Applied Soil Ecology 135 (2019) 120–128

Contents lists available at ScienceDirect

Applied Soil Ecology

journal homepage: www.elsevier.com/locate/apsoil

# Soil dwelling beetle community response to tillage, fertilizer and weeding intensity in a sub-humid environment in Zimbabwe

Nilton Mashavakure[a,*], Arnold B. Mashingaidze[a], Robert Musundire[a], Nhamo Nhamo[b], Edson Gandiwa[c], Christian Thierfelder[d], Victor K. Muposhi[c]

[a] School of Agricultural Sciences and Technology, Chinhoyi University of Technology, Private Bag 7724, Chinhoyi, Zimbabwe
[b] Institute of Research, Innovation and Technological Solutions, Zimbabwe Open University, 29 Samora Machel Avenue, P O Box MP1119, Harare, Zimbabwe
[c] School of Wildlife, Ecology and Conservation, Chinhoyi University of Technology, Private Bag 7724, Chinhoyi, Zimbabwe
[d] CIMMYT, P.O. Box MP 163, Mount Pleasant, Harare, Zimbabwe

A R T I C L E I N F O

*Keywords:*
Basin planting
Coleopteran
Detritivore
Herbivore
Predator
Rip line seeding

A B S T R A C T

Soil dwelling beetles contribute greatly to biodiversity and offer important services in agroecosystems including predation, weed herbivory and decomposition. An experiment was conducted in the 2013/2014 and 2014/2015 cropping seasons at Chinhoyi University of Technology experiment station, Zimbabwe, to investigate the impact of tillage system (conservation tillage and conventional tillage), fertilizer application rate and weeding intensity on beetle communities in maize. The experiment was laid out in a split-split plot using a randomized complete block design and replicated three times. Beetles were sampled using un-baited pitfall traps. A total of 6020 beetles were collected comprising 53 species, nine families and four functional groups. Tillage system had the strongest effects on beetle diversity. Advanced constrained analysis using principal response curves revealed that the abundances of *Anchophthalmus oncotipes* decreased under conservation tillage. In contrast, abundances of *Zophosis boei*, *Gonocephalum simplex*, *Renatiella reticulata* and *Stenethmus tentyriniformis* increased under conservation tillage relative to conventiona tillage (CT). Detritivore abundances were 50.8% and 45% greater under rip line seeding than CT during the hot dry season of 2014 and cold dry season of 2015, respectively. Predator abundances were almost double in basin planting relative to CT during the cold dry season of 2014 and hot humid season of 2015. In the 2014/2015 cropping season, maize grain yield significantly increased ($P < 0.05$) from 4963 kg $ha^{-1}$ in CT to 7848 kg $ha^{-1}$ in basin planting tillage. Application of a high rate of fertilizer increased maize grain yield by 31.2% compared to the low and medium fertilizer application rates. Weeding twice resulted in the highest maize grain yield but there was no yield benefit in increasing weeding intensity more than twice per season. Our results suggest that there is potential for increasing density and diversity of beneficial beetle species through conservation tillage with crop residue retention.

## 1. Introduction

Beetles are among some macro-invertebrates that offer beneficial functional services in agroecosystems including pest predation, weed herbivory, fungivory and organic matter decomposition (Bellamy et al., 2018; Diekotter et al., 2010; Lang et al., 1999; Oberg et al., 2007). Intensive agricultural management practices such as soil inversion tillage, high fertilizer application and high weeding intensity contribute to loss in biodiversity, including macro-arthropod diversity (Tsiafouli et al., 2015). An earlier review by Kromp (1999) shows that carabid density and species richness decrease with increasing intensity of agricultural management. Apart from loss of biodiversity in the form of species richness, the loss of ecosystem functional services is considered to be a crucial predicament in agroecosystems when intensity of agricultural management is increased (Gobbi and Fontaneto, 2008). An understanding of the functional role of macroinvertebrates such as arthropods in agroecosystems is important for designing sustainable ecologically-based crop management systems and making use of their potential (Barberi et al., 2010). Agroecological studies need to focus on biodiversity at both taxonomic and functional group level in order to fully understand the interactions occurring in the system. In this study, a functional group is considered as an assemblage of species that offer the same ecological services, e.g., predators and decomposers (Blondel, 2003).

* Corresponding author.
*E-mail address:* n.mashavakure@gmail.com (N. Mashavakure).

https://doi.org/10.1016/j.apsoil.2018.12.001
Received 29 January 2018; Received in revised form 4 December 2018; Accepted 5 December 2018
Available online 07 December 2018

Agricultural management systems that involve minimum tillage with plant residue retention can enhance biodiversity and associated beneficial biological processes in agroecosystems. A review of no-till in Europe revealed that density and diversity of surface dwelling fauna such as macro-arthropods increase under no-till systems compared to conventional tillage (Soane et al., 2012). Arthropod response to minimum tillage occurs in different ways: (1) alteration of the soil-dwelling arthropods' vertical and horizontal distribution, (2) amelioration of soil temperature and moisture due to creation of a more stable environment for arthropod survival due to absence of tillage and stubble retention, (3) provision of food for detritivorous and granivorous arthropods due to stubble retention, and (4) provision of shelter and overwintering sites for arthropods as weed communities shift from annual towards perennial species (Meiss et al., 2010; Stinner and House, 1990).

Plant biomass production has been shown to increase whilst plant species diversity decreases with increasing soil fertility (Hong et al., 2017). The effect of soil fertility on plant communities is expected to further directly and indirectly influence arthropod communities. Weedy vegetation can provide vegetative diversity which is usually absent in cropping systems. Therefore weeds can increase arthropod diversity and associated ecosystem services such as enhanced natural enemy populations, pest suppression and organic matter decomposition (Haddad et al., 2009; Showler and Greenberg, 2003). It is therefore, expected that optimum combinations of tillage, fertilizer application rate and weeding intensity should collectively increase the number of species (species richness), their relative abundances, and concomitantly relative contribution of species to the sum of ecological functions and services (Rusch et al., 2013). Reports on the effects of fertiliser regime and weeding intensity combined with minimum tillage systems on arthropods are often contradictory because they depend on site and environmental circumstances (Brust and House, 1988; van der Laat et al., 2015; Westerman et al., 2003). Moreover, a survey of literature suggests that most of these studies have been limited to the United States of America, Europe and Australia with scarce reports of similar work in the sub-tropics particularly sub-Saharan Africa (Hong et al., 2017; Norris and Kogan, 2000; Soane et al., 2012; Stinner and House, 1990). Furthermore, most of these studies focus on single arthropod groups as opposed to multiple arthropod groups in a single managed habitat over a continuous sampling period.

This study was conducted to investigate the response of different surface dwelling beetles to tillage, fertilizer and weeding regimes in a single habitat under a sub-humid environment in Zimbabwe. We tested the hypotheses that beetle activity density and community diversity: (1) are greater under conservation (basin planting and rip line seeding) than conventional tillage; (2) decrease with increasing inorganic fertilizer application; (3) are higher under low than high weeding intensity. The findings from this study are expected to enable design of agricultural management practices that enhance biodiversity and improve ecosystem services such as natural biological pest control and nutrient cycling under a sub-tropical environment.

## 2. Materials and methods

### 2.1. Site description

An experiment was conducted at Chinhoyi University of Technology Experiment Station, Zimbabwe (17°20′S, 30°14′E). The site is situated in a sub-tropical environment in sub-Saharan Africa with an altitude of 1140 m a.s.l. Based on climatic data for the 1991–2015 time period, mean annual rainfall for the study site is 810 mm (Worldbank.org, 2018). The rainfall is unimodal, occurring between November and April. The mean maximum temperature during summer is about 27 °C whereas the mean minimum temperature during the cold dry season is 7 °C (Climatemps.org, 2017). There are three distinct climatic seasons in Zimbabwe: (1) a rainy season that occurs from mid-November to mid-April each year and is generally hot and humid, (2) a cool season that is dry and sunny and occurs between mid-April to mid-August, and (3) a short dry period of intense heat that occurs between mid-August and mid-November (Climatestotravel.com, 2017). The soils found at the study site are Cambisols (WRB, 2015).

