Ecology and Development Series No. 56, 2007

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The contribution of different fauna communities to improved soil health: A case of Zimbabwean soils under conservation agriculture

ABSTRACT

For improved and sustainable soil productivity, the application of soil conserving cropping systems is important. This study characterizes soil fauna as a basis for comparing conservation agriculture and conventional ploughing systems and focuses on soil health of sandy, sandy loam and clayey soils in smallholder farms under sub-humid and semi-arid conditions in Zimbabwe. Fauna contribution to soil health was explored.

Beetle larva (Coleoptera), earthworm (Opisthophora), mycorrhiza spore (Glomales), nematode (Tylenchida and Dorylaimida) and termite (Isoptera) densities were measured in conventionally ploughed (CP), direct seeded (DS), ripped (RR) and basin (BA) treatments on farms at Henderson, Chinyanga, Kajengo (all in agro-ecological zone II), Makwara and Zhinya (agro-ecological zone IV). Maize and soyabean were used as test crops. Rates of maize mulch loss were determined for winter and summer seasons. Shannon Wiener indices were used to analyse the changes in species and genera of weeds and nematodes respectively. Weed species responses to treatments and weed management regimes were explored at each site. Perceptions of soil fauna on the farms were sought from farmers in Shamva and Zimuto. High species richness was measured under mulched ripper and direct seeder treatments. Beetle larvae and termite densities increased significantly ($P < 0.05$) under DS and RR compared to CP across all sites. Nematode densities were not responsive to the mulch and tillage treatments. There was a near balanced ratio between densities of phyto-parasitic and free living nematodes over the two seasons (2006 and 2007). There was an increase in densities with time, though low numbers were measured. Planting soybean after maize increased nematode genera evenness (2.16) and diversity (5.70) on ripped and direct seeded treatments on clayey soils. Low dominance of phyto-parasitic nematode genera suggests low risk of maize infection. Termite activities resulted in an increased gallery construction especially on mulched DS and RR treatments. Gallery material built on the surface of sandy soils contained more clay, soil organic mater and silt compared to adjacent soils, but on clayey soil, the clay fraction of gallery material (3 %) was lower than on the adjacent soil (39 %). The mycorrhiza spore densities in the gallery material were always lower than those in the soil. In the litter bag experiment, the decomposition of mulch material was determined. Lower decomposition rates of surface mulch were measured in winter (8 - 20 %) compared to summer (45-65 %), with highest losses in the semi-arid zone at Makwara. The decomposition constants k calculated from the exponential decay function $y = a.e^{-kx}$ during summer were 10-fold those in winter. The k values were lowest at Henderson, (0.017 and 0.17) and highest at Makwara (0.025 and 0.24) for winter and summer, respectively. *Richardia scabra*, *Galinsoga parviflora* and *Eleusine indica* were common weeds across the five sites. Introducing a late weeding treatment reduced weed densities significantly at Henderson compared to other sites. Participatory rapid appraisal results show that farmers perceived termites as the dominant fauna on the farm and as a pest to maize. Under conventional ploughing systems, complete crop residue removal is practised. Management of maize residues after harvest is mainly meant to secure livestock feed during the dry winter season. On a small scale, mulching was practiced using crop residues and tree litter in vegetable gardens.

On farms with *Chromic Luvisol, Ferrali-Gleyic Arenosol* and *Gleyic Luvisols* and *Brachstegia-Julbernadia* dominated *miombo* savanna vegetation in eastern and southern Africa, in the short term, beetle larvae and termites densities responded to conservation agriculture better than nematodes and earthworms. The increased fauna biomass improves soil health. Macrofauna participates in decomposition, soil turnover and modification. Gallery building by termites, for example, increases surface clay, silt and organic matter contents in sandy soils. Furthermore, termites through their galleries, participate in mycorrhiza spore inoculation of the soil.

Der Beitrag verschiedener Faunengemeinschaften zu verbesserter Bodengesundheit: Der Fall von Böden in Zimbabwe unter bodenschonenden Anbauverfahren

KURZFASSUNG

Für eine verbesserte und nachhaltige Bodenproduktivität sind bodenschonende Anbausysteme wichtig. Diese Studie untersucht Bodenfauna als eine Grundlage für den Vergleich zwischen Bodenschonenden Anbauverfahren (*conservation agriculture*) und konventionellem Anbau und legt dabei den Schwerpunkt auf Bodengesundheit in kleinbäuerlichen Farmen mit sandigen, sandig-lehmigen und lehmigen Böden in sub-humiden und semi-ariden Gebieten in Zimbabwe.

