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RESEARCH ARTICLE



Clean weeding showed positive effects on earthworm communities following six years of minimum tillage in a maize field in northern Zimbabwe

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ABSTRACT

Earthworms are a major component of soil fauna communities with positive effects on soil chemical, biological and physical processes. A study was carried out to investigate the medium-term effects of cultural practices on earthworm communities in an agricultural field. Data were collected in the 2018/2019 cropping season from a six-year-old experiment with tillage system, fertiliser application rate and weeding intensity as the main, sub- and sub-subplots, respectively. *Lumbricus* (34.4%) and *Diplocardia* (38.3%) were the dominant genera, while endogeic earthworms (48.4%) dominated the community structure among other earthworm functional groups. Clean weeded plots under the basin planting system had higher *Lumbricus* abundance (quadruple), genus richness (76.4%) and Shannon diversity index (56.0%) than all other treatments. Inorganic fertiliser application in the conventional tillage system reduced *Eisenia* abundance and genus evenness by 100.0% and 73.3%, respectively. These results suggest that in minimum tillage systems, frequent hand weeding confers positive effects on earthworms including increased abundance. In conventional tillage systems, application of high doses of inorganic fertiliser is detrimental to earthworm communities. Further studies need to focus on identifying the most sustainable and cost-effective hand weeding frequency for enhanced earthworm diversity and increased crop productivity.

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Anecic; basin planting;
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Introduction

Earthworms contribute to overall soil biomass, biological diversity and some biochemical soil processes (Smith et al. 2008). They ingest large amounts of organic matter and excrete altered materials (casts) that influence soil chemical and physical properties. Their activity has been shown to increase soil structure, soil fertility and concomitantly, water infiltration, retention and availability to plants (Deibert and Utter 1994; Kale and Karmegam 2010). Earthworm activity also increases soil aeration, promote plant root growth, plant residue decomposition and microbial mineralisation cycles hence they are important for providing a variety of beneficial ecological services in cropping systems (Bertrand et al. 2015). Compared with other soil invertebrates such as arthropods, earthworms are less mobile and can therefore be restricted to microhabitats created in small plots under field studies. This makes earthworms reliable candidates for studies of biological processes in microhabitats that are created when experimental treatments are applied on field plots. Earthworms are also considered to be reliable bioindicators in soil

health studies as they are easy to classify and very sensitive to changes of both physical and chemical soil parameters (Long et al. 2017).

Earthworms play a vital role in soil formation including bringing soil from deeper horizons to the surface, with some species having been shown to consume between 50 and 90 tonnes of soil ha⁻¹ year⁻¹ (Feller et al. 2003). In particular, Feller et al. (2003) observed that typical earthworm populations can easily consume five tonnes of dry matter ha⁻¹ year⁻¹, partly digesting and mixing it with soil thereby recycling nutrients and increasing nutrient availability. Raw (1962) found that earthworms may remove up to 90% of leaf-fall in orchards. In the absence of a rich population of soil biota, 500–1000 years are required to create an inch of topsoil, but under favourable conditions, earthworms can speed up this process to only five years (Curry et al. 2002). Because of their role in the soil ecosystem, earthworm activities have been shown to increase crop yield (Bertrand et al. 2015; van Groenigen et al. 2014).

Earthworms have detritivorous as well as poly-, meso- and oligo-humic feeding habits and are generally

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categorised into three main functional groups: epigeic, anecic and endogeic (Bouché 1977; Tondoh et al. 2019). Epigeic earthworm species dwell and feed on soil surface litter, anecic earthworms burrow vertically into the soil but forage on the soil surface and are important in the burial of surface litter, while endogeic species burrow horizontally and feed mainly in the rhizosphere and subsoil.

Evidence shows that conventional farming systems such as soil inversion tillage, inorganic fertiliser application as well as intensive chemical and mechanical weed management have negative impacts on earthworm communities (Smith et al. 2008; Bertrand et al. 2015; Moos et al. 2017). Mechanical soil tillage frequently causes physical disruption of habitats and directly damages macro-organisms, reducing their abundance and diversity (Smith et al. 2008). Whilst these farming systems have been shown to increase crop productivity, they simultaneously damage the agroecosystem. However, in a review of studies conducted in Germany, Van Capelle et al. (2012) concluded that ploughing can positively influence endogeic species by increasing organic matter availability, while it has an opposite effect on anecic species.

The application of chemical fertilisers and other agrochemicals may cause toxic effects to soil life (Haynes and Naidu 1998; Bertrand et al. 2015). However, fertiliser application may have some positive bottom-up effects on earthworms through increasing plant biomass production and providing more food resources for earthworms (Whalen et al. 1998). While the application of inorganic fertiliser has a negative effect on earthworm communities, their abundance and diversity increase when organic soil amendments are used (Tiwari 1993; Rahman et al. 2007). Most earthworms prefer a pH range of 6.0–7.0, and their diversity and abundance decrease at $6 < \text{pH} > 7.0$ (Karmegam and Thilagavathy 2007; Rakhmatullaev et al. 2010).

The specific impacts of cultural practices such as tillage, inorganic fertiliser application and weeding on the earthworm communities are well documented, although little information is available for some geographical locations, particularly sub-Saharan Africa. These cultural practices (tillage, fertiliser application and weeding) occur together in a number of agricultural fields but studies focusing on the effects of their interaction are rare. This study was therefore conducted to determine the interactive impact of cultural practices on the abundance and diversity of earthworms in red clay soil in Zimbabwe. It was hypothesised that (1) soil inversion tillage, high inorganic fertiliser application rate and frequent hand weeding have negative impacts on earthworm abundance and diversity in the plough

layer and (2) there is no relationship between earthworm abundance and maize (*Zea mays* L.) grain yield.