### 2.2. Experimental design and treatments

The experimental design was a split-split-plot in randomized complete blocks with three replications. The research plots were established in the 2012/2013 cropping season, and one season after establishment of the long-term tillage trial. This study was undertaken during the 2013/2014 and 2014/2015 cropping seasons. Treatments are repeated on the same plots in this long term trial. Tillage system (basin planting, rip line seeding and conventional tillage), fertilizer application rate (zero, micro-dosing, medium and high) and weeding intensity (twice, four times and clean weeding) were the main-, sub- and sub-subplots, respectively. Planting basins were made using hand held hoes at an inter-row spacing of 0.9 m and in-row spacing 0.5 m; each basin measuring about 15 × 15 × 15 cm (Mazvimavi and Twomlow, 2009; Sims et al., 2012). Rip lines were marked along the planting row at a spacing of 90 cm and to a depth of about 15 cm using a tractor-mounted ripper. Basin planting and rip line seeding represented conservation tillage systems. Conventional tillage (CT) treatments were prepared using a disc plough as primary tillage to a depth of about 30 cm followed by secondary tillage using a disc harrow. For fertilizer application rate, control plots (NF) were not fertilized. The microdosing (low fertilizer rate, LF) treatment received 4444 kg ha$^{-1}$ of cattle manure, 80 kg ha$^{-1}$ of a compound fertilizer (8 N: 14 $P_2O_5$: 7 $K_2O$) and 80 kg ha$^{-1}$ ammonium nitrate (34.5% N) to provide a total of 35.2 kg ha$^{-1}$ N, 12.2 kg ha$^{-1}$ $P_2O_5$ and 6.6 kg ha$^{-1}$ $K_2O$ ha$^{-1}$. Micro-dosing is a fertilizer regime that is recommended for smallholder farmers with limited resources under conservation agriculture (CA) in sub-Saharan Africa (Twomlow et al., 2008). In micro-dosing, the application of both inorganic fertilizers and manure is recommended because the two complement each other. Medium fertilizer rate (MF) plots received 100 kg ha$^{-1}$ of compound (8 N: 14 $P_2O_5$: 7 $K_2O$) and 100 kg ha$^{-1}$ ammonium nitrate (34.5% N) fertilizer to supply a total of 41.5 kg ha$^{-1}$ N, 14 kg ha$^{-1}$ $P_2O_5$ and 7 kg ha$^{-1}$ $K_2O$ ha$^{-1}$. In the high fertilizer rate (HF) treatment, plots received 200 kg ha$^{-1}$ of compound (8 N: 14 $P_2O_5$: 7 $K_2O$) and 200 kg ha$^{-1}$ ammonium nitrate (34.5% N) fertilizer giving a total of 83 kg ha$^{-1}$ N, 28 kg ha$^{-1}$ $P_2O_5$ and 14 kg ha$^{-1}$ $K_2O$. In the treatment that required weeding twice, plots were weeded at two and four weeks after crop emergence (WACE), while for treatments that were weeded three times, weeding was done at two, four, six and eight WACE. No weed growth was allowed in the clean weeding plots throughout the growing season. There were 36 treatments and 108 plots in this experiment. Maize crop residues were removed after harvesting in the CT plots and retained (about 30% soil cover) in the conservation tillage plots. There were 36 treatments and 108 plots in this experiment. Maize crop residues were removed after harvesting in the CT plots and retained (about 30% soil cover) in the conservation tillage plots.

### 2.3. Agronomic practices

Primary tillage was done between May and June whilst secondary tillage was done in October of each year. Basins and rip lines were prepared in November of each year. Compound fertilizer (7% N: 14% $P_2O_5$: 7% $K_2O$) and manure were applied at planting, about 5 cm below and 5 cm beside the crop seed. Top dressing fertilizer (ammonium nitrate, 34.5% N) was applied 4–6 weeks after crop emergence when at least 40 mm of rainfall were received. All the fertilizer was applied according to treatments. Weeding was done using a hand held hoe. All weed biomass was removed from the plots after every weeding operation. In all treatments, a commercial maize (*Zea mays* L.) variety ZAP61 was used as the test crop, planted at four seeds per planting position and thinned to two plants per planting position three weeks after crop emergence at a plant spacing of 90 cm inter-row by 50 cm intra-row to give a plant population of 44,444 plants $ha^{-1}$. The 2013/2014 maize crop was planted in December 2013 and harvested in April 2014 whilst the 2014/2015 maize crop was planted in December 2014 and harvested in April 2015. Plot sizes were informed by the need to control variables such as soil characteristics (color, texture, drainage and fertility) which all had potential effects on the functionality of the agroecosystem. In particular, (1) main plots (tillage system) were 27.6 m long × 27 m wide, (2) sub-plots (fertilizer regime) were 27 m long × 7.2 m wide, and (3) sub-sub-plots (weeding intensity) were 8 m long × 7.2 m wide (Supplementary material Fig. S1). Main plots were separated by 12 m whilst both sub- and sub-sub-plots were separated by 1.8 m pathways, respectively. Measurements were taken from four central rows of each sub-sub-plot.

### 2.4. *Effect of agronomic management practices on beetle community composition*

To determine the effect of tillage system, fertilizer application rate and weeding intensity on beetle activity density and diversity in the agroecosystem, beetles were sampled using un-baited pitfall traps placed within each net plot (four central rows). Despite its drawbacks, pitfall trapping is an acceptable method for sampling surface dwelling arthropods because the method is simple, less costly and effective (Greenslade, 1964; Prasifka et al., 2007; Skvarla et al., 2014). The traps were made of plastic jars measuring 13 cm diameter and 1000 $cm^3$ in volume. The traps were half filled with a mixture of 20% alcohol and 80% water to collect and preserve fauna samples. Two pitfall traps were set up in random positions in the four central rows of each plot but maintaining a distance of at least 2 m apart. Each sampling occasion involved placing pitfall traps in the study plots and leaving them in place to collect insects for seven days after which the traps were closed for 14 days as a resting period before the next seven-day sampling occasion. Closing of the traps at the end of the seven-day sampling period was done to avoid continuous trapping of arthropods. During each seven-day sampling period, pitfall catches were collected from the traps after every two days by filtering out beetle specimens through a strainer. Beetle count data for each plot was pooled together (total catches from the two traps for each sampling period) to form one sample. The cropping season at the study site starts in December and ends in April of the following calendar year. In this study, sampling commenced almost one month after planting, i.e., in January in each cropping season. In particular, sampling during the study period commenced in January 2014 and ended in August 2015. Two cropping cycles of the 2013/2014 and 2014/2015 agricultural seasons were covered.

Based on the three seasons described in sub-section 2.1 (i.e. a rainy, hot and humid season; cool, dry and sunny season and, intensively hot and dry season), the study period spanned five climatic seasons and data from each climatic season was combined for analysis. A total of 216 pitfall traps were maintained over the study period. Our study considered the population estimates from traps to be "activity density" in line with Hatten et al. (2007) who noted a direct relationship between individual pitfall samples and beetle densities as well as activity.

Beetle specimens were placed in tubes filled with a solution of 70% alcohol: 30% water for further processing. Collected specimens were counted and identified to species level using the keys by Lindroth (1968), Triplehorn and Spilman (1973) and Tarnawski and Buchholz (2008). The identified species were compared with reference collections at the Natural History Museum, Bulawayo, Zimbabwe. Species names were further verified by experts at Ditsong National Museum for Natural History, Pretoria, South Africa in January 2017. Beetle samples were assigned to genus-level functional groups according to their activity identities. The assignment of functional groups at genus level is likely to reveal clearer community composition than at higher taxonomic resolution such as order and family. Such an approach has been used by Susilo et al. (2009). All the preserved beetle specimens were deposited in the insect repository at Chinhoyi University of Technology, Zimbabwe.

