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**To cite this article:** Lindah Muzangwa, Pearson Nyari Stephano Mnkeni & Cornelius Chiduza (2021) Soil C sequestration and CO<sub>2</sub> fluxes under maize-based Conservation Agriculture systems in the Eastern Cape, South Africa, *South African Journal of Plant and Soil*, 38:3, 276-283, DOI: [10.1080/02571862.2020.1836274](https://doi.org/10.1080/02571862.2020.1836274)

**To link to this article:** <https://doi.org/10.1080/02571862.2020.1836274>



Published online: 15 May 2021.



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# Soil C sequestration and CO<sub>2</sub> fluxes under maize-based Conservation Agriculture systems in the Eastern Cape, South Africa<sup>†</sup>

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Traditional farming methods deplete soil carbon and contribute to carbon dioxide (CO<sub>2</sub>) emissions. We investigated the effects of Conservation Agriculture principles on C sequestration and CO<sub>2</sub> flux from two agroecological regions in the Eastern Cape province, South Africa, over five cropping seasons in the period 2012–2015. The field trials were laid in a split-split plot design. The main treatments were the tillage system, as conventional tillage or no-till. The sub-treatments were the crop rotation pattern: maize–fallow–maize (MFM); maize–fallow–soybean (MFS); maize–wheat–maize (MWM); or maize–wheat–soybean (MWS). Residue management after each crop in rotation was residue removal (R<sup>-</sup>) or residue retention (R<sup>+</sup>). The biomass and C-inputs by the crop rotations were both in the order: MWM > MWS > MFM > MFS. R<sup>+</sup> resulted in greater levels of particulate organic matter (POM) than R<sup>-</sup>. The former was the only factor to significantly ( $p < 0.05$ ) increase soil organic carbon (SOC) in the 0–5 cm depth layer at both sites after two years. CO<sub>2</sub> flux under conventional tillage was 20% higher than with no-till. The CO<sub>2</sub> fluxes were significantly influenced by air temperature ( $p < 0.001$ ,  $r^2 = 0.41$ ) and soil bulk density ( $p < 0.001$ ,  $r^2 = 0.16$ ). The results suggest that MWM or MWS crop rotation in conjunction with R<sup>+</sup> under no-till offer the greatest potential for biomass and C-inputs, and consequently C sequestration, in sub-humid and semi-arid agroecological regions of South Africa.

**Keywords:** crop residues, greenhouse gas mitigation, particulate organic matter, soil organic carbon, soil health

<sup>†</sup> This article is part of a special issue on *Conservation Agriculture*

## Introduction

Climate change due to greenhouse gases presents a global challenge. Traditional farming methods contribute to climate change by releasing soil carbon. In particular, excessive use of the plough and crop residue removal depletes soil organic carbon (SOC), which contributes to CO<sub>2</sub> emissions (Chivenge et al. 2007). CO<sub>2</sub> fluxes from agricultural soils are mostly from microbial decay of organic materials, burning plant residues, and soil organic matter (SOM) decomposition (Smith et al. 2008). Hopes of reducing CO<sub>2</sub> emission from cropped fields and consequently its effects on climate change are pinned on the use of technologies that capture and/or minimise CO<sub>2</sub> emissions (Smith et al. 2008).

Conservation Agriculture (CA) is based on managing crop residues on the soil surface, minimal soil disturbance, and diversified crop rotations as one approach to foster carbon (C)-sequestration (Chivenge et al. 2007; FAO 2014). The technology allows for a net decrease of CO<sub>2</sub> entering the atmosphere (Dendooven et al. 2012; Gonzalez-Sanchez et al. 2012). Estimates by Lal et al. (1999) indicate that the world C sequestration potential of crop residues is ~2 251 940 Mg C per year. However, significant changes in SOC after adoption of CA practices are not always apparent in the short-term. Quantification of SOM fractions directly

linked to SOC, such as particulate organic matter (POM), is an important early indication of C sequestration trends due to management changes (Liang et al. 2014; Carbonell-Bojollo et al. 2015).

Apart from the soil management factors, the CO<sub>2</sub> flux is also controlled by the organic matter input rate, soil type, soil water content and climate (Dendooven et al. 2012). Residues retained on the soil surface provide a carbon source for microbial activity, resulting in the production of CO<sub>2</sub> (Dyer et al. 2012). CO<sub>2</sub> fluxes can increase with a rise in soil temperature (Almaraz et al. 2009) and be negatively correlated with soil water content (Dendooven et al. 2012). Soil temperature and water content both control microbial activity and the resultant CO<sub>2</sub> production. Soil texture, bulk density and electrical conductivity affect the magnitude of CO<sub>2</sub> fluxes (Setia et al. 2011; Abdalla et al. 2014). The observed influence of both the climate and soil type indicates the importance of evaluating the effects of CA on C sequestration and CO<sub>2</sub> fluxes on specific agroecological units for informed eco-specific recommendations. In South Africa, the sub-humid and semi-arid regions are among the major climatic zones, with a coverage of 24.6% and 18.5% of the land surface, respectively (Palmer and Ainslie 2006).