Materials and methods

Site description

The study was conducted on a medium-term tillage experiment at Chinhoyi University of Technology (CUT) experimental farm (17°20'S, 30°14'E, 1140 m above sea level). The site is located in Mashonaland West Province, Zimbabwe, about 100 km north-west from the capital city, Harare. The area falls under agro-ecological region IIa, with a mean annual rainfall of 750–1000 mm and temperature of 14°C to 19°C in winter and 20°C to 29°C in summer (Climatempo.org 2017). The soil for this area is red clay Cambisol (WRB 2014).

Experimental design and treatments

The experiment was established in December 2012, and tillage, fertiliser and weeding treatments had been repeatedly applied on the same plots since then. The experiment was laid out as a split-split plot in a randomised complete block design with three replications. Tillage system was the main plot factor (basin planting: BASIN, rip lines: RIP and conventional tillage: CT); fertiliser application rate the subplot factor (zero fertiliser: NF, low rate: LF, medium rate: MF and high rate: HF), and weeding frequency + weed residue mulch the sub subplot factor (weeding twice: TWI, four times: FOU and clean weeding: CLE). There were 36 treatments and 108 plots in total. For tillage systems, basins were made using hand hoes, each measuring 15 cm length × 15 cm width × 15 cm depth (Mazvimavi and Twomlow 2009); rip lines were made using a tractor-drawn ripper to a depth of 15–20 cm while CT involved deep ploughing using a disc plough as primary tillage followed by secondary tillage using a disc harrow. Basin planting and rip line seeding represented minimum tillage, and these are the common practices that are used by smallholder farmers who practise conservation agriculture in Zimbabwe. In the basin planting and rip line seeding plots, crop residues were retained on the soil surface to achieve about 30% permanent soil cover but were completely removed from all CT plots immediately after harvesting the test crop to emulate typical smallholder farmer practice in Zimbabwe. Fertiliser treatments were applied as follows: (1) no fertiliser (NF) in which plots did not receive fertiliser treatments, (2) micro dosing (LF): 35.2 kg N + 12.2 kg P₂O₅ + 6.6 kg K₂O ha⁻¹, (3) medium fertiliser rate (MF): 41.5 kg N + 14 kg P₂O₅ + 7 kg K₂O ha⁻¹ and (4) high fertiliser rate

(HF): 83 kg N + 28 kg P_2O_5 + 14 kg K_2O ha^{-1} . Micro dosing is a fertiliser management practice regime that is recommended for resource-constrained smallholder farmers who practice conservation agriculture in sub-Saharan Africa (Twomlow et al. 2008). The practice involves application of 100 g of manure per plant position ($5 t ha^{-1}$) + 80 kg ha^{-1} compound fertiliser (8% N: 14% P_2O_5 : 7% K_2O) at planting + 80 kg ha^{-1} ammonium nitrate (34.5% N) at 4–6 weeks after crop emergence. For MF and HF, the compound fertiliser supplied all the P_2O_5 and K_2O plus 30% of N while the remaining 70% of N requirement was applied as top dressing using ammonium nitrate. Weeding involved light cultivation using a hand-held hoe, disturbing the top 2–5 cm of the soil, with the weed biomass left on the surface as mulch. In particular, timing of hand weeding for the three treatments was as follows: (1) weeding twice: weeding at two and four weeks after crop emergence (WACE), (2) weeding four times: weeding at two, four, six and eight WACE and (3) clean weeding: continuous weeding to make sure that no weed growth occurred in the plots. Plot sizes were 25.5×25.2 m, 25.5×5.4 m and 5.4×7.5 m for main plots, subplots and sub-subplots, respectively.

Crop management

Land preparation was done according to the tillage treatments. The maize crop spacing was 90 cm (inter-row) \times 50 cm (in row) with two plants per planting station to give a total plant population of 44,444 plants ha^{-1} . A compound fertiliser (8% N: 14% P_2O_5 : 7% K_2O) and farm yard manure were used as basal and ammonium nitrate (34% N) was used as top-dressing fertilisers. The fertilisers were applied according to the treatments. Manual weeding using hand hoes was carried out according to weeding frequency treatments. Fall armyworm (*Spodoptera frugiperda*) being an emerging devastating pest at the site, scouting of the fields was done and the pest was controlled using a single application of Proclaim 5SG[®] (emamectin benzoate 5%) insecticide at a rate of 1.5 g active ingredient ha^{-1} at four WACE. At physiological maturity in April 2019, maize grain was harvested from the four central rows of the sub-subplot, discarding 1 m from either side of each row. The cobs were shelled and then grain weight from each plot was determined, adjusted to 12.5% moisture content and expressed per hectare.

Earthworm sampling and identification

Earthworms were sampled at planting in December 2018, and then monthly from January to March 2019

when the maize crop reached physiological maturity. Earthworm samples were taken from the four central rows of each sub-subplot after discarding two rows from either side of the plot and 1 m from either side of the row. Earthworms were sampled by selecting two random positions in each sub-subplot plot and digging pits using a spade, each pit measuring $20 \times 20 \times 20$ cm (length, width and depth, respectively) (Van Vliet and De Goede 2006). Soil from each sub-subplot was placed on a plastic bag, mixed and earthworms were visually isolated by hand sorting and counting. The collected earthworm specimens were then placed into plastic bottles with perforated lids along with a sufficient amount of soil, packed in a cooler box and transported to the laboratory. Earthworm density from soil monoliths was calculated per m^2 . The earthworms were narcotised by dropping them into 70% ethanol and then removed after their movement stopped. They were transferred and fixed in 4% formalin for preservation (Smith et al. 2008).