### 2.5. *Statistical analysis*

Canonical Correspondence Analysis (CCA) was used to establish the relationship between agronomic management practices (tillage system, fertilizer application rate and weeding intensity) and beetle species, based on beetle activity density data using CANOCO 5 (ter Braak and Smilauer, 2012). The CCA was used because the beetle data had a gradient length of 6.1 SD units and was the most appropriate technique (Smilauer and Lepš, 2014). Management variables that aligned with the axes were considered to have strong effects on beetle species composition. An advanced constrained analysis technique, Principal Response Curves (PRC) was then done using these management variables to examine treatment effects on beetle species composition relative to the standard (conventional tillage). The Monte Carlo method was performed on the first canonical axis of the CCA to test if the PRC generated by the analysis had significant treatment variance. Results are presented only for the PRCs that showed significant ($P \leq 0.05$) effects of agronomic practices on beetle species composition. Species with scores between $-0.5$ and 0.5 on the PRC were excluded from further statistical analysis as they had little effect on the PRC (Whitehouse et al., 2014).

Beetle species with absolute score values above 0.5 were further analyzed using linear mixed effects model analysis (Restricted Maximum Likelihood, REML). Shannon diversity (H), richness and evenness (Shannon and Weaver, 1949) for beetle activity density data were calculated using Paleontological Statistics (PAST) package version 3.14 (Hammer et al., 2001). Beetle activity, beetle species diversity and maize grain yield data were tested for normality and homogeneity of variance using the Shapiro-Wilk's and Bartlett's tests respectively. Beetle diversity and maize grain yield were found to satisfy the normality assumptions. However, beetle activity data was $\text{Log}(n + 1.5)$ transformed to achieve normality of data distribution and homogeneity of variance. Beetle diversity and log-transformed activity density data were analyzed using the REML procedure to determine the effect of management practices on mean beetle activity densities. Tillage system (main plot), fertilizer application rate (sub-plot), weeding intensity (sub-sub-plot), sampling season and their respective interactions were used as fixed effects (Fixed model: Constant + Tillage + Fertilizer rate + Weeding intensity + Sampling season + Tillage × Fertilizer rate + Tillage × Weeding intensity + Fertilizer rate × Weeding intensity + Tillage × Sampling season + Fertilizer rate × Sampling season + Weeding intensity × Sampling season + Tillage × Fertilizer rate × Weeding intensity + Tillage Fertilizer rate × Sampling season + Tillage × Weeding intensity × Sampling season + Fertilizer rate × Weeding intensity × Sampling season + Tillage × Fertilizer rate × Weeding intensity × Sampling season). Plots were used as random effects in the model. (Random model: Tillage + Tillage system/Fertilizer rate + Tillage system/Fertilizer rate/Weeding intensity). Analyses of both beetle activity density and maize grain yield data were done using GenStat Version 10 (VSN-International, 2011).

## 3. Results

### 3.1. *Beetle community diversity*

A total of 6,020 surface-dwelling beetles were collected between January 2014 and July 2015. These represented nine families (i.e., Carabidae, Chrysomelidae, Coccinellidae, Curculionidae, Erotylidae, Meloidae, Scarabaeidae, Tenebrionidae and Trogidae) and 53 species. The beetle functional groups from the study site were arranged in

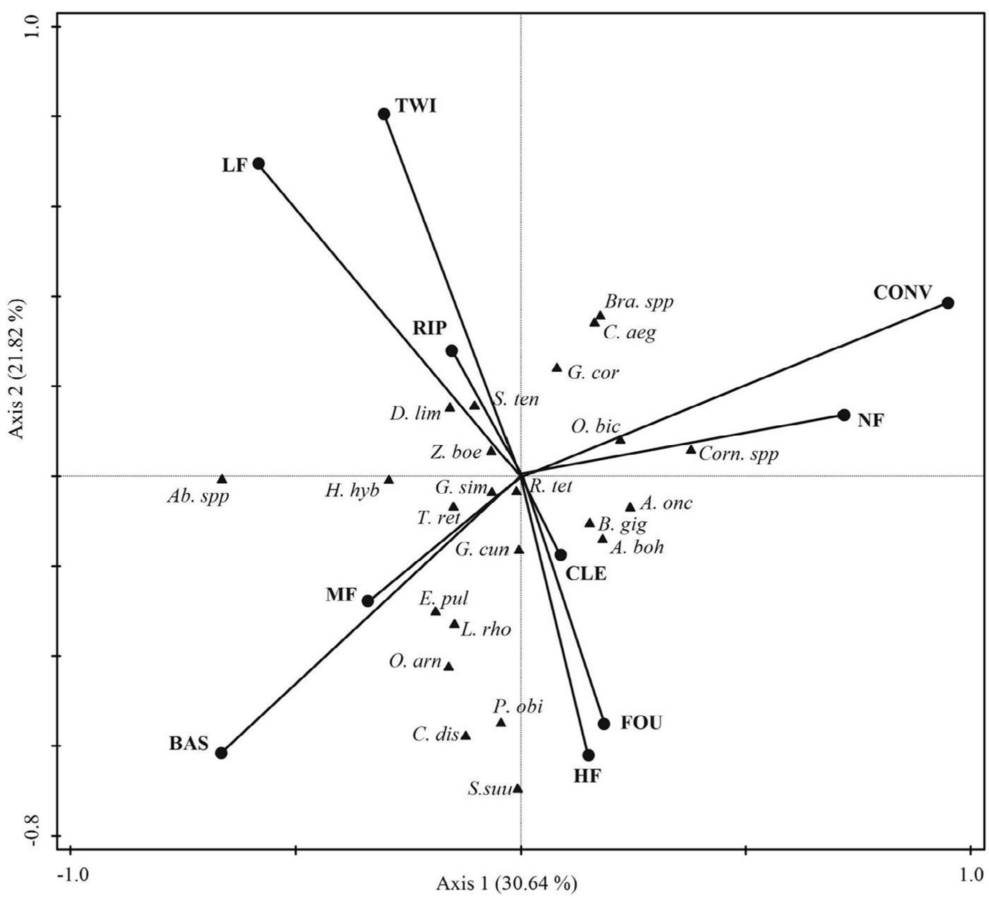


**Fig. 1.** Projection of beetle species data and agricultural management practices (tillage system, fertilizer regime and weeding intensity) of canonical correspondence analysis (CCA) for a study at Chinhoyi University of Technology Experiment Station, Zimbabwe, between January 2014 and August 2015. Bi-plot with management practices and species: *A. bohemani* (A. boh), *A. mascilicata* (A. mas), *A. oncotipes* (A. onc), *Abacetus* spp (Ab. sp), *B. gigantea* (B. gig), *B. servillei liopterus* (B. lio), *C. dusaultii discrepans* (C. dis), *Cornopterus* spp (Cor. sp), *D. limpompoipana* (D. lim), *D. tarsalis* (D. tar), *E. pulla* (E. pul), *G. cordiger* (G. cor), *G. cuneiformis* (G. cun), *G. simplex* (G. sim), *H. hybridus* (H. hyb), *O. arnoldi* (O. arn), *O. bicarvifrons* (O. bic), *R. reticulata* (R. ret), *S. suucpennis* (S. suu), *S. tentyriniformis* (S. ten), *T. reticulatus* (T. ret), *Z. boei* (Z. boe), *Brachinus* spp (Bra. Spp), *Cypholoba tenuicollis aegnima* (C. aeg), *Graphipterus cordiger* (G. cor), *Cornopterus* spp. (Cor. Spp), *Lagria* spp. (L. rho), BAS (basins), CONV (conventional tillage, RIP(rip line), TWI (weeding twice), FOU (weeding four times), CLE (clean weeding), NF(no-fertilizer), LF (low fertilizer), MF (medium fertilizer) and HF (high fertilizer).

