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Research article

Carbon stock, aggregate stability and hydraulic properties of soils under tillage, crop rotation and mineral fertiliser application in sub-humid Zimbabwe

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ABSTRACT

Appropriate tillage and crop diversifications can improve soil quality leading to yield sustainability. Our objective was to quantify tillage, crop rotation and mineral fertiliser application effects on carbon sequestration, aggregation and soil water movement after two cropping cycles in the smallholder sector of Zimbabwe. Two split-plot experiments were set up at four sites on sandy, loamy and clayey soils. At experiment 1, crop rotation (maize-soya bean; continuous maize) was the main plot and mineral fertiliser (($NPKS$ ($180\ N + 30P_2O_5{+}30K_2O{+}6.5SO_3$ kg ha^{-1}); control (no fertiliser added)) was the sub-plot. At experiment 2, tillage (reduced, conventional) was the main plot and mineral fertiliser (NPKS; control) was the sub-plot. Soil samples collected from 0 to 0.2 m and 0.2–0.4 m layers were analysed for soil organic matter (SOM) content, bulk density and proportion of water stable aggregates. Saturated hydraulic conductivities (K_s), steady state infiltration rates (i_s) and soil sorptivities (S_p) were estimated from fitting field infiltration data into the Phillip model. SOM stocks (mean = 3.483 Mg ha^{-1}) were significantly increased by reduced tillage at the sandy site and higher ($p < 0.05$) in 0–0.20 m than in 0.20–0.40 m layers at clayey sites. Proportion of water stable aggregates increased ($p < 0.05$) under reduced tillage compared with conventional tillage and under rotation compared with continuous maize system. Bulk densities were 11% lower ($p < 0.05$) in the 0–0.20 m than in 0.20–0.40 m layers. The estimated K_s(1×10^{-4}-$8x10^{-4}$ cm s^{-1}) and i_s ($7.08–55 \times 10^{-4}$ cm s^{-1}) were at least 100% higher ($p < 0.05$) under rotation compared with continuous maize whilst sorptivities (0.050–0.143 cm s^{-05}) did not vary across the treatments. NPKS fertiliser reduced ($p < 0.05$) i_s by up to 1.8 fold compared with the control. Short term adoption of reduced tillage and maize-soya bean rotation can mitigate soil structural degradation; increase water recharging and increase carbon sequestration quicker in sands than in the buffering clays making the practices more relevant in the smallholder sector.

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1. Introduction

Conservation agriculture (CA) aims to achieve high and sustained crop yields based on minimal soil disturbance, permanent surface cover and crop rotations [1]. Simultaneous incorporation of the three CA practices improves soil organic carbon (SOC) stocks and related soil quality attributes [2–4]. Soil carbon sequestration enhances food security and reduces carbon emissions under CA, contributing immensely towards the achievement of the Sustainable Development Goals [3,5]. Soil organic carbon is important for agro ecosystem services. Other equally important soil attributes for agro ecosystem functionality include bulk density, aggregate stability, porosity, infiltration, hydraulic conductivity [6–8].

Mulching has the greatest impact on crop yields and soil physical quality compared with the other two CA practices [9,10]. However, adequate crop residues for mulching are difficult to secure in the smallholder sector in sub-Saharan Africa (SSA) due to competing utilization as fodder [3,11]. The CA package in the sub-Saharan Africa region has inevitably excluded the vital mulching practice resulting in low carbon input at mean rates of 0.55 g kg^{-1} soil yr^{-1} [12].

In SSA, about 65% of agricultural lands are dominated by poor fertility and severely degraded soils which can be reclaimed through promotion of SOC pool build up [13–16]. However, accelerated soil erosion occurs when conventional tillage breaks down soil aggregates exposing SOC to decomposition [5,15]. The SOC pool gradually declines throughout the erosion stages of detachment, breakdown, transport and sediment deposition [17].

Degradation of soil physical quality through conventional tillage leads to poor crop yields as reported by several authors in Zimbabwe [18–23]. Certain conventional tillage operations, though detrimental are still required in soils with undesirable physical conditions (such as hard setting, capping or compacted subsoil) to improve in-field water harvesting in the short term [24].

Adoption of reduced tillage, mulching and crop rotation under CA, in combination with mineral fertiliser application (the proposed fourth CA practice) could improve soil physical quality in sub-Saharan Africa [25–29]. The reduced tillage practices improve soil aggregation and SOC sequestration [30,31]. However, in Southern Africa, short term (<7 years) reduced tillage practices have marginally increased carbon stocks [12]. Elsewhere, peak carbon sequestration rates have been attained within 5–10 years after conversion to no-tillage practices under CA [32].

Reduced tillage systems coupled with addition of organic material and balanced nitrogen, phosphorus, potassium, sulphur (NPKS) fertiliser management lead to high crop yields and increase the prospects for reversing soil degradation [16,33,34]. Crop management practices that increase nitrogen availability particularly accelerate the carbon input into the soil, raising SOC sequestration [12,35].

The effect of tillage systems on the soil physical parameters is of importance in sustainable crop production. Bulk density is useful in determining and establishing compaction effects of tillage systems, while infiltration and hydraulic conductivity have a direct bearing on soil water balance [36].

Amelioration of physically degraded agricultural soils has been based on mulching in the smallholder sector of sub-Saharan Africa [11]. Most studies in Zimbabwe have focused on the effect of mulching under CA on soil physical properties without paying much attention to reduced tillage and crop rotation practices and the possible role of mineral fertiliser application in enhancing SOC sequestration [19,27,37,38]. Rotating crops with different rooting patterns combined with minimal soil disturbance in CA systems is envisaged to also promote good soil health [39]. The maize-soya bean rotation is commonly practiced in Zimbabwe to restore and maintain soil fertility. We therefore hypothesize that reduced tillage and maize-soya bean rotation combined with NPKS fertiliser application can significantly improve physical and hydraulic soil properties in the short term under smallholder farming conditions.

2. Materials and methods

2.1. Field site characteristics

The study was conducted between 2015/16 and 2017/18 growing seasons at one on-station and three on-farm experimental sites. Rainfall at all the sites is unimodal (November–April). The on-station site was located at Hunyani Farm of the Chinhoyi University of Technology (17° 19 ′47 ″ S; 30° 13 ′ 44 ″ E and 1140 m.a.s.l) in north western Zimbabwe. The site receives a mean annual rainfall

Table 1
Selected soil characteristics measured at study sites before the start of experiments in northern Zimbabwe.

Site	Depth (m)	% Clay	% Silt	% Sand	pH[†]	SOM (%)	CEC[‡]	Texture Class[§]	WRB soil class[¶]
Gara	0–0.2	40	27	33	5.0 ± 0.1	2.65 ± 0.11	25.0 ± 1.4	CL	Rhodic Ferralsol
	0.2–0.4	39	26	35	5.0 ± 0.1	1.94 ± 0.08	19.1 ± 0.9	C	
Hunyani	0–0.1	15	17	68	6.0 ± 0.2	1.48 ± 0.13	6.9 ± 0.3	fSaL	Chromic Luvisol
	0.1–0.2	16	18	66	5.9 ± 0.4	1.22 ± 0.01	6.7 ± 0.7	fSaCL	
Chibanda	0–0.2	4	2	92	3.8 ± 0.1	0.88 ± 0.02	4.7 ± 0.2	mS	Eutric Regosol
	0.2–0.4	7	4	89	5.6 ± 0.2	0.50 ± 0.09	5.8 ± 0.9	mS	
Mavhunga	0–0.2	16	2	82	5.0 ± 0.3	1.50 ± 0.03	4.3 ± 0.3	mSaL	Chromic Luvisol
	0.2–0.4	37	8	55	5.5 ± 0.3	0.71 ± 0.18	9.0 ± 1.0	mSaC	

NB: [†] measured using 0.01M$CaCl_2$ method, [‡] units are $cmol_+$ kg^{-1}; [§] texture class: CL = clay loam,C = clay, mLS = medium loamy sand, mSaL = medium sandy loam, mSaC = medium sandy clay, fSaL = fine sandy loam, fSaCL = fine sandy clay loam. [¶] soil classification according to IUSS Working Group (WRB, 2014).

total ranging between 750 and 1000 mm [40]. The soils at the site are derived from dacite (an intermediate volcanic rock) and comprise fine grained sandy loams over sandy clay loams classified as Chromic Luvisols [41]. In addition, the soils are prone to capping due to high content of silt and fine sand fractions (2–200 μm) [42].

