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Tillage and crop rotation effects on soil carbon and selected soil physical properties in a Haplic Cambisol in Eastern Cape, South Africa

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Abstract: The effects of tillage and crop rotation on the soil carbon, the soil bulk density, the porosity and the soil water content were evaluated during the 6th season of an on-going field trial at the University of Fort Hare Farm (UFH), South Africa. Two tillage systems; conventional tillage (CT) and no-till and crop rotations; maize (*Zea mays* L.)-fallow-maize (MFM), maize-fallow-soybean (*Glycine max* L.) (MFS); maize-wheat (*Triticum aestivum* L.)-maize (MWM) and maize-wheat-soybean (MWS) were evaluated. The field experiment was a 2 × 4 factorial, laid out in a randomised complete design. The crop residues were retained for the no-till plots and incorporated for the CT plots, after each cropping season. No significant effects ($P > 0.05$) of the tillage and crop rotation on the bulk density were observed. However, the values ranged from 1.32 to1.37 g/cm^3. Significant interaction effects of the tillage and crop rotation were observed on the soil porosity ($P < 0.01$) and the soil water content ($P < 0.05$). The porosity for the MFM and the MWS, was higher under the CT whereas for the MWM and the MWS, it was higher under the no-till. However, the greatest porosity was under the MWS. Whilst the no-till significantly increased ($P < 0.05$) the soil water content compared to the CT; the greatest soil water content was observed when the no-till was combined with the MWM rotations. The soil organic carbon (SOC) was increased more ($P < 0.05$) by the no-till than the CT, and the MFM consistently had the least SOC compared with the rest of the crop rotations, at all the sampling depths (0–5, 5–10 and 10–20 cm). The soil bulk density negatively correlated with the soil porosity and the soil water content, whereas the porosity positively correlated with the soil water content. The study concluded that the crop rotations, the MWM and the MWS under the no-till coupled with the residue retention improved the soil porosity and the soil water content levels the most.

Keywords: conservation agriculture; crop residue; residue retention; soil physical properties

Tillage and crop rotation are crucial factors influencing soil quality, crop production and the sustainability of cropping practices (Munkholm *et al*. 2013). Mismanagement of these agricultural practices can result in unsustainable agro-ecosystems. However, conservation agriculture (CA) provides an opportunity for farmers to manage tillage and crop rotation practices in a sustainable way leading to the reduction and/or reversal of soil degradation. CA can also enhance soil organic carbon (SOC) resulting in a better soil health, improving the crop yields and minimising the production costs by administering the following principles: (*i*) minimum tillage and soil disturbance (*ii*) maintaining the organic soil cover by retaining crop residues and (*iii*) crop diversification through crop rotations (Hobbs *et al*. 2008).

Many studies have been carried out on the effect of no-till and other tillage systems on the soil's physical

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quality, but contradictory results have been reported in some instances. For example, tillage was found to have no effect on the soil bulk density by Huggins *et al*. (2007) whereas studies by Halvorson *et al*. (2002) observed a higher bulk density under the no-till than conventional tillage (CT). Velykis and Satkus (2005) reported that the physical soil degradation caused by CT reduced the soil bulk density relative to the no-till. However, Nyamadzawo *et al*. (2007) cited by Njaimwe (2010) reported a higher soil bulk density in CT relative to the no-till on kaolinitic sandy Chromic Luvisols in Zimbabwe. In contrast, Gwenzi *et al*. (2009) found no difference in the soil bulk density between the CT, the minimum tillage and the no-till on sandy loams after 6 years. The contrasting findings suggest that the soil type and previous crop production practices had an influence on how the tillage affects the soil's physical properties indicating the need to assess the impact of CA for each soil type and set of management practices.