Earthworms were identified by a local expert at CUT, based on external anatomy using earthworm identification keys by means of a binocular microscope (Synder 2010; Harry and Lowe 2015). Individuals were grouped into two classes, adults and juveniles, based on the presence or absence of the clitellum. Clitellate individuals were counted and identified to genus level. Identification of earthworms to genus level has been shown to provide reliable information in agro-ecosystems and the approach was recently used by Mcinga et al. (2020). Identified earthworm specimens were then assigned to functional groups according to Bouché (1977). Specimens without heads and pre-clitellate individuals could not be identified to genus level and were included in analyses of total earthworm abundance only.

Statistical analysis

Earthworm genus richness, genus evenness index (E) and Shannon-Weaver Index (H') were estimated using Paleontological Statistical Package (PAST) (Shannon and Weaver 1949; Hammer et al. 2001). The estimation of diversity parameters at the genus level is an acceptable approach that has been used in studies of other fauna (Oliveira-Silva et al. 2012; Mashavakure et al. 2019b). Due to non-homogeneity of variances in the earthworm abundance data $\log_{10}(x + 1.5)$ transformation was used to normalise data distribution and homogeneity. Earthworm diversity and maize grain yield data did not require transformation. Data on earthworm abundance and diversity were subjected to analysis of variance using Genstat Discovery edition (VSN-

International 2011). The general analysis of variance (split-split plot) procedure was used with tillage system, fertiliser application rate and weeding frequency and all their interactions as explanatory variables, while earthworm abundance, earthworm diversity and maize grain yield were the response variables. Where statistical differences were detected, the standard error of difference (SED) at $P \leq .05$ was used to separate means. Pearson's correlation analysis was performed using PAST (Hammer et al. 2001) to determine the relation between earthworm abundance and maize grain yield.

Results

Season quality

The total annual rainfall during the period of study was 410 mm, representing 61.2% of the 10 year mean annual rainfall for the study site (Table 1). Precisely, the rainfall that was received during the period of earthworm sampling (January–March 2019) was 67% lower compared to the same period for the 10-year mean annual precipitation.

Earthworm abundance

There was no evidence of the main effects ($P > .05$) of weeding intensity + weed residue mulch on earthworm abundance (Table 2), six years after successive application of the treatments. For the main effects of tillage system and fertiliser application rate, significant effects ($P < .05$) were only observed on *Lumbricus* genus and total earthworm abundance, respectively (Table 2). Total earthworm abundance declined by 22.9% in HF plots relative to all other fertiliser treatments. *Lumbricus* genus abundance was 84.2–86.8% higher in the basin planting than in conventional and rip line tillage systems (Table 3), but this response was confounded

in the significant ($P < .05$) tillage \times weeding interaction effect on the same genus (Table 2). The interactive effects of tillage and weeding revealed that in basin planting, *Lumbricus* was up to four times more abundant in clean weeded plots compared to those that were weeded twice and four times (Table 3). These effects of weeding intensity on *Lumbricus* were absent in conventionally tilled plots (Table 3). There was also a significant interaction ($P < .05$) of tillage and fertiliser application rate on *Eisenia* (Table 2). In particular, in CT plots, there was complete absence of the genus in fertiliser treated plots compared with 1.3 earthworm individuals m^{-2} in unfertilised plots (Table 4). On the other hand, in basin planting and rip line seeding plots, there was no response of *Eisenia* to fertiliser application. Meanwhile, all other interactions were not significant ($P > .05$, Table 4).

Earthworm diversity

A total of 1460 earthworm individuals from seven genera (*Apporectodea*, *Diplocardia*, *Eudrilus*, *Eiseniella*, *Lumbricus*, *Eisenia* and *Octolasion*), three families (Acanthodrilidae, Eudrilidae and Lumbricidae) and three functional groups (anecic, endogei and epigeic with relative abundances of 51.5%, 44.6% and 3.9%, respectively) were collected and identified during the study (Table 5). The genera, *Diplocardia* and *Lumbricus*, were the most and second most dominant (38.3% and 34.4%, respectively), while *Octolasion* was least (1.6%) abundant. The Adult: Juvenile ratio was 27:292. Some earthworm individuals (37.5%) could not be identified as they were unknown juveniles or damaged specimens and were used in total earthworm abundance values only.

Earthworm Shannon-Weaver index showed a significant response ($P < .05$) to weeding intensity + weed residue mulch although this effect was confounded in the significant interaction effects ($P < .05$) of tillage \times weeding (Table 6). Meanwhile, the main effects of tillage and fertiliser on earthworm diversity parameters were not significant ($P > .05$, Table 6). There were also significant interactions ($P < .05$) of tillage and fertiliser as well as tillage and weeding + weed residue mulch on earthworm genus evenness and richness, respectively (Table 6). The interaction effects revealed that in the basin planting system, both earthworm genus richness (Figure 1) and Shannon-Weaver index (Figure 2) were greater (74.8–77.9% and 56%, respectively) in clean weeded plots than those that were weeded twice and four times. Furthermore, the results showed that in CT, the application of a high fertiliser rate (HF) resulted in a 71.5% reduction ($P < .05$) in earthworm genus evenness relative to no fertiliser application

Table 1. Average monthly rainfall for Chinhoyi University of Technology experimental farm.

Month	Average rainfall (mm)	
	10-year mean*	2018/19 cropping **
September	0.0	0
October	8.0	0
November	57.4	64
December	168.0	74
January	191.6	114
February	117.1	115
March	87.3	8
April	38.2	67
May	5.0	0
June	0.6	0
July	0.3	4
August	0.0	0

*Based on (Worldweatheronline.com 2020), **Based on data collected at the study site during the 2018/19 cropping season.