The three on-farm sites were set up in smallholder farmer fields located in Mount Darwin, in northern Zimbabwe. Mount Darwin town is 156 km north of Harare, the capital of Zimbabwe. One site, on clayey soil classified as Rhodic Ferralsol (Gara farm; 16°48′33.6″ S; 31°34′41.8″E and 984 m.a.s.l), receives a mean of 750–1000 mm rainfall year^{-1}. The other two sites, one on sandy soil classified as Eutric Regosol (Chibanda farm: 16° 29′ 48.2″ S; 31° 41′ 1.7″E; 982 m.a.s.l) and another on clayey soil classified as Chromic Luvisol (Mavhunga farm: 16° 30′ 47.1″ S; 31° 40′ 4.3″E; 1011 m.a.s.l), were located in a region that receives a mean of 650–800 mm rainfall year^{-1} with higher intra-season dry spell frequencies.

Characterisation of soils at the sites was done before establishment of experiments in 2014 (Hunyani Farm) and 2015 (Mount Darwin sites). Composite soil samples collected on each block of the experimental sites were air dried, sieved (<2 mm) and analysed for texture, pH, organic matter, cation exchange capacity [43]. The soils were then classified according to WRB system [41]. The results for the soil analyses are given in Table 1.

2.2. Experimental procedure and treatments

Two experiments were set up in a randomised split-plot design with three replications (Fig. 1a a and Fig. 1b) To investigate the

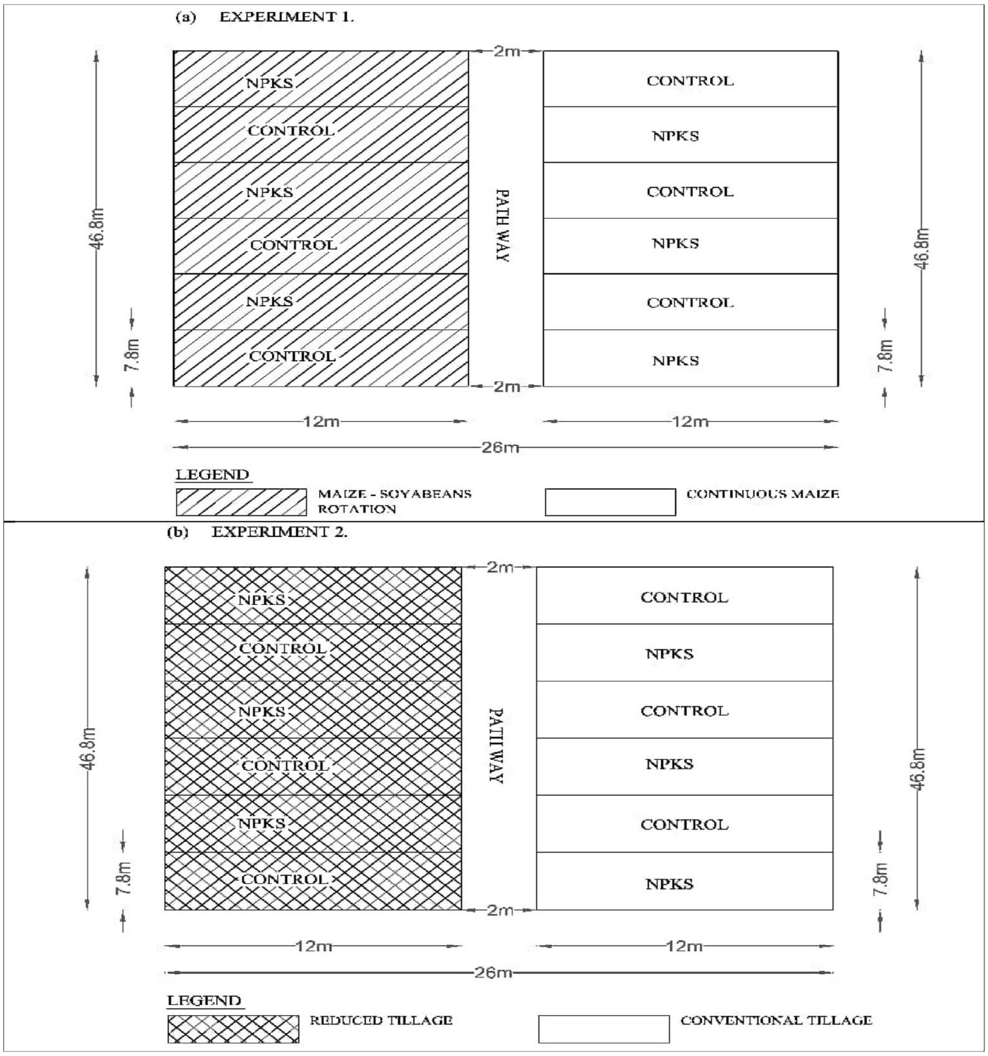

Fig. 1. Field layout plan for: (a) Experiment 1-main plot treatments were maize-soya bean rotation and continuous maize whilst the sub-plots were mineral fertiliser treatments comprising NPKS (180 N + $30P_2O_5$+$30K_2O$+$6.5SO_3$ kg ha^{-1}) and control (no fertiliser added)) (b) Experiment 2: main plot treatments were reduced tillage and conventional tillage while mineral fertiliser application comprising NPKS (180 N + $30P_2O_5$+$30K_2O$+$6.5SO_3$ kg ha^{-1}) and control (no fertiliser added) were the sub-plot treatments.

effect of rotation and mineral fertiliser application on soil physical properties under reduced tillage, the first experiment (Fig. 1a) was set up at Chibanda (sandy), Mavhunga (clay) and Gara (clay) smallholder sites with the following cropping sequences: (1) continuous maize, and (2) maize followed by soya beans. The main plot factor was crop rotation (maize-soya bean; continuous maize) whilst the sub-plot factor was mineral fertiliser application with the following treatments: (i) NPKS: Ammonium nitrate (34.5% N) + Single Super Phosphate (19.3% P_2O_5; 12%S) + Muriate of potash (60%K_2O) and (ii) No fertiliser added. The nutrient application rates were: 180 kg N ha^{-1} (applied as Ammonium nitrate-30% was at planting and the balance at 4–6 weeks after planting depending on rainfall distribution); 30 kg P_2O_5 and 6.5 kg SO_3 ha^{-1} applied as Single Super Phosphate and 30 kg K_2O ha^{-1} as muriate of potash at planting. The 180 N + $30P_2O_5$+$30K_2O$+$6.5SO_3$ kg ha^{-1} (NPKS) mineral fertilizer treatment represents the practice by resource-endowed farmers in sub-Saharan Africa who can afford mineral fertiliser while the control treatment represents the practice by resource-constrained farmers who do not use any fertility inputs due to poverty and lack of access to the fertilisers [16]. The experimental plots of mineral fertiliser application measured 12 m × 7.8 m (Fig. 1a).

The second experiment was set up at Chibanda sandy, Hunyani loamy and Gara clayey sites to quantify the effects of tillage mineral fertiliser application on SOM, bulk density, proportion of water stable aggregates, infiltration, sorptivity and saturated hydraulic conductivity under continuous maize (Fig. 1b). At each site, tillage (reduced tillage, conventional tillage) was the main plot factor and mineral fertiliser application ((NPKS (180 N + $30P_2O_5$+$30K_2O$+2.6S kg ha^{-1}); control (no fertiliser added)) was the sub-plot factor. At both experiments, soil sampling was done in the 0–0.2 m and 0.2–0.4 m layers.