The accumulation of plant residues in the no-till plays a vital role in reducing the soil bulk density, because the products from the residue decomposition promote more aggregation (Acharya *et al*. 2005). Van Donk *et al*. (2010) noted that the increased soil aggregation with the crop residue addition on the soil surface was essential in the soil water conservation. In comparison with CT, Pagliai *et al*. (2004) stated that a minimum tillage enhanced the soil porosity by increasing the storage pores. McVay *et al*. (2006), observed an increase in the soil water content that was at 0–10 cm in the soil depth under the no-till than that of the CT. Water conservation is made possible by the reduced evaporation through the residue retention from the previous crop compared to the bare soil (Olivier & Singels 2012). Plots with no residues were observed to have reduced water storage and increased matric potential compared to plots where residues were retained (Awe *et al*. 2014). The better soil aggregation with the crop residue retention is attributed to the associated increase in the SOC. SOC facilitates aggregation and the formation of faunal pores, together increasing the macro-porosity of the soil, which leads to more infiltration and soil water content (Bot & Benites 2005). The aggregation is more apparent under the no-till with the residue retention due to less oxidation of the organic matter compared to where the tillage is practised (Saha *et al*. 2010).

Crop rotation practised under CA improves the soil aggregate stability, organic matter content, and soil water content (Indoria *et al*. 2017). Appropriate crop rotation generates several micro and macro-pores that enable the movement of water, nutrients, and air into the soil promoting good root growth (Indoria *et al*. 2017). Thus, the integration of the no-till with the crop rotation might have valuable effects on the soil's physical properties. Nonetheless, these effects have not been adequately quantified in the Eastern Cape agro-ecologies and limited studies have concentrated on the combined influence of the tillage and crop rotation on the soil's physical properties. Therefore, the study seeks to evaluate the effects of the tillage and crop rotations on the soil bulk density, porosity and soil water content from an ongoing trial in the semi-arid environment of Eastern Cape, South Africa. The study hypothesised that the use of conservation agricultural practices of the no-till and rotational cropping can sustain or enhance the soil's physical properties of a Haplic Cambisol in Eastern Cape, South Africa.

MATERIAL AND METHODS

The experimental site. The field trial was established at the University of Fort Hare research farm (UFH) in the 2012/2013 season (Figure 1). The UFH site (32°47'S and 27°50'E) is at an elevation of about 508 m a.s.l. The experimental site is in a semi-arid area and receives an average amount of 575 mm annual precipitation. About 30% of the annual rainfall is received in winter and the rest in summer (Palmer & Ainslie 2006). According to the Soil Classification Working Group (1991), the site has surface layer soils of the Oakleaf form, classified as a Haplic Cambisol in the World Reference Base (WRB) classification (IUSS Working Group WRB 2006). The soil is fairly deep and of alluvial origin and classified as an Inceptisol in the USDA classification system (USDA Soil Taxonomy 1999). The general geology of the area is composed of the grey mudstone, shale, sandstone of the Balfour formation. Prior to the establishment of the trial, the land was under alfalfa (*Medicago sativa*) production.

The experimental design and field procedures. The experiment was carried out from an on-going field trial that was arranged in a split-split plot design consisting of 16 treatments with 3 replicates. The main plots were allocated to the no-till and conventional tillage. The main plots were split into four rotational crops which include maize-fallow-maize (MFM), maize-fallow-soybean (MFS), maize-winter wheat-

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maize (MWM) and maize-winter wheat-soybean (MWS). The sub sub-plots were allocated to the residue management at two levels; residue removal (R–) and residue retention (R+). The main plot sizes were 32.5 × 10 m, the sub plots were 7 × 10 m and the sub-sub plots were 5 × 7 m. The net plot measured 3 × 4 m. However, for the purpose of this study, only the tillage and crop rotations under the residue retention were considered to give a 2 × 4 factorial experiment laid out in a randomised complete design.

The experimental site was ploughed to a 30 cm depth using a three-furrow frame plough, disked and harrowed to create uniform conditions before the initial crop establishment. A short season and prolific maize cultivar (BG 5785BR, DuPont Pioneer, South Africa) was planted in the summer (October–February) targeting a population of 25 000 plants/ha, recommended for the dryland conditions in the central part of the Eastern Cape Province (Department of Agriculture 2003). The maize was spaced at 1 m inter rows and 0.4 m intra rows targeting a maize plant population of 25 000 plants/ha. The planting hills were opened using hoes and three seeds were dropped per hole at a depth of 7 cm, and later two maize seedlings were removed and one plant was left per station at 2 weeks after emergence (WACE). An early maturing, dryland spring wheat cultivar (SST015) was planted in winter (May–August) at a seeding rate of 100 kg/ha. A soybean cultivar (PAN 5409RG) was sown in the summer targeting a population of 250 000 plants/ha (~100 kg/ha). Both the soybean and the wheat were planted in rows spaced at 0.5 m apart and at a depth of 3–5 cm. An inorganic fertiliser was only applied to the summer maize crop at a rate of 90 kg N, 45 kg P and 60 kg K per ha in all the plots for a target yield of 5 t/ha. All the P, K and a 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 a limestone ammonium nitrate (LAN) at 6 weeks after planting by banding. The soybean was inoculated with *Rhizobium leguminosarium* before sowing. No irrigation was applied. All the residues were retained soon after harvesting each crop, whereas the tillage treatments were implemented just before planting of each cropping cycle (Table 1).