Although CA was introduced to the smallholder farms of the Eastern Cape about two decades ago, its adoption is still low. Crop rotations and residue retention on the soil surface are key challenges for the adoption of CA, more so for the majority of farmers with crop–livestock systems (Muzangwa et al. 2017). The common practice of free-range livestock grazing on crop residues conflicts with the recommended practice of residue retention. Furthermore, most smallholder farmers are farming under rainfed conditions, thus biomass production is often limited. There is a need to identify suitable CA components that can generate high biomass and carbon (C) input for C sequestration and reduced CO<sub>2</sub> emissions. Therefore, this work aimed to investigate tillage, crop rotation, and residue management effects on C sequestration and CO<sub>2</sub> fluxes from semi-arid and sub-humid agroecological regions of the Eastern Cape Province.

## Materials and methods

### Experimental sites

The field experiment was carried out at two sites: the University of Fort Hare research farm (UFH) (32°47' S and 27°50' E) and Phandulwazi High School (Phandulwazi) (32°39' S and 26°55' E), from October 2012 to October 2015. The UFH site is at an altitude of 508 m and receives an average annual rainfall of 575 mm; the Phandulwazi site is at an altitude of 735 m and receives 750 mm average annual rainfall (Muzangwa 2016). Both sites receive 30% of the annual rainfall in winter and the rest in summer. Based on the total rainfall, the two sites are classified as semi-arid and sub-humid, respectively (Palmer and Ainslie 2006). Both sites have surface-layer soils of the Oakleaf form (Soil Classification Working Group 1991) or Eutric Cambisol, as classified in the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB 2006). However, the UFH soil has a sandy loam surface texture, whereas the Phandulwazi soil is a sandy clay loam (Gura 2016). Physico-chemical properties of the soils at the beginning of the trials were: UFH – bulk density 1.56 g cm<sup>-3</sup>, macro-aggregate stability 0.24 mwd, electrical conductivity 49 uS cm<sup>-1</sup>, and pH 6.52; Phandulwazi – bulk density 1.55 g cm<sup>-3</sup>, macro-aggregate stability 0.79 mwd, electrical conductivity 24 uS cm<sup>-1</sup>, and pH 6.09 (Gura 2016). Before the establishment of the trials, the Phandulwazi site had been under kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov) whereas the UFH site was under lucerne (*Medicago sativa* L.).

### Experimental design and agronomic practices

The field trial was a split–split plot design with 16 treatment combinations and 3 replicates. Main plots were allocated to no-till and conventional tillage (CT). The main plots were split into four crop rotations: maize (*Zea mays* L.)–fallow–maize (MFM), maize–fallow–soybean (*Glycine max* L.) (MFS), maize–winter wheat (*Triticum aestivum*)–maize (MWM), and maize–winter wheat–soybean (MWS). The crop rotations over the experimental period are shown in Table 1. The sub-subplots were allocated to residue management at two levels: residue removal (R<sup>-</sup>) and residue retention (R<sup>+</sup>), which was realised after the harvesting of each rotational crop by cutting the residues at the soil level. The sub-subplot sizes were 5 × 7 m for UFH, and 5 × 6 m for Phandulwazi, but the net plot sizes measured 3 × 4 m at both sites.

Experimental sites were ploughed, disked, and harrowed to create uniform conditions before the initial crop establishment in October 2012. A short-season and prolific maize cultivar (BG 5785BR) was planted in summer (October to February) targeting a population of 25 000 plants ha<sup>-1</sup>, recommended for dryland conditions in the central Eastern Cape Province. An early-maturing, dryland-suitable spring wheat cultivar (SST 015) was planted in winter (May to August) at a seeding rate of 100 kg ha<sup>-1</sup>. Soybean cultivar (PAN 5409RG) was sown in summer targeting a population of 250 000 plants ha<sup>-1</sup>. The summary of all the crop rotations during the study period are shown in Table 1. Fertiliser was applied only to the summer maize crop at a rate of 90 kg N, 45 kg P, and 60 kg ha<sup>-1</sup> K in all plots, for a target yield of 5 tons ha<sup>-1</sup>. All the P and K and one third of the N fertiliser was applied at planting as a compound (6.7% N; 10% P; 13.3% K + 0.5% Zn) and the rest (60 kg) as limestone ammonium nitrate at 6 weeks after planting by banding. Soybean was inoculated with *Rhizobium leguminosarum* before sowing. No irrigation was applied.