In season 2 of the maize-soya bean rotation, Seed Co. variety (SC-Serenade) of soya bean seed inoculated with rhizobia (strain- MAR 1491 or USDA 110) was planted (0.45 m × 0.05 m) in reduced tillage plots with basal fertiliser applied at a rate of 7.5 N + $18P_2O_5$+$36K_2O$+ $13.3SO_3$ kg ha^{-1}. No top dressing of N was done presuming it was supplied from biological nitrogen fixation.

Planting basins for maize were dug with hand hoes on reduced tillage plots where a uniform maize stover mulch was then applied (3 Mg $ha^{-1}$$season^{-1}$). Each basin measured 0.15 m (deep) x 0.15 m (wide) [27]. On conventional tillage plots, crop residues were removed following the current farmers' practices where the residue is stored and later fed to livestock when the quality of natural pasture has significantly declined. An ox-drawn mouldboard plough was used for tillage (0.15 m deep) at on-farm sites while at Hunyani farm site, land was prepared by disking (0.20 m) using a tractor-drawn mouldboard plough and holing out was later done at planting when the first effective rains were received. A short season commercial maize hybrid variety, Pan 413 (130 days to maturity) was planted at the smallholder sites in the three consecutive growing seasons (2015/16–2017/18). At Hunyani site, the following mid-season maize varieties (125–140 days to maturity) were grown: Pan 53 (2015/16; 2017/18 seasons) and ZAP 61 (2016/17 season). Three seed kernels were planted per station and later thinned to two after emergence. Maize planting was done at spacings of: 0.90 m × 0.30 m (Gara site) and 0.90 m × 0.50 m (Hunyani, Chibanda and Mavhunga sites).

2.3. *Determination of soil physical quality parameters*

The infiltration rate, bulk density and organic carbon were determined at harvesting in the second growing season (2016/17).

2.3.1. *Bulk density*

The bulk density of the soils was determined on oven-dried (at 105 °C) intact cores (100 cm^3) collected at depths of 0–0.2 m and 0.2–0.4 m. The bulk density of each core sample was calculated based on the oven dry weight.

2.3.2. *Water stable aggregates*

Soil samples for aggregate stability analysis were collected from 0 to 0.2 m and 0.2–0.4 m soil layers and measured by the wet sieving method [44]. The proportion of water stable aggregates (WSA) was calculated as the mass of soil aggregates obtained in the "NaOH cans" divided by the sum of the masses obtained in NaOH cans and distilled water cans (equation (1)):

$$WSA = \frac{Mds}{Mds + Mdw} \tag{1}$$

where, WSA is the proportion of water stable aggregates *Mds* is the mass of aggregates dispersed in the dispersing solution (NaOH) and *Mdw* is the mass of aggregates dispersed in distilled water.

2.4. *Organic carbon and carbon stocks*

Soil organic matter content was estimated by the loss on ignition (LOI) method on drying about 2 g of sieved (<425 μm) soil samples at 105 °C for 24 h in an oven which were cooled in a desiccator and weighed [45]. The samples were further dried at 550 °C in a muffle furnace for 4–6 h, cooled and weighed. The organic matter content was calculated as LOI_{550} (equation (2)):

$$LOI_{550} = \frac{100 * (M_{105} - M_{550})}{M_a} \tag{2}$$

where LOI_{550} is the loss on ignition percentage at 550 °C, M_{105} is mass of sample after heating at 105 °C, M_{550} is mass of sample after heating at 550 °C and M_a is the mass of air dry sample.

Soil organic matter stocks (Mg C ha^{-1}) for each 0.20 m layer (SOMi) was calculated according to Equation (3) [46]:

$$SOM_i = \frac{D_i * \rho_b}{10} \tag{3}$$

Where, SOM_i is soil organic matter content (g kg^{-1}) is the soil organic matter stock of the *i*th layer, $i = 0–0.2$ m or 0.2–0.4 m, D_i is the ith soil layer thickness (m), ρ_b is the dry bulk density (Mg m^{-3}), 10^{-1} is the correction factor (m^2 ha^{-1}).

2.5. Hydraulic properties

2.5.1. Infiltration measurement

The cumulative infiltration of water into the soil was measured *in situ* using a mini disk infiltrometer (Decagon Devices, Inc.) [48]. The mini disk infiltrometer comprises a graduated reservoir chamber and a bubble chamber connected via Mariotte tube to give a constant pressure head or suction. At its bottom, the mini disk infiltrometer has a porous sintered disk (diameter = 45 mm and thickness = 3 mm). The water filled infiltrometer was placed on the soil surface and the water volume in the reservoir chamber was recorded at 0.5-min intervals as the infiltration process proceeded and stopped on stabilisation after 6–9 min. A suction head of 0.02 m (equivalent to −0.2 kPa pressure head) was chosen at the clay sites and 0.04 m (or −0.4 kPa) at sandy sites.

The measurements were conducted in control plots (without mineral fertiliser application) and plots that received NPKS in reduced tillage, conventional tillage, continuous maize and maize-soya bean sequences at the sites. Infiltration measurements were done at three points per plot.

2.5.2. Fitting the Philip model

In this study, data on cumulative infiltration were plotted against time to fit into the Philip function for vertical infiltration into dry soil ([47]; Equation (4)):

$$I = C_1 t + C_2 t^{0.5} \tag{4}$$

where, I (cm) is the cumulative infiltration (cm) while C_1 (cm s^{-1}) is related to the saturated hydraulic conductivity (K_s) and C_2 (cm $s^{-0.5}$) is related to the soil sorptivity and t is the elapsed time (s).

The hydraulic conductivity of the soil was calculated according to equation (5).:

$$K_s = \frac{C_1}{A_1} \tag{5}$$

where, C_1 (cm s^{-1}) is the slope of the curve of the cumulative infiltration vs. the square root of time, and A_1 (unitless) is a value relating the Van Genuchten parameters for a given soil type to the suction and radius of the infiltrometer disk [48,49]. A plot of cumulative infiltration vs square root of time produced a quadratic function and the quadratic coefficient was equivalent to C_1, which was then used to compute K_s of a given soil according to equation (5).

The soil sorptivity was calculated using equation (6):

$$S_p = \frac{C_2}{A_2} \tag{6}$$

where, S_p is the soil sorptivity (cm $s^{-0.5}$) and A_2 is a value relating the Van Genuchten parameters for a given soil type, suction and radius of the disk infiltrometer [49].

2.6. Statistical data analyses

Organic carbon, bulk density, total porosity, steady state infiltration rate, proportion of water stable aggregates, sorptivity and K_s data were first tested for normality. The Shapiro-Wilk test showed that data on saturated hydraulic conductivity were not normally distributed requiring a log-transformation. All the data were then subjected to analysis of variance (ANOVA) using the general linear model in GenStat (14th edition) (Rothamsted Experimental Station, UK) to test for the individual and interactive effects of tillage, rotation, soil depth and mineral fertiliser application. Separation of treatment means was done using the least significant differences (LSDs) at 5% level of probability.

3. Results

3.1. Background soil characteristics

The soils at Gara, Hunyani and Mavhunga sites had high content of the clay (<2 μm), silt (2–20 μm) and fine sand fractions (20–200 μm) belonging to the fine sandy loam to clay (160–400 g clay kg^{-1}) textural classes which are vulnerable to surface capping and subsoil compaction (Table 1). Sandy soils (40–100 g clay kg^{-1}) dominated by the medium sand fraction (200–500 μm) were observed at Chibanda site (Table 1). The SOM concentrations were low among the sites (<26.48 g kg^{-1}) [50].

