhanced soil structure and mean PSD in addition to effects of SOC. Similar results were reported by Eusufzai and Fujii (2012) who found enhanced soil structure and aggregate stability under CA compared with CT systems.

Conclusion

The study showed that CA sequestered more carbon, enhanced the stable fraction of the soil organic matter, increased total soil porosity, and enhanced PSD compared with CT using a hand hoe. In areas characterised by low rainfall, carbon sequestration in CA practices was higher under sole maize cropping compared with maize–legume intercropping; however, in areas receiving higher amounts of annual rainfall, CA-ML sequestered more carbon than CA-SM. Although the study showed a positive increasing trend of the stable fraction of soil organic matter under CA, the results suggest that it will take several years before for a significant build-up of the stable SOC fraction is attained. The study also indicated that SOC was prominent in the top 60 cm of the soil profile but a larger proportion of the soil carbon was still concentrated in the top 20 cm. The improvement in SOC under CA also enhanced the water retention capacity of the soil. The degraded soils of smallholder farmers in Malawi associated with poor residue management after crop harvest calls for the wide-scale adoption of CA to increase soil organic matter which is critical for sustainable agriculture.

Conflicts of interest

The authors declare no conflicts of interest.

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