### Field and laboratory measurements

Residues for dry weight measurements were sampled at harvest of each crop; however, soybean biomass was sampled only at physiological maturity to reduce leaf loss when the plants completely dried. Crop residues and weed residues in fallow plots were destructively sampled by cutting at the ground level. Grain yield was determined from biomass measurements. Samples were oven-dried at 70 °C to a constant mass for dry weight determination and further chemical analysis. The amount of residue input in each plot was reported after summing the residue dry weights over the five cropping seasons. After each season,

**Table 1:** Summary of crops in rotation for the trials at the University of Fort Hare and Phandulwazi experimental sites, Eastern Cape, South Africa. Summer months are October to February; winter months are May to August. MFM = maize–fallow–maize; MFS = maize–fallow–soybean; MWM = maize–wheat–maize; MWS = maize–wheat–soybean

Crop rotation	Summer 2012/13 (Season 1)	Winter 2013 (Season 2)	Summer 2013/14 (Season 3)	Winter 2014 (Season 4)	Summer 2014/15 (Season 5)
MFM	Maize	Fallow	Maize	Fallow	Maize
MFS	Maize	Fallow	Soybean	Fallow	Maize
MWM	Maize	Wheat	Maize	Wheat	Maize
MWS	Maize	Wheat	Soybean	Wheat	Maize

plant samples were ground to pass through a 1-mm sieve, and carbon content was determined by dry combustion (TruSpec CN analyser; Leco Corp., St Joseph, Michigan). From this information, aboveground biomass C-inputs were estimated by finding the product of the residue carbon content and dry weights. Like residue input, the biomass C-input was reported after summing the total C-input over the five cropping seasons.

Soil samples were collected at the beginning of the study for base-line analysis, and again in November 2014, just before the last cropping season. Six soil cores were collected randomly to make a composite sample for each plot at two depths (0–5 and 5–10 cm) after removing the surface litter layer. The samples were stored in a cold room (4 °C) until use. Before laboratory work, soils were air-dried and passed through a 2-mm sieve. POM was determined using the weight loss on ignition procedure as described by Cambardella and Elliot (1992). Fifty grams of each sample was dispersed in 100 ml of 5 g l<sup>-1</sup> sodium hexametaphosphate for 18 h on a reciprocating shaker at 120 reciprocations per minute. The dispersed soil samples were passed through a 0.053-mm sieve, washed with deionised water until clean, backwashed into an evaporation dish, and dried at 55 °C for 24 h. The oven-dried sand particles plus POM were placed in dry porcelain crucibles and heated in a muffle furnace at 450 °C for 4 h. After cooling, the amount of POM was determined as follows:

$$\text{POM g kg}^{-1} = \frac{(\text{Weight at } 55^{\circ}\text{C} - \text{Weight at } 450^{\circ}\text{C})}{\text{at } 55^{\circ}\text{C}} \quad (1)$$

SOC was determined by dry combustion (TruSpec CN analyser; Leco Corp., St Joseph, Michigan). Undisturbed samples were also collected for bulk density determination, using a core sampler with a diameter of 10.7 cm, height of 7.6 cm, and volume of 683.5 cm<sup>3</sup> (Dane and Hopmans 2002).

The monitoring of CO<sub>2</sub> fluxes was done after two years of the trial establishment. These were carried out every two weeks between March and April 2015 as well as during the following winter and part of the spring (June–October 2015). An automated soil CO<sub>2</sub> flux system (LI-COR Biosciences, Lincoln, Nebraska), composed of an infrared analyser, multiplexer system and 16 LI-COR 8100A long-term chambers, was used for the CO<sub>2</sub> flux measurements. One PVC collar, compatible with the LI-COR 8100A long-term chamber, was inserted into each of the plots a day before the initial measurement, and kept in the field during the measurement period. Each of the 16 chambers was connected to soil temperature probes inserted at 5-cm depth. The machine was calibrated automatically using the surrounding air as a reference before each measurement. Gas sampling was done between 0900 and 1100 hrs to minimise diurnal variation in gas measurement and to reflect the mean daily temperature. CO<sub>2</sub>-flux measurement for each plot was programmed to take 2 minutes. The automated soil CO<sub>2</sub> flux system allowed the once-off measurement of the CO<sub>2</sub> fluxes in one block, after which the system was shifted to the next block. Soil water content from 10-cm depth was measured using a moisture probe (Hydro Sense II; Campbell Scientific, Logan, Utah), with

three measurements across each plot at each sampling time. Daily air temperature and rainfall data were collected using automatic weather stations (Weather Link, Davis Instruments, Hayward, California) located at both sites.

### Data analyses

Analysis of variance for all the measured parameters was performed using JMP statistical package version 11.1 (SAS Institute, Cary, North Carolina). Mean CO<sub>2</sub> fluxes, soil temperature, and water content was calculated over the experimental period. Means were separated using Fisher's least significant difference at  $\alpha = 0.05$  probability level. Orthogonal contrast analyses were performed to determine the comparative significance of soybean crop in rotations relative to cereal-only rotations on the biomass and C-input by the crop residues. Regression analyses were performed to test the effects of bulk density and air temperature on CO<sub>2</sub> fluxes.