3.2. Tillage and mineral fertiliser application effects on soil quality parameters

3.2.1. Soil organic matter

The soil organic matter (SOM) concentration was significantly increased ($p < 0.05$) under reduced tillage compared with conventional tillage systems at Chibanda sandy site (Table 2). The NPKS fertiliser application and soil depth had no significant effect ($p > 0.05$) on SOM concentration. At Mavhunga clayey site, the SOM concentration was not affected by tillage system, mineral fertiliser application and soil depth ($p > 0.05$; Table 2). However, tillage x soil depth interaction was significant ($p < 0.01$) at Mavhunga, such that the SOM concentrations were highest in the 0–0.2 m layer under reduced tillage and least in the 0.2–0.4 m layer under conventional tillage. In addition, tillage x soil depth x mineral fertiliser application interaction was significant ($p < 0.05$) at Mavhunga such that the highest SOM concentration was observed in the 0–0.2 m layer where no fertiliser was applied under reduced tillage (Table 2).

The SOM concentration was not affected by tillage system and mineral fertiliser application at Hunyani on-station loamy site ($p > 0.05$; Table 2). Nevertheless, the 0–0.2 m layer had 12.7% higher ($p < 0.05$) SOM concentration compared with the 0.2–0.4 m layer at this site (Table 2).

The SOM stocks ranged from 2.41 Mg ha^{-1} (Chibanda conventional tillage) to 4.56 Mg ha^{-1} (Mavhunga reduced tillage) (Table 2). The reduced tillage system significantly increased ($p < 0.05$) the soil organic matter stock by 7% compared with conventional tillage at Chibanda sandy site. However, tillage system had no effect on SOM stocks at Mavhunga and Hunyani clayey sites (Table 2). The organic matter stocks were generally higher under NPKS fertilizer application compared with control but the differences were not significant ($p > 0.05$). Tillage x soil depth interaction was significant ($p < 0.05$) at Mavhunga clayey site where the 0–0.2 m layers sequestered more carbon than the corresponding 0.2–0.4 m layers under reduced tillage and conventional tillage systems. The clayey and loamy sites had an average of 1.20 Mg ha^{-1} higher SOM stocks compared with the Chibanda sandy site.

3.2.2. Bulk density

Tillage and NPKS fertiliser application had no effect on bulk density after two seasons at Chibanda, Hunyani and Gara sites ($p > 0.05$; Table 3).The mean bulk densities were 8.4–9.3% lower ($p < 0.05$) in 0–0.2 m soil layers compared with the 0.2–0.4 m layers at Chibanda and Hunyani sites but were not different between the two layers at Gara clayey site ($p > 0.05$; 1.16–1.19 Mg m^{-3}) (Table 3). There were no significant treatment interaction effects on bulk density at the three sites.

Crop rotation, NPKS fertiliser and soil depth had no significant effect ($p > 0.05$) on soil bulk density at Mavhunga and Gara clayey sites (Table 4). However, at Chibanda sandy site, the bulk density was 13.4% lower ($p < 0.001$) in 0–0.2 m layer compared with the 0.2–0.4 m layer.

3.2.3. Water stable aggregates

The mean proportion of water stable aggregates (WSA) were medium to high (0.417–0.583) for the continuous maize system at Chibanda, Gara and Hunyani sites (Table 3). At the sandy Chibanda site, WSA under reduced tillage was 37.4% higher ($p < 0.05$) compared with the conventional tillage system. The NPKS fertiliser application significantly increased ($p < 0.05$) the proportion of water stable aggregates by 15.7% compared with the control. Tillage, NPKS fertiliser application and soil depth had no influence ($p >$

Table 2
Effects of tillage (reduced tillage; conventional tillage); inorganic fertiliser application (NPKS and control) and soil depth on soil organic matter concentration (g kg^{-1}) and carbon stocks in continuous maize system at Chibanda, Hunyani and Mavhunga farm sites in the 2016/17 season.

Treatment	Chibanda	Hunyani	Mavhunga	Chibanda	Hunyani	Mavhunga
	Organic matter concentration (g kg^{-1})			Organic matter stocks (Mg ha^{-1})		
Tillage (T)						
Reduced tillage	10.82 ± 0.087b	13.93 ± 0.043a	12.90 ± 0.03a	2.58 ± 0.204b	4.02 ± 0.139a	4.56 ± 0.107a
Conventional tillage	10.03 ± 0.087a	12.21 ± 0.043a	13.16 ± 0.03a	2.41 ± 0.204a	3.70 ± 0.139a	3.49 ± 0.107a
Sig.	*	NS	NS	*	NS	NS
Inorganic fertiliser application (FA)						
Control	9.41 ± 0.087a	13.07 ± 0.043a	13.07 ± 0.03a	2.36 ± 0.204a	3.92 ± 0.139a	3.41 ± 0.107a
NPKS	10.29 ± 0.087a	13.07 ± 0.043a	12.9 ± 0.03a	2.53 ± 0.204a	3.80 ± 0.139a	3.63 ± 0.107a
Sig.	NS	NS	NS	NS	NS	NS
Depth (m) (D)						
0–0.20	10.92 ± 0.087a	13.76 ± 0.043a	13.24 ± 0.03a	2.51 ± 0.204a	4.28 ± 0.139a	3.63 ± 0.107a
0.20–0.40	8.77 ± 0.087a	12.21 ± 0.043b	12.9 ± 0.03a	2.37 ± 0.204a	3.44 ± 0.139a	3.41 ± 0.107a
Sig.	NS	*	NS	NS	NS	NS
Interactions				NS		
TxFA	NS	NS	NS	NS	NS	NS
TxD	NS	NS	**	NS	NS	*
FAxD	NS	NS	*	NS	NS	NS
TxFAxD	NS	NS	*	NS	NS	NS

Note: NPKS = $180N + 30P_2O_5+30K_2O+6.5SO_3$ kg ha^{-1}. T x FA: Tillage x inorganic fertiliser application interaction; TxD: TillagexDepth interaction; FAxD: inorganic fertiliser application xDepth interaction, TxDxFA: TillagexDepthx inorganic fertiliser application interaction, Sig.: significant differences at probability, $p < 0.05$ (*), NS:not significant at $p = 0.05$. Means in the same column followed by different letters are significantly different at $p < 0.05$ for a given treatment.

Table 3

Effects of tillage (reduced tillage; conventional tillage); inorganic fertiliser application (NPKS and control) and soil depth on bulk density and proportion of water stable aggregates (WSA) in a continuous maize system at Chibanda, Hunyani and Gara sites in the 2016/17 season.

Treatment	Chibanda	Hunyani	Gara	Chibanda	Hunyani	Gara
	Bulk density (Mg m^{-3})			WSA		
Tillage (T)						
Reduced tillage	1.44 ± 0.034a	1.46 ± 0.031a	1.19 ± 0.026a	0.573 ± 0.0487a	0.484 ± 0.019a	0.527 ± 0.0628a
Conventional tillage	1.45 ± 0.034a	1.49 ± 0.031a	1.16 ± 0.026a	0.417 ± 0.0487b	0.491 ± 0.019a	0.559 ± 0.0628a
Sig.	NS	NS	NS	**	NS	NS
Inorganic fertiliser application (FA)						
Control	1.44 ± 0.034a	1.50 ± 0.031a	1.18 ± 0.026a	0.459 ± 0.0487a	0.505 ± 0.019a	0.503 ± 0.0628a
NPKS	1.44 ± 0.034a	1.45 ± 0.031a	1.17 ± 0.026a	0.531 ± 0.0487b	0.471 ± 0.019a	0.583 ± 0.0628a
Sig.	NS	NS	NS	*	NS	NS
Depth (D) (m)						
0–0.20	1.37 ± 0.034a	1.41 ± 0.031a	1.16 ± 0.026a	0.484 ± 0.0487a	0.491 ± 0.019a	0.534 ± 0.0628a
0.20–0.40	1.51 ± 0.034b	1.54 ± 0.031b	1.19 ± 0.026a	0.506 ± 0.0487a	0.484 ± 0.019a	0.553 ± 0.0628a
Sig.	***	*	NS	NS	NS	NS
Interactions						
TxFA	NS	NS	NS	NS	NS	NS
TxD	NS	NS	NS	NS	NS	NS
FAxD	NS	NS	NS	NS	NS	NS
TxFAxD	NS	NS	NS	NS	NS	NS
C.V.%	4.7	7.3	8.1	24.1	18.3	28.3

Note: C.V: Coefficient of variation, NPKS = $180N + 30P_2O_5+30K_2O+6.5SO_3$ kg ha^{-1}; T x FA: Tillage x inorganic fertiliser application interaction; TxD: TillagexDepth interaction; FAxD: inorganic fertiliser application × depth interaction, TxDxFA: TillagexDepthx inorganic fertiliser application interaction, Sig.: significant differences at probability, $p < 0.05$ (*), NS:not significant at $p = 0.05$. Means in the same column followed by different letters are significantly different at $p < 0.05$ for a given treatment.