Die Dichten von Käferlarven (Coleoptera), Regenwürmern (Opisthophora), Mykorrhiza-Sporen (Glomales), Nematoden (Tylenchida and Dorylaimida) und Termiten (Isoptera) wurden erfasst in auf konventionelle Weise gepflügten (CP) Feldern sowie Feldern unter Behandlung mit Direktsaat (DS), Untergrund-(Tiefen)-Lockerer (*ripper*; RR) and als "Becken" (BA) bei Kleinbauern in Henderson, Chinyanga, Kajengo (alle in der agroökologischen Zone II), Makwara und Zhinya (Zone IV). Mais und Soya wurden als Testanbaupflanzen eingesetzt. Maismulch-Verlustraten wurden für die Winter- und Sommersaison bestimmt. An jedem Standort wurde die Reaktion der Unkräuter auf Behandlungen und Unkrautmanagementmaßnahmen erfasst. Die Wahrnehmung der Bodenfauna durch Farmer wurde in Shamva and Zimuto erfasst. Shannon Wiener Indizes wurden benutzt, um die Änderungen in der Arten- und Gattungs-Zusammensetzung der Unkräuter und der Nematoden zu analysieren. Eine hohe Artenvielfalt wurde unter den gemulchten RR- und DS-Behandlungen bestimmt. Die Dichte von Käferlarven und Termiten nahm signifikant ($P < 0.05$) an allen Standorten bei RR und DS - verglichen mit CP - zu. Die Nematodendichte wurde durch die Mulch- bzw. unterschiedlichen Bodenbehandlungen nicht beeinflusst. Die Dichte von phytoparasitisch und frei lebenden Nematoden war ähnlich über beide Jahreszeiten (2006 and 2007). Der Anbau von Sojabohnen im Anschluss an Mais auf den tonhaltigen Böden bewirkte eine Zunahme der Gleichförmigkeit in der Zusammensetzung (evenness) der Nematodengattungen (2.16) und Vielfalt (5.70) unter den RR- und DS-Behandlungen. Eine geringe Dominanz von phytoparasitischen Nematodengattungen deutet auf ein geringeres Risiko hinsichtlich Maisbefall hin. Insbesondere auf den gemulchten DS- und RR-Flächen wurde eine verstärkte Galeriebautätigkeit durch Termiten beobachtet. Galerien sind überbaute Laufgänge und ein Indikator der Termitentätigkeit. Auf den sandigen Böden enthielt das Galerienmaterial mehr Ton, bodenorganisches Material und Schluff als der umliegende Boden; auf tonhaltigen Böden war allerdings der Tonanteil (3 %) niedriger als im umliegenden Boden (39 %). Die Dichte der Mycorrhizasporen in dem Galeriematerial war jedoch immer niedriger als im Boden. Im Netzbeutel-Versuch wurde der Abbau von Mulchmaterial untersucht. Es ergaben sich niedrigere Mulch-Abbauraten im Winter (8-20 %) als im Sommer (45-65 %); die höchsten Werte wurden in Makwara beobachtet. Im Sommer waren die Abbaukonstanten k, berechnet aus der exponentiellen Abbaufunktion $y = a.e^{-kx}$, 10-mal höher als die Werte im Winter. Die k-Werte im Winter bzw. Sommer waren am niedrigsten in Henderson (0.017 bzw. 0.17) und am höchsten in Makwara (0.025 bzw. 0.24). Häufige Unkrautarten an allen Standorten waren *Richardia scabra*, *Galinsoga parviflora* und *Eleusine indica*. Ein spätes Entfernen des Unkrauts reduzierte die Unkrautdichte signifikant stärker in Henderson als an den anderen Standorten. Die Ergebnisse einer partizipativen Schnellerfassung (*rapid participatory appraisal*) zeigen, dass die Bauern die Termiten als die am häufigsten vorkommende Fauna und als Maisschädling beurteilten. Daten zu Schädlingsbefall bei Mais konnten diese Ansicht allerdings nicht bestätigen. Bei den konventionellen Bodenbearbeitungssystemen werden die gesamten Ernterückstände entfernt, hauptsächlich für Tierfutter während des trockenen Winters. In geringem Umfang wird Mulchen mit Ernterückständen sowie Baumstreu in den Gemüsegärten eingesetzt.

Auf Farmen mit *Chromic-Luvisol*, *Ferrali-Gleyic-arenosol* und *Gleyic-Luvisol*-Böden unter *Brachystegia-Julbernadia*- dominierter Miombo-Vegetation im östlichen und südlichen Afrika erhöht sich unter bodenschonenden Anbauverfahren die Dichte von Termiten und Käferlarven kurzfristig schneller als die von Nematoden und Regenwürmern. Die erhöhte Faunendichte führt zu einer verbesserten Bodengesundheit. Die Makrofauna beteiligfts ich an Zersetzung, Bodenturbation und –modifikation. Die Galeriekonstruktion durch die Termiten erhöht bei sandigen Böden den Gehalt an Ton, organischem Material und Schluff an der Bodenoberfläche. Die Termiten sind durch ihre Galerien außerdem an der Inokulation des Bodens mit Mycorrhizasporen beteiligt.

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LIST OF ABBREVIATIONS, ACRONYMS AND DEFINITIONS

ACT	African Conservation Tillage Network
CA	Conservation agriculture – a group name for farming system based on a combination of three principles; minimal soil disturbance, crop rotations and soil cover maintenance. CA's aims are to reduce production costs, maintain soil fertility and conserve water in order to achieve sustainable agriculture and improved livelihoods.
CIMMYT	International Maize and Wheat Improvement Center (*Centro Internacional de Mejoramiento de Maíz y Trigo*). CIMMYT is one of the 15 CGIAR Future Harvest Centers that is headquartered in Mexico and has offices in Harare, Zimbabwe and Nairobi, Kenya. It is dedicated to the development and improvement of sustainable Maize and Wheat system.
CGIAR	Consultative Group on International Agricultural Research
CP	Conventional ploughing – farming practices where a moldboard plough is used to prepare a seedbed for sowing crop seeds. In smallholder farms; use of the plough or cultivators for mechanical weed control, together with crop residue removal from the fields are also part of this practice.
FAO	Food and Agriculture Organization of the United Nations
Fitarelli no. 12	Animal drawn direct planting equipment manufactured by a Brazilian company, Fitarelli Agricultural Machines (www.fitarelli.com.br).
IRRI	International Institute of Rural Reconstruction
masl	meters above sea level
nd	not determined
SOM	Soil organic matter
ZimPlough	Zimbabwe Plough Manufacturing Company – A manufacturing company and distributor of farm implements including moldboard plough, harrows, cultivators. They also supply spare parts for the implements.