## Results and discussion

### Residue biomass and carbon inputs

Production of high biomass is key to the success of the African smallholder CA systems, wherein the residues must satisfy multiple uses, such as feed for grazing livestock and covering the soil surface. In this study, the interaction effects of tillage, crop rotation and residue management were not significant ( $p > 0.05$ ) with respect to cumulative biomass and C-input at both sites (Table 2). Crop rotation was the only significant factor at Phandulwazi ( $p < 0.001$ ). However, crop rotation ( $p < 0.001$ ) and residue management ( $p < 0.01$ ) and their interaction ( $p < 0.01$ ) were significant at UFH. This study revealed the potential of the MWM and MWS rotations for producing large quantities of biomass and, hence, C-input under dryland conditions of the semi-arid and sub-humid conditions of the sites. The biomass yields by crop rotations across the sites followed the order MWM > MWS > MFM > MFS (Table 2). The higher biomass from the MWM and MWS rotations is a result of increased cropping intensity associated with these rotations as compared with MFS and MFM. Increased cropping intensity provides additional soil health benefits by keeping living roots in the ground for most of the year. Furthermore, the cropping intensity increased the total biomass production and C-inputs relative to fallow. The living roots improve soil health by providing a food source, in the form of root exudates, for beneficial soil microorganisms (Fuhrer 2017).

Contrast analysis showed increased biomass and C-input with non-legume rotations when compared with rotations with legumes ( $p < 0.01$ ) (Table 2). This underpins the importance of crop choice in terms of the biomass and C-input of CA systems. The experience gained thus far on both field and cover crops have shown the potential of cereal species in producing large quantities of biomass (Murungu et al. 2011). This could explain the MWM rotation's advantage over the MWS rotation regarding biomass and C-input.

### Soil organic carbon and particulate organic matter

The baseline soils showed higher average SOC at UFH compared with at Phandulwazi. The UFH site had SOC

**Table 2:** Crop rotation treatment and residue management effects on plant biomass and carbon inputs (Mg ha<sup>-1</sup>) at the Phandulwazi and University of Fort Hare (UFH) experimental sites, Eastern Cape, South Africa. Uppercase letters denote differences between means within a column for specific main factors (last row or column in each section) and lowercase letters denote differences between the interaction means (either biomass input or C-input for a given site); LSD = least significant difference. MFM = maize–fallow–maize; MFS = maize–fallow–soybean; MWM = maize–wheat–maize; MWS = maize–wheat–soybean

	Phandulwazi					UFH				
	MFM	MFS	MWM	MWS	Mean	MFM	MFS	MWM	MWS	Mean
<i>Biomass input</i>										
Residue retention (R <sup>+</sup> )	14.50	11.38	21.39	17.69	16.05	15.80 <sup>e</sup>	11.47 <sup>f</sup>	23.86 <sup>a</sup>	19.11 <sup>c</sup>	17.55 <sup>A</sup>
Residue removal (R <sup>-</sup> )	13.80	11.24	20.52	17.49	15.97	15.81 <sup>e</sup>	11.80 <sup>f</sup>	22.33 <sup>b</sup>	17.84 <sup>d</sup>	16.95 <sup>B</sup>
Mean	14.19 <sup>c</sup>	11.31 <sup>D</sup>	20.96 <sup>A</sup>	17.59 <sup>B</sup>		15.81 <sup>c</sup>	11.64 <sup>D</sup>	23.10 <sup>A</sup>	18.48 <sup>B</sup>	
LSD	Crop rotation***					Crop rotation*** Residue management*** Crop rotation × residue management**				
CV (%)	8.93					13.67				
<i>Carbon input</i>										
R <sup>+</sup>	5.05	3.88	6.44	4.83	49.68	5.37 <sup>cd</sup>	3.83 <sup>f</sup>	6.98 <sup>a</sup>	5.52 <sup>c</sup>	5.42 <sup>A</sup>
R <sup>-</sup>	4.73	3.82	6.18	4.82	49.64	5.07 <sup>e</sup>	3.90 <sup>f</sup>	6.53 <sup>b</sup>	5.11 <sup>de</sup>	5.15 <sup>B</sup>
Mean	4.89 <sup>B</sup>	3.84 <sup>C</sup>	6.31 <sup>A</sup>	4.82 <sup>B</sup>		5.23 <sup>B</sup>	3.87 <sup>C</sup>	6.75 <sup>A</sup>	5.32 <sup>B</sup>	
LSD	Crop rotation***					Crop rotation*** Residue management*** Crop rotation × residue management*				
CV (%)	11.95					15.65				

\* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$

values of 1.49% and 1.26% at the 0–5 and 5–10 cm depths, respectively, whereas the Phandulwazi site had 1.17% and 1.07% at the 0–5 and 5–10 cm depths, respectively. The high SOC values at UFH compared with Phandulwazi could explain the better biomass production observed at the former site (Table 2). SOC content measured after five cropping seasons and application of the treatments showed a decline from the baseline values. This could be a result of a shift away from the more stable ecosystem of the sites before the experiment, when both sites were maintained as undisturbed perennial pasture fields. Furthermore, the SOC levels at both sites were less than 2% (Table 3); thus, the experimental plots are classified as very low in SOC (Landon 1991), indicating greater C sequestration potential until equilibrium.