Table 4

Effects of crop rotation (continuous maize; Maize-soya bean); inorganic fertiliser application (NPKS; Control) and soil depth on bulk density and proportion of water stable aggregates (WSA) under reduced tillage in the 2016/17 season at Chibanda, Mavhunga and Gara sites.

Treatment	Chibanda	Mavhunga	Gara	Chibanda	Mavhunga	Gara
	Bulk density (Mg m^{-3})			WSA		
Rotation sequence (R)rowheadrowheadrowhead						
Maize-soya bean	1.42 ± 0.034a	1.41 ± 0.04a	1.21 ± 0.039a	0.573 ± 0.0537a	0.560 ± 0.038a	0.559 ± 0.09a
Continuous maize	1.44 ± 0.034a	1.38 ± 0.04a	1.16 ± 0.039a	0.484 ± 0.0537b	0.483 ± 0.038b	0.495 ± 0.09b
Sig.	NS	NS	NS	*	*	*
Fertiliser application (FA)rowhead						
Control	1.42 ± 0.034a	1.41 ± 0.04a	1.20 ± 0.039a	0.513 ± 0.0537a	0.520 ± 0.038a	0.514 ± 0.09a
NPKS	1.43 ± 0.034a	1.38 ± 0.04a	1.17 ± 0.039a	0.544 ± 0.0537a	0.524 ± 0.038a	0.540 ± 0.09a
Sig.	NS	NS	NS	NS	NS	NS
Soil depth (D) (m)rowhead						
0–0.20	1.34 ± 0.034a	1.40 ± 0.04a	1.18 ± 0.039a	0.587 ± 0.0537a	0.509 ± 0.038a	0.517 ± 0.09a
0.20–0.40	1.52 ± 0.034b	1.39 ± 0.04a	1.19 ± 0.039a	0.479 ± 0.0537b	0.535 ± 0.038a	0.537 ± 0.09a
Sig.	***	NS	NS	*	NS	NS
Interactionsrowhead						
RxFA	NS	NS	NS	*	NS	NS
RxD	NS	NS	NS	NS	NS	NS
FAxD	NS	NS	NS	NS	NS	NS
RxFAxD	NS	NS	NS	NS	NS	NS
C.V.%	5.5	7.0	7.4	20.8	18.0	16.9

Note: C.V: Coefficient of variation, NPKS = $180N + 30P_2O_5+30K_2O+6.5SO_3$ kg ha^{-1}, RxFA: Rotation x inorganic fertiliser application interaction, RxD: Rotation × Depth interaction; FAxD: inorganic fertiliser application × Depth interaction, RxDxFA: Rotation x Depth x inorganic fertiliser application interaction, Sig.: significant differences at probability, $p < 0.05$ (*), N.S. not significant at $p = 0.05$. Means in the same column followed by different letters are significantly different at $p < 0.05$ for a given treatment.

0.05) on proportion of water stable aggregates at Gara clayey site and Hunyani loamy site.

In the maize-soya bean rotation sequence, mean proportion of water stable aggregates ranged between 0.479 and 0.587 (medium to high) at Gara, Chibanda and Mavhunga sites (Table 4). The maize-soya bean rotation significantly ($p < 0.05$) increased the proportion of water stable aggregates by 12–19% compared with continuous maize system across the three sites. The NPKS fertiliser application and soil depth had no effect on the proportion of water stable aggregates at Mavhunga and Gara clayey sites. At Chibanda sandy site, the 0–0.2 m layer had 22.5% higher ($p < 0.05$) proportion of water stable aggregates compared with the 0.2–0.4 m layer.

There was a significant interaction ($p < 0.05$) of rotation and mineral NPKS fertiliser on the proportion of water stable aggregates observed at Chibanda site. The proportion of water stable aggregates under continuous maize with NPKS fertiliser application was 31% higher ($p < 0.05$) compared with the control. In addition, the proportion of water stable aggregates under maize-soya bean rotation was 23–48% higher ($p < 0.05$) under NPKS fertiliser application compared with the control.

3.3. *Saturated hydraulic conductivity and soil sorptivity*

The mean saturated hydraulic conductivity values ranged between 0.97 and 2.20 cm h^{-1} at based on Philip model (Equation (4); Table 5). The maize-soya bean rotation significantly ($p < 0.05$) increased K_s (by 2.26 fold) compared with continuous maize (Table 5). Moderate K_s (1.8–18 cm h^{-1}) were observed under the maize soya bean rotation compared with continuous maize system which had a low mean K_s value of 0.97 cm h^{-1} (Table 5). Although NPKS fertiliser application and interactions of treatments did not affect ($p > 0.05$) the response of K_s, the values were 4.4% lower ($p > 0.05$) in the NPKS treatment than in the control.

The estimated soil sorptivity, S_p at the study sites ranged between 0.0501 and 0.1430 cm s^{-05} (Table 5). No differences ($p > 0.05$) in sorptivity were observed when maize soya bean rotation sequence was compared with continuous maize sequence and NPKS fertiliser application was compared with control.

3.3.1. *Infiltration rates*

The influence of tillage, NPKS fertiliser application, rotation on steady state infiltration rates (i_s) is shown on Figs. 2–4. The extrapolated initial infiltration rates (i_o) ranged from 10.8 cm h^{-1} (Hunyani loamy site without mineral fertiliser) to 79.2 cm h^{-1} (Chibanda sandy site receiving NPKS fertiliser under maize soya bean rotation). The initial rates decayed to the steady state infiltration rates (i_s) that varied widely across the sites and management regimes. The i_s ranged from 2.55 cm h^{-1} (Hunyani loamy site under conventional tillage) to 19.8 cm h^{-1} (Chibanda sandy site under reduced tillage). Under the reduced tillage system, the i_s at the control soils were 1.45–1.6 fold higher compared with NPKS fertiliser application (Fig. 2). Chibanda sandy soils had 1.7–2 fold higher ($p < 0.05$) i_s than the Mavhunga clayey soils under the reduced tillage system (Fig. 2).

Under the reduced tillage system, the i_s range was: 4.18–13.32 cm h^{-1}. The NPKS fertiliser reduced i_s of the soils by 1.8 fold (Chibanda sand; $p < 0.05$), 1.36 (Mavhunga clay; $p > 0.05$) and 1.25 (Hunyani loam; $p > 0.05$) compared with the control (Fig. 3). At Chibanda sandy site, the i_s was 55.8% significantly lower under reduced tillage than conventional tillage ($p < 0.05$) but statistically similar ($p > 0.05$) at Mavhunga clayey and Hunyani loamy site due to disparities in compaction levels under the two tillage systems (Fig. 4). The greatest impact of the reduced tillage system on i_s rate of soils was observed at Hunyani loamy site where it was 4.75 fold higher than under the conventional tillage system ($p < 0.05$) (Fig. 4).

4. Discussion

The SOM concentrations in this study were low (9–14 g kg^{-1}) suggesting limited organic matter input and the tropical conditions promoted rapid oxidative breakdown of the organic matter. This consequently led to a slow build-up of organic carbon levels in the soils. The observed SOM levels were 18–48% below the minimum threshold of 17.2 g kg^{-1} (recalculated) for well managed soils [23].