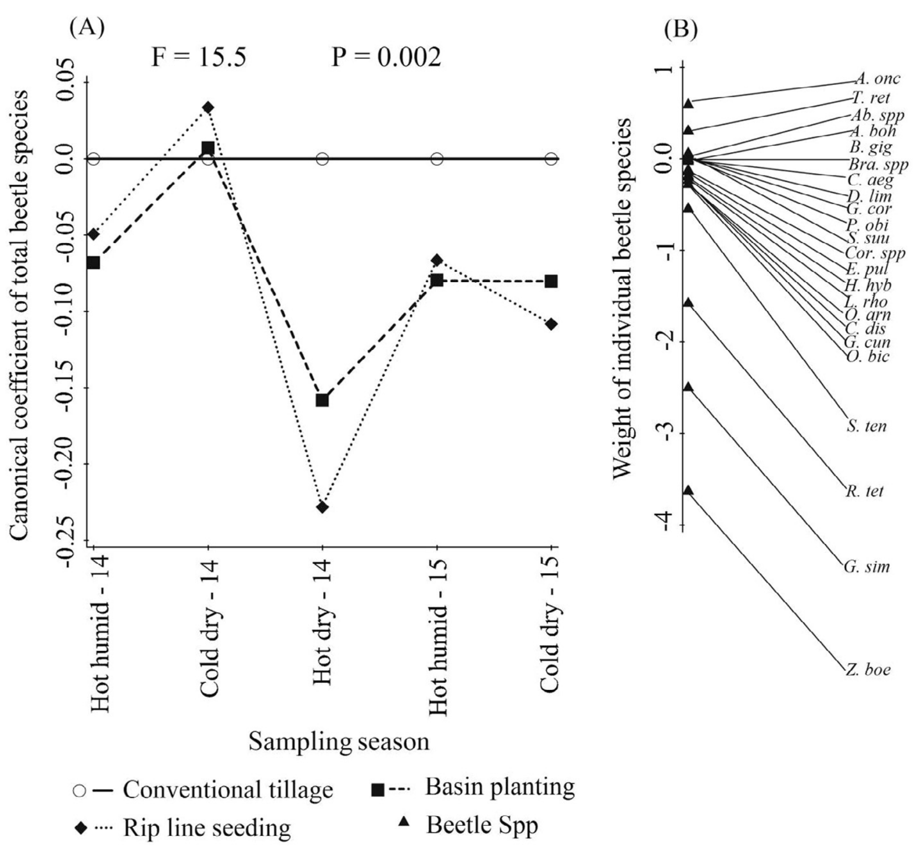


**Fig. 2.** (A) Principal response curves (PRCs) showing the response of beetle species to two conservation tillage systems (basin planting and rip line seeding) relative to the standard (conventional tillage). (B) Species weights indicating the relative contribution of individuals beetle species to the beetle community response. The beetles were sampled from an experiment at Chinhoyi University of Technology Experiment Station, Zimbabwe, between January 2014 and August 2015. *A. bohemani* (A. boh), *A. mascilicata* (A. mas), *A. oncotipes* (A. onc), *Abacetus* spp (Ab. sp), *B. gigantea* (B. gig), *B. servillei liopterus* (B. lio), *C. dusaultii discrepans* (C. dis), *Cornopterus* spp (Cor. sp), *D. limpompoipana* (D. lim), *D. tarsalis* (D. tar), *E. pulla* (E. pul), *G. cordiger* (G. cor), *G. cuneiformis* (G. cun), *G. simplex* (G. sim), *H. hybridus* (H. hyb), *O. arnoldi* (O. arn), *O. bicarvifrons* (O. bic), *R. reticulata* (R. ret), *S. suucpennis* (S. suu), *S. tentyriniformis* (S. ten), *T. reticulatus* (T. ret), *Z. boei* (Z. boe), *Brachinus* spp (Bra. Spp), *Cypholoba tenuicollis aegnima* (C. aeg), *Graphipterus cordiger* (G. cor), *Cornopterus* spp. (Cor. Spp), *Lagria* spp. (L. rho), Hot humid – 14 (hot humid season of 2014), Cold dry – 14 (cold dry of season 2014), Hot dry – 14 (hot dry season of 2014), Hot humid – 15 (hot humid of season 2015) and Cold dry – 15 (cold dry season of 2015).

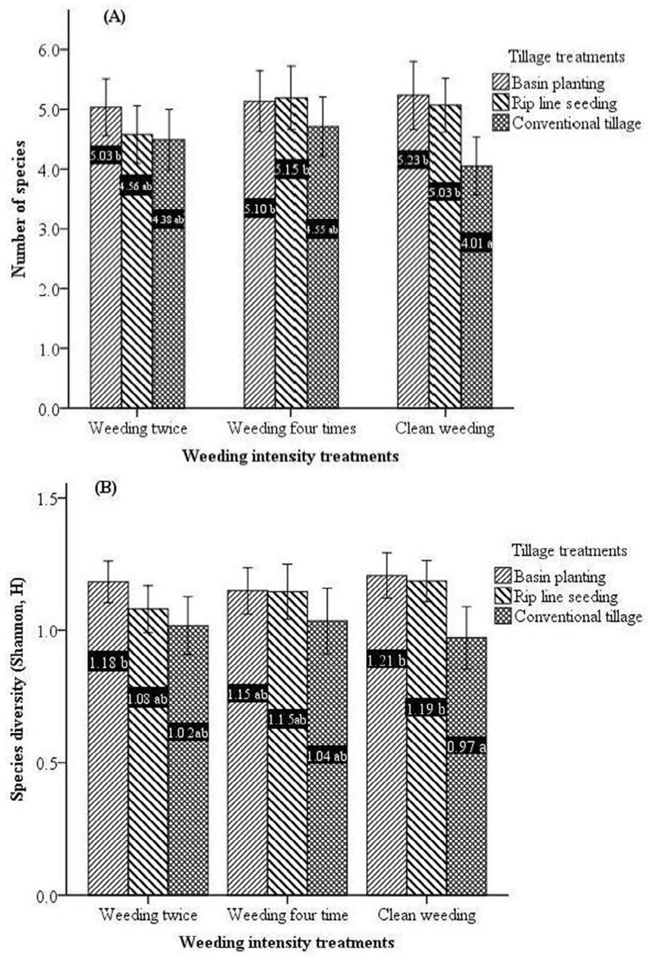


**Fig. 3.** Effect of tillage system and weeding intensity on beetle species richness (A) and diversity (B) at Chinhoyi University of Technology Experiment Station, Zimbabwe, between January 2014 and August 2015. Mean values followed by the same letter within and across treatments are not significantly different at $P \leq 0.05$.

descending order of activity density as follows: detritivores (16 species, 4,523 individuals and 75.1% relative abundance) > herbivores (14 species, 1,155 individuals and 19.2% relative abundance) > predators (342 individuals, 22 species and 5.7% relative abundance) > fungivores (1 individual, 1 species and < 0.1% relative abundance).

The CCA biplots provided evidence of association between agronomic management practices (tillage system, fertilizer regime and weeding intensity) and beetle species composition. The first axis explained 26.3% of the variance (eigenvalue = 0.03) whilst the second axis explained 19.4% of the variance (eigenvalue = 0.02) (Fig. 1). Alignment of tillage treatments with the first axes gave indications of their strong effect on the beetle composition. The first axis defines a gradient from beetle species associated with management practices such as low to moderate mechanical soil disturbance (BAS and RIP), low to medium fertilizer (LF and MF) and low weeding intensity (TWI), e.g., *Zophosis boei*, *Gonocephalum simplex* and *Renatiella reticulata* to species associated with management practices such as high mechanical soil disturbance (CONV), high fertilizer (HF), low fertilizer (LF) and high weeding intensity (CLE) e.g. *Anchophthalmus oncotipes*. The second axis distinguishes species associated with management practices such as no to low fertilizer (NF and LF), moderate to high mechanical soil disturbance (RIP and CONV) and low weeding intensity (TWI) including *Brachinus* spp., *Stenethmus tentyriniformis* and *Z. boei* from species associated with management practices such as low disturbance, medium to high fertilizer and high weeding intensity including *S. tentyriniformis*, *T. reticulatus*, *R. reticulata*, *E. pulla* and *G. simplex*. PRC analysis showed a clear difference in species composition between CT and conservation tillage practices (Monte Carlo test, F = 15.5, P = 0.002, Fig. 2A). Except during the cold dry season of 2014, there were distinct variations in beetle species diversity between CT and the two conservation tillage systems, with a general decline in beetle species diversity under conservation tillage throughout the study period.

According to the species score diagram (Fig. 2B), species that were most affected by conservation tillage systems were *Zophosis boei*, *Gonocephalum simplex*, *Renatiella reticulata*, *Stenethmus tentyriniformis* and *Anchophthalmus oncotipes*. In particular, *A. oncotipes* had the highest positive species weight and its activity density is inferred to be reduced most strongly under conservation tillage (Fig. 2). In contrast, *Z. boei*, *G. simplex*, *R. reticulata* and *S. tentyriniformis* had high negative species weights indicating increased activity densities of these species under conservation tillage. Some 78.3% of the beetle species (18 species) had weights between –0.5 and +0.5, showing a weak response to the management practices.