POM is biologically and chemically active, forming the easily decomposable pool of SOM. Depending on the management of soil, POM accounts for ~20% or more of the SOC (Carter et al. 2002). In this study, POM after five cropping seasons was more responsive to crop rotation and residue management treatments compared with SOC, but both parameters were not responsive to tillage (Tables 3 and 4). This observation is consistent with earlier research where POM was found to be a sensitive and appropriate indicator for the short-term dynamics of SOM (Liang et al. 2014; Carbonell-Bojollo et al. 2015). This was reflected by the higher number of significant treatment effects on POM than on SOC (Tables 3 and 4). Residue management effects on POM were significant ( $p < 0.05$ ) at both sites at 0–5 and 5–10 cm depths. SOC levels were significantly ( $p < 0.05$ ) influenced by residue management at only the 5–10 cm depth at Phandulwazi, but at both the 0–5 and 5–10 cm depths at UFH. Retention of crop residues increased both soil POM and SOC across sampling depths and sites. The observed increase in POM with R<sup>+</sup> is due to the latter being a source of SOM (Lal 2010).

MWM rotation increased POM at both sites as compared

**Table 3:** Tillage, crop rotation treatment and residue management effects on soil organic carbon (%), at the 0–5 and 5–10 cm soil depths, at the Phandulwazi and University of Fort Hare (UFH) experimental sites. Different letters in each column and factor indicate significant differences among treatments; LSD = least significant difference. MFM = maize–fallow–maize; MFS = maize–fallow–soybean; MWM = maize–wheat–maize; MWS = maize–wheat–soybean

Factor	Phandulwazi		UFH	
	0–5 cm	5–10 cm	0–5 cm	5–10 cm
<i>Tillage</i>				
Conventional tillage	0.84	0.67	1.17	1.15
No-till	0.97	0.66	1.15	1.04
LSD	ns	ns	ns	ns
<i>Crop rotation</i>				
MFM	0.97	0.67	1.15	1.09
MFS	0.95	0.69	1.16	1.05
MWM	0.84	0.64	1.16	1.15
MWS	0.86	0.66	1.18	1.10
LSD	ns	ns	ns	ns
<i>Residue management</i>				
Residue removal (R <sup>-</sup> )	0.90	0.64 <sup>b</sup>	1.13 <sup>b</sup>	1.06 <sup>b</sup>
Residue retention (R <sup>+</sup> )	0.91	0.69 <sup>a</sup>	1.20 <sup>a</sup>	1.14 <sup>a</sup>
LSD	ns	*	*	*
CV (%)	22.61	10.96	8.79	9.31

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

with the rest of the rotations, at the 0–5 cm depth. At the 5–10 cm depth at Phandulwazi, MWM had higher POM; however, the difference was not significant from MWS and MFS. The MFM rotation had the least POM. Generally, the biomass and C-input by crop rotations followed the order of MWM > MWS > MFM > MFS; however, this was not reflected in the changes in POM, indicating that biomass and C-input did not influence POM levels in the short

term. For instance, MFM had higher biomass input than MFS, yet MFS resulted in greater POM addition in the top 0–5 cm soil layer. This could be attributed to differences in the chemical composition of the residues produced under the various crop rotations. Residues from cereal crops, such as with MWM and MFM, have high lignin and cellulose content and are characterised by high C:N ratios (Murungu et al. 2010). Such residues with high C:N ratios take longer to disintegrate into POM compared with residues from legume rotations, such as MFS.

### Carbon dioxide fluxes

The CO<sub>2</sub> flux across the treatments and sites ranged from 0.28 to 5.47 μmol m<sup>-2</sup> s<sup>-1</sup> (Table 5) and fell within reported ranges under similar semi-arid and/or sub-humid temperate climates (Wang et al. 2010). The mean CO<sub>2</sub> flux calculated over the experimental period at both sites showed a significant effect ( $p < 0.05$ ) of tillage and residue management (Table 5). Higher CO<sub>2</sub> flux was observed with CT than no-till (Table 5; Figure 1). Only air temperature and bulk density significantly ( $p < 0.001$ ) influenced CO<sub>2</sub> flux data. The relationship between air temperature and CO<sub>2</sub> flux was positive (Figure 2), while a negative relationship occurred between bulk density and CO<sub>2</sub> flux (Figure 3). The CO<sub>2</sub> fluxes from the two sites were generally comparable, however, with variations in a few of the sampling dates (Figure 1a).