Table 2. Mean density of earthworm genera in response to tillage system, fertiliser application rate and weeding intensity at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season.

Treatments	Earthworm density (individuals m ⁻²)							Total
	<i>Apporectodea</i>	<i>Diplocardia</i>	<i>Eisenia</i>	<i>Eiseniella</i>	<i>Eudrilus</i>	<i>Lumbricus</i>	<i>Octolasion</i>	
<i>Tillage system</i>								
Basin	0.41	2.84	0.26	0.78	0.41	7.37 ^a	0.13	350.87
Rip	0.00	1.81	0.00	0.26	0.41	1.17 ^b	0.00	253.77
CT	0.00	2.02	0.26	0.26	0.73	0.97 ^b	0.00	334.24
<i>P</i>	0.160	0.912	0.605	0.626	0.444	0.013	0.444	0.105
SED	0.049	0.281	0.075	0.126	0.057	0.111	0.028	0.052
<i>Fertiliser application rate</i>								
NF	0.17	1.86	0.35	0.61	0.80	2.10	0.17	333.47 ^a
LF	0.00	3.54	0.00	0.35	0.35	2.96	0.00	328.87 ^a
MF	0.35	2.60	0.18	0.35	0.57	1.66	0.00	329.63 ^a
HF	0.00	1.18	0.17	0.35	0.35	2.99	0.00	254.95 ^b
<i>P</i>	0.595	0.409	0.359	0.898	0.701	0.745	0.415	0.053
SED	0.078	0.164	0.050	0.091	0.090	0.163	0.033	0.045
<i>Weeding intensity</i>								
Twice	0.13	2.31	0.00	0.26	0.26	2.81	0.00	305.40
Four times	0.13	1.38	0.13	0.29	0.57	2.24	0.00	303.99
Clean	0.13	3.10	0.41	0.73	0.73	2.12	0.13	320.61
<i>P</i>	1.000	0.314	0.222	0.35	0.465	0.842	0.375	0.656
SED	0.040	0.134	0.060	0.079	0.085	0.136	0.028	0.027
Till × Fert	ns	ns	*	ns	ns	ns	ns	ns
Till × Weed	ns	ns	ns	ns	ns	*	ns	ns
Fert × Weed	ns	ns	ns	ns	ns	ns	ns	ns
Till × Fert × Weed	ns	ns	ns	ns	ns	ns	ns	ns

Different superscript letters within each column indicate significant difference ($P \leq .05$). Basin, basin planting; Rip, rip line seeding; CT, conventional tillage; Twice, weeding twice; Four times, weeding four times; Clean, clean weeding; NF, no fertiliser; LF, low fertiliser; MF, medium fertiliser; HF, high fertiliser; Till, tillage system; Fert, fertiliser application rate; Weed, weeding intensity; ns, not significant at $P \leq .05$, and, *Significant at $P \leq .05$.

(Figure 3). No differences in earthworm genus evenness were observed among fertiliser application treatments in both basin planting and rip line seeding (Table 7).

Maize grain yield

There was no evidence of maize grain yield response to the main effects of tillage system, fertiliser application and weeding intensity ($P > .05$) during this sixth year of continuous application of the treatments (Table 8). The interaction effects of treatment factors on maize were only significant ($P < .001$) for tillage system × fertiliser application rate (Table 8). These significant interaction effects revealed that in the basin planting system, HF resulted in 155% more maize grain yield relative to NF, while in the CT system, maize grain yield was higher in

NF (90.8%) and MF (121.1%) relative to LF plots (Figure 4). Correlation analysis showed that maize grain yield was significantly negatively correlated with *Diplocardia* ($r = -0.21$, $P = .033$) and positively correlated with total earthworm ($r = 0.34$, $P < .001$) abundance (Table 5).

Discussion

Earthworm abundance

While total and all other earthworm genera showed no significant response to tillage system, *Lumbricus* was 87% more abundant in basin planting than CT. This is probably because tillage systems that invert the soil physically damage the earthworms and destroy their vertical burrows (Jeffery et al. 2010; Moos et al. 2017).

Table 3. Mean density of *Lumbricus* genus in response to tillage system and weeding intensity at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season.

Weeding intensity	Tillage system (individuals m ⁻²)		
	Basin	Rip	CT
Twice	6.52 ^b	1.58 ^b	1.75 ^b
4 times	3.75 ^b	2.63 ^b	0.92 ^b
Clean	15.17 ^a	0.00 ^b	0.41 ^b
SED	0.2219*		

Different superscript letters within each column indicate a significant difference ($P \leq .05$). Basin, basin planting; Rip, rip line seeding; CT, conventional tillage; Twice, weeding twice; Four times, weeding four times; Clean, clean weeding. '*' denotes significance at $P \leq .05$.

Table 4. Mean density of *Eisenia* genus in response to tillage system and fertiliser application rate at Chinhoyi University of Technology experimental farm during the 2018/19 season.

Fertiliser application rate	Tillage system (individuals m ⁻²)		
	Basin	Rip	CT
NF	0.00 ^b	0.00 ^b	1.34 ^a
LF	0.00 ^b	0.00 ^b	0.00 ^b
MF	0.57 ^b	0.00 ^b	0.00 ^b
HF	0.57 ^b	0.00 ^b	0.00 ^b
SED	0.1058*		

Different superscript letters within each column indicate significant difference ($P \leq .05$). Basin, basin planting; Rip, rip line seeding; CT, conventional tillage; NF, no fertiliser; LF, low fertiliser application rate; MF, medium fertiliser application rate and HF, high fertiliser application rate. '*' denotes significant at $P \leq .05$.