1 GENERAL INTRODUCTION

1.1 Background

Conventional ploughing, which involves the manipulation of the soil to improve its tilth and workability, has been reported as a major driver of land degradation (Elwell 1985; Whitlow 1987). In Sub-Saharan Africa, this practice is common and is the basis of most of the food, fiber and fodder production. Historically, ploughing was introduced to the farming communities in the 19th century and it enabled the farmers to till more land and control problematic weeds (Stocking 1989). Currently, farmers plough their field at the beginning of the cropping season and often practice no planned rotation of crops. On poorly structured soils, continuous cultivation results in the loss of the physical, chemical and biological properties that are responsible for maintaining and enhancing soil health. Contrary to reduced tillage systems that leave residues on the soil surface, annual cultivation reduces the level of organic matter in the soil (Chivenge et al. 2007; Constantini et al. 2006).

The biotic factor, which encompasses soil fauna, is important in soil formation (Lavell nd Spain 2001). Soil fauna affects and influences processes, and is often a driver of the soil system (Coleman et al. 2004; Kladivko 2001). The faunal groups respond to both environmental and management factors. Regulation of farming systems affects food webs and the interactions as influenced by the environment (Swift 1999). Limited soil organic matter also reduces the prevalence of soil organisms that use soil organic matter as their source of energy. Therefore, systems that turn the soil continuously without adequate replacement of soil organic matter and that use clear cutting and mechanized tillage reduce the densities of soil animals (Okwakol 1994) and hence ecological soil health.

With the harvest, nutrients built up in plant biomass are constantly removed from crop lands. Returning crop residues to the fields could reduce nutrient mining; however, the many uses of crop residues principally on smallholder farms explain their limited availability for redistribution on the croplands. Crop residues, for example, are used on smallholder farms as fuel, livestock feed and for construction (Garcia 2001; Lal 2002). The tradition of burning crop residues, which is common in southern Africa, reduces soil cover and enhances soil and water losses (Eggleton et al. 2002a; Bwalya and Mulenga 2002; Kumwenda 2002; Nyamudeza 1993). Fire is often used during hunting, land clearing for cultivation, and for removing dry grass on pasturelands. These all lead to high losses of sequestered carbon and increased greenhouse gasses in the atmosphere. It is not clear how these complex scenarios affect the potential of rebuilding soil health in croplands through conservation agriculture.

Conservation agriculture involves the combined use of minimum tillage, crop rotation and soil cover crops in the management of crop production and soil health (FAO 2001). It is a farming system that has evolved since the 1960s and aims at increased crop yields, reduction of production costs, and maintenance of soil fertility and conservation of water. Conservation agriculture has three basic principles: (1) disturbing the soil as little as possible, (2) keeping the soil covered as much as possible and (3) mixing and rotating of crops (IRRI and ACT 2005). Dumanski et al. (2006) defined it as, the integration of ecological management with modern science-based agricultural production. Management practices directed towards addressing soil water and fertility have a bearing on crop productivity, chemical and physical soil properties, and below-ground biological communities. In areas of low agricultural potential, biomass production is low and hence less organic matter is added to the soil system each year, leading to poor soil health. Conservation agriculture practices potentially help in building up the soil organic matter, which would lead to higher soil quality and thus, higher crop production potential, and reduced water and soil losses from cropping lands. Studies by Elwell (1989) suggested that reducing tillage on weakly structured soils works better with retention and management of crop residues on the soil surface. The effect of these conservation management approaches on individual fauna groups have not been studied in detail.

Conservation agriculture systems, that involve the use of various combinations of soil covers, rotations and reduced tillage, have been tested in South America, Europe, Australia and other parts of the world, with positive results on crop production (Derpsch 1998; Holland 2004). Conservation agriculture developed from the experiences on conservation tillage and no-till systems of the past years. In southern Africa, conservation agriculture has been practiced on some commercial farms in Zambia and Zimbabwe, but the farming system has not been extensively tested on smallholder farms. Smallholder farmers, who work on degraded soils and can contribute up to 60 %

of the food crop production (CSO 2004), are suitable primary targets for sustainable farming systems. Further, little attention has been paid to the dynamics of soil organisms under these systems. Under conservation agriculture the application of low tillage and organic materials fosters the re-development of soil organisms and hence their role in improving soil health.

Weed pressure has been reported as one of the challenges under no-till systems (Vogel 2004). Without a feasible management plan, weeds could lead to limited crop yields and benefits to farmers in the short-term. Weed control and understanding the nature of interaction are therefore important in conservation agriculture systems.

Soil cover can be achieved by using crop residues as mulch. Use of crop residues as mulch, which often is loosely controlled on smallholder farms, is a major management difference between conservation agriculture and conventional ploughing systems. Whilst there are reports of high prospect of using crop residues for fertility improvement (Nhamo et al. 2002), the farmers perceptions regarding use as surface mulch on cropping fields are not clear.