Observed significant increases in CO<sub>2</sub> flux under CT relative to no-till are consistent with the literature (e.g. Almaraz et al. 2009; Dendooven et al. 2012). Increased CO<sub>2</sub> flux under CT is attributed to the fact that the tillage operation promotes soil aeration, improving the supply of oxygen and facilitating the breakdown of soil organic matter and residues by soil microbes (Almaraz et al. 2009; Dendooven et al. 2012). The rapid increase in CO<sub>2</sub> flux with tillage has also been attributed to the release of entrapped CO<sub>2</sub> from the soil, in addition to the decomposition of organic matter (Reicosky et al. 1997). The placement of residues on the soil surface and without incorporation under no-till, minimised contact of the residues with soil microbes, reducing decomposition of organic matter and CO<sub>2</sub> flux compared with the results of CT.

The retention of residues increased CO<sub>2</sub> flux in the experimental plots at both sites (Table 5; Figure 1d). The observed significant increase in CO<sub>2</sub> flux with R<sup>+</sup> compared with R<sup>-</sup> is consistent with the findings of Tanveer et al. (2013) and Shaaban et al. (2015). It was attributed to the availability of easily decomposable organic matter under R<sup>+</sup>, which tends to stimulate microbial activity and CO<sub>2</sub> production (Dyer et al. 2012; Shaaban et al. 2015). The increase in CO<sub>2</sub> flux with R<sup>+</sup> did not, however, lead to a net loss in soil C sequestration, as the POM and SOC were still significantly increased by residue retention than by removal.

High seasonal variability of CO<sub>2</sub> fluxes appeared to be largely linked to fluctuations in air temperature, regardless of site and treatment. The air temperature was responsible for ~41% ( $r^2 = 0.41$ ) of the variation in CO<sub>2</sub> flux (Figure 2). As a result, subdued CO<sub>2</sub> fluxes were recorded during the cold months of June to August compared with the warmer months of September to April (Figure 1). Almaraz et al. (2009) and Dendooven et al. (2012) reported similar

**Table 4:** Tillage, crop rotation treatment and residue management effects on POM (g kg<sup>-1</sup>), at the 0–5 and 5–10 cm soil depths, at the Phandulwazi and University of Fort Hare (UFH) experimental sites. Different letters in each column and factor indicate significant differences among treatments; LSD = least significant difference. MFM = maize–fallow–maize; MFS = maize–fallow–soybean; MWM = maize–wheat–maize; MWS = maize–wheat–soybean

Factor	Phandulwazi		UFH	
	0–5 cm	5–10 cm	0–5 cm	5–10 cm
<i>Tillage</i>				
Conventional tillage	7.04	5.68	7.61	5.61
No-till	8.07	6.55	8.36	5.97
LSD	ns	ns	ns	ns
<i>Crop rotation</i>				
MFM	7.18 <sup>b</sup>	5.67 <sup>b</sup>	7.50 <sup>b</sup>	5.89
MFS	7.23 <sup>b</sup>	6.03 <sup>ab</sup>	8.00 <sup>b</sup>	5.62
MWM	8.23 <sup>a</sup>	6.65 <sup>a</sup>	8.67 <sup>a</sup>	5.74
MWS	7.55 <sup>b</sup>	6.11 <sup>ab</sup>	7.78 <sup>b</sup>	5.93
LSD	**	**	**	ns
<i>Residue management</i>				
Residue removal (R <sup>-</sup> )	5.78 <sup>b</sup>	5.73 <sup>b</sup>	7.26 <sup>b</sup>	5.32 <sup>b</sup>
Residue retention (R <sup>+</sup> )	6.61 <sup>a</sup>	6.51 <sup>a</sup>	8.71 <sup>a</sup>	6.27 <sup>a</sup>
LSD	***	***	***	***
CV (%)	11.26	18.63	11.48	13.97