Table 5. Relative abundance of earthworm genera at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season.

Order	Family	Genus	Functional group (% of total abundance)		
			Endogeic	Anecic	Epigeic
Il-Haplotaxidae	Acanthodrilidae	<i>Diplocardia</i>	38.2	–	–
Il-Haplotaxidae	Eudrilidae	<i>Eudrilus</i>	–	10.2	–
Il-Haplotaxidae	Lumbricidae	<i>Lumbricus</i>	–	34.4	–
		<i>Apporectodea</i>	3.1	–	–
		<i>Eisenia</i>	–	–	3.9
		<i>Octolasion</i>	1.6	–	–
<i>Eiseniella</i>	8.6	–	–	–	–

Mcinga et al. (2020) observed a similar trend and suggested that CT systems experience high losses of organic matter owing to increased oxidation of organic matter during tillage. Furthermore, removal of crop residues in CT systems at the end of each cropping season as is normally practised by smallholder farmers hampers soil organic matter build-up, creating unfavourable conditions for earthworm survival. Meanwhile, for the basin planting system, the retention of surface crop residues on the soil surface probably provided additional food sources to support anecic earthworms in the soil (Estevez et al. 1996; Mcinga et al. 2020). Apart from acting as a food source for earthworms, plant residues that were retained on the soil surface improve soil moisture availability, creating favourable

conditions for earthworm survival and growth (Mcinga et al. 2020). Similar to our findings, Crittenden et al. (2014) observed higher *Lumbricus* abundance under no-till than soil inversion tillage. However, the impact of tillage on earthworm survival and soil organic matter was not quantified in the present study. With regard to total and all other earthworm genera, our results (Table 2) are contrary to those of Crittenden et al. (2014) and Manono (2016) who found evidence of tillage effects in the Netherlands and New Zealand, with a tendency for reduced earthworm density under CT relative to reduced tillage.

After six years of successive application of the treatments, total earthworm abundance declined by 22.9% when HF was applied relative to other fertiliser treatments as shown in Table 2. With respect to mineral fertiliser effects, our results on total earthworm density (Table 2) are similar to Blakemore (2018) who found evidence that synthetic fertiliser application reduced earthworm populations by 70%. The negative effects of mineral fertilisers, particularly those containing nitrogen, may be attributed to their acidifying effect on the soil environment, which is fatal to earthworms (Haynes and Naidu 1998; Bertrand et al. 2015). Contrary to our findings, Lofs-Holmin (1983) found no effect, while Estevez et al. (1996) observed increased earthworm abundance when synthetic fertiliser was applied compared with zero fertiliser. These contrasting results support the view that fertiliser effects on earthworm populations are variable (Estevez et al. 1996), depending on factors such as soil and fertiliser type and climatic conditions. Meanwhile, we observed no effects of fertiliser on the abundance of individual earthworm genera. It appears the studies focusing on the effects of mineral fertiliser regime on specific earthworm genera are rare.

Consistent with recent findings on other soil biota including spiders and beetles in the same study area (Mashavakure et al. 2019a; Mashavakure et al. 2019b), we found no main effects of weeding regime on earthworm populations (Table 2). It can therefore be inferred that for the edaphic and environmental conditions of this specific site, weeding regime when applied alone

Table 6. Effect of tillage system, fertiliser application rate and weeding intensity on earthworm diversity at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season.

Treatment factors	Evenness	Richness	Shannon-Weaver index
<i>Tillage system</i>			
Basin	0.736	1.306	0.32
Rip lines	0.469	0.639	0.104
CT	0.498	0.639	0.095
SED $p \leq .05$	0.1723	0.3727	0.1192
<i>Fertiliser application rate</i>			
NF	0.622	0.963	0.186
LF	0.619	0.889	0.169
MF	0.514	0.889	0.21
HF	0.516	0.704	0.126
SED $p \leq .05$	0.0779	0.1919	0.0879
<i>Weeding intensity</i>			
Twice	0.582	0.806	0.144 ^b
Four times	0.549	0.722	0.101 ^b
Clean	0.573	1.056	0.273 ^a
SED $p \leq .05$	0.1154	0.172	0.0623*
<i>Interaction effects</i>			
Till × Fert	*	ns	ns
Till × Weed	ns	*	*
Fert × Weed	ns	ns	ns
Till × Fert × weed	ns	ns	ns

Different superscript letters within each column indicate significant difference ($P \leq .05$). Basin, basin planting; Rip, rip line seeding; CT, conventional tillage; NF, no fertiliser; LF, low fertiliser application rate; MF, medium fertiliser application rate and HF, high fertiliser application rate; Twice, weeding twice; Four times, weeding four times; Clean, clean weeding; Till, tillage system; Fert, fertiliser application rate; Weed, weeding intensity; ns, not significant at $P \leq .05$, and, *Significant at $P \leq .05$, **Significant at $P \leq .01$, **Significant at $P \leq .001$.