1.2 Justification

In eastern and southern Africa where smallholder farmers contribute significantly to maize production and hence household food security, conservation agriculture can occupy an important position in the build up of sustainable farming systems. Current cultivation practices do not support beneficial soil faunal communities. Further, the variability in soil types and climatic conditions under smallholder farms require biologically functional soils. The introduction of conservation agriculture and efforts to promote it in eastern and southern Africa avails a range of soil management options for smallholder farmers. Fauna plays an important role in soil improvement. Therefore, there is a need to study the role of the beneficial soil fauna (beetle larvae, earthworms, nematodes, mycorrhiza fungi and termites) in relation to the changes in the food web under conventional and conservation agriculture systems on different soil types and rainfall zones. Although it is recorded that conservation agriculture is beneficial in the long run, the short-term contribution of individual fauna groups are not clear.

1.3 Approach and scope

The approach taken in this study is based on the definition of ecology as the scientific study of the distribution and abundance of organisms and the interactions that determine distribution and abundance (Townsend et al. 2003). The study sought a proximate explanation of the relationships between conservation agriculture as a cropping system and biota community structures for use in predictive understanding of the ultimate soil condition. The densities of beetle larvae, earthworms, nematodes, and termites in the two cropping systems were monitored over two years, 2006 and 2007. Furthermore, diversity indices of nematode genera and weed species were calculated. Below-ground fauna measurements were combined with above-ground crop and weeds biomass together with biogenic structure in this study; farmers' knowledge of soil fauna and cropping systems was also assessed and it linked experimental results to their perceptions. These analyses were used to assess the role of the four fauna groups in conservation agriculture systems.

1.4 Objectives and hypotheses

The main objective of the study was to evaluate the dynamics of four important soil fauna groups that are involved in the below-ground soil food web and assess their effects in conservation farming at selected sites in Henderson Research Station, Chinyanga, Kajengo, Makwara and Zhinya, Zimbabwe. The specific objectives were to:

1. Characterize and monitor beetle larvae, earthworm, nematode and termite densities under conventionally ploughed and conservation agriculture (direct seeding) treatments.
2. Study the effect of surface residues retention on nematode genera composition and activity.
3. Determine the rate of surface residue decomposition at sites in different agroecological zones and soil types.
4. Determine the changes in weeds densities and species following weed management practices under conservation agriculture.
5. Evaluate the perceptions of farmers to soil fauna in relation to current residue management practices on the farms.

The following hypotheses were tested:

- Reduced tillage and use of cover crop treatments significantly increase activities, densities and diversity of termites, beetle larvae, nematodes and earthworms in sandy soils in the short to medium term.
- The rates of surface residue decomposition during both summer and winter allow for a relative increase in soil cover over time on directly seeded plots.
- Weed densities and species change in the short term following management strategies targeted at the soil weed-seed bank.
- The knowledge farmers have on soil fauna does not explain the current residue utilization practices.

1.5 Conservation agriculture and conventional ploughing treatments

Conservation agriculture is the integration of ecological management with modern scientific agricultural production. It is based on the optimization of yields, profits and achievement of a balance of agricultural, economic and environmental benefits (Dumanski et al. 2006). Conservation agriculture combines the management of crop rotations, reduction of tillage and the utilization of soil cover. Zero tillage, often referred to as no-till or direct drill, is the mainstay of conservation agriculture. In this study, conservation agriculture involved the use of crop residues from previous season maize and wheat crops. Grass collected from the veld was sometimes used to supplement the maize residues.

During this study, minimal tillage was applied to allow planting of crops. Two animal-drawn implements; direct seeder (DS) and rippers (RR) without furrow openers, and hand hoes for making basins (BA) were tested against conventional ploughing (CP).

1. **Conventional ploughing** is widely used in Zimbabwe. It is a system where land preparation for planting is done using a moldboard plough with cattle or donkeys as draught power. Ploughing is done uniformly to prepare a fine seed bed and also to control the early weeds on the field. Farmers follow-up this using a cultivator or the same plough between the maize rows to control weed pressure during the cropping season. Often, mechanical turning of the soil is used together with hand hoe weeding by most farmers; these practices were also part of the conventional ploughing treatment used in this study.

2. **A Brazilian animal-drawn direct seeder** (Fitarelli No. 12, cf. www.fitarelli.com.br) was used for direct seeding at all sites (Figure 1.1a). Its main features include vegetation and mulch cutter (disk) and a chisel point for opening the seed and fertilizer furrow. A rear wheel covers the seed and fertilizer dropping just behind the chisel. Seed spacing can be adjusted using gears on the planter. All these are fitted onto a bean which can be attached to the yoke used by draught animals.

3. Two types of **rippers** were used i.e., the Magoye ripper, originally designed in Zambia, and the Zimbabwean manufactured ZimPlough ripper (Figure 1.1b and c). The Magoye ripper consists of a ripper tine that can be fitted on a normal moldboard plough beam (IRRI and ACT 2005).

4. **Hoes**, often used for weed control, were used in making planting basins (Figure 1.1d). Each basin covered an area of 15 cm x 30 cm and was 15 cm deep. The basins were dug 50 cm apart within each row and 90 cm inter-row. Seed and fertility inputs were applied into these basins during planting operations and later in the season. This treatment was only applied at Henderson research station and was missing on all on-farm sites.