The total SOM stocks were significantly increased under the reduced tillage system compared with the conventional tillage system at Chibanda sandy site. This trend can be attributed to a higher sensitivity of sandy soils than that of clays and loams to SOM input resulting from maize stover applied annually to the RT plots. This suggests a higher buffering capacity of the clayey soils which caused a lag in SOM build up under the reduced tillage system. However, C sequestration benefits from reduced tillage adoption have been reported to accrue in the medium to long term (10–20 years) in most soils [32,51]. In addition, under the conventional tillage system, the SOC protected macroaggregates were converted to C depleted micro aggregates resulting in lower C sequestration than under the reduced tillage system where there was SOM accumulation [52,53].

Higher carbon sequestration was observed at the loamy (Hunyani) and clayey (Mavhunga) sites than at the Chibanda sandy site

Table 5

Estimated mean saturated hydraulic conductivity and soil sorptivity (Sp) under reduced tillage in response to crop rotation (continuous maize; maize-soya bean) and inorganic fertiliser application (control; NPKS) in 2016/17 season at the smallholder sites.

Treatment	Saturated hydraulic conductivity, K_s (x 10^{-4} cm s^{-1})	†K_s rating	Sorptivity, Sp (cm $s^{-0.5}$)
Rotation sequence (R)			
Maize-soya bean	6.1 ± 0.11b	moderate	0.0501 ± 0.04a
Continuous maize	2.7 ± 0.23a	low	0.143 ± 0.07a
Sig.	*		NS
Inorganic fertiliser application (FA)			
control	4.5 ± 0.28a	low	0.1409 ± 0.06a
NPKS	4.3 ± 0.31a	low	0.0523 ± 0.038a
Sig.	NS		NS
Interactions			
RxFA	NS		NS

Note: NPKS = $180N + 30P_2O_5+30K_2O+6.5SO_3$ kg ha^{-1}, RxFA: Rotation x Inorganic fertiliser application interaction, Sig.: significant differences at probability, $p < 0.05$ (*), NS. not significant at $p = 0.05$. Means in the same column followed by different letters are significantly different at $p < 0.05$ for a given treatment. † Ks rating scale ($\times 10^{-4}$ cms^{-1}): very low (<1); low (1–5); moderate (5–50), high (50–100), very high (>100)- Adapted from Reynolds et al. (2003).

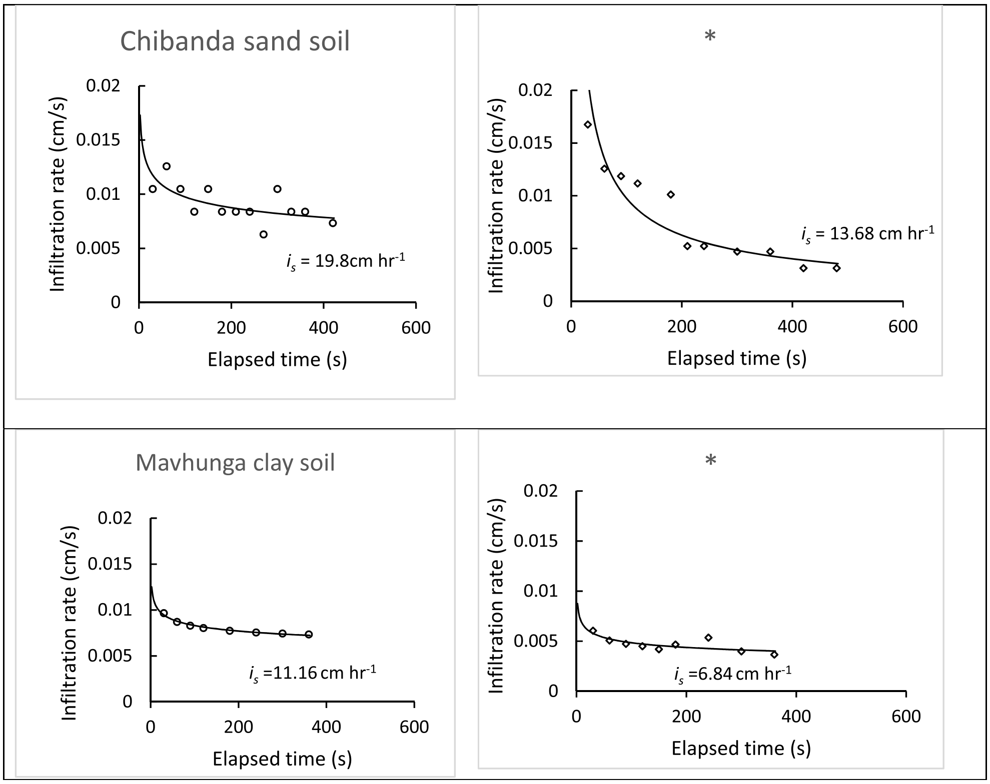

Fig. 2. Effect of inorganic fertiliser application (control-ο-; NPKS -◇-) on infiltration rate of soils under maize-soya bean rotation at Chibanda and Mavhunga smallholder sites. i_s is the steady state infiltration rate according to the Philip model. *significant differences in overall i_s at probability, $p < 0.05$.

(Tables 1 and 2). The superiority of C sequestration in clayey soils can be attributed to the formation of stable organic-clay mineral complexes leading to higher SOM content (Table 1). The complexes curtailed soil organic matter decomposition and promoted its accumulation. Similar findings were reported in weathered tropical soils with high sesquioxide content that promoted soil organic matter build up and soil aggregation [13,52,54].

A significant interaction effect of tillage and soil depth on SOM led to better C sequestration under reduced tillage system in the top soil. This interaction was attributed to limited exposure of C to oxidative decomposition as the soil was not turned much under the reduced tillage system. However, there was shallow tilling depth (of up to 20 cm) by the ox drawn mouldboard ploughs used at the smallholder sites under the conventional tillage system. There was limited mixing of top and sub soil layers suggesting maintenance of SOC stratification. Consequently, the soil organic matter stratification was not significantly disrupted under conventional tillage in the 2 years the experiment ran.

Soil organic matter stocks were generally higher but similar under NPKS fertiliser compared with control (no fertiliser) under both tillage systems. This is attributed to the fact that the mineral fertilisers did not accelerate build-up of C stocks in soils in the short term and organic carbon stabilisation in the soil was also minimal. The SOM build up would indirectly depend on the quantity of biomass produced from the fertiliser application. The mineral fertiliser application indirectly improves soil organic carbon levels as a spin-off benefit. However, long-term studies on CA practices have shown that nutrient availability through fertiliser application (organic and mineral) increase plant biomass production (C input) and improve SOC sequestration rates [35]. Despite a compromised capacity of mineral fertilisers to promote C sequestration, mineral nitrogen application is a catalytic practice that accelerates C sequestration under CA systems through large biomass production.

The soil structural stability and aggregation indicate the soil's ability to withstand erosion and maintain good porosity. This study showed that the proportion of water stable aggregates was significantly improved by the maize-soya bean rotation compared with the continuous maize system at Chibanda, Mavhunga and Gara sites (Table 4). Crop rotation consistently improved the proportion of water stable aggregates across the sites suggesting the importance of the legume crop (soya bean) included in the rotation system in enhancing aggregation irrespective of the soil texture [55,56]. Improved soil aggregation was similarly increased in a rotation system that intercropped maize with three legumes (alfalfa, clover and hairy vetch) compared with a continuous maize system in a 3 year study [57].