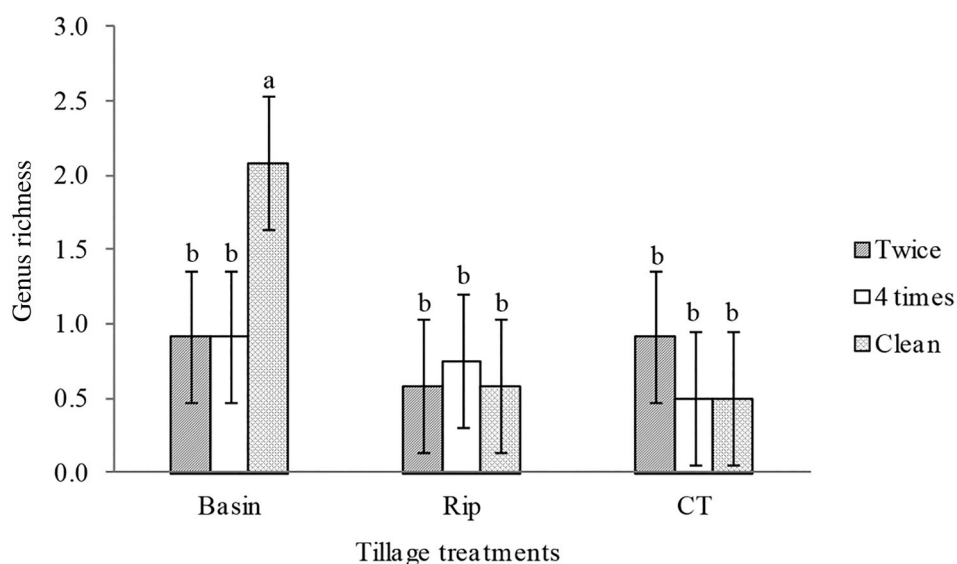


Figure 1. Effect of tillage system and weeding intensity and tillage system on earthworm genus richness at Chinhoyi University of Technology experimental during the 2018/19 cropping season. Error bars are \pm SED for the comparison of weeding intensity means within and across tillage systems, CT = conventional tillage, Rip = rip line seeding, Basin = basin planting. Different letters on the graphs indicate a significant difference ($P \leq .05$).

may not be an important driver of soil biological processes. Our results suggest that in a single agroecosystem, the interactive effects of cultural practices are important in driving earthworm processes, and that earthworm response to these practices is genus specific. As shown in Table 3, the density of *Lumbricus* genus in basin planted plots quadrupled under clean weeding relative to weeding twice and four times but was not affected by weeding treatments in CT. The observed positive effects of clean weeding in basin planting plots may have been through increased soil aeration, incorporation of plant residues and more even distribution of organic matter into the surface layers due to the repeated shallow cultivation (Edwards and Lofty 1977). This creates favourable microhabitats for earthworm faunae which either dwell on the surface or frequently visit this zone from the subsurface layers to access food. This is supported by Edwards and Bohlen (1996) who suggested that the distribution of earthworms is greatly influenced by the distribution of organic matter and soils that are poor in organic matter do not usually support large numbers of earthworms.

Combining CT with all rates of fertiliser application proved to be detrimental to *Eisenia* (Table 4). This observation is contrary to some earlier research findings which showed higher populations of earthworms when conventionally tilled fields were treated with either organic or inorganic soil fertility amendments (Tiwari 1993; Edwards and Lofty 1977). However, similar to our findings, Long et al. (2017)

and Haynes and Naidu (1998) found that the application of high doses of inorganic fertiliser reduced populations of earthworm communities including *Eisenia foetida*. The application of inorganic fertiliser, particularly nitrogen-based fertilisers is thought to reduce soil pH to <6.0 , which is deleterious to earthworm survival (Ma et al. 1990; Haynes and Naidu 1998; Bertrand et al. 2015). *Eisenia* are important in agriculture since they decompose organic matter and release nutrients that are locked up in dead plant and animal material making them available for use by living plants (Domínguez et al. 1997).

Earthworm diversity

This study found that at the genus level, *Diplocardia* and *Lumbricus* were dominant while endogeic genera were the dominant functional group, within the plough layer of crop fields (Table 5). These groups have similarly been reported to be among the dominant earthworm faunae inhabiting agricultural systems in some countries including the United States of America, southern Africa and Europe (Whalen et al. 1998; Smith et al. 2008; Nxele et al. 2015; Cardinael et al. 2019).

Contrary to our hypothesis, the main effects of both tillage system and fertiliser application rate on all three diversity parameters (genus evenness, richness and Shannon-Weaver index) were not significant (Table 6). This observation is surprising and contradicts some previous researchers who observed significant responses of

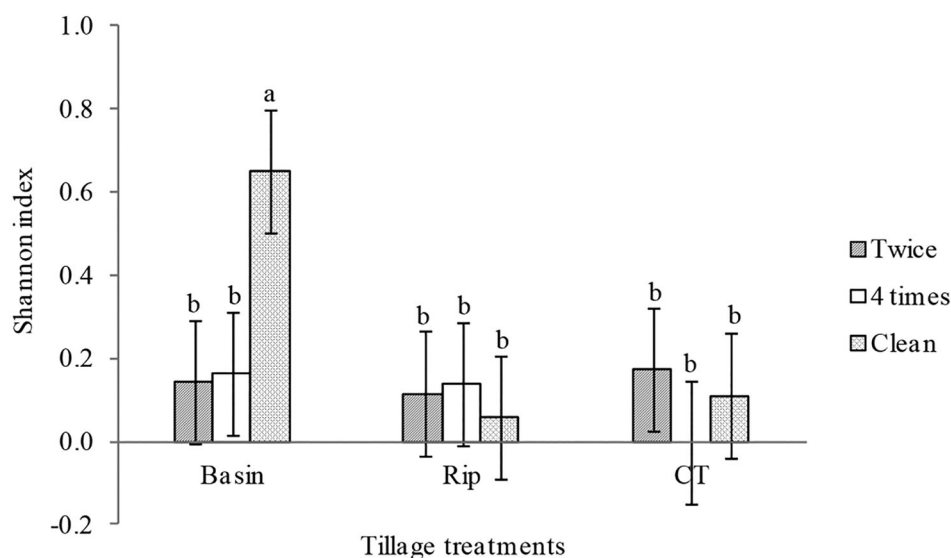


Figure 2. Effect of tillage system and weeding intensity on earthworm Shannon Wiener index at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season. Error bars are \pm SED for the comparison of weeding intensity means within and across tillage systems, CT = conventional tillage, Rip = rip line seeding, Basin = basin planting. Different letters on the graphs indicate a significant difference ($P \leq .05$).

