



Research article

Soil macrofauna response to integrated soil fertility management under maize monocropping in Zimbabwe

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ABSTRACT

The continued decline in both populations and diversity of soil macrofauna in agroecosystems remains a major concern for sustainable food production in Southern Africa. Macrofauna abundance and diversity were examined in a maize monocropping system following repeated incorporation of *Calliandra calothyrsus*, *Crotalaria juncea*, cattle manure, maize stover, and *Pinus patula* sawdust at 1.2 or 4.0 t C ha⁻¹ with or without nitrogen (120 kg N ha⁻¹) for 13 years (seasons). All treatments received phosphorus (P), potassium (K), and sulphur (S) at 16.0, 14.7 and 4.6 kg ha⁻¹, respectively, at each planting time in December. Using the ISO/TSBF (Tropical Soils Biology and Fertility Institute) monoliths procedure, macrofauna were collected to a depth of 0.30 m fortnightly from February to mid-May 2016. *Lumbricus terrestris* and Isoptera were significantly ($P < 0.001$) affected by organic treatment and seasonal time, while organic treatment alone significantly affected Elateridae. A fluctuating trend characterised Diplopoda, *L. terrestris* and Isoptera with two general peaks for *L. terrestris* and a significant Isoptera peak under maize stover. Rainfall significantly influenced *L. terrestris* and Isoptera abundance, while within-season sampling time explained the observed fluctuations in Diplopoda, *Holotrichia serrata*, Araneae, Acrididae, and Formicidae. While Araneae was prevalent under maize stover, Elateridae, *H. serrata* and Araneae showed no distinct pattern in abundance. At low application rate, higher Shannon-Wiener diversity indices were apparent except for maize stover. Increasing application rate of the different organics amplified stimulation, abundance and persistence of macrofauna, and significantly increased diversity relative to the control. Application of N-based mineral fertiliser appeared to be detrimental to selective macrofauna (e.g., *L. terrestris*, Isoptera and Elateridae). Monte Carlo permutation test identified ammonium nitrate as the most influential and detrimental variable followed by organic resource quality, soil organic carbon (SOC) and application rate. Long-term co-application of organic and inorganic resources thus stimulated macrofaunal populations and maintained diversity. To sustain the productivity of the predominantly maize-based smallholder cropping systems, it is proposed that extension packages promote the inclusion of a minimum of at least 1.2 t carbon ha⁻¹ annually towards improved soil health.

1. Introduction

Natural systems with diverse tree-cover support high soil macrofauna diversity promoting a sustainable soil ecosystem (Kamau et al., 2017). Macrofauna survival and proliferation hinges on food provisions with adequate protein for growth and reproduction, and carbon for energy (Coleman et al., 2000). Several studies have pointed towards the manipulation of faunal populations and diversity particularly where tree biomass was added to soils (Ayuke et al., 2003; Andrews et al., 2008; Salamon et al., 2011; Manyanga et al., 2014) and when pastures were established (Velasquez et al., 2012). Likewise, plant biomass in

grasslands and plantations manipulate macrofauna community structure (Warren and Zou, 2002).

Macrofauna are known to multiply in the presence of their preferred food resource (Sayad et al., 2012; Velasquez et al., 2012). However, land use changes from natural to cropping affects macrofauna community structures through removal of shading effect, destruction of nests, and removal of food substrates (Karanja et al., 2009; Barrios et al., 2012; Steinwandter et al., 2017). Use of fire during forest clearing and field preparation has also been linked to reduction of macrofauna richness in Eastern Amazonia and parts of Sub-Saharan Africa (Mathieu et al., 2004; Sileshi and Mafongoya, 2006). Furthermore, application of high rates of

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inorganic fertilizers, herbicides, and clean weeding are some of the agronomic practices which impact negatively on macrofaunal diversity under intensified farming systems (Salamon et al., 2011; Muchane et al., 2012). While it may not be that apparent, reduced macrofaunal diversity results in consequent organic matter depletion, nutrient mining and low yields leading to field abandonment (Mapfumo et al., 2005; Nezomba et al., 2015; Tully et al., 2015).

Soil macrofauna are pivotal for optimal crop yield attainment as they play a role in improving soil structure, infiltration and facilitating decomposition to supply nutrients (Linden et al., 1994; Ayuke et al., 2009). Given that the quality of organic resources changes over time during the growing season, macrofauna diversity is critical in the decomposition and mineralization processes as food availability and quality changes. Thus, high diversity will allow for a steady supply of nutrients to the growing crop. Diverse macrofauna also supply nutrients from their excretory products and decomposition after death. In addition, those excretory products can house beneficial microbes to interact with the crop, facilitate nutrient solubilization and decomposition. On the other hand, some macrofauna (e.g., Isoptera, Elateridae, *Holotrichia serrata*) can affect the growth of the crops as pest, or the duration of mulch, such that monitoring their dynamics can help to control the potential damage. It is therefore imperative to understand the impact of various innovations on the dynamics of soil macrofauna during the growing season.

There is increasing interest towards the adoption and use of integrated soil fertility management (ISFM) and conservation agriculture to foster sustainable agricultural production in Africa. According to Mapfumo (2009), ISFM hinges on combined utilization of different pillars of innovations such as organic plus inorganic fertilizers, improved germplasm and systematic legume-based rotations basing on farmer endowment and production circumstances. On the other hand, conservation agriculture builds on three key pillars of minimum soil disturbance, maintaining a permanent soil cover and crop rotations and diversification to achieve sustainable productivity (PFA, 2007; Stevenson et al., 2014). Both innovations have resulted in increased productivity and conserved farmers' resources in most parts of Southern Africa. Nhamo (2007) documented the impact of conservation agriculture in maintaining soil macrofauna diversity but such information is unavailable on ISFM practices.

In the 2002/3 season, an experiment was established based on ISFM pillars with the main aim of investigating the short to long-term effects of organic resource quality, quantity and N fertilization on SOC dynamics and maize productivity (Mapfumo et al., 2001). Over the years, most studies on the experiment have focused on yield, soil nitrogen dynamics and physico-chemical properties of soils but there is hardly any information available on soil macrofauna dynamics. Since its establishment in the 2002/3 season, management of the experiment has been the same but the question about the long-term effect of the treatments on soil macrofauna remain unanswered. Likewise, the impact of different quality organic resources used by farmers on macrofauna abundance also remains unknown. Most studies provide snapshot (once off sampling) scenarios of the soil macrofauna dynamics (Nhamo, 2007; Mutema et al., 2013; Manyanga et al., 2014; Mutsamba et al., 2016) leaving a knowledge gap on what happens to macrofauna during the growing season. In this study, we hypothesized that co-application of inorganic fertilizers and different quality organic resources create unique environments within a season and long-term to promote macrofauna abundance and diversity. We further hypothesize that increasing the application rate of

different quality organic nutrient resources amplify habitation environment for macrofauna survival. The main objective therefore was to determine the effect of long-term organic nutrient resources and inorganic inputs application on soil macrofauna abundance and diversity under maize monocropping.

2. Material and methods

2.1. Study site

The experiment was established at Domboshawa Training Centre, approximately 30 km northeast of Harare (17°36'S; 31°08'E; 1542 ma.s.l.), in natural region (NR) II receiving >800 mm of rainfall annually (FAO, 2006). The main mandate of Domboshawa Training Centre site is to evaluate agricultural innovations and technologies for later dissemination to smallholder farmers with the view of increasing productivity. As such, no special permission was required for conducting this study. The soils are sandy clay loams derived from granite, the major parent material for most soils used for crop production in Zimbabwe's smallholder farming systems. These soils are generally of low fertility and acidic, broadly classified as Lixisol (FAO, 2006). Prior to establishing the experiment, the land was fallowed for a year and before that, it was under continuous unfertilized maize. Initial characterisation of soil macrofauna composition was not determined at time zero of the trial. The initial soil properties at the beginning of the study are in Table 1.