PRC analysis showed no significant effect of fertilizer application rate (Monte Carlo test, F = 4.7, P = 0.375) and weeding intensity (Monte Carlo test, Experiment 1: F = 4.3, P = 0.552, Experiment 2: F = 4.1, P = 0.220) on beetle species composition. According to REML analysis, there were some interaction effects of tillage system × weeding intensity on beetle species richness and diversity (Table 2). Generally, when plots were kept completely weed free (clean weeding) during the study period, beetle species richness and diversity were least in conventional compared to conservation tillage treatments (Fig. 3A & B).

### 3.2. Temporal dynamics of beetle communities

There was no significant (P > 0.05) interaction between tillage and sampling season on beetle species evenness and on some beetle groups such as *A. oncotipes*, *R. reticulata*, *S. tentyriniformis* and herbivores (Table 1). Beetle species richness ranged between 2.7 and 7.1, and was significantly (P < 0.05) lower in CT during the cold dry season of 2014, hot dry season in 2014 and hot humid season of 2015 than in conservation tillage during the same period (Fig. 4A). Beetle species diversity (Shannon index) mostly followed a similar trend as species richness with values ranging between 0.6 and 1.4 (Fig. 4B). Moreover, beetle species richness and diversity correspondingly showed similar trend to the PRC (Fig. 2A).

For beetle functional traits, there were also significant (P < 0.001) interactions between tillage and sampling season on detritivores and predators (Table 1). Activity densities of detritivores were significantly (P < 0.05) greater under rip line seeding during the hot dry season of 2014 (50.8%) and cold dry season of 2015 (45%) relative to CT (Fig. 5A). Compared to CT, predator activity density was almost double in basin planting during the cold dry season in 2014 and hot humid season in 2015 (Fig. 5B). For individual beetle species, *G. simplex* activity densities were lower in CT in the hot dry season (2014) compared to conservation tillage (Fig. 6A). On the other hand, except during the cold dry season of 2014, *Z. boei* activity densities were lower under CT compared to conservation tillage (Fig. 6B). Total beetle activity density tended to be greater during the cold dry season compared to the other two climatic seasons (hot dry and hot humid) and was generally lower in conventional tillage compared to conservation tillage (Fig. 6C).

### 3.3. Maize grain yield

Treatment effects on maize grain yield were not significant (P > 0.05) in the 2013/2014 cropping season but were significant (P < 0.05) in the 2014/2015 season (Table 2). In the 2014/2015 cropping season, maize grain yield decreased with increasing intensity of mechanical soil disturbance from 7848 kg $ha^{-1}$ in basin planting tillage to 4963 kg $ha^{-1}$ in CT. During the same season (2014/2015)

**Table 1**
Results of linear mixed effects models analysis showing tillage effects on beetle activity density and diversity (combined for two pitfall traps per plot) collected at Chinhoyi University of Technology Experiment Station between January 2014 and August 2015.

| Predictor variable | Beetle groups | | | | | Beetle FFG | | | Beetle diversity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Overall | *A. onco* | *G. simp* | *S. tent* | *Z. boei* | De | Pre | He | E | S | H |
| T | * | ns | ns | ns | * | *** | *** | *** | ** | *** | *** |
| F | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| W | ns | ns | ns | ns | ns | Ns | ns | * | ns | ns | ns |
| Ss | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| T × F | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| T × W | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ** | ** |
| F × W | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| T × Ss | *** | ns | *** | ns | *** | * | *** | ns | ns | ns | ns |
| F × Ss | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| W × Ss | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| T × F × W | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| T × F × Ss | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| T × W × Ss | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| F × W × Ss | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |
| T × F × W × Ss | ns | ns | ns | ns | ns | Ns | ns | ns | ns | ns | ns |

*Notes*: Basins (basin-planting), conv (conventional tillage), rip-line (rip line seeding), SED (standard error of difference) for log-transformed data, F (F-statistic), P (observed P-value). Values in parentheses represent $\log(x + 1.5)$ transformed means. Back-transformed values are mean beetle counts combined for two pitfall traps per plot. Different superscripts (a, b, c) in the same row for each experiment indicate significant differences at $P \le 0.05$. Mean separation is only shown if treatment effect was significant based on analysis of variance ($P \le 0.05$). Means are averaged over all sampling time points and years. Only beetle species whose score values lied outside the −0.5–0.5 range were used in the linear mixed effects analysis and are shown in this table. For predictor variable: T (tillage system), F (fertilizer rate), W (weeding intensity) and Ss (sampling season); for beetle groups: Overall (total beetle activity density), *A. oncotipes* (A. onco), *G. simplex* (G. simp) and *S. tentyriniformis t* (S. ten); for beetle FFG: FFG (feeding functional group), De (detritivores), Pre (predators) and He (herbivores); and for beetle diversity: E (beetle species evenness, S (beetle species richness) and H (beetle Shannon Weaver index).

**Table 2**
Effects of tillage system, fertilizer regime and weeding intensity on maize grain yield (kg ha$^{-1}$) at Chinhoyi University of Technology Experiment Station, Zimbabwe, in 2013/2014 and 2014/2015 cropping seasons.

| Treatments | Cropping season | |
|---|---|---|
| | 2013/2014 | 2014/2015 |
| *Tillage system* | | |
| Basin planting | 8622 | 7848$^{c}$ |
| Rip line seeding | 7677 | 6279$^{b}$ |
| Conventional tillage | 8771 | 4963$^{a}$ |
| F-Statistic (P-value) | 2.13 (0.126) | 28.9 (< 0.001) |
| SED | 575 | 380 |
| *Fertilizer regime* | | |
| No fertilizer | 7951 | 5686$^{a}$ |
| Low fertilizer | 9017 | 6327$^{a}$ |
| Medium fertilizer | 5563 | 5979$^{a}$ |
| High fertilizer | 7896 | 7461$^{b}$ |
| F-Statistic (P-value) | 1.29 (0.83) | 6.27 (< 0.001) |
| SED | 664 | 438 |
| *Weeding intensity* | | |
| Weeding twice | 8099 | 7163$^{b}$ |
| Weeding four times | 8058 | 5085$^{a}$ |
| Clean weeding | 8913 | 6842$^{b}$ |
| F-Statistic (P-value) | 0.252 (1.41) | 17.33 (< 0.001) |
| SED | 575 | 380 |
| *Interaction effects* | | |
| Tillage × Fertilizer | NS | NS |
| Tillage × Weeding | NS | NS |
| Weeding × Fertilizer | NS | NS |
| Tillage × Fertilizer × Weeding | NS | NS |

*Notes*: SED denotes standard error of difference between means. Different superscripts (a, b, c) in the same row for each experiment indicate significant differences at $P \le 0.05$. Mean separation is only shown if treatment effect was significant based on analysis of variance ($P \le 0.05$). NS represents non-significant effects.

maize grain yield in the high fertilizer rate treatment was significantly higher ($P < 0.001$) by 17.9, 24.8 and 31.2% than the low fertilizer, medium fertilizer and no-fertilizer treatment, respectively. The highest maize grain yield was recorded after weeding twice but it did not significantly ($P > 0.05$) differ with clean weeding throughout the season. Weeding four times reduced ($P < 0.05$) maize grain yield compared to weeding twice and clean weeding. Interaction effects on maize grain yield were not significant ($P > 0.05$) over both cropping seasons.

## 4. Discussion

### 4.1. Beetle community diversity

Our results showed that detritivores and herbivores were the two most predominant groups, together constituting 92.2% of total beetle catches. The presence of a variety of functional groups suggests that certain management practices employed in this study have the potential to enhance the efficiency of the system in provisioning services such as pest predation, weed seed dispersal, seed predation as well as nutrient cycling. The increased beetle species richness and diversity under conservation tillage found in this study agreed with the results of some earlier research (Kromp, 1999; Shearin et al., 2007; Soane et al., 2012) which showed that conservation tillage increased beetle species diversity and richness when compared to CT. These results were evident after the hot humid season of 2014, which was also the second cropping season under conservation tillage treatments, implying that species diversity and richness increased with age of the conservation tillage system. This could be due to increased accumulation of plant residues and stable undisturbed sites with increased age of the conservation tillage system. Lack of soil disturbance and presence of plant debris in conservation tillage treatments could have caused profound effects on different beetle groups, providing refuge from predation and facilitating foraging both directly and indirectly. Tilled systems cause direct mortality of beetle pupae and diapausing larvae when it exposes them to direct sunlight (Hatten et al., 2007; Shearin et al., 2007). Tillage also causes habitat destruction and food depletion, and this, coupled with the removal of surface organic debris, has the potential to reduce beetle activity density under conventional tillage treatments. This study provides evidence that conservation tillage systems can contribute to increased biological activity and number of beneficial beetle species in cropping systems in a sub-tropical environment.