earthworm diversity to tillage and fertiliser application, with a tendency for reduced diversity in inorganically fertilised and tilled systems (Bertrand et al. 2015). It is noteworthy that in this study, earthworm diversity was estimated at the genus level and different results may be obtained if earthworm species-level data are used. Furthermore, the amount of precipitation that was received during the study season was 39% of the 10-year average rainfall and could have influenced our

results. However, relationship between soil moisture and earthworm dynamics was beyond the initial scope of the study but our results suggest that this subject warrants further investigation. We found no response of earthworm genus evenness and richness to weeding intensity, while clean weeding doubled earthworm Shannon-Weaver index although this effect was confounded in the interactive effect of tillage system and weeding intensity.

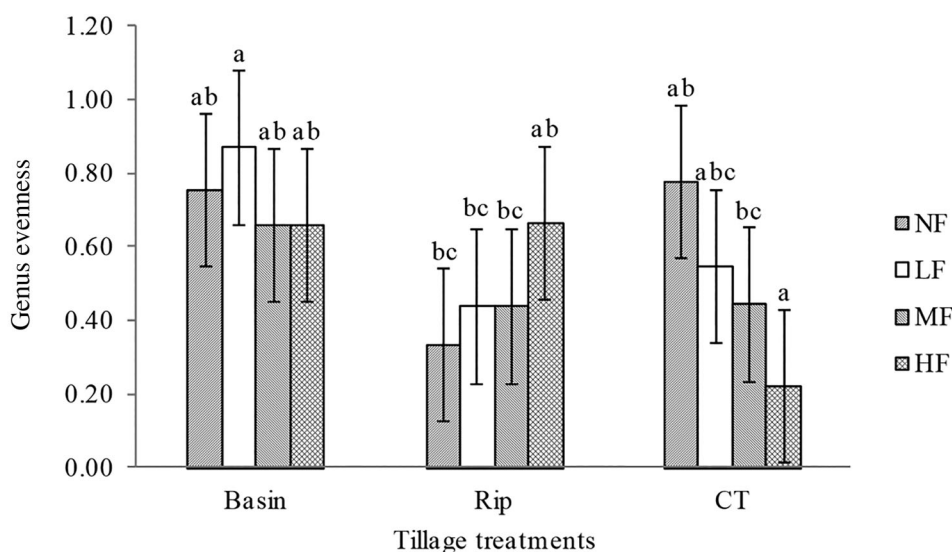


Figure 3. Effect of tillage system and fertiliser application rate and tillage system on earthworm genus evenness at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season. Error bars are \pm SED for the comparison of fertiliser application rate means within and across tillage systems, CT = conventional tillage, Rip = rip line seeding, Basin = basin planting, NF = no fertiliser, LF = low fertiliser, MF = medium fertiliser, HF = high fertiliser. Different letters on the graphs indicate a significant difference ($P \leq .05$).

Table 7. Effects of two tillage systems, four fertiliser application rates and three weeding intensity treatments on maize grain yield (kg ha^{-1}) following six years of consecutive treatment applications at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season.

Tillage system		Fertiliser application		Weeding intensity	
Basin	735	NF	699	Twice	677
Rip	566	LF	739	4 times	741
CT	1011	MF	799	Clean	894
		HF	846		
SED _{p ≤ 0.05}	190.6		103.6		128.6
Interaction effects					
Till × Fert	*				
Till × Weed	ns				
Fert × Weed	ns				
Till × Fert × Weed	ns				

Basin, basin planting; Rip, rip line seeding; CT, conventional tillage; NF, no fertiliser; LF, low fertiliser application rate; MF, medium fertiliser application rate and HF, high fertiliser application rate; Twice, weeding twice; four times, weeding four times; Clean, clean weeding; Till, tillage system; Fert, fertiliser application rate; Weed, weeding intensity; ns, not significant at $P \leq .05$, and, *Significant at $P \leq .05$, **Significant at $P \leq .01$, ***Significant at $P \leq .001$.

Table 8. Correlation between maize grain yield and earthworm genus abundance (individual and total) at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season.

Earthworm group	Pearson's r	P-value
<i>Lumbricus</i>	0.02	.857
<i>Diplocardia</i>	−0.21	.033
<i>Eudrilidae</i>	−0.19	.055
<i>Eiseniella</i>	−0.11	.239
<i>Eisenia</i>	0.12	.198
<i>Apporectodea</i>	−0.03	.779
<i>Octolasion</i>	−0.08	.434
Total	0.34	<.001