2.2. Background to the experimental design and treatments

The study was based on a long-term field experiment established during the 2002/03 season under the project 'Managing soil organic matter for improved nutrient use efficiency on smallholder farms in Zimbabwe' (Mapfumo et al., 2001). The initial main objective of the project was to determine the short to long-term effect of organic resource quality and quantity, N management on soil organic carbon and maize productivity (Mapfumo et al., 2001). In most parts of Zimbabwe and Southern Africa, smallholder farmers utilize different quality or quantity of organic resources and inorganic fertilizers depending on availability and their endowment. For example, manure rate applied depends on size of the herd, with those with more livestock applying high rates. Therefore, this experiment was based on the need to balance crop nutrients demand, available resources (organic and inorganic) and building soil organic matter while simulating smallholder farmers' fertility management practices. It was also underpinned on repeated co-application of different quality organic resources and inorganic fertilizers with the view of building soil organic matter (Nicholson et al., 1997), increasing crop N availability and building soil fertility of degraded soils in the short and long term (Mapfumo and Giller, 2001; Mtambanengwe et al., 2006). *Crotalaria juncea* (hereafter *Crotalaria*), *Calliandra calothyrsus* (hereafter *Calliandra*), cattle manure (hereafter manure), *Zea mays* stover (hereafter maize stover) and *Pinus patula* sawdust (hereafter sawdust) were the five different quality organic resources used in this experiment. In terms of quality, *Crotalaria*, *Calliandra*, manure, maize stover and sawdust represented high, medium, variable, low and very low respectively covering, potential resource base for farmers. To ensure that the study covered different farmer typologies that govern quantity of resources utilized, organic resources were applied at low (1.2 t C ha⁻¹) and high (4.0 t C ha⁻¹) rates in main plots measuring 12 m × 6 m. Incorporation was done to a depth of 0.15–0.20 m using a hoe in early December after the start of

Table 1. Initial soil properties of the top 20 cm at Domboshawa, Zimbabwe.

Sand%	Silt%	Clay%	pH (CaCl ₂)	Organic C (%)	Total N (%)	Min N (ppm)	Available P (ppm)	Exchangeable cations (cmol kg ⁻¹)		
								Ca	Mg	K
73	5	22	4.5 (0.3)	0.73 (1)	0.07 (0.1)	40 (0.2)	6.3 (0.51)	0.8 (0.1)	0.7 (0.06)	0.2 (0.04)

Figures in parentheses indicate standard errors (Adapted and modified from Mtambanengwe et al., 2006).

Table 2. Treatments imposed and repeated under the SOFECSA trial at Domboshawa, Zimbabwe, in 2015/16 season.

Treatment	Biomass application rate (t C ha ⁻¹)	Basal fertilizers	Nitrogen Application (Kg ha ⁻¹)	Replication
<i>Crotalaria</i>	1.2	Full rate	0	3
<i>Crotalaria</i>	1.2	Full rate	120	3
<i>Crotalaria</i>	4.0	Full rate	0	3
<i>Crotalaria</i>	4.0	Full rate	120	3
<i>Calliandra</i>	1.2	Full rate	0	3
<i>Calliandra</i>	1.2	Full rate	120	3
<i>Calliandra</i>	4.0	Full rate	0	3
<i>Calliandra</i>	4.0	Full rate	120	3
Cattle manure	1.2	Full rate	0	3
Cattle manure	1.2	Full rate	120	3
Cattle manure	4.0	Full rate	0	3
Cattle manure	4.0	Full rate	120	3
Maize stover	1.2	Full rate	0	3
Maize stover	1.2	Full rate	120	3
Maize stover	4.0	Full rate	0	3
Maize stover	4.0	Full rate	120	3
Sawdust	1.2	Full rate	0	3
Sawdust	1.2	Full rate	120	3
Sawdust	4.0	Full rate	0	3
Sawdust	4.0	Full rate	120	3
Control	0.0	Full rate	0	3
Control	0.0	Full rate	120	3

Full rate = 16 kg P ha⁻¹ + 14.7 kg K ha⁻¹ + 4.6 kg S ha⁻¹; 1.2 t C ha⁻¹ = Low rate; 4 t C ha⁻¹ = High rate; *Crotalaria* = *Crotalaria juncea*; *Calliandra* = *Calliandra calothyrsus*; Sawdust = *Pinus patula* sawdust.

the rainy season, which is the normal planting time for most smallholder farmers (Rurinda et al., 2013). An additional main plot without any organic resources applied was created (hereafter referred to as control).

Since most sandy soils in Zimbabwe are inherently infertile, and most organic resources have low nutrient, particularly phosphorus (Giller, 2001), thus all main plots received basal fertilizers. Phosphorus, potassium and sulphur were applied at 16.0, 14.7 and 4.6 kg ha⁻¹ correspondingly using a basal fertilizer with 32% P₂O₅:16% K₂O: 5%. To offset the possible negative effects of nitrogen (N) immobilisation, organic resources are often applied in combination with nitrogen fertilizers to influence mineralization and enhance maize yields. Therefore, the main plots were split into two sub-plots, one with and the other without inorganic N fertilizer. Ammonium nitrate (34% N) was split-applied to the maize crop to attain 120 kg N ha⁻¹ (Table 2). The test crop was a

hybrid cultivar SC513 (137 to maturity), planted to attain 37 000 plant ha⁻¹. The first 30% split was applied at two weeks after crop emergence (WAE) (V2 stage) followed by 40% at six WAE (V12 stage) and the last 30% at nine WAE (R1 stage) to meet the maize nitrogen requirements (Figure 1; Ciampittie et al., 2011). Overall, the experiment was a 5 × 2 × 2 factorial arranged in a split-plot design with three replications per treatment (Mapfumo et al., 2007). Weeds were manually controlled and the trial was followed during dry season (April–October).

2.3. Biomass generation for the experiment

Crotalaria biomass was generated by chopping shade-dried crop which was harvested at 50% flowering, grown on adjacent fields to the experimental field. Similarly, maize stover collected from nearby fields at harvesting and stored was chopped prior to application. *Calliandra* biomass was essentially shade dried leaf biomass harvested just before winter each season from World Agroforestry Centre within Domboshawa Training Centre. On the other hand, cattle manure was collected from pens at Domboshawa Training Centre from the livestock unit mainly comprised of the local *Mashona* breed typical of those in Zimbabwe's smallholder farming areas. During the day, the herd would graze in paddocks with natural grass and penned overnight without any bedding material thus only having dung and urine in the manure. Lastly, sawdust was collected from forestry training centres outside Harare. The quality of the organic resources was managed the same thus having similar chemical properties across all seasons (Table 3).

2.4. Highlights from previous studies on the site

Mtambanengwe and Mapfumo (2006) determined the differential N supply effects of different qualities and quantities of organic nutrient resources on maize productivity from a replicate trial in Makoholi Experiment Station. The study showed consistent results between nitrogen release patterns with resource quality while maize yield correlated to size of profile mineral N fluxes. *Crotalaria* and *Calliandra* released 24% and 13% of added N respectively compared to 5–6% for other biomass applied in the first three weeks after incorporation. High-rate *Crotalaria* attained the highest yield but was also associated with highest NO₃-N leaching losses. At high rates maize stover and sawdust promoted N immobilization by 30% and 42%, respectively, relative to the control. Overall, Maize yields increased proportionally with total N added to resources in combination with N fertilizer while available soil N in the root zone mid-season (onset of maize flowering) significantly accounted for the grain yield.