Across all sites maize (*Zea mays* L.) was used as a test crop. At Chinyanga and Kajengo soybean (*Glycine max* L.) was rotated with maize between 2006 and 2007 cropping seasons. *Mucuna purensis* (L.) was used as an intercrop with maize in the Magoye ripper treatment at Henderson Research Station.

a. b. c. d.

Figure 1.1: Four tillage implement used during the experiments (a) direct seeder (b) ZimPlough ripper manufactured in Zimbabwe (c) Magoye ripper originally designed in Zambia and (d) hand hoes for making basins and weeding

1.6 Study sites

Zimbabwe is located in the tropics between 15^{o} 40’ S and 22^{o} 30’ S (latitude) and 25^{o} 12’ E and 33^{o} 04’ E (longitude). There is close relationship between the seasonal rainfall pattern and the annually migrating Inter-Tropical Convergence Zone (ITCZ), which dominate effective summer precipitation south of the equator. The summer rainy season begins in November, sometimes as late as December, and lasts until late March into April (Figure 1.2). The main winds that converge at the ITCZ are the south-east trades (Congo airstreams) of the Atlantic Ocean, which collect most of the moisture from the Congo rainforest, the mostly dry south-east trades of the Indian Ocean, and the dry north-east monsoon from the northern hemisphere. Generally, rainfall decreases southwards and westwards (Nhandara et al. 1991). Two main features that influence the altitude are the highveld forming the central water shed and the great dyke. The highveld stretches from the Botswana border in the south-west to Harare, where it branches eastwards and north-westwards. The Great dyke is a lopolith complex, which extends some 540 km from Mberengwa in the south-west across the country to the Zambezi escapement in the north-east. This lopolith has high mineral deposits and is hence important for the mining industry in Zimbabwe (Nyamapfene 1991).

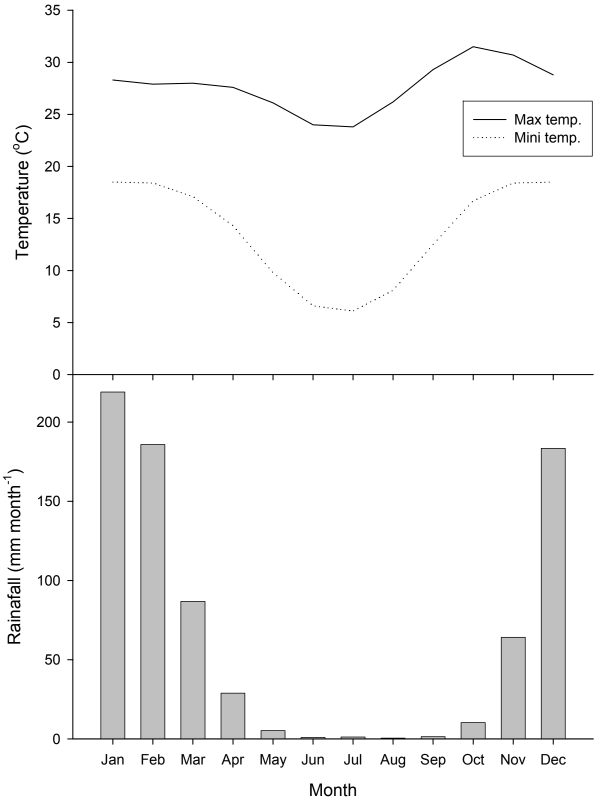


Figure 1.2: Mean monthly rainfall, maximum and minimum temperature for Zimbabwe (averaged over 30 years). Source: www.fao.org. country profiles

Four vegetation biomes are dominant in Zimbabwe, the largest of them being the *Brachystegia-Julbernadia miombo* woodlands. *Barkiabeingea plurijuga-Pterocarpus antunesii*, *mopane* and shrub woodlands also occupy a significant proportion of the Zimbabwean plateau, with the remainder being classified as undifferentiated bushveld and woodlands (van Wyk and van Wyk 1997). Though the composition of the flora varies from one area to the other, the three study sites were classified under the open *Brachystegia-Julbernadia miombo* woodlands. Vegetation maps and an ethno-botanical survey were used to determine the broad categories of flora and land use practices in each study area.

Five agro-ecological zones (I-V) were defined for Zimbabwe by Vincent and Thomas (1960) with additions on the soil aspects by Thompson and Purves (1979), mainly based on rainfall and soils. Based on the mean annual rainfall, zone I is humid (>1000 mm per year), II sub-humid (800 – 1000 mm per year), zones III and IV semi-arid, and zone V arid. They also represent the suitability of the regions for various forms of agriculture with intensive specialized agriculture in zone I and II, and extensive cattle production in zones IV and V. The study sites were located in zone II (three sites) and IV (three sites), which are representative of 15 % and 37.8 % of Zimbabwean land, respectively (Anderson et al. 1993). The main factors determining the dominant soil type are parent material, climate, topography and the duration for which soil formation has been going on. Sandy soils that are derived from granite rocks are the most extensive and agriculturally important soils. They are found in *Luvisols, Lixisols, Arenosols, Acrisols* and some are *Ferralsol* and *Nitisols* soil groups in the FAO classification (Nyamapfene 1991). Mafic rock-derived red clays, *Gleyic Luvisols,* are also important in crop production due to their high fertility. They have high clay and silt contents; the later makes them prone to surface crusting.