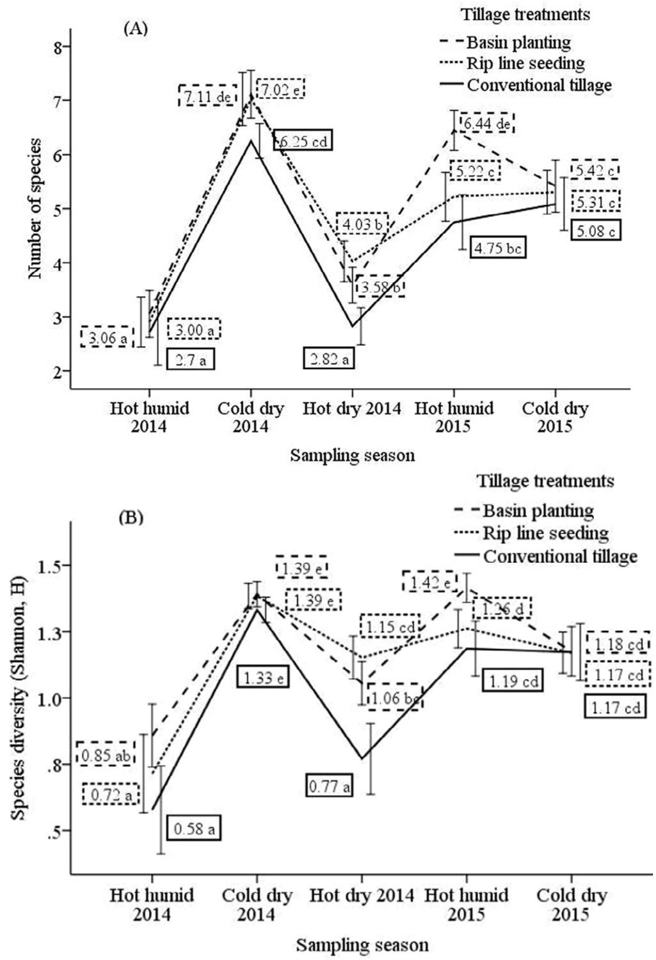


**Fig. 4.** Effect of tillage system and sampling season on beetle species richness (A) and diversity (B) at Chinhoyi University of Technology Experiment Station, Zimbabwe, between January 2014 and August 2015. Mean values followed by the same letter within and across sampling time points are not significantly different at P ≤ 0.05. Hot humid 2014 (hot humid season of 2014), Cold dry 2014 (cold dry of season 2014), Hot dry 2014 (hot dry season of 2014), Hot humid 2015 (hot humid of season 2015) and Cold dry 2015 (cold dry season of 2015).

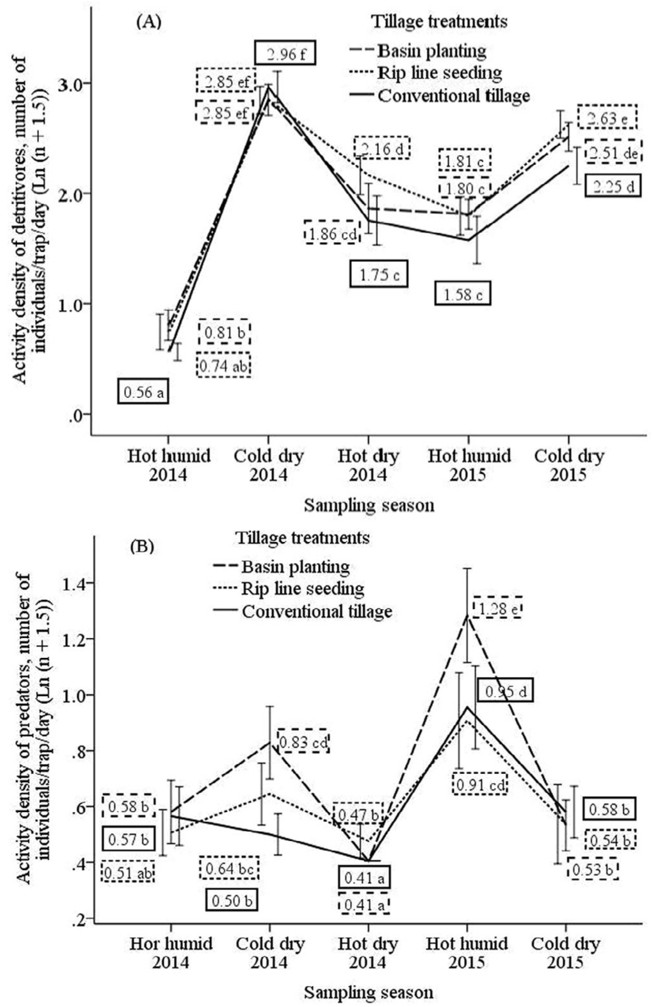


**Fig. 5.** Effect of tillage system and sampling season on beetle activity density (ln-transformed) of detritivores (A) and predators (B) at Chinhoyi University of Technology experiment station, Zimbabwe, between January 2014 and August 2015. Values followed by the same letter within and across sampling time points are not significantly different at P ≤ 0.05. Hot humid 2014 (hot humid season of 2014), Cold dry 2014 (cold dry of season 2014), Hot dry 2014 (hot dry season of 2014), Hot humid 2015 (hot humid of season 2015) and Cold dry 2015 (cold dry season of 2015).

There was little evidence from this study of the main effects of fertilizer regime and weeding intensity on beetle community diversity. However, consistent with García-Ruiz et al. (2018), we found reduced beetle species richness and diversity under high weeding intensity (clean weeding) particularly in CT plots. Complete removal of weedy vegetation coupled with removal of crop residues under CT possibly destroys refuge and food resources for beetles and is therefore detrimental to beetle diversity.

### 4.2. Temporal dynamics of beetle communities

Overall, detritivores and total beetle species appeared to exhibit higher activity densities under conservation tillage during cold dry seasons. The results seem to indicate that lack of soil disturbance during the rainy season is beneficial to detritivores and total beetle activity in the subsequent cold dry season. Moreover, it seems that the activity densities of some detrivorous species such as *G. simplex* and *Z. boei* were greater under conservation tillage than CT. To some extent these results corroborate other research findings where reduced soil disturbance and retention of crop residues on the soil surface supported higher macro-invertebrate density than disturbed habitats (Law, 2012; Magagula and Nzima, 2015; Menalled et al., 2007; Quinn et al., 2016).