The field and laboratory measurements. The samples for the bulk density were taken after harvesting the 2015 winter wheat. Three soil samples were randomly taken at a 7.5 cm soil depth for the bulk density determination. A coring metal ring of 7.5 cm in height and a radius of 5.25 cm was driven into the soil using a core cylindrical sampler. The soil cores that were sampled were trimmed to the precise volume of the cylinder 649.43 cm^3 and dried at a temperature of 105°C for 24 h using an oven. The dry bulk density was determined from the ratio of mass of the dry soil per unit volume of the soil cores using Eq. (1) below:

$$\text{Bulk density} = M_d/V \quad (1)$$

where:
M_d – the mass of the dry soil sample (g)
V – the soil volume (cm^3)

The total porosity of the soil was determined from the dry bulk density values and the particle density of 2.65 Mg/m^3 was used. The results were multiplied by 100 to get the total porosity in a percentage as shown by Eq. (2) below.

$$\text{Total porosity (\%)} = \frac{1 - (\text{dry bulk density})}{\text{particle density}} \times 100 \quad (2)$$

The soil water content determination was done at the same time as mentioned above at a soil depth of 0–10 cm. Five sub-samples were collected for each treatment and were placed in tins of known mass. The tins were wrapped immediately to avoid any moisture loss from evaporation. The soils were weighed immediately after sampling. The total mass of the tin plus the soil was recorded and dried at

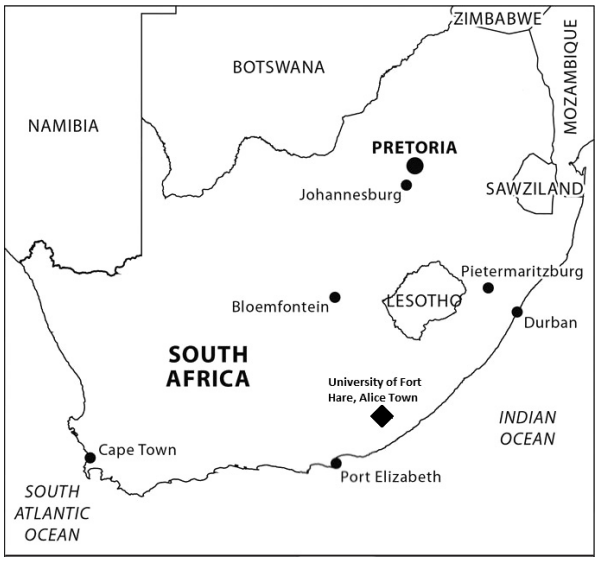

Figure 1. A map indicating the experimental site at the University of Fort Hare in the Eastern Cape Province of South Africa (map source: Google Maps)

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Table 1. The summary of the crop rotation treatments at the University of Fort Hare Farm, South Africa experimental site

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	Winter 2015 season 6
MFM	maize	fallow	maize	fallow	maize	fallow
MFS	maize	fallow	soybean	fallow	maize	fallow
MWM	maize	wheat	maize	wheat	maize	wheat
MWS	maize	wheat	soybean	wheat	maize	wheat

MFM – maize-fallow-maize; MFS – maize-fallow-soybean; MWM – maize-wheat-maize; MWS – maize-wheat-soybean; the summer season months are October, November, December, January and February; the winter season months are May, June, July and August

60°C for at least 72 h. After subtracting the mass of the tin, the soil mass was used to determine the soil water content. The soil samples for the SOC were collected at the same time as for the bulk density and these included five soil cores, which were sampled randomly to make a representative sample from each plot at three soil depths, at 0–5; 5–10 and 10–20 cm. The surface litter layer was cleared away before the sample collection. The samples were stored in a cold room (4°C) until use. The soil samples were air-dried and sieved using a 2 mm sieve in preparation for the analysis. The SOC was determined by dry combustion (Tru-Spec C/N, LECO, USA).