Mtambanengwe et al. (2006) investigated the short-term nutrient supply capacity of the five organic resources with or without nitrogen fertilization under the long-term experiment. At Domboshawa, seven t

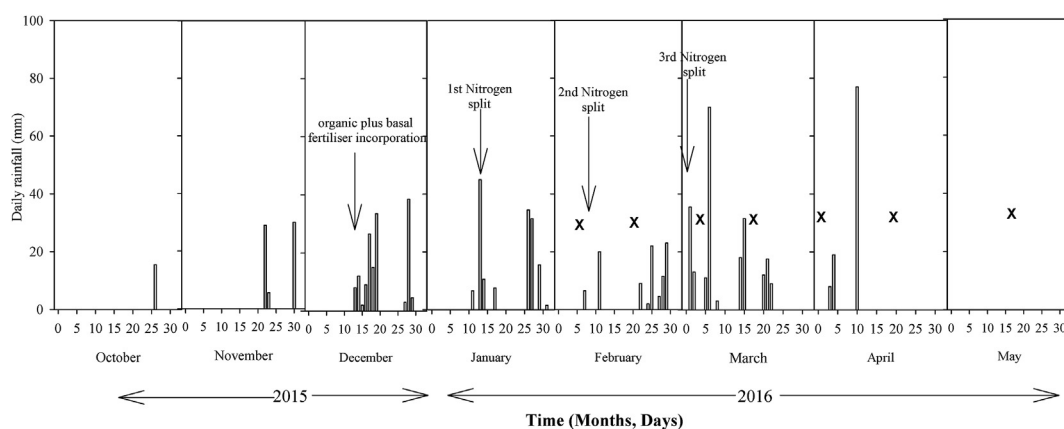


Figure 1. Rainfall distribution during 2015/16 season at Domboshawa (total = 807 mm). (Major events are indicated by arrows while macrofauna sampling event by X which corresponded to 58, 72, 86, 100, 114, 128 and 158 days after organic plus basal fertilizer incorporation).

Table 3. Quality attributes of the organic resources used in experiment.

Quality parameters	Organic resource				
	<i>Crotalaria juncea</i>	<i>Calliandra calothyrsus</i>	Cattle manure	Maize stover	<i>Pinus patula</i> sawdust
Carbon (g kg ⁻¹)	45	45	31	45	44
Nitrogen (g kg ⁻¹)	44	32	9	6	0.4
Lignin (g kg ⁻¹)	32	115	83	11	295
Polyphenols (g kg ⁻¹)	30	121	2	295	17
C/N ratio	10	14	31	69	122
Phosphorus (g kg ⁻¹)	2	1	6	1	0.1
Calcium (g kg ⁻¹)	14	12	15	3	0.8
Potassium (g kg ⁻¹)	11	5	35	8	0.5
Magnesium	5	5	7	3	0.2
Overall quality status	High	Medium	variable,	low	Very low

Adopted and modified from Mtangadura et al. (2017).

ha⁻¹ was the average grain yield attributed to the sandy-clay loams in the first season while there were significant treatment differences in nutrients uptake. However, on sandy soils, the study highlighted that combining nitrogen fertilizers with *Crotalaria*, *Calliandra* and manure resulted in between 24% and 104% increase in maize yield compared to sole fertilizer. On the other hand, combining low quality resources (maize stover and sawdust) with mineral N fertilizer gave a seven-fold grain yield increase relative to sole application of both resources. It implied an increased nutrient recovery by maize under organic plus inorganic treatments. The study also reviewed that the final yield could be determined by maize biomass at 2 weeks after crop emergency ($R^2 = 0.82$). In conclusion, the study indicated the importance of soil mineral N as a determinant factor for maize productivity under poor sandy soils and that maize biomass at 2 weeks is a useful tool for early potential yield assessment.

Mapfumo et al. (2007) quantified the interactive effects of organic resources quality and management on SOM formation and subsequent maize yield under contrasting soil types. Organic resource quality effects on particulate organic matter (POM) enrichment were significant at 12–14 weeks after incorporation in the macro-POM fractions of both soil types as reflected in 15–30% of total soil carbon (C) under coarse sand and 5–10% on sandy clay loam. *Calliandra* and sawdust showed the highest increases in macro-POM and sub-soil enrichment. The study highlighted that high-quality resources released no more than 25 mg N kg⁻¹ in sandy clay loams due to reduced short-term mineralization that protect added C. However, under coarse sands, the organo-mineral fraction released 50 mg N kg⁻¹ and 8–18 mg N kg⁻¹ under medium to high- and low-quality resources, respectively. There was significant linear relationship between maize grain yield and mineralizable N in the macro-POM fraction ($R^2 = 0.50$; $p < 0.01$) on sandy clay loams while the best maize yield predictor under coarse sands was the total amount of mineralizable N from the same pool ($R^2 = 0.86$). Overall, the study concluded that maize productivity hinged on different soil organic fractions that require different management strategies.

In 2008/9 season, Manyanga et al. (2014) compared macrofauna order diversity and abundance under this long-term trial, improved fallows established at World Agroforestry Centre and miombo woodland. The major groups identified were Isoptera, *Lumbricus terrestris*, Coleoptera, Diplopoda and Formicidae. The study indicated that *Crotalaria* had five orders, while other organically amended treatment had more than three orders relative to one order identified under unfertilized maize. The overall trend in order diversity was *Calliandra* > maize stover > manure > *Crotalaria* > fully fertilized maize > unfertilized maize (control without N). This study concluded that both improved organic nutrient resources and use of improved fallows significantly influenced macrofauna order diversity and abundance.

Mtangadura et al. (2017) analyzed the maize yield and soil chemical property trends for the first nine years of the long-term experiment

(2002–2012). Despite the increase in fertility (soil organic matter, total N and available phosphorus), there was a general decline of maize grain yields by 22%–88% across treatments. The main reason for the decline in maize yields in the nine seasons was attributed to exchangeable bases (Ca ($r = 0.51$), Mg ($r = 0.62$) and K ($r = 0.53$)) and soil pH ($r = 0.49$). These findings advocated for application of high rate of organic amendments to supply the much-needed exchangeable bases for sustainable maize production in the region.

Crop development and final yield is partly determined with seasonal dynamics of soil nutrients and biological activities. Macrofauna is key in soil fertility restoration thus being beneficial or can be detrimental to the crop following introduction of innovations. It is therefore imperative to understand the impact of various innovations on the dynamics of soil macrofauna as the crop develops during the growing season.

2.5. Macrofauna sampling and processing

Sampling for macrofauna was carried out in the 13th season from February 2016 with subsequent samples collected fortnightly thereafter until mid-May (Figure 1). Basing on ISO/TSBF (Tropical Soil Biology and Fertility Institute) procedure, two replicates were randomly selected from each treatment for macrofauna sampling using a metallic monolith (0.25 m length × 0.25 m width × 0.30 m depths) (Brown et al., 2001; Bignell et al., 2008). A macrofauna sampling buffer zone of 0.5 m was demarcated between treatments to reduce crossover effects. The monolith was driven into the soil using a nylon hammer to a depth of 0.30 m to cover the depth of biomass incorporation. The soil outside the monolith was rapidly removed to isolate the block and limit loss of macrofauna such as Isoptera. The soil within the monolith was removed and macrofauna visible to the naked eye (>2 mm in diameter) were hand-sorted and counted (Lavelle et al., 2003). Sorting involved moving soil from the left side to the right side while picking and counting identified macrofauna. Unidentified macrofauna were preserved in 70% alcohol (Dangerfield, 1993) for further identification by an entomologist. To reduce nutrient and microbial loss under the long-term trial, the soil and identified macrofauna were returned at each site of excavation after counting and preservation of unidentified macrofauna. Composite soil sample (0–30 cm) from each treatment was also collected, air dried sieved to pass through a 2 mm sieve before analysing soil organic carbon.

2.6. Data analysis

Macrofauna abundance was tested for normality using Shapiro-Wilk's and did not satisfy the normality assumptions. To achieve normality, species population data was transformed $\sqrt{(x+0.5)}$ first before further analysis. Alpha diversity measure i.e., Shannon-Wiener (H') (Schloss et al., 2009) was calculated in Paleontological Statistics (PAST) package version 4.02 (Hammer et al., 2001). General linear model (GLM)

procedure was used to separate treatments, application rate, ammonium nitrate application and seasonal time effects on species population, and diversity in SPSS. Multivariate analysis was then used to establish relationships among macrofauna and several environmental variables (organics quality attributes, soil organic carbon, application rate and ammonium nitrate application) using CANOCO 4.5 (ter Braak and Smilauer, 2012). Data was subjected to gradient analysis and redundancy analysis (RDA) was identified as the appropriate technique to use, as gradient was less than three (ter Braak and Smilauer, 2012). Variables that aligned with axes have strong effects on macrofauna species composition. Furthermore, permutation tests examined relationships amongst variables and macrofauna abundance relative to the control treatment. Finally, the Monte Carlo test validated the permutation tests to identify variables explaining results from the RDA analysis.