At Chibanda sandy site, the reduced tillage system significantly increased the proportion of water stable aggregates by 37% compared with conventional tillage where the continuous maize system was used (Table 3). This was attributed to the key role played by SOM in aggregation. The SOM was higher under reduced tillage leading to a higher proportion of water stable aggregates. The lower

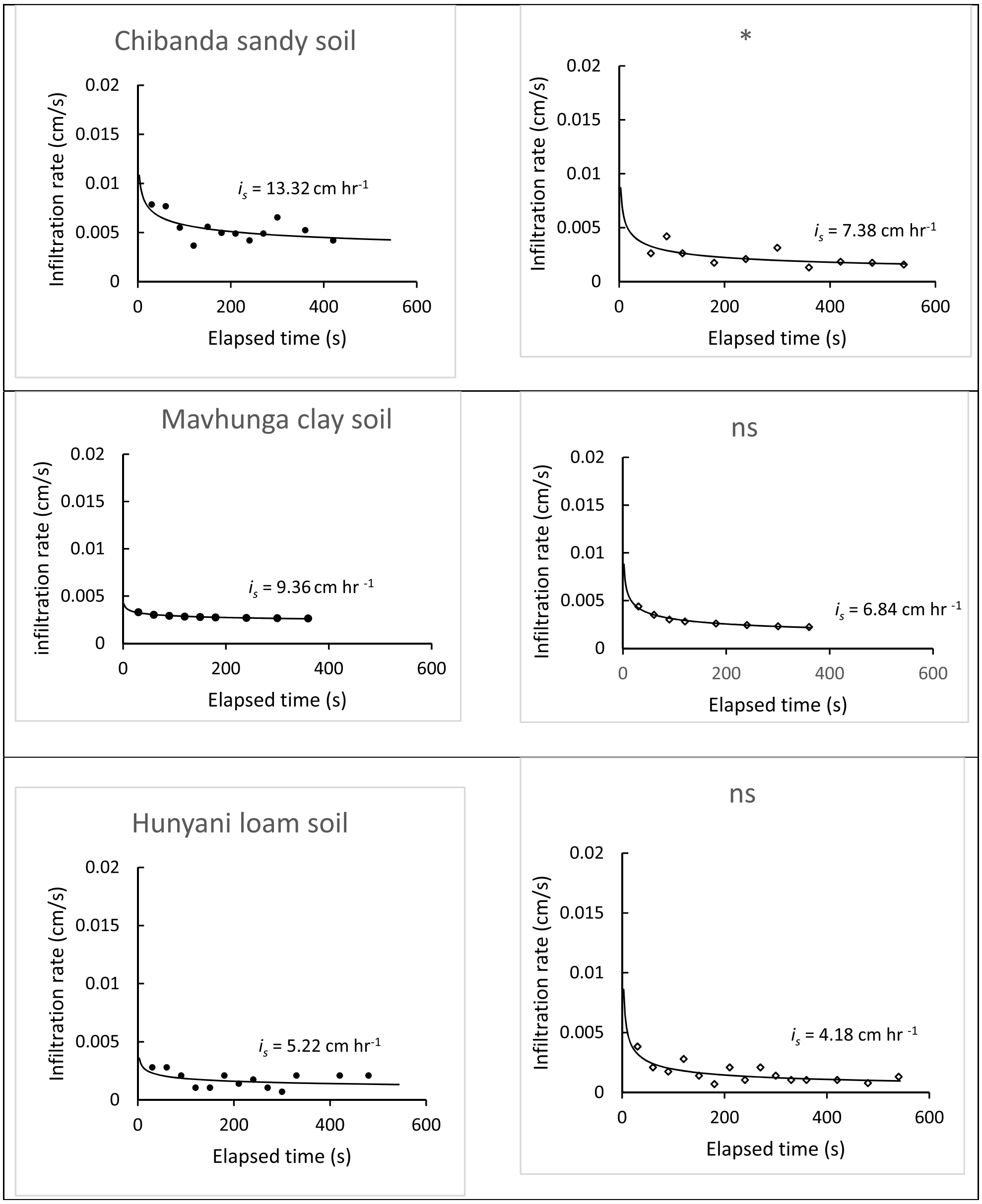

Fig. 3. Effect of inorganic fertiliser application (control-●-, NPKS-◇-) on infiltration rate of soils under reduced tillage at Chibanda, Mavhunga and Hunyani sites. i_s is the steady state infiltration rate according to the Philip model. *significant differences in overall i_s at probability, $p < 0.05$ and ns-not significant at $p = 0.05$.

buffer capacity of sands also facilitated a rapid increase in proportion of water stable aggregates at Chibanda sandy site under reduced tillage. A 40% increase in soil aggregate stability was similarly reported from enhanced macro-aggregation under no tillage system at a 4-year study on a Canadian clay soil through better protection of SOM in macro-aggregates [58,59]. In Zimbabwe a 9% increase in water stable aggregates under CA compared with conventional tillage systems on sandy soils was reported due to limited exposure of SOC to decomposition under CA [60].

The dry bulk density indicates the soil physical condition which influence air, nutrient and water fluxes. Compacted soils were observed at Chibanda and Hunyani with bulk densities of 1.37–1.54 Mg m^{-3} (Table 3). The high bulk densities can be attributed to low SOM levels at the sandy and loamy sites while the fine sand fraction that dominate the soils at Hunyanifurther caused formation of densely packed layers. The bulk density values observed in this study were above the optimum range (0.9–1.2 Mg m^{-3}) and root growth restriction is anticipated in the compacted horizons [23,61].

There was a general decrease in bulk density with an increase in clay content across the sites irrespective of the treatments (Table 3). This was attributed to better aggregation facilitated by the clay fraction. This observation was consistent with results