Similar to abundance, there is evidence from this study that interactive effects of tillage, fertiliser application and hand weeding are important in regulating earthworm diversity (Table 6). As shown in Figures 1 and 2, clean weeding increased earthworm genus richness and Shannon-Weaver index in the basin planting system, but there were no effects of weeding in rip line and CT systems. This is most likely because in the basin planting system, the preservation of surface burrows coupled with clean weeding created favourable microhabitats for diverse communities of earthworms. While the positive effects of reduced tillage systems on earthworm diversity have been widely reported (Chan 2001; Smith et al. 2008; Briones and Schmidt 2017; Moos et al. 2017), the interactive role of tillage and manual weeding in regulating earthworm communities has not been previously documented, as far as we could ascertain. We hypothesise that the frequent incorporation of plant residues into the soil in the clean weeded plots modified the physical and chemical environment of the soil and created a variety of favourable micro-niches that accounted for the higher levels of earthworm genus richness and diversity as observed by Koné et al. (2012) in *Chromolaena odorata* fallows in West Africa. However, it needs to be pointed out that continuous weeding such as clean weeding in crop production is impractical and uneconomical. High earthworm genus richness is important in agriculture because earthworms have been shown to provide beneficial ecosystem services such as improving soil structure, water regulation, nutrient cycling, soil formation

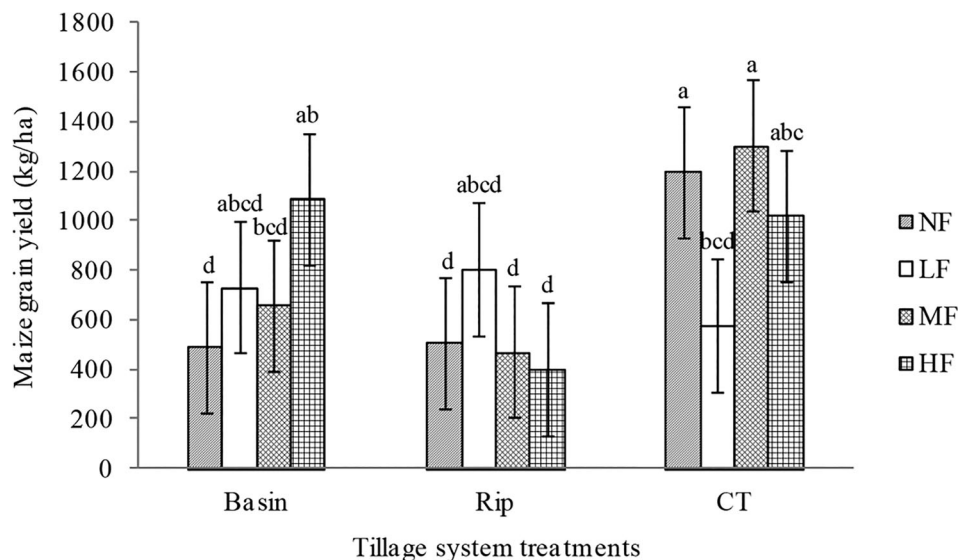


Figure 4. Effect of tillage system and fertiliser application rate on maize grain yield at Chinhoyi University of Technology experimental farm during the 2018/19 cropping season. Error bars are \pm SED for the comparison of weeding intensity means within and across tillage systems, CT = conventional tillage, Rip = rip line seeding, Basin = basin planting, NF = no fertiliser, LF = low fertiliser, MF = medium fertiliser, HF = high fertiliser. Different letters on the graphs indicate a significant difference ($P \leq .05$).

and improving plant growth (Curry et al. 2002; Feller et al. 2003). Earthworm genus evenness declined by 71.5% due to application of HF under CT but no effect of fertiliser treatments were observed in the two minimum tillage systems (Figure 3). The high genus evenness in HF plots suggests that some genera were more dominant, probably those that are tolerant to high fertiliser application, than others. The differential effects of inorganic fertiliser application on earthworm have been reported in other studies. For instance, the abundances of certain species such as *Eisenia foetida* have been reported to decline (Haynes and Naidu 1998; Long et al. 2017) while those of others increase (Tiwari 1993; Edwards and Loft 1977) when high doses of inorganic fertiliser were applied.

Maize grain yield and relationship with earthworm communities

Compared with the normal rainfall pattern for the study site, the 2018/19 cropping was drier and this probably dampened the potential effects of treatment factors on maize grain yield (Table 1). Although weak, the positive correlation ($r = 0.34$) between total earthworm abundance and maize grain yield (Table 8) is evidence to suggest that earthworm activity in the soil could provide beneficial ecological services that increased crop growth and yield as previously reported by van Groenigen et al. (2014). These results agree with Baker et al. (1999) who observed a linear increase in crop production as earthworm abundance increased.

Conclusions

The results of our study confirmed our first hypothesis that soil inversion tillage and high inorganic fertiliser application negatively affect earthworm abundance and diversity. Specifically, the results showed that at more intensive levels, the individual effects of tillage system and fertiliser application rate reduced *Lumbricus* and total earthworm abundance, respectively. On the other hand, higher levels of weeding frequency + weed residue mulch had a positive effect on the Shannon-Weaver index. However, no individual effects of treatment factors were evident on all other earthworm parameters. The effects were visible when in interaction, with desirable responses including increased earthworm abundance and diversity in minimum tillage systems due to frequent weeding coupled with weed residue. Finally, contrary to our second hypothesis, maize grain yield was positively correlated with total earthworm abundance. Further studies should focus on identifying the most sustainable and cost-effective hand weeding

frequency for enhanced earthworm diversity and increased crop productivity.

Geolocation information

Chinhoyi, Zimbabwe: 17°20' S, 30°14' E.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data accessibility

Upon acceptance of the manuscript, all the data that support the findings of this study will be openly available in Dryad.

Author Contributions

N. Mashavakure designed and initiated the experiment and supervised data collection. B. Gutukunhuwa collected the data. B. Gutukunhuwa, N. Mashavakure and A. B. Mashingaidze analysed the data. B. Gutukunhuwa, N. Mashavakure, A. B. Mashingaidze and E. Gandiwa interpreted the data and wrote the manuscript. All authors read and approved the manuscript.

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