Results largely suggest that seasonal changes in humidity, temperature, soil moisture and probably day length interact with micro-habitat disturbance to regulate beetle species activity density and diversity. Some individual species and detritivorous groups appear to be adapted to the cold and dry conditions compared to the humid season. This can be considered to be an evolutionary strategy for these species to evade competition and predation from other arthropods by restricting their activity to the period of the year when a majority of species will be in diapause. These beetle groups could be beneficial for organic matter decomposition and nutrient cycling particularly during the cold dry season when biological activity is generally low due to adverse climatic conditions. Contrary to findings by Quinn et al. (2016) and van der Laat et al. (2015) where no effect of tillage on predators was observed, our study showed an increase in predator activity density during the hot humid season. This observation seems to be rational on the basis of high vegetation density and diversity during the humid period. Diverse and dense vegetation cover is usually associated with a concomitant increase in densities of herbivorous prey (Haddad et al., 2009). Greater activity densities of detritivores and predators under conservation tillage suggests the likelihood of these groups utilizing

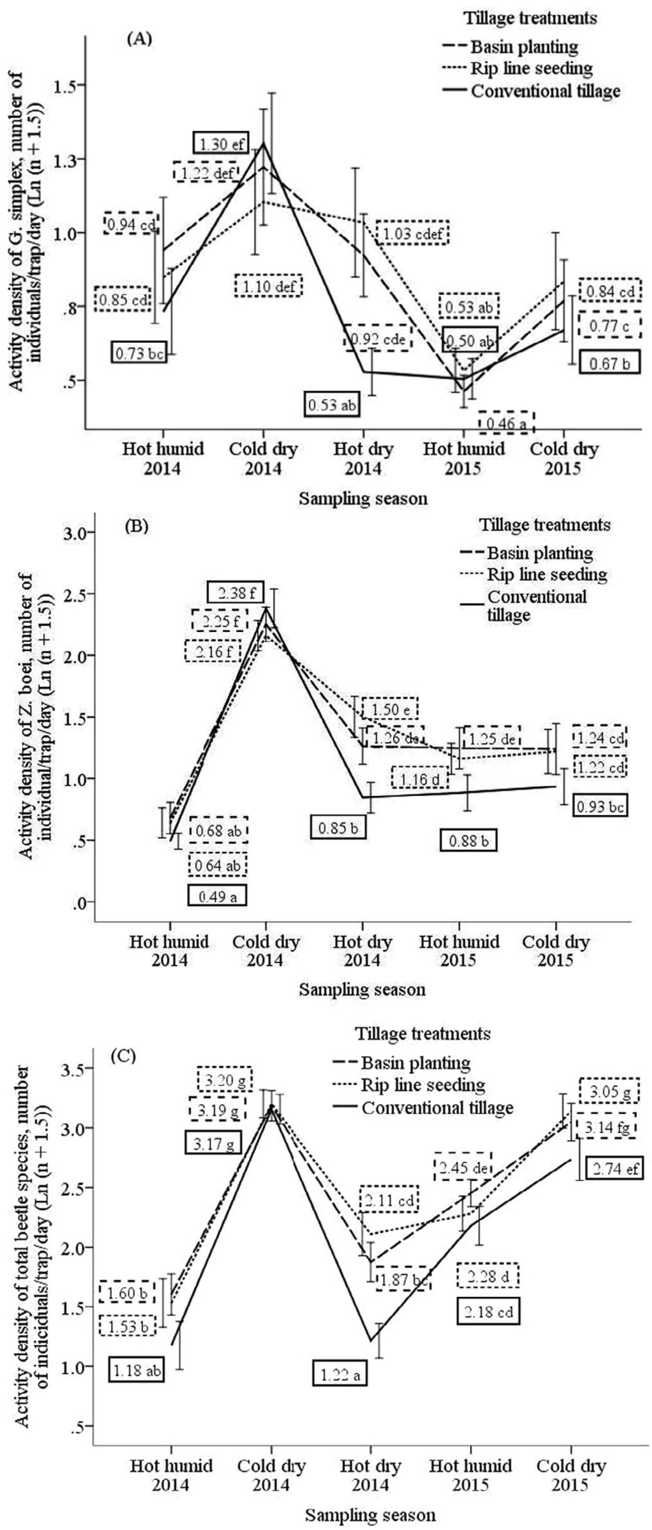


**Fig. 6.** Effect of tillage system and sampling season on ln-transformed activity density of *G. simplex* (A), *Z. boei* (B) and total beetle catches (C) at Chinhoyi University of Technology Experiment Station, Zimbabwe, between January 2014 and August 2015. Mean values followed by the same letter within and across sampling time points are not significantly different at $P \leq 0.05$. Hot humid 2014 (hot humid season of 2014), Cold dry 2014 (cold dry of season 2014), Hot dry 2014 (hot dry season of 2014), Hot humid 2015 (hot humid of season 2015) and Cold dry 2015 (cold dry season of 2015).

abundant detritus resources in an environment of moderated temperature and moisture micro-habitats provided by permanent plant residue retention that is maintained under less disturbed habitats.

### 4.3. Maize grain yield

The effects of tillage on maize grain yield were only evident in the third season of treatment implementation. This was most likely because at this stage, soil structural and biological conditions start to improve leading to enhance cropping system productivity. These results agree with Soane et al. (2012) who contend that crop yields under conservation tillage usually start to surpass those of CT after about three years of implementation. For fertilizer treatments, our findings agreed with Lundy et al. (2015) who reported high maize grain yield with increased fertilizer application. Our results further suggest that there is no yield benefit in increasing weeding more than twice during the cropping season. However, additional studies could be useful to establish consistency of fertilizer and weeding effects under the environmental and management conditions of the study site.

## 5. Limitations

Results from our study could have been an artifact of a number of limitations. Firstly, it is important to note that the experimental site that was used in this study was young, having gone through three years of conservation tillage treatments being imposed on the same plots. Secondly, the small plot sizes that were used in the study especially sub-sub-plots could have influenced our results. Beetles are mobile and could therefore probably not be restricted to the microhabitats created in these plots. One key observation in this study was that the effects of tillage (which formed the larger main plots) were significant whilst treatment effects of the rather smaller sub-(fertilizer rate) and sub-sub-plots (weeding intensity) were non-significant. Thirdly, pitfall traps as a tool for beetle sampling has been shown to selectively catch certain beetle species compared to others (Skvarla et al., 2014). These aspects could have differentially influenced species richness and diversity in our study. Additional studies should therefore be conducted in order to conclusively determine the effect of fertilizer application rate and weeding intensity on beetle communities under subtropical environments. Further studies also need to focus on the long term impacts of these treatments on beetle community diversity.

## Acknowledgements

We are grateful to Dr. Moira Fitzpatrick, the entire Entomology Department staff of the Natural History Museum of Zimbabwe for their assistance in identifying beetles. Ruth Muller of Ditsong National Museum for Natural History (former Transvaal Museum), Pretoria, South Africa, verified beetle species names. Financial support for this research was jointly provided by Chinhoyi University of Technology (CUT) and the German Academic Exchange Program (DAAD). We thank the MAIZE CGIAR Research program for supporting this study. We are also grateful to Professor Taurai Bere of CUT for his tremendous assistance in exploring our data using CANOCO 5. Our special gratitude goes to Stewart Maganyani, Rumbidzai Makanda, Albert Chinyati, Lawrence Gweme as well as the CUT experiment station field staff who assisted with data collection and data handling from the field through to the laboratory.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsoil.2018.12.001.

## References


Barberi, P., Burgio, G., Dinelli, G., Moonen, A.C., Otto, S., Vazzana, C., Zanin, G., 2010. Functional biodiversity in the agricultural landscape: relationships between weeds and arthropod fauna. Weed Res. 50, 388–435.

Bellamy, A.S., Svensson, O., van den Brink, P.J., Gunnarsson, J., Tedengren, M., 2018. Insect community composition and functional roles along a tropical agricultural production gradient. Environ. Sci. Pollut. Res. Int. 25, 13426–13438.

Blondel, J., 2003. Guilds or functional groups: does it matter? Oikos 100, 223–231.

Brust, G.E., House, G.J., 1988. Weed seed destruction by arthropods and rodents in low-input soybean agroecosystems. Am. J. Altern. Agric. 3, 19–25.

Climatemps.org, 2017. Chinhoyi Climate & Temperature. http://www.chinhoyi.climatemps.com/ (accessed 4 December 2017).

Climatestotravel.com, 2017. Climate in Zimbabwe: temperature, rainfall, prevailing weather conditions, when to go, what to pack. www.climatestotravel.com/climate/zimbabwe (accessed 21 November 2017).

Diekotter, T., Wamser, S., Wolters, V., Birkhof, K., 2010. Landscape and management effects on structure and function of soil arthropod communities in winter wheat. Agric. Ecosyst. Environ. 137, 108–112.

García-Ruiz, E., Loureiro, I., Farinós, G.P., Gómez, P., Gutiérrez, E., Sánchez, F.J., Escorial, M.C., Ortego, F., Chueca, M.C., Castañera, P., 2018. Weeds and ground-dwelling predators response to two different weed management systems in glyphosate-tolerant cotton: a farm-scale study. PLoS ONE 13 (Accessed 27 November 2018).