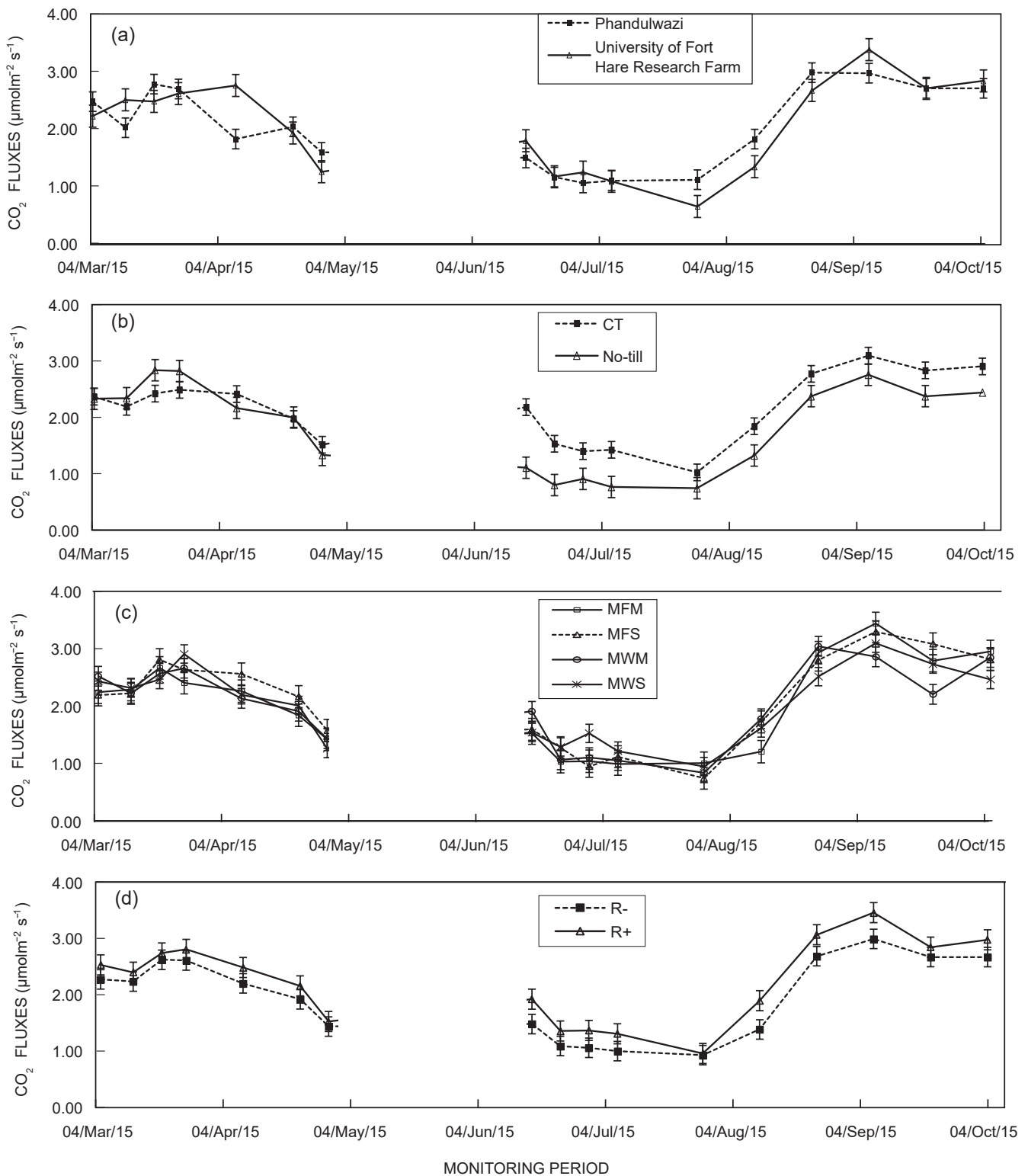
\*\* $p < 0.01$ ; \*\*\* $p < 0.001$ ; ns = not significant ( $p > 0.05$ )

**Table 5:** Tillage crop rotation and residue management effects on the mean CO<sub>2</sub> fluxes (μmol m<sup>-2</sup> s<sup>-1</sup>) at the Phandulwazi and University of Fort Hare (UFH) experimental sites. Different letters in each column and factor indicate significant differences among the treatments; LSD = least significant difference. MFM = maize–fallow–maize; MFS = maize–fallow–soybean; MWM = maize–wheat–maize; MWS = maize–wheat–soybean

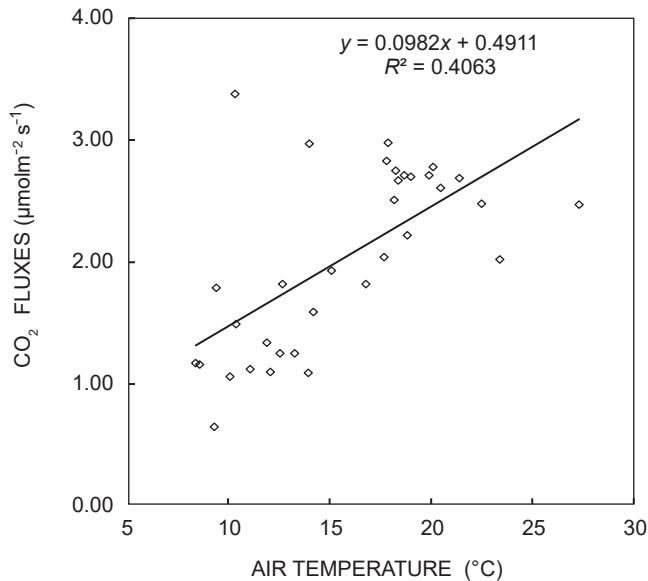
Factor	Phandulwazi	UFH
	<i>Tillage</i>	
Conventional tillage	2.16 <sup>a</sup>	2.26 <sup>a</sup>
No-till	1.19 <sup>b</sup>	1.81 <sup>b</sup>
LSD	*	*
<i>Crop rotation</i>		
MFM	2.07	1.93
MFS	2.14	2.04
MWM	1.94	2.07
MWS	1.97	2.08
LSD	ns	ns
<i>Residue management</i>		
Residue removal (R <sup>-</sup> )	1.89 <sup>b</sup>	1.91 <sup>b</sup>
Residue retention (R <sup>+</sup> )	2.18 <sup>a</sup>	2.16 <sup>a</sup>
LSD	*	*
CV (%)	23.11	14.75