The statistical analysis. The collected data were subjected to a statistical analysis using the analysis of variance (ANOVA) techniques as described by Gomez and Gomez (1984). A JMP statistical package version 13.1 (SAS Institute Inc.) was used for the analysis of variance. The treatment means were separated using Fisher's unprotected least significant difference test at a 5% probability level. The regression analyses were performed to determine the relationships between the different physical parameters of the soil.

RESULTS

Soil physical properties

Bulk density. No significant ($P > 0.05$) effect of the tillage and crop rotation nor their interaction was observed on the soil dry bulk density. The bulk density ranged between 1.32 and 1.37 g/cm^3, across the treatments.

Porosity. The tillage × crop rotations interaction effects were significant ($P < 0.01$) on the measured soil porosity. The crop rotation main effects were significant ($P < 0.05$) whilst the tillage effects were not ($P > 0.05$) (Table 2). The CT increased the po-

Table 2. The interactive effects of the tillage and crop rotation effect on the soil porosity (%) measured at the University of Fort Hare Farm, South Africa experimental site

Tillage	Crop rotations				Mean
	MFM	MFS	MWM	MWS	
CT	45.28^{a}	38.06^{b}	33.52^{c}	48.18^{a}	41.25
No-till	35.28^{bc}	44.13^{a}	45.36^{a}	46.85^{a}	42.91
Mean	40.28^{B}	41.10^{B}	39.44^{B}	47.49^{A}	
Grand mean					42.08
ANOVA parameters	probability of > F				
Tillage (T)	0.14^{ns}				
Crop rotation (C)	0.03*				
T × C	0.01**				
CV (%)	10.4				

CT – the conventional tillage; MFM – maize-fallow-maize; MFS – maize -fallow-soybean; MWM – maize-wheat-maize; MWS – maize-wheat-soybean; *, ** significant at $P \leq 0.05$ and 0.01, respectively; ns – not significant; CV – the coefficient of variation; the capital letters show the differences between the main factor treatments and the small letters indicate differences between the interaction means at $P \leq 0.05$

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Table 3. The interactive effects of the tillage and crop rotation on the soil water content (%) measured at the University of Fort Hare Farm, South Africa experimental site

Tillage	Crop rotations				Mean
	MFM	MFS	MWM	MWS	
CT	11.36^{d}	11.40^{d}	10.43^{e}	10.50^{e}	10.92^{B}
No-till	14.77^{c}	15.57^{b}	16.57^{a}	15.43^{bc}	15.59^{A}
Mean	13.07	13.49	13.5	12.97	
Grand mean					13.25
ANOVA parameters	probability of > *F*				
Tillage (T)	0.01**				
Crop rotation (C)	0.095^{ns}				
T × C	0.05*				
CV (%)	3.17				

CT – the conventional tillage; MFM – maize-fallow-maize; MFS – maize -fallow-soybean; MWM – maize-wheat-maize; MWS – maize-wheat-soybean; *, ** significant at $P \leq 0.05$ and 0.01, respectively; ns – not significant; CV – the coefficient of variation; the capital letters show the differences between the main factor treatments and the small letters indicate differences between the interaction means at $P \leq 0.05$

rosity values of the MFM and MWS, and reduced the porosity for the rest of the rotations (Table 2). However, when all the rotations were averaged, a higher porosity was found under the MWS, whilst the rest of the rotations had significantly lower ($P < 0.05$) and comparable values.