Gobbi, M., Fontaneto, D., 2008. Biodiversity of ground beetles (Coleoptera: Carabidae) in different habitats of Italian Po lowland. Agric. Ecosyst. Environ. 127, 273–276.

Greenslade, P.J.M., 1964. Pitfall trapping as a method for studying populations of Carabidae (Coleoptera). J. Anim. Ecol. 33, 301–310.

Haddad, N.M., Crutsinger, G.M., Gross, K.J., Haarstad, J., Knops, J.M.H., Tilman, D., 2009. Plant species loss decreases arthropod diversity and shifts trophic structure. Ecol. Lett. 12, 1029–1039.

Hammer, Ø., Harper, D.A.T., Paul, D.R., 2001. Past: paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4, 1–9.

Hatten, T.D., Bosque-Pérez, N.A., Labonte, J.R., Guy, S.O., Eigenbrode, S.D., 2007. Effects of tillage on the activity density and biological diversity of carabid beetles in spring and winter crops. Environ. Entomol. 36, 356–368.

Hong, M.G., Nam, B.E., Kim, J.G., 2017. Effects of soil fertility on early development of wetland vegetation from soil seed bank: focusing on biomass production and plant species diversity. J. Plant Biol. 60, 241–248.

Kromp, B., 1999. Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. Agric. Ecosyst. Environ. 74, 187–228.

Lang, A., Filser, J., Henschel, J.R., 1999. Predation by ground beetles and wolf spider on herbivorous insects in maize crop. Agric. Ecosyst. Environ. 72, 189–199.

Law, J.J., 2012. Granivorous invertebrates and weed seed predation: an ecological approach to weed management, Graduate School Intercollege – Graduate Degree Program in Ecology. https://etda.libraries.psu.edu/catalog/16175 (accessed 4 December 2017).

Lindroth, C.H., 1968. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Lund, Sweden.

Lundy, M.E., Pittelkow, C.M., Linquist, B.A., Liang, X., Groenigen, K.J., Lee, J., Six, J., Venterea, R.T., van Kessel, C., 2015. Nitrogen fertilization reduces yield declines following no-till adoption. Field Crops Res. 183, 204–210.

Magagula, C.N., Nzima, B.A., 2015. Interaction between habitat characteristics and insect diversity using ground beetles (Coleoptera: Carabidae) and ants (Hymenoptera: Formicidae) within a variety of agricultural habitats. Appl. Ecol. Environ. Res. 13, 863–876.

Mazvimavi, K., Twomlow, S., 2009. Socioeconomic and institutional factors influencing adoption of conservation agriculture by vulnerable households in Zimbabwe. Agric. Syst. 101, 20–29.

Meiss, H., Le Lagadec, L., Munier-Jolain, N., Waldhardt, R., Petit, S., 2010. Weed seed predation increases with vegetation cover in perennial forage crops. Agric. Ecosyst. Environ. 138, 10–16.

Menalled, F.D., Smith, R.G., Dauer, J.T., Fox, T.B., 2007. Impact of agricultural management on carabid communities and weed seed predation. Agric. Ecosyst. Environ. 118, 49–54.

Norris, R.F., Kogan, M., 2000. Interactions between weeds, arthropod pests, and their natural enemies in managed ecosystems. Weed Sci. 48, 94–158.

Oberg, S., Ekbom, B., Bommarco, R., 2007. Influence of habitat type and surrounding landscape on spider diversity in Swedish agro-ecosystems. Agric. Ecosyst. Environ. 122, 211–219.

Prasifka, J.R., Lopez, M.D., Hellmich, R.L., Lewis, L.C., Dively, G.P., 2007. Comparison of pitfall traps and litter bags for sampling ground-dwelling arthropods. J. Appl. Entomol. 131, 115–120.

Quinn, N.F., Brainard, D.C., Szendrei, Z., 2016. The effect of conservation tillage and cover crop residue on beneficial arthropods and weed seed predation in acorn squash. Environ. Entomol. 45, 1543–1551.

Rusch, A., Bommarco, R., Chiverton, P., Oberg, S., Wallin, H., Wiktelius, S., Ekbom, B., 2013. Response of ground beetle (Coleoptera, Carabidae) communities to changes in agricultural policies in Sweden over two decades. Agric. Ecosyst. Environ. 176, 63–69.

Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana.

Shearin, A.F., Reberg-Horton, S.C., Gallandt, E.R., 2007. Direct effects of tillage on the activity density of ground beetle (Coleoptera: Carabidae) weed seed predators. Environ. Entomol. 36, 1140–1146.

Showler, A.T., Greenberg, S.M., 2003. Effects of weeds on selected arthropod herbivore and natural enemy populations, and on cotton growth and yield. Environ. Entomol. 32 (1), 39–50.

Sims, B.G., Thierfelder, C., Kienzle, J., Friedrich, T., Kassam, A., 2012. Development of the conservation agriculture equipment industry in sub-Saharan Africa. Appl. Eng. Agric. 28, 813–823.

Skvarla, M.J., Larson, J.L., Dowling, A.P.G., 2014. Pitfalls and preservatives: a review. J. Entomol. Soc. Ont. 145, 15–43.

Smilauer, P., Lepš, J., 2014. Multivariate Analysis of Ecological Data Using CANOCO 5. Cambridge University Press.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. Soil Tillage Res. 118, 66–87.

Stinner, B.R., House, G.J., 1990. Arthropods and other invertebrates in conservation tillage agriculture. Annu. Rev. Entomol. 35, 299–318.

Susilo, F.X., Indriyati, Hardiwinoto, S., 2009. Diversity and abundance of beetle (Coleoptera) functional groups in a range of land use system in Jambi, Sumatra. Biodiversitas 10, 195–200.

Tarnawski, D., Buchholz, L., 2008. Polish insects identification key. Part XIX. Beetles – Coleoptera. Click-beetles – Elateridae. Subfamily: Athoinae. Torun 34b.

ter Braak, C.J.F., Smilauer, P., 2012. Canoco reference manual and user's guide: software for ordination, version 5.0.

Triplehorn, C.A., Spilman, T.J., 1973. A review of Strongylium of America north of Mexico, with descriptions of two new species (Coleoptera: Tenebrionidae). Trans. Am. Entomol. Soc. 99, 1–27.

Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., de Ruiter, P.C., van der Putten, W.H., Birkhofer, K., Hemerik, L., de Vries, F.T., Bardgett, R.D., Brady, M.V., Bjornlund, L., Jørgensen, H.B., Christensen, S., Hertefeldt, T.D., Hotes, S., Gera Hol, W.H., Frouz, J., Liiri, M., Mortimer, S.R., Setälä, H., Tzanopoulos, J., Uteseny, K., Pižl, V., Stary, J., Wolters, V., Hedlund, K., 2015. Intensive agriculture reduces soil biodiversity across Europe. Glob. Change Biol. 21, 973–985.

Twomlow, S., Hove, L., Mupangwa, W., Masikati, P., Mashingaidze, N., 2008. Precision conservation agriculture for vulnerable farmers in low-potential zones, 9th WaterNet/WARFSA/GWP-SA Annual Symposium. WaterNet, Johannesburg, South Africa.

van der Laat, R., Owen, M.D.K., Liebman, M., Leon, R.G., 2015. Post-dispersal weed seed predation and invertebrate activity-density in three tillage regimes. Weed Sci. 63, 828–838.

VSN-International, 2011. GenStat for Window 10th Edition. VSN International, Hemel Hempstead, UK.

Westerman, P.R., Wes, J.S., Kropff, M.J., van der Werf, W., 2003. Annual losses of weed seeds due to predation in organic cereal fields. J. Appl. Ecol. 40, 824–836.

Whitehouse, M.E.A., Wilson, L.J., Davies, A.P., Cross, D., Goldsmith, P., Thompson, A., Harden, S., Baker, G., 2014. Target and nontarget effects of novel “triple-stacked” Bt-transgenic cotton 1: canopy arthropod communities. Environ. Entomol. 43, 218–241.

Worldbank.org, 2018. Climate change knowledge portal: country historical climate – Zimbabwe. www.sdwebx.worldbank.org/climateportal/index.cfm (accessed 4 December 2018).

WRB, IUSS Working Group, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. Food and Agriculture Organization (FAO), Rome.