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

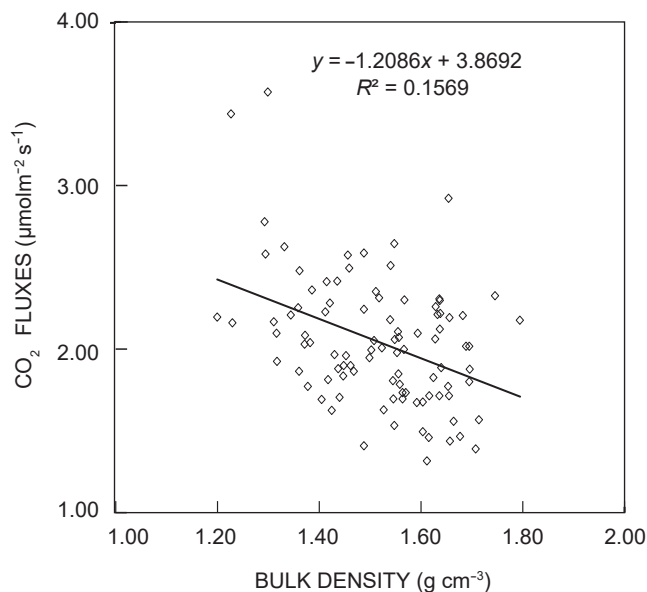
findings and they attributed the reduced CO<sub>2</sub> flux in a cold climate to reduced microbial activity. Previous studies have observed a close association between soil moisture and CO<sub>2</sub> flux, where CO<sub>2</sub> flux was higher under low soil moisture and lower under high soil moisture (Almaraz et al. 2009; Abdalla et al. 2014). No association between soil moisture and CO<sub>2</sub> flux was found in the present study. This could be because of differences in the rainfall distribution



**Figure 1:** Effects of (a) site, (b) tillage, (c) crop rotation, and (d) residue management on CO<sub>2</sub> fluxes with time, at the two experimental sites. Error bars represent least significant difference at  $\alpha = 0.05$ . CT = conventional tillage; MFM = maize–fallow–maize; MFS = maize–fallow–soybean; MWM = maize–wheat–maize; MWS = maize–wheat–soybean; R<sup>-</sup> = residue removal; R<sup>+</sup> = residue retention



**Figure 2:** Relationship between air temperature and CO<sub>2</sub> fluxes across the Phandulwazi and University of Fort Hare and crop treatments



**Figure 3:** Relationship between bulk density and CO<sub>2</sub> fluxes across the Phandulwazi and University of Fort Hare experimental sites and crop treatments

between the cited literature study sites and the current study. Most of the sites in the literature have a unimodal rainfall distribution with extended dry periods, while the Phandulwazi and UFH sites receive both winter and summer rainfall (Muzangwa 2016), and, as such, there was not much variation in soil moisture.

The reduced CO<sub>2</sub> fluxes with an increase in high bulk density (Figure 3) was as reported by Novara et al. (2012), who attributed this to reduced gas diffusivity with increased

bulk density, consequently reducing the oxidation rate, soil respiration and CO<sub>2</sub> flux. The wider difference between CT and no-till observed in June (Figure 1b) coincided with the time for tillage operations done in preparation for the winter trials. According to Carbonell-Bojollo et al. (2011), the maximum influence of tillage on CO<sub>2</sub> flux occurs during the first few weeks following the implementation of tillage.

## Conclusions

The study provided insights into the short-term effects of CA on C sequestration and CO<sub>2</sub> flux. Crop rotation and residue management are important determinants of biomass and carbon from crop residues under dryland CA systems of the Eastern Cape Province. Residue retention was critical in the improvement of POM and SOC; as such, it is a key principle for C sequestration in sub-humid and semi-arid agroecological regions. The crop rotations MWM and MWS have potential to be part of the solution to increase biomass and C-inputs, as well as improve soil biodiversity, in rain-fed smallholder farming in the Eastern Cape. Soil tillage, which involves ploughing, disking, and harrowing, increased CO<sub>2</sub> flux by 20% compared with no-till, regardless of site, underscoring the importance of no-till as a climate-smart agriculture tool.

**Acknowledgments** — We are grateful for funding from the Department of Agriculture Forestry and Fisheries (DAFF) through its Zero Hunger Project, the South African National Research Foundation (NRF), and the Govan Mbeki Research and Development Centre (GMRDC) of the University of Fort Hare. We thank Prof. Diane E Stott and Prof. Weldeclassie T Araya for their contribution to making the carbon-flux measurements.

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