3. Results

3.1. Treatment effects on macrofauna abundance

Thirty different types of macrofauna were identified and grouped into 14 orders including Achatinoidea, Araneae, Coleoptera, Diptera, Geophilomorpha, Hymenoptera, Isoptera, Lepidoptera, Metastigmata-Ixodida, Ordanata, Orthoptera, Spirobolida and Haplotaxida or Lumbriculida. Dominant macrofauna were Coleoptera such as Elateridae, *Holotrichia serrata* and *Aleochara bilineata* followed by Hymenoptera (e.g., Formicidae and *Apis mellifera*) and Lepidoptera (e.g., *Busseola fusca* and *Agrotis ipsilon*). Identified macrofauna included predators, organotrophs, polyphagous, pollinators, pest and others looking for suitable mating microclimate. Litter-transporters and engineers included Formicidae, Isoptera, *Lumbricus terrestris*, Elateridae and Diplopoda (Table 4).

Organic resources significantly influenced the abundance of Elateridae while organic resources and seasonal time significantly influenced abundance of *L. terrestris* and Isoptera. Seasonal time significantly affected the dynamics of *H. serrata*, Diplopoda, Araneae, Acrididae and medium black Formicidae abundance. Fluctuating trend characterised *L. terrestris* and Isoptera with two general peaks for *L. terrestris* and a significant peak under maize stover for Isoptera (Figure 2). Rainfall pattern influenced abundance of *L. terrestris* and Isoptera. At 86 days after organic resource and basal fertilizers incorporation (DAI), low-rate

manure had highest *L. terrestris* (33/m²) followed by sawdust which had 20 *L. terrestris*/m². However, at 128 DAI low-rate sawdust had significantly higher *L. terrestris* (50/m²) than low-rate manure, *Calliandra* and *Crotalaria*. At 128 DAI, high rate *Calliandra* and maize stover had highest *L. terrestris* of >70/m². However, high rate of sawdust significantly reduced *L. terrestris* from 50 to eight *Lumbricus terrestris*/m² at 128 DAI (Figure 2b). Low-rate maize stover attained two peaks at 86 DAI with 1325 Isoptera/m² and at 114 DAI with 6250 Isoptera/m² (Figure 2c). Isoptera persisted under low rate *Calliandra* attaining seasonal peak of 1279/m² at 114 DAI. Increasing biomass of *Calliandra* and *Crotalaria* suppressed Isoptera at most sampling points. Seventy-two DAI, both high-rate maize stover and *Calliandra* attained peak Isoptera abundance of 5417/m² and 1325/m², respectively, while 12500/m² in the control (Figure 2d).

Elateridae and *H. serrata* showed no distinct pattern within the season, both were characterised by stimulations, suppressions, increases, decreases and stagnation in abundance (Figure 3). The control had no Elateridae while application of manure, maize stover, *Calliandra* and *Crotalaria* at low-rate promoted stimulation until late March. However, increasing *Calliandra* and *Crotalaria* biomass caused disappearance and partial suppression of Elateridae, respectively. Elateridae only become visible in mid-April under high-rate *Crotalaria*. Elateridae attained a peak of 16/m² at 72 DAI under high-rate manure (Figure 3b). *Crotalaria* attained peak of 20 *Holotrichia serrata*/m² at 58 DAI (Figure 3c). From 86 to 100 DAI *Calliandra* had highest *H. serrata* abundance (20/m²). Low-rate *Calliandra* supported *H. serrata* throughout while manure partially suppressed them earlier and later in season. Control was only able to sustain eight *Holotrichia serrata*/m² at 86 and 128 DAI (Figure 3c). Increasing *Calliandra* rate to 4 t C ha⁻¹ reduced abundance and caused partial disappearance of *H. serrata*. However, high-rate treatments of maize stover, manure and sawdust promoted *H. serrata* persistence (Figure 3d).

Fluctuating trend also characterised Diplopoda with <10/m² abundance noted across low-rate treatments. Diplopoda was absent under low-rate *Crotalaria* and manure (Figure 4a). Increasing *Calliandra* and sawdust stimulated Diplopoda at 58 and 114 DAI, respectively. Furthermore, increasing *Calliandra* and *Crotalaria* suppressed Diplopoda from 72 DAI until the end of the season (Figure 4b). Araneae showed no distinct pattern within the season with most treatments housing 4

Table 4. Macrofauna identified at the UZ-SOFECSA long-term experiment during 2015/16 season at Domboshawa in Zimbabwe.

Order	Latin name	Common name	Survival strategy
Achatinoidea	<i>Helix aspersa</i>	Snail	Herbivorous
Araneae	Araneae	Spider	Carnivorous
Coleoptera	<i>Naupactus cervinus</i>	Fuller rose weevil	Herbivorous
Coleoptera	<i>Holotrichia serrata</i>	White grub	Organotrophs or polyphagous
Coleoptera	Coccinellidae	Lady bird	Carnivorous
Coleoptera	<i>Naupactus leucoloma</i>	White fringed beetle larvae	Feeds on root system
Coleoptera	<i>Calleida decora</i> , <i>Scaphidium quadrimaculatum</i> , <i>Aleochara bilineata</i> and Elateridae	Ground beetle, Shinning fungus beetle, Rove beetle and Wireworm	Pest
Diptera	<i>Musca domestica</i>	Housefly	Carnivorous
Geophilomorpha	<i>Geophilus flavus</i>	Centipede	Organotrophs or Predator
Hymenoptera	<i>Apis mellifera</i>	Bee	Pollinator
Hymenoptera	Formicidae, <i>Vespula vulgaris</i> , <i>Forficula auricularia</i>	Ant, Wasp and Lacewing earwig	Carnivorous
Isoptera	Isoptera	Termite	Pest or Organotrophs
Lepidoptera	<i>Eacles imperialis</i>	Moth pupa	N/A
Lepidoptera	<i>Busseola fusca</i> , <i>Agrotis ipsilon</i> , <i>Gonocephalum simplex</i>	Stock borer, Cut worm and Dust surface beetle	Pest
Metastigmata = Ixodida	Ixodida	Tick	Parasite
Neuroptera	<i>Distoleon tetragrammicus</i> larva	Ant lion	Carnivorous larva
Odanata	Mantodea	Praying mantis	Carnivorous
Orthoptera	Acrididae, <i>Gryllus</i> spp.	Locust and Cricket	Pest
Haplotaxida	<i>Lumbricus terrestris</i>	Earthworm	Organotrophs
Spirobolida or Julida	Diplopoda	Millipede	Organotrophs