Soil water content. The interaction of the tillage and crop rotation was significant ($P < 0.05$) with respect to the measured soil water content. The tillage main effects were also significant ($P < 0.01$) whilst the crop rotation main effects were not ($P > 0.05$) (Table 3). The MWM recorded the least soil water content (10.43%) under the CT, but had the highest soil water content (16.57%) under the no-till (Table 3). The MFS gave a higher soil water content value (11.40%) under the CT, but recorded the second highest value (15.57%) under the no-till. Whilst the rotation treatments were statistically similar, a slightly higher soil water content value was observed on the MWM (13.50%) and the MFS (13.49%) compared to the MFM (13.07%) and the MWS (12.97%) (Table 4). The no-till significantly increased ($P < 0.05$) the soil water content compared to the CT, across the crop rotations

Soil organic carbon

The tillage and crop rotation had a significant effect ($P < 0.05$) on the SOC at all the soil depths. Averaged across the soil depths, the no-till had a higher (1.30%) SOC compared to the CT (1.10%) (Table 4). The MFM consistently had the least SOC compared with the rest of the crop rotations, which were comparable, at all of the sampling depths. The interaction of the tillage and crop rotation was not

Table 4. The tillage and crop rotation effects on the soil organic carbon (SOC, %) at the University of Fort Hare Farm, South Africa experimental site measured from the different soil depths

Treatment	Soil depth (cm)		
	0–5	5–10	10–20
Tillage			
CT	1.17^{b}	1.06^{b}	1.09^{b}
No-till	1.36^{a}	1.25^{a}	1.28^{a}
$LSD_{0.05}$	0.08	0.04	0.03
Crop rotations			
MFM	1.08^{b}	1.00^{c}	1.02^{b}
MFS	1.28^{a}	1.22^{a}	1.19^{a}
MWM	1.30^{a}	1.15^{b}	1.16^{a}
MWS	1.40^{a}	1.25^{a}	1.18^{a}
$LSD_{0.05}$	0.11	0.05	0.15
CV (%)	11.72	11.11	7.89

MFM – maize-fallow-maize; MFS – maize-fallow-soybean; MWM – maize-wheat-maize; MWS – maize-wheat-soybean; the different letters in each column and the factor indicate the significant differences amongst the treatments; LSD – the least significant difference; ns – treatment not significant at $P \leq 0.05$ probability level; CT – the conventional tillage; CV – the coefficient of variation

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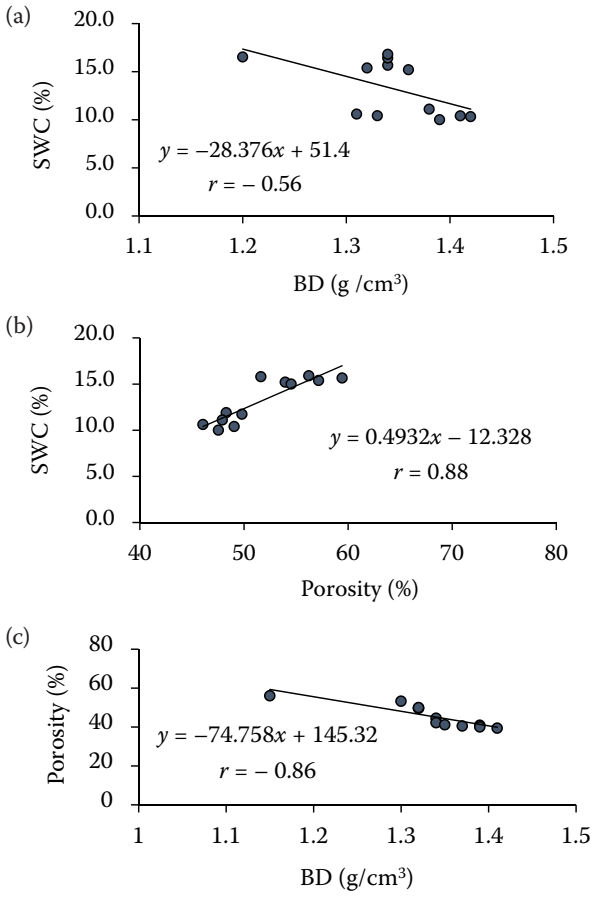

Figure 2. The correlation between the soil water content (SWC) and the bulk density (BD) (a), the SWC and the porosity (b), and the porosity and the BD (c)

significant ($P > 0.05$) on the SOC at all the sampling depths (Table 4).

The relationship between the soil's physical parameters

A negative correlation ($r = -0.56$) was found between the soil water content and the bulk density. The soil water content decreased with an increase in the bulk density (Figure 2a). There was a strong correlation ($r = 0.88$) observed between the soil water content and the soil porosity (Figure 2b). Again, a negative correlation ($r = -0.86$) between the bulk density and the soil porosity was observed where the soil porosity increased with a decrease in the bulk density (Figure 2c).