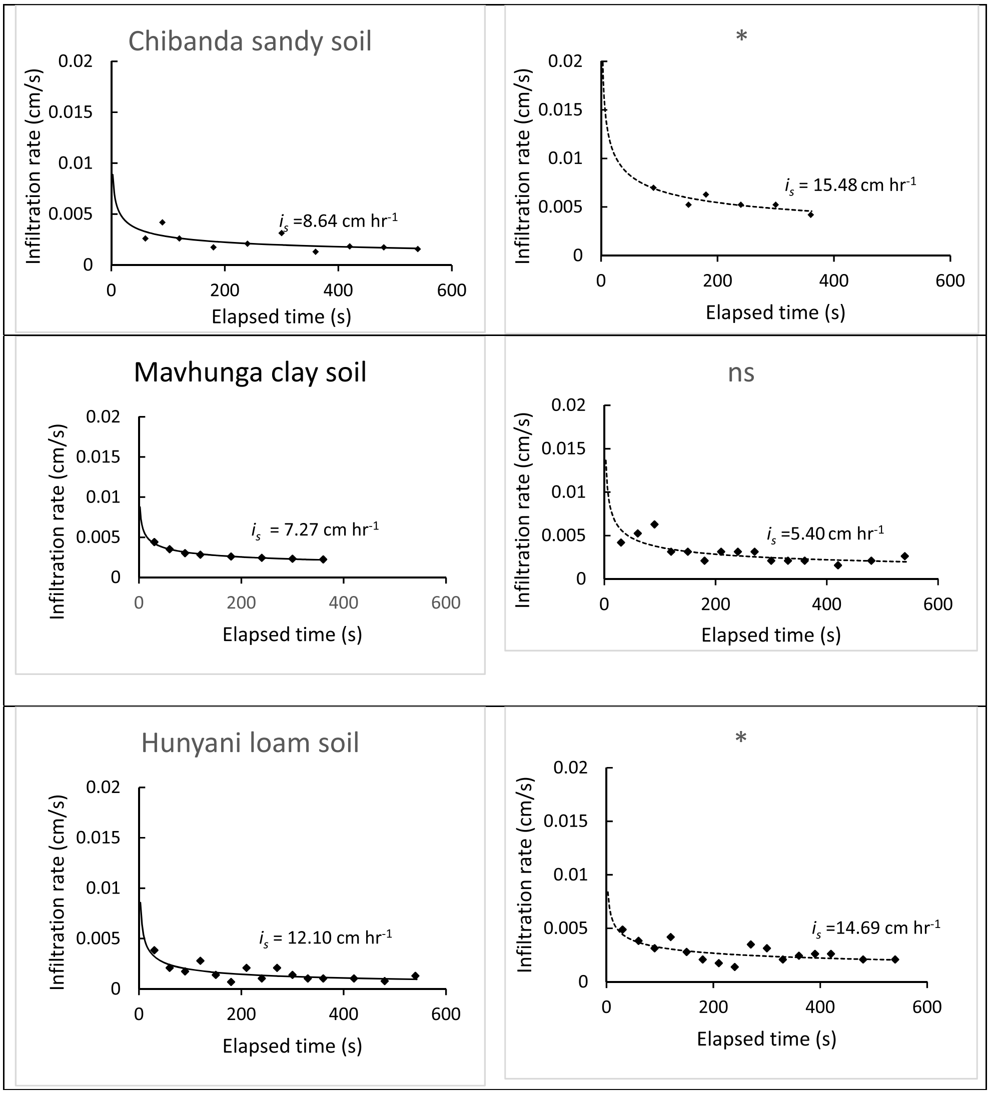

Fig. 4. Effect of tillage (reduced tillage ———, conventional tillage——) and soil type on infiltration rate of soils under a combination of continuous maize and inorganic fertiliser application at Chibanda, Mavhunga and Hunyani sites. i_s is the steady state infiltration rate according to the Philip model. *significant differences in overall i_s at probability, $p < 0.05$ and ns-not significant at $p = 0.05$.

reported elsewhere, where bulk density negatively correlated with clay content [62].

NPKS fertiliser application had no significant effect on bulk density after two seasons at Chibanda, Gara and Hunyani sites (Table 3). The NPKS fertiliser does not contribute to soil aggregation and consequently, had no direct effect on soil bulk density in the short term. These findings are similar to what has been reported elsewhere [63,64]. On the contrary, mineral fertiliser application in CA systems in the long term promote more root growth and indirectly improve aggregation impacting positively on structural soil properties. For example, mineral fertiliser application even at sub-optimal rates (<50% of standard NPK fertiliser application) reduced bulk density among other improved soil physical properties at a long term CA study [65]. Lack of response of bulk density to mineral N fertiliser was similarly observed at a study conducted in China, where application of up to 345 kgN ha^{-1} did not affect bulk density [66]. However, appropriate tillage coupled with mineral fertiliser application is necessary for improved soil physical quality that include bulk density reduction [67].

The short duration of the study minimised the response of bulk density and proportion of water stable aggregates to tillage and rotation practices (Tables 3 and 4). This concurs with findings of several authors who argue that significant positive tillage effects on soil physical properties including bulk density reduction are obtained from long-term practices of CA [68] [69–73]. On the contrary, a significant drop in bulk density within 12 months was reported in soils with high organic matter content under no tillage systems [74]. However, a negative correlation between soil bulk density and the degree of soil disturbance by tillage practices was reported during an 8 week seasonal experiment [75]. On the contrary, least favourable physical conditions that include highest bulk density under no-tillage while conventional tillage (disc ploughing followed by disc harrowing) had the better physical properties under cowpea

(*Vigna unguiculata (L) Walp*) production after two seasons in Ghanaian smallholder sector on a loamy sand soil [76].

Infiltration is the main intermediary water input process to the root zone taking place at the soil-atmosphere inter-phase. The infiltration process is dependent on the availability of a more conductive pore system based on pore size distribution and continuity [77].Soil texture played an important role in influencing infiltration rate of the soils in this study. The i_s rate was highest at Chibanda sandy site. Sandy soils have a large proportion of conductive macropores important for water transmission during the infiltration process. In addition, macro aggregation associated with reduced tillage further improves the process [36]. However, the i_s was significantly lower under reduced tillage than under conventional tillage at Chibanda. This suggests that macroporosity for fluid transmission was more dependent on the large sized sandy particles rather than the macro aggregation at Chibanda site. Consequently, infiltration was not improved significantly by reduced tillage and rotation practices that promote aggregation. This is contrary to the findings from other Zimbabwean studies where a 47% higher infiltration rate for CA compared with CT was reported on similar sandy soils [31].

There was an inconsistent response of i_s to tillage system, NPKS fertiliser application and rotation at Mavhunga, Chibanda and partly at Hunyani sites in this study. The application of NPKS fertiliser had no influence on soil hydraulic properties at the sites further emphasising its limited contribution towards soil aggregation. Soil structure is essential for transmission pore development. At Hunyani loamy soils, reduced tillage significantly increased i_s (by >500%) compared with conventional tillage due to better macroporosity development associated with larger and stable soil aggregates in the former system. This scenario demonstrates the high sensitivity of infiltration to changes in management systems at field level. Higher i_s on CA compared with conventional tillage have been reported in farmer's fields across Zimbabwe due to soil compaction and poor aggregation resulting from the tillage processes involved [31,60]. In addition, greater infiltration rates under CA practices compared with conventional tillage practices were reported for an array of soils (4–50% clay) in Northern Zimbabwe [78].

The K_s was significantly higher under maize-soya bean rotation compared with the continuous maize system (Table 5). This can be attributed to large conductive pores associated with macropores. The crop rotation system that included soya bean aggregated the soils resulting in creation of interstitial macropores vital for water transmission leading to higher Ks. Moderate mean K_s values were observed under maize-soya bean rotation (2.20 cm h^{-1}) which is in line with effective porosity related to macropore development [79–82]. Therefore, crop rotation can improve water recharge in the root zone and groundwater aquifers. The recharging of these hydrological systems is essential in mitigating the impact of climate change. Low K_s values (<1.8 cm h^{-1}) were observed under the continuous maize system. These low K_s values in the continuous maize system could expose the soil to water logging or runoff depending on the degree of sloping. This could lead to increased N loss from the soil through denitrification or soil erosion if water management is inefficient.

Soil surface disturbance through tillage had no effect on sorptivity in this study. Soil sorptivity gives a measure of the soil capacity to absorb water through capillary action which dominate the early stages of the infiltration process. In this short term study, the sorptivity fell within the typical range of: 1×10^{-2} cm $s^{-0.5}$ (very fine) to 40×10^{-2} cm $s^{-0.5}$ (coarse) for the studied soils. However, a combination of: reduced tillage or crop rotation with NPKS fertiliser application had no effect on sorptivity implying that these interventions had minimal effect on soil matric potential. On the contrary, increased water sorptivity from a combination of high mulching rates and no tillage systems was reported in a long term study under semi-arid conditions in USA with the potential to increase precipitation use efficiency [83]. This suggests that the mulching pillar and long term duration continue to be important requirements in improving soil physical quality parameters under CA systems.

5. Conclusion

In the short term (2 years), adoption of reduced tillage and crop rotation in combination with mineral fertiliser application improved C sequestration; soil hydraulic and structural properties at Chibanda sandy site which was consistent with the hypothesis tested. At clayey sites, significant treatment effects were limited to rotation and soil depth on soil structure linked properties (proportion of water stable aggregates and bulk density) while interactions of tillage system with NPKS fertiliser application or soil depth on soil carbon stocks were significant. We conclude that rotation, reduced tillage and NPKS fertiliser application rapidly improve most soil physical quality parameters of sandy soils and can therefore be recommended as first stage practices in the reclamation of soils undergoing structural degradation to improve root zone water recharge in the smallholder sector of Zimbabwe. The practices had limited influence on soil physical quality parameters at sites with loamy to clayey soils and smallholder farmers on such soils should strive to include the mulching pillar in the short term in order to improve soil carbon sequestration, soil structural and hydraulic properties. It is also recommended to undertake further studies on soil chemical properties as influenced by the studied pillars of conservation agriculture and fertiliser application to have a balanced impression on sustainability.

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Author contribution statement

Gotosa J; Nyamangara J: Conceived and designed the experiments.
Gotosa J, Kodzwa J: Performed the experiments.
Gotosa J, Kodzwa J, Nyamangara J: Analysed and interpreted the data.

Gotosa J, Gwenzi W, Nyamangara J: Contributed reagents, materials, analysis tools or data.
GotosaJ, Kodzwa J, Gwenzi J, Nyamangara J: Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

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