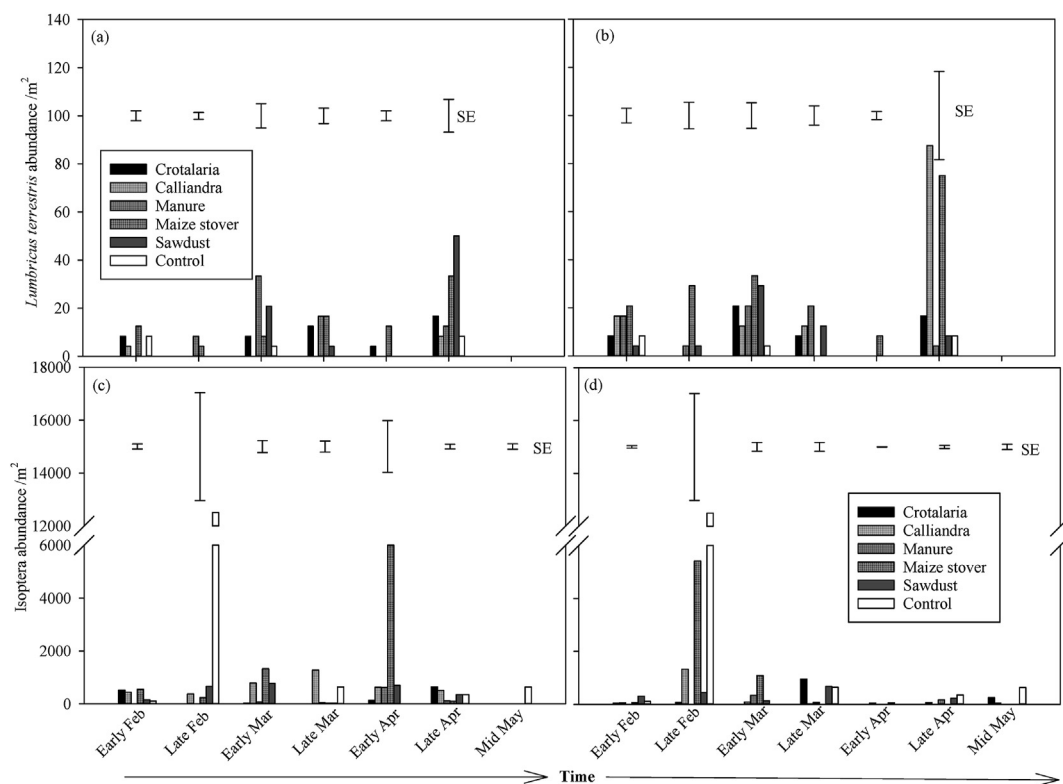


Figure 2. Changes in abundance of *Lumbricus terrestris* (a) $1.2 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$, (b) $4 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$ and Isoptera (c) $1.2 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$, (d) $4 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$ at Domboshawa during 2015/16 rainfall season.

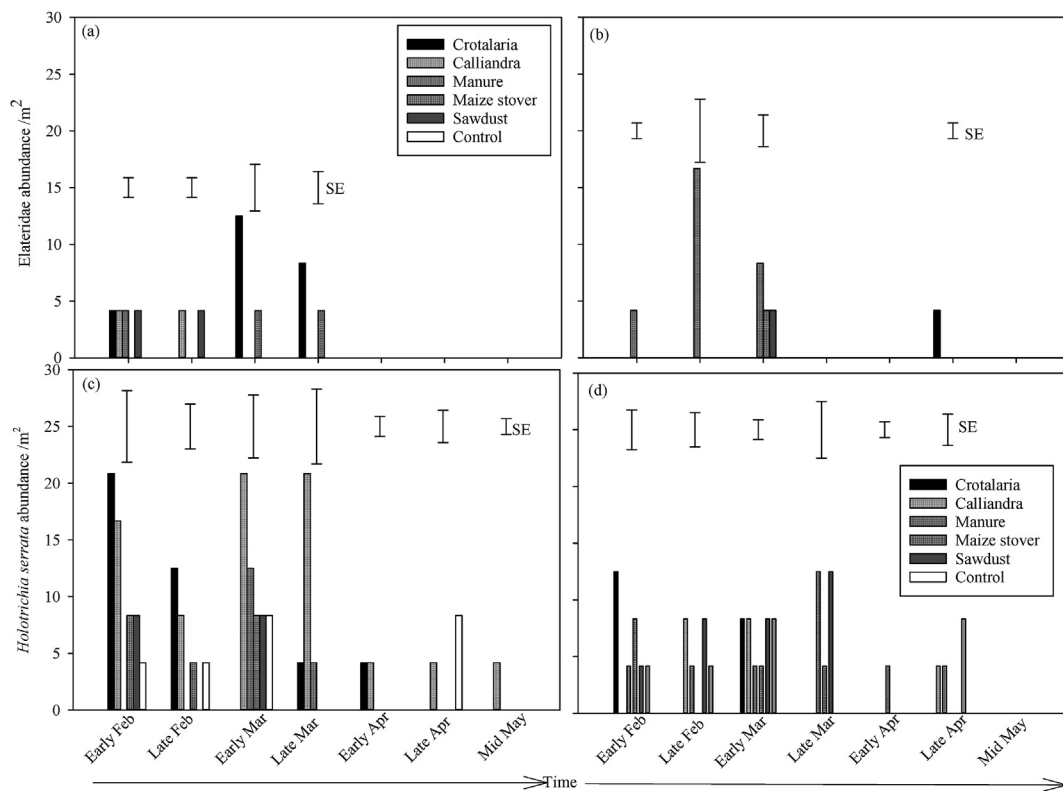


Figure 3. Changes in abundance of Elateridae (a) $1.2 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$, (b) $4 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$ and *Holotrichia serrata* (c) $1.2 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$, (d) $4 \text{ t C ha}^{-1} + 0 \text{ kg N ha}^{-1}$ at Domboshawa during 2015/16 rainfall season.

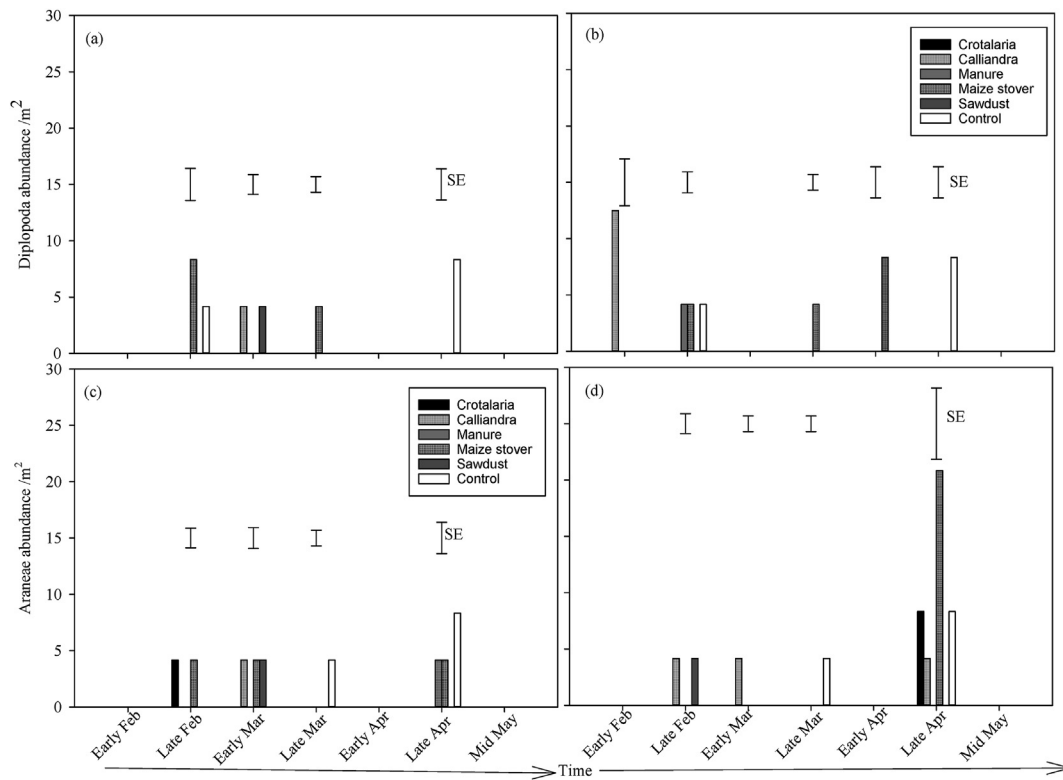


Figure 4. Changes in abundance of Diplopoda (a) 1.2 t C ha⁻¹ + 0 kg N ha⁻¹, (b) 4 t C ha⁻¹ + 0 kg N ha⁻¹ and Araneae (c) 1.2 t C ha⁻¹ + 0 kg N ha⁻¹, (d) 4 t C ha⁻¹ + 0 kg N ha⁻¹ at Domboshawa during 2015/16 rainfall season.