DISCUSSION

The non-significant effect of the tillage and crop rotation observed with the bulk density data could be due to the short duration of the experiment. A short-term increase in the bulk density is likely under the no-till, but will later decrease after a certain period due to the development of the soil pores, which originate from the biological activity (Jemai *et al.* 2013). The current experiment could be going through a transition phase, involving a build-up of humus, regaining the structural ability as well as the spore space restoration. However, the average bulk density values fell within the ideal range of 1.1–1.3 g/cm^3 for the optimum root growth in a medium textured soil with about 50 percent pore space (Eluozo 2013). Though there was a significant ($P < 0.05$) increase in the SOC under the no-till compared to the CT (Table 4), this did not translate to significant bulk density differences between the two tillage treatments (Table 2). This is in support with Mielke & Wihelm (1998) who pointed out that the tillage treatments affected the soil's physical properties when the same tillage system is practiced for a longer time.

The higher soil porosity with the MWS demonstrates the significance of the legume-based rotation in the soil's health. The inclusion of the soybean in a rotation system has the potential to create macropores after decomposition (Kavdir *et al.* 2005). No significant effect of the tillage on the porosity was observed in the present study and this was in agreement with the findings by Borresen (1999) who reported that the tillage, and the straw treatments had no significant effect on the total porosity and the pore size distribution. However, Allen *et al.* (1997) highlighted that the minimal tillage could result in an increase in the number of big pores. According to Costa *et al.* (2006), there were inconsistent reports by other researchers on the effects of soil tillage on the total porosity. For instance, Lipiec *et al.* (2006) reported that soils under CT usually have a lower bulk density and an accompanying increase in the total porosity within the plough layer than under the no-till. An increased bulk density reduces the soil volume and large pores are compressed causing a reduction in the soil porosity. The tillage effect on the soil's physical parameters can be attributed to many factors, such as the climate (Munkholm *et al.* 2013), the soil texture, the soil layer, the time of sampling, the organic matter content, the cropping systems, and the intensity of the machinery traffic (Alvarez & Steinbach 2009), resulting in the inconsistencies commonly observed in the results.

The study results suggest the important role played by crop rotation in improving the soil quality. The observed increase in the soil porosity under the MWS rotation comparative to the MWM and MFM rotations

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could be attributed to the relatively greater effect of the MWS treatment to increase the soil organic carbon (Table 4). This could most likely be because soybean residues undergo decomposition and get converted to organic matter faster than non-leguminous crop residues (Heine *et al.* 2011). The increased organic matter may have increased aggregation and concomitantly porosity. According to Eash *et al.* (1994), crop rotation with a lower organic matter supply leads to a loss of water stable aggregates and alongside a decline in the pore size. Kesik *et al.* (2010) pointed out that increasing the SOM levels and reducing the extent of the soil disturbance will increase the soil porosity and improve the structure. The significant increase in the soil water content in the no-till treatment compared to the CT could be linked to the potential higher surface retention under the no-till to conserve the water than the latter. Furthermore, the non-disruption of the soil pores under the no-till promoted the surface infiltration compared to the CT where the soil pores are disrupted and discontinued by converting the soil. Therefore, the adoption and practice of the no-till is one of the main methods, which can be utilised for water conservation in a dry land agriculture such as that in the Eastern Cape of South Africa. This ability to conserve water through the CA provides an opportunity for better crop production in the semi-arid areas of the Eastern Cape, where the rainfall is limited.

CONCLUSION

The tillage and crop rotation did not influence the bulk density during the short duration of this study. A longer monitoring period is recommended to allow sufficient time for the humus to build up, regain its structural ability and restore the spore space. The no-till with residue retention significantly improved the soil water conservation as shown by a significantly higher soil water content and is, therefore, recommended for the semi-arid conditions of the Eastern Cape. The crop rotation treatments, the MWM and the MWS improved the soil porosity and the soil water content levels the most. It is, therefore, concluded that the MWM and MWS crop rotations under the no-till coupled with the residue retention provide an effective approach for ensuring the good physical conditions of the soil in maize-based conservation farming in the rain-fed areas of the Eastern Cape.

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