Henderson Research station, 17^o 34.435'S; 30^o 59.190' E on an altitude of 1268 meters above seal level (masl), is located 36 km north-east of Harare, in the Mazoe valley. On-farm study sites were hosted at Chinyanga, 17^o 11.398'S; 31^o 29.590' E on an altitude of 1158 masl and Kajengo 17^o 06.643'S; 31^o 25.653' E on an altitude of 1090 masl in north-eastern Zimbabwe. The two on-farm sites are about 120 km from Harare. In southern Zimbabwe, Makwara 19^o 51,035' S; 30^o 52.573' E on an altitude of 1219 masl, Zhinya 19^o 51,035' S; 30^o 52.573' E on an altitude of 1214 masl and Chimbwa, 19^o 50,897' S; 30^o 51.861' E on an altitude of 1212 masl, were the study sites and all are about 300 km south of Harare.

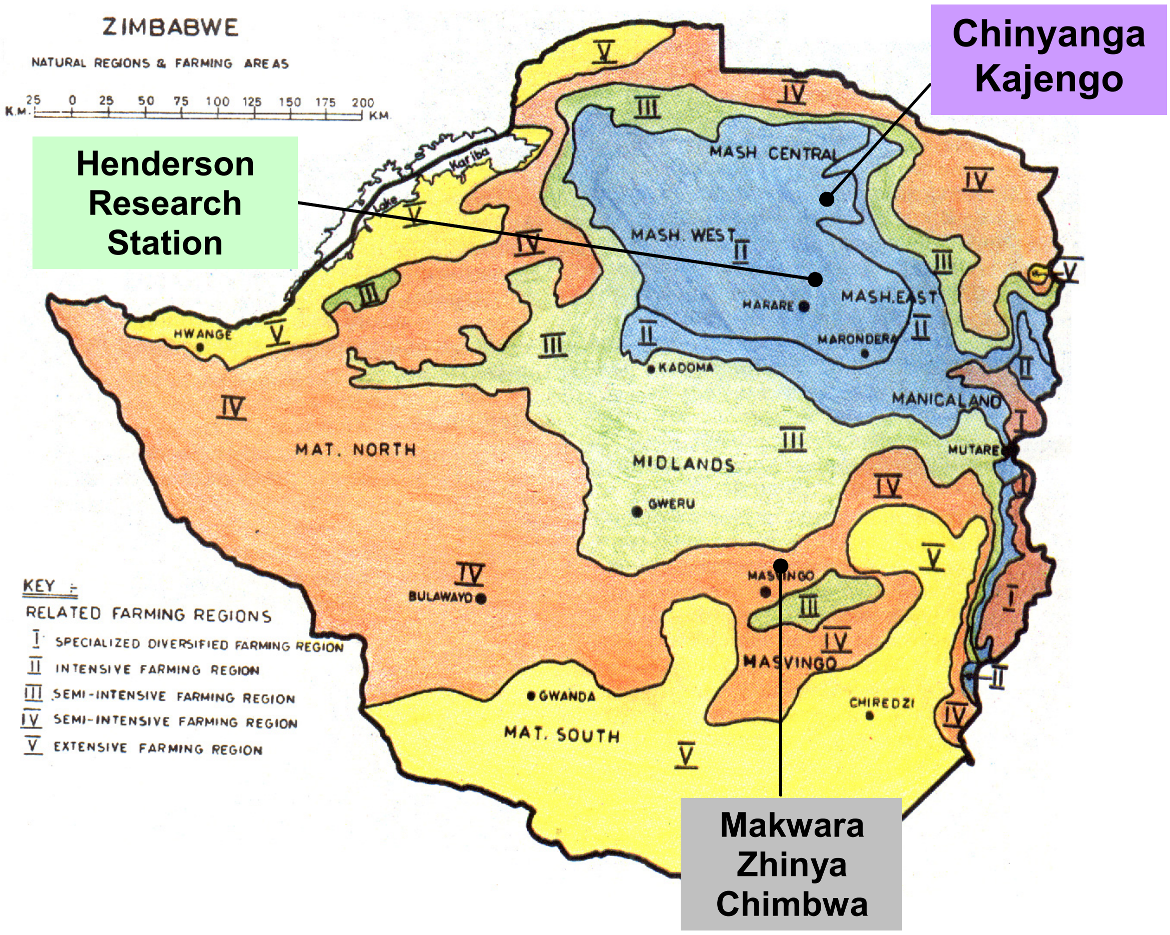


Figure 1.3: Map of Zimbabwe showing the study sites and the five agro-ecological zones. Source: Surveyor General Office, Harare, Zimbabwe

1.7 Thesis structure

This thesis consists of a total of 8 chapter, the constituents of each of the following chapter is summarized in Table 1.1. Chapter 2 shows the measured abundances of beetles, earthworms, nematodes and termites from four sites. The details of the nematode species found on the study sites and their responses to treatments are presented in Chapter 3. Activities of termites on the cropping fields, which can be viewed as being either negative or positive, are discussed in Chapter 4. In Chapter 5, the loss rates of surface-applied maize residues are discussed, and in Chapter 6 weed species density changes between 2006 and 2007 are reported. Chapter 7 presents findings on the perceptions of farmers on the use of residues vis-à-vis the promotion of conservation agriculture and the role of fauna on the farms. General discussions, conclusions and recommendations make up Chapter 8.