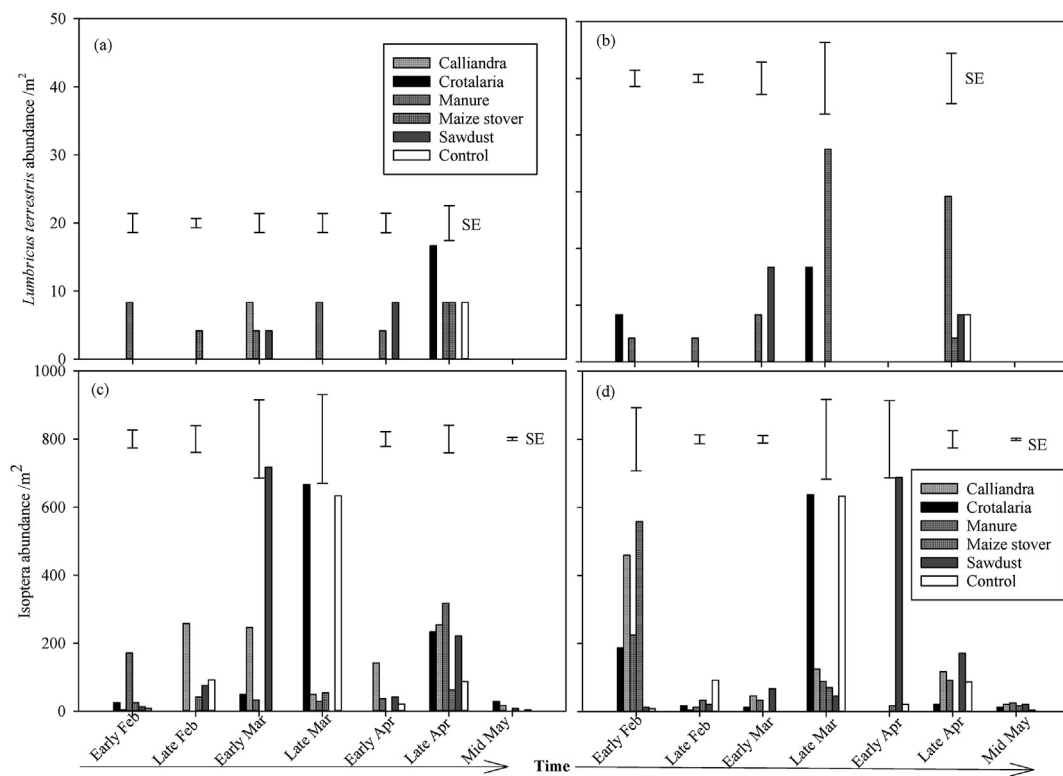


Figure 5. Effects of ammonium nitrate on *Lumbricus terrestris* (a) 1.2 t C ha⁻¹ + 120 kg N ha⁻¹, (b) 4 t C ha⁻¹ + 120 kg N ha⁻¹ and Isoptera (c) 1.2 t C ha⁻¹ + 120 kg N ha⁻¹, (d) 4 t C ha⁻¹ + 120 kg N ha⁻¹ abundance at Domboshawa during 2015/16 rainfall season.

Araneae/m² except at 128 DAI under the control which supported 8 Araneae/m². Araneae was most prevalent and persisting under low-rate maize stover while under low-rate *Crotalaria* and manure it only appeared once at 58 and 114 DAI, respectively (Figure 4c). Increasing manure application rate caused Araneae to vanish from the system. However, high-rate maize stover supported 20 Araneae/m² followed by *Crotalaria* with 8 Araneae/m² at 128 DAI (Figure 4d).

3.2. The impact of ammonium nitrate on macrofauna abundance

Overall, application of ammonium nitrate to low-rate treatments (1.2 t C ha⁻¹) reduced *L. terrestris* to <10/m² throughout the season except under *Crotalaria* at 128 DAI (Figure 5a). Ammonium nitrate addition partially suppressed *L. terrestris* under control, low-rate *Crotalaria*, high-rate treatments of *Crotalaria* and maize stover. *Lumbricus terrestris* only resurged under low-rate *Crotalaria* and high-rate maize stover at 128 DAI (16/m²) and 100 DAI (37/m²), respectively (Figure 5). *Lumbricus terrestris* abundance was significantly reduced from >75/m² to <5/m² under high-rate *Crotalaria* and maize stover following ammonium nitrate application. Similarly, ammonium nitrate suppressed *L. terrestris* under high-rate *Calliandra* 128 DAI (Figure 5b). Isoptera was reduced to <712/m² following ammonium nitrate application across all low-rate treatments (Figure 5c). However, ammonium nitrate application to high-rate sawdust increased Isoptera from 58 to 688/m² at 114 DAI. Ammonium nitrate application reduced Isoptera population under the control (Figure 5d).

Elateridae vanished under low rate (i.e., *Calliandra*, maize stover, sawdust) and high rate (i.e., *Calliandra* and sawdust) treatments following ammonium nitrate addition. Under manure plus ammonium nitrate Elateridae was partially suppressed and resurged at 158 DAI to attain 4/m² (Figure 6a). Application of ammonium nitrate to control

stimulated 4 Elateridae/m² at 86 and 128 DAI. However, ammonium nitrate addition stimulated Elateridae under high-rate treatments of *Crotalaria* and maize stover at 58 and 158 DAI, respectively (Figure 6b). *Holotrichia serrata* vanished under low-rate *Calliandra* while it was partially suppressed under maize stover following ammonium nitrate addition (Figure 6c). Likewise, ammonium nitrate addition to high-rate treatments of *Crotalaria*, maize stover and manure suppressed *H. serrata* from 114 DAI onwards. In contrast, *H. serrata* persisted under low-rate (i.e., *Crotalaria* and manure) and high-rate (*Crotalaria* and *Calliandra*) treatments following ammonium nitrate addition (Figure 6d).

Application of ammonium nitrate caused Diplopoda to vanish under the control, low-rate treatments (i.e., maize stover, and sawdust) while partial suppression was noted until 100 DAI under *Calliandra*. Similarly, Diplopoda only appeared at 114 DAI under high-rate *Crotalaria* attaining 4/m². Ammonium nitrate application to low-rate treatments of *Calliandra*, *Crotalaria* and sawdust increased Araneae abundance to 8, 4 and 4 Araneae/m², respectively at 128 DAI. *Calliandra* + ammonium nitrate produced a distinct peak at 114 DAI with 75 Araneae/m². Araneae vanished under the control while under low-rate maize stover visibility only at 58 DAI following ammonium nitrate application.

RDA biplot produced twenty-two clusters. *L. terrestris*, Isoptera, Diplopoda and Elateridae negatively correlated to organic resources nitrogen, soil organic carbon and lignin content. Isoptera also negatively correlated to ammonium nitrate and application rate. However, Araneae positively correlated to organic resources nitrogen, soil organic carbon and lignin content. *Holotrichia serrata* and medium black Formicidae negatively correlated to polyphenols content. *Geophilus flavus* and Acrididae were in the same cluster and positively correlated to applied N and polyphenols content. Application of ammonium nitrate was the most influential variable affecting macrofauna abundance followed by resource total N > application rate and soil organic carbon > polyphenols

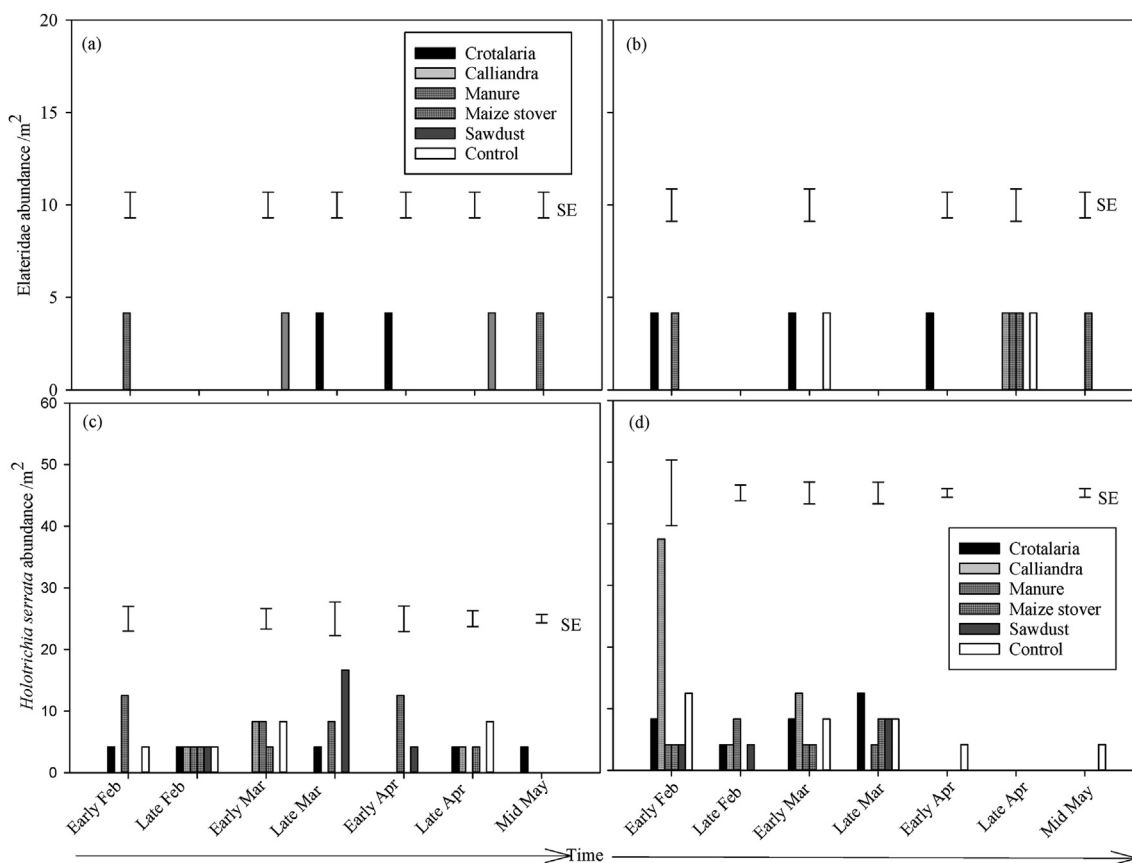


Figure 6. Effects of ammonium nitrate on Elateridae (a) 1.2 t C ha⁻¹ + 120 kg N ha⁻¹, (b) 4 t C ha⁻¹ + 120 kg N ha⁻¹ and *Holotrichia serrata* (c) 1.2 t C ha⁻¹ + 120 kg N ha⁻¹, (d) 4 t C ha⁻¹ + 120 kg N ha⁻¹ abundance at Domboshawa during 2015/16 rainfall season.

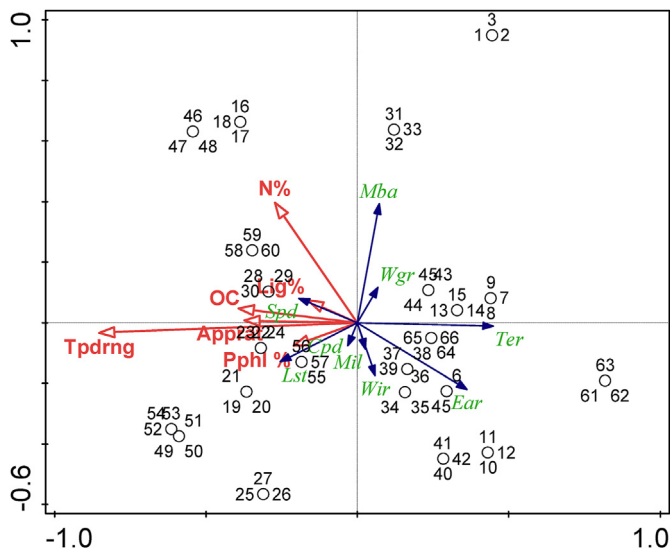


Figure 7. Redundancy analysis ordination biplot of 66 sites classified as 20 treatments which are classified as combination of different organic and inorganic nutrient resources. Vectors represent different macrofauna and explanatory variables. Macrofauna (Ear = *Lumbricus terrestris*, Ter = Isoptera, Wir = Elateridae, Cpd = *Geophilus flavus*, Wgr = *Holotrichia serrata*, Mba = medium black Formicidae, Mil = Diplopoda, Lst = Acrididae, Spd = spider). External variable (Tpdrrng = Ammonium nitrate application; OC = Soil organic carbon; N = total N in organic amendment; Appr = application rate; Pphl = polyphenol content; Lig = Lignin content).

and least factor being lignin content. Monte Carlo permutation test indicated that ammonium nitrate had a significant influence on macrofauna abundance (Figure 7).

3.3. Community structure and diversity under the different ISFM options

Application of organic resource at low-rate (1.2 t C ha⁻¹) significantly increased community diversity relative to the control except for maize stover. However, there were no significant differences in diversity amongst the low-rate treatments. Application of ammonium nitrate to across low-rate treatments significantly increased diversity relative to the control except for *Crotalaria* while no differences were noted relative to control + N. Increasing application of organic resources to 4 t C ha⁻¹ had no effect on diversity compared to their respective low-rate treatments. However, relative to the control increasing application to 4 t C ha⁻¹ significantly increased diversity across treatments except for *Calliandra*

and maize stover while no difference was noted relative to control + N. There were no differences in diversity amongst high-rate treatments with or without ammonium nitrates (Figure 8).

4. Discussion

The observed stimulation in numbers and increase in diversity in macrofauna following application of organic resources is indicative of the critical role played by organic resources in creating habitable conditions. Basing on Sprengel-Liebig Law of the minimum (Van der Ploeg et al., 1999), organic resource is the limiting factor for macrofauna survival relative to the control. Given that no differences in diversity were noted between the low and high-rate treatments suggest that low application of organic amendments can reverse biota deprivation and the negative impact of land use change from the natural system mentioned in other studies (Kamau et al., 2017; Steinwandter et al., 2017). Most communal farmers are resource constrained (Mapfumo and Giller, 2001; Mtambanengwe and Mapfumo, 2005) and such macrofauna restoration following even low rates of organic matter application will stimulate the productive capacity of the predominantly degraded soils typifying most smallholder farming systems in Zimbabwe. These findings also support our first hypothesis on the creation of unique environment for macrofauna survival and proliferation by provision of all the basics pillars (water, diverse food, space and cover) within a habitat.

High *L. terrestris* abundance under sawdust, maize stover and manure suggests that quality attributes had little influence than rainfall events. Similarly, Warren and Zou (2002) also highlighted soil moisture as being a more influential factor than quality of resources in determining macrofauna abundance. Incorporation of the organic resources helped in moisture retention of the rains, cover provision and easy access of food for soil macrofauna. Water is key in kick starting macrofauna activities (movement, foraging and feeding) and the decomposition process. Soil moisture attributed to rainfall event and dry spells significantly influenced abundance of *L. terrestris* and Isoptera. As soils become drier, *L. terrestris* particularly surface dweller and shallower burrower species, move into deeper soil horizons while Isoptera move to the surface and vice versa depending on moisture conditions (Dibog et al., 1998; McDaniel et al., 2013; Yeyinou Loko et al., 2017). Furthermore, the combined effect of mulch reduction linked to decomposition and less rainfall as the season progressed led to increase in Isoptera from mid-season onwards. Organic resources have the capacity to house macrofauna and maintain a diverse community beyond the rainfall season but limited by moisture.