Table 1.1: A summary of data and treatments used in each of the result chapters of this thesis

Chapter	Sites	Data	Treatment	Time of sampling
2	Chinyanga, Henderson, Kajengo, Makwara	Fauna densities- Beetle larvae, earthworms, nematodes and termites	CP, DS, RR, MR_H $BA_{H,}$	2006 and 2007 summer (cropping seasons)
3	Chinyanga, Henderson, Kajengo, Makwara	Nematodes densities	CP, DS, RR, MR_H $BA_{H,}$	2006 summer and 2007 summer
4	Chimbwa, Chinyanga, Henderson, Kajengo, Makwara, Zhinya	Termites activities – Galleries and attack on maize	CP, DS, RR, MR_H $BA_{H,}$	2006 and 2007 winter (after crop harvest)
5	Chinyanga, Henderson, Kajengo, Makwara, Zhinya	Litter bag experiment- Maize litter losses	CP, DS, RR, MR_H $BA_{H,}$	2006 winter and 2007 summer
6	Chinyanga, Henderson, Kajengo, Makwara, Zhinya	Weed species and densities	CP, DS, RR, MR_H $BA_{H,}$	2006 and 2007 winter
7	Shamva (North-eastern Zimbabwe), Zimuto (Southern Zimbabwe)	Farmer interviews – Fauna perceptions	-	August 2006
8	Chinyanga, Henderson, Kajengo, Makwara	General discussion	-	-

H -Indicates treatments only applied at Henderson (Hand-hoe made basins and Magoye ripper), CP = Conventional ploughing using a moldboard plough, DS = Direct seeder, RR/MR = Ripper, BA = Basins

2 SOIL FAUNA DENSITIES IN SUB-HUMID AND SEMI-ARID AGROECOLOGICAL ZONES

2.1 Introduction

Soil fauna is important because of its involvement in below-ground biological, chemical and physical processes. The majority of processes that enhance the quality and health of soils under crop production are driven by soil fauna. Several factors affect the densities and prevalence of soil organisms. Among the biophysical factors, climate and soil type stand out as important determinants. These change local level soil temperature, moisture and humidity, which all affect densities and survival of soil fauna (Jouquet et al. 2006). Farming systems can also influence the soil fauna community by modifying the soil environment bio-chemically and/or physically. On degraded soil where multiple deficiencies and soil-limiting conditions occur (Cech Jr. et al. 1998), the role of fauna is hardly noticeable. Application of contrasting farming systems such as conventional ploughing and conservation agriculture (CA) on these soils affect the ecology of fauna and hence their role in a soil. Often the interactions of residues/organic matter and tillage management on fields have a bearing on densities of soil fauna (Weilbull and Ortmann 2003). In conservation agriculture, soil cover and minimum tillage is applied to the soil. The short-term response of soil fauna to the application of CA on degraded soil is not known.

To date, few reports are available on the quantitative changes that take place following the use of conservation farming practices in eastern and southern Africa. Among the soil faunal groups, beetles, earthworms, nematodes, mycorrhizae fungi and termites are important and of interest to study under different farming systems. As reported by Ndiaye et al. (2004), the ecosystem “engineers” beetle larvae, earthworms and termites are responsible for modifying both the biotic and abiotic soil environment. The tunnels they build in the soil facilitate water and air exchange (Lal et al. 2000).

Beetles are the biggest fauna group in the tropics, and the white grub beetle larva is associated with decomposing organic materials on the farm (Lawton et al. 1998; Frolov and Schortz 2003; Coleman et al. 2004). Beetle larvae are often found around the root zone of crops such as maize; these relationships make it an important indicator of soil improvement in crop production.

Earthworms are commonly found on low-lying wetland margins on moist soils with high clay, organic matter and silt content (Lavelle and Spain 2001). On up-land fields, their presence is related to the soil water table depth. Clayey soils host more earthworms than sandy soils with low fertility and are thus indicators of both soil water and potential soil productivity. Reports of the contribution of earthworm casts to stabilizing soil structure are numerous from outside southern Africa and in Europe, and America. Farming systems and in particular soil disturbance, influence earthworm populations in the soil (Chan 2001; Emmerling 2001). Swift and Bignell (2001) grouped earthworms based on habitat and food source showing the importance of the two factors on their growth.

Mycorrhiza fungi associations improve the host plant's capacity to access more water and nutrients (Finlay 2005). Given the wide availability of mycorrhizae genera in soils in Zimbabwe, improved densities increase the chances of crops to overcome disease, low nutrient and water stresses. Use of organic materials and land history are factors that can influence mycorrhizae density on sandy soils (Makonese et al. 1999; Jefwa et al. 2006).

Nematodes infect plant roots, causing a shift in the balance of exudation and internal energy levels in crops. In maize-based cropping systems, nematode genera that parasitize the graminaie family of crops are found in abundance. The situation is worse under the commonly practised conventional ploughing where no proper rotation are practiced. However, where rotations are practised, reports of *mucuna*, *crotalaria* species reducing the nematode infection risk of the next cereal documented recently, imply progress in research on phyto-parasitic nematodes. Even more interesting are findings that *crotalaria* could enhance free living nematodes and support soil health (Wang et al. 2004). The presence of nematodes in diverse environments makes them a useful bio-indicator of soil health (Coyne et al. 2007).