The co-benefit of organic resources and rainfall/moisture is across communities but the selective macrofauna habitation, multiplication and fluctuations is dependent on preference, food supply from decomposition

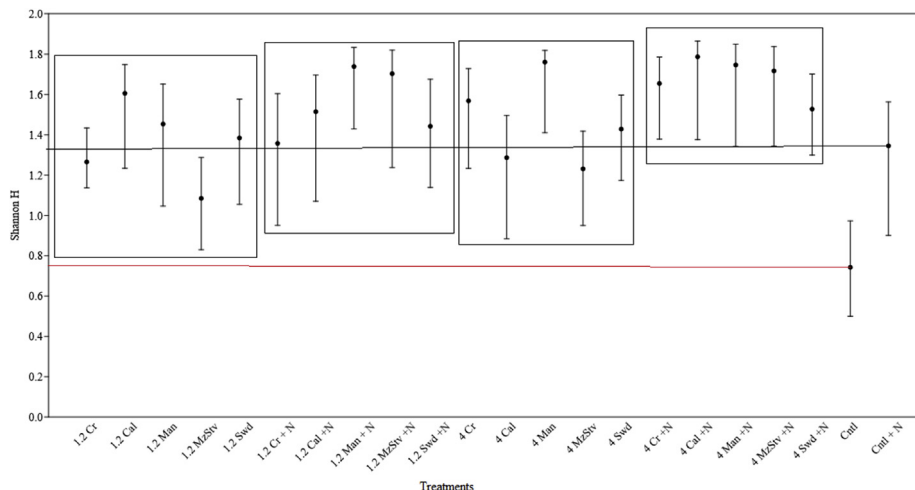


Figure 8. Shannon Wiener diversity indices for macrofauna under different treatments at Domboshawa in 2015/16 rainfall season.

and mineralization processes, and availability of alternative food sources. Depending on organic resource quality and soil conditions, decomposition will release food source (nutrient/energy) in various levels over time while macrofauna consumption efficiency will determine abundance. Accordingly, macrofauna will multiply in the presence of their preferred food resource (Sayad et al., 2012; Velasquez et al., 2012). For instance, Isoptera preferred maize stover and *Calliandra* as shown by high population even at low application rate. Preference of Isoptera to maize and its residues compared to millet, sorghum, cassava and yam in sub-Saharan Africa is known (Obi et al., 2008; Mutsamba et al., 2016; Yéyinou Loko et al., 2017). Nyeko et al. (2004) reported Isoptera problems in 1-year *Calliandra* fallows. Isoptera is able to utilize *Calliandra* biomass despite the high lignin and polyphenol content due to formation of anisymbiotic association with fungi (Wardle and Lavelle, 1997) that facilitate harnessing of the resource. Macrofauna diversity increase and creation of habitat cover within the new environment attracted predators such as Araneae (e.g., under maize stover a low-quality resource) as noted in other studies (Toft, 1999; Salamon et al., 2011; Pommeresche et al., 2013). *Geophilus flavus*, *Forficula auricularia*, Ixodida and *Distoleon tetragrammicus* larva are also predatory species that hunted across treatments and as such, either treatment or seasonal time had no influence on their population. Predators will also avoid hunting prey which bioaccumulate toxins (Toft, 1999), which explains Araneae preference to forage under the cover of maize stover over those in *Crotalaria* and *Calliandra*.

Calliandra and *Crotalaria* showed signs of inhibition to specific macrofauna survival despite being medium to high quality organic resources, and this disproves our first hypothesis. The presence of detrimental phenolic compounds such as terpenes and flavonoids is known to reduce species diversity and abundance (Reich et al., 2005). In this case, *Crotalaria* tissue contains delta-hydroxynorleucine, an allelochemical amino acid compound (Wilson and Bell, 1979; Wang et al., 2002; Gill et al., 2010), which may have contributed to the absence and suppression of Diplopoda and *H. serrata*. Considering the quality attributes of *Calliandra* relative to maize with specific reference to the high polyphenolic content, and sawdust (high in lignin), the high measure of these two compounds may likely explain the low macrofauna abundance observed. Adler and Chase (2007) also suggest that high soil organic matter and clay content adsorb allelochemicals thereby reducing phytotoxicity impacts on weeds. The difference in phytotoxicity difference observed at low application rates, was attributed to low soil organic carbon under *Crotalaria*, high soil organic carbon under *Calliandra* (Mtangadura et al., 2017), and the levels and types of allelochemicals while clay content impact was cross-cutting. As a result, greater inhibition was expected under *Crotalaria* than *Calliandra* while the target species had different sensitivity to the released chemicals.

Application of organic resources at high rate amplified stimulation, increased abundance, and persistence of macrofauna due to an increase in cover, providing a mulching effect, and food supply to support our second hypothesis. However, no significant change in diversity was noted as a result of increasing organic resource application rates hence confirming that low amounts of organic matter is needed to kick-start the presence of beneficial macrofauna in arable soils. In this study, Araneae was positively correlated to application rate, soil organic carbon, resource total N and lignin content which explain high abundance under maize stover and *Crotalaria* as more prey was stimulated by the higher mulch. Mashavakure et al. (2019) noted similar results as high mulch provided the best hunting and foraging ground (refuge and cover) and habitat for Araneae. However, an increase in soil moisture retention subsequently reduced Isoptera which does not favour water (Yéyinou Loko et al., 2017). Nevertheless, mulching effect for fast decomposing organics such as *Crotalaria* and *Calliandra* or those actively consumed by macrofauna (e.g., maize stover) can provide a short-term solution to bring back some species such as Isoptera. Increasing application of *Crotalaria* might have improved egg-layering conditions (nesting preference) for Elateridae (Andrews et al., 2008) at season onset that led to hatching and presence of Elateridae towards season cessation. The fact that there

was no change in diversity at high application rate also suggest that something else besides increased carbon, cover, water and space may have been limiting the system.

Increasing *Crotalaria* and *Calliandra* application rates might have been adding more repellents to affect Isoptera, Elateridae and Diplopoda. This supports lower-order diversity also noted by Manyanga et al. (2014). *Crotalaria juncea* has been known to suppress nematodes by its repelling effect (Wang et al., 2012) and has been known to even cause mortality of the Lepidopteran, *Elasmopalpus lignosellus*, due to released allelochemicals (Gill et al., 2010). Further research is required to evaluate the mechanism of inhibition and affected growth aspects on the target species from the allelochemicals. Mtangadura et al. (2017) indicated increased soil organic carbon at high applications of *Crotalaria* and according to Adler and Chase (2007), the phytotoxicity would reduce but more suppression noted is suggestive of another inhibitor in the system. Disappearance and suppression of Elateridae, Isoptera and *H. serrata* under high rate *Calliandra* and *Crotalaria* is due to high nitrate build-up as noted by Mtambanengwe et al. (2006).

Ammonium nitrate was detrimental to selective macrofauna as shown by decrease in abundance, partial suppression and/or total suppression. Applied nitrogen affected macrofauna directly (contact reactions) or indirectly by habitat acidification. Similarly, Rai et al. (2014) and Meuti (2008) noted that mineral N was toxic to *L. terrestris* and Isoptera, respectively as was linked to mortality. Zhu and Zhu (2015) also noted lower macrofauna population under fully fertilized treatments compared to organically amended treatments. Farmers who do not apply organic amendments and yet apply high rates of mineral nitrogen affect survival of selective macrofauna. Nitrogen from organic resources also affected abundance of Isoptera, *L. terrestris*, Elateridae and *G. flavus* as shown by their negative correlation to resource total nitrogen. Application of mineral nitrogen stimulate mineralisation (Palm et al., 2001; Mtambanengwe et al., 2006) which amplify the effect of nitrogen to macrofauna particular from high to medium quality resources.

5. Conclusions

The long-term co-application of different quality organic and inorganic nutrient resources under maize mono-cropping stimulated and maintained macrofauna diversity while the decomposability of the applied organic substrates controlled seasonal abundance and persistence of different groups and species of macrofauna. Macrofauna responded differently to organic resources depending on their food preference, feeding strategies, their life cycle, rainfall events and presence of detrimental compounds while organic resource quantity had little effect. Increasing application rate amplified benefits or detrimental effects or simply triggered expression of detrimental effects. Rate of application of organic nutrient resources also appeared to shift seasonal peaks different macrofauna depending on resource quality. Application of ammonium nitrate caused a decrease in abundance, partial suppression and/or total suppression of macrofauna particularly *L. terrestris*, Elateridae, Isoptera and *G. flavus*. We advocate for smallholder farmers to include the provision of applying at least some organic amendments, albeit at low rates approximating 1.2 t C ha⁻¹ annually in their maize cropping cycles, to stimulate, restore and sustain soil macrofauna diversity. However, further research is needed to understand the effects of co-application of organic and inorganic resource under ISFM on microfaunal abundance and diversity.

Declarations

Author contribution statement

Tauro T.P.: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mtambanengwe F.: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mpepereki S.: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mapfumo P.: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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