Termites are found on farm land and have no documented contribution beyond comminution of residues. Termite activity is enhanced where residues are kept on the soil surface, and where soil conditions are close to or can be modified to meet their auto-ecological requirements for proliferation. Watson (1972; 1976) and Nyamapfene (1985) reported three main genera, *Macrotermes*, *Odontotermis* and *Rhainotermes,* across Zimbabwe in forest soils, however, no reports have been made on crop lands.

The objective of the study was to assess the short term changes in densities of four fauna groups, i.e., beetles, earthworms, nematodes and termites, over two seasons as affected by the level of soil disturbance in conventional ploughing and mulched conservation agriculture treatments. In addition, within season variation was determined using two sampling periods in 2007.

2.2 Material and methods

2.2.1 On-station and on-farm work

The study was conducted on-station at Henderson Research Station in Mazoe Valley and on-farms in southern and north-eastern Zimbabwe. Three soil types were studied, heavy clay (*Chromic Luvisols),* sandy loam (*Gleyic Luvisols)* and coarse sandy soils (*Ferrali-Gleyic arenosol*). Kajengo, Henderson and sites in southern Zimbabwe are found on *Gleyic luvisols* and *arenosols*; these soil types represent 60 % of soil that are under agriculture in Zimbabwe (Anderson et al. 1993). The sandy soils are derived from similar granitic parent material and the spartial variability they exhibit is related to the mineral composition. Chinyanga, Henderson and Kajengo sites are located in agro-ecological zone II of Zimbabwe which receives an average of 800 mm of summer rainfall that occur between October and April. The site in southern Zimbabwe, Makwara, receives an average of 650 mm annually characteristically variable and is in agroecological zone IV.

Table 2.1: Soil texture, soil organic carbon and pH (0-30 cm) at Chinyanga, Henderson, Kajengo, Makwara and Zhinya sites in Zimbabwe

Site	Clay (%)	Silt (%)	Fine Sand (%)	Medium Sand (%)	Course Sand (%)	Org. Carbon (%)	pH ($CaCl_2$)
Chinyanga	39	14	27	14	7	2.0	6.3
Henderson	5	7	nd	nd	88	0.71	5.2
Kajengo	14	9	43	22	13	1.42	5.7
Makwara	6	2	28	27	39	1.02	5.3

nd = not determined

Among the sites with soils derived from granitic parent material, Kajengo had higher clay content compared to other sites. Soil at Chinyanga, which are derived from a mafic parent material, is high in clay, organic matter and soil pH (Table 2.1).

2.2.2 Land use history

The site at Henderson Research Station had been under cultivation since the mid-1970s. The open woodland surrounding the site was used for livestock pasture and controlled harvesting of forest products and trees was practiced. However, veld fires are common in this area. Burning has led to losses of flora biomass though it enhances regeneration of a few fire-tolerant species hence, it has contributed to shaping the current flora structure (Lawton 1980). During the dry windy and cold winter and spring months between June and September incidences of human initiated fires are high under the open savannah vegetation of Henderson farm. When the rains start during October and November a few fires are initiated by lightning. Mixed crop-livestock farming was practiced at Henderson farm; the cropped section covering the smallest area of the farm. A large area is under woodland and pastures for livestock rearing. The fields are surrounded by the natural woodland and pastures.

The sites in north-eastern Zimbabwe have been under crop cultivation since the late 1980s. Formerly, land use practice was commercial cattle ranching with minimal forest harvesting. The human population in this area has increased since the mid 1980s, while the livestock population dropped when commercial agriculture gave way to smallholder farming. In southern Zimbabwe, conversion of natural woodlands into cultivated land has been going on since the 1960s, and this was accelerated with the high population growth rates experienced from 1970 to the 1990s (CSO 2000). The increase in the livestock and human population has increased pressure on the natural woodland resources in the area.

The natural woodlands adjacent to the crop fields are targeted for conversion into cultivated fields. Besides clearing for cultivation, the natural woodlands of the open savannah forest are a source of forest products like fuel wood, poles for construction, decomposed plant litter for fertilizing crop fields and gardens, carpentry raw materials and rope products. Except for Henderson research station, land tenure system is communal on study sites in both north-eastern and southern Zimbabwe and this influences management of natural resources in these smallholder farms.

At all sites, the normal practice was that of inverting the soil using an animal traction moldboard plough at the beginning of the cropping season. Ploughing produces a fine seedbed for planting and also acts as an early weeding exercise (Nyamudeza

1993). In addition, farmers often apply one or two other tillage operations during crop growth to reduce weed pressure, subject to availability of draught power.

2.2.3 Treatments

At Henderson (on-station), plots were sampled that were under conventional moldboard ploughing (CP), direct seeding using an animal traction seeder (DS), direct seeding with a Magoye ripper (MR) and hand-hoe basins (BA). Three treatments were used at Chinyanga, Kajengo and Makwara; conventional ploughing (CP), direct seeding using an animal traction seeder (DS) and direct seeding using an animal traction ZimPlough ripper (RR) (Figure 1.2). The Magoye and ZimPlough rippers are similar but manufactured by different companies.

2.2.4 Sampling procedure

Soil monoliths of 25 cm x 25 cm x 30 cm deep were extracted from which three layers (0-10 cm, 10-20 cm and 20-30 cm) were handled separately. The samples from the monoliths were hand-sorted for macrofauna, beetle larvae, earthworms and termites. The fauna collections were stored in 70 % alcohol for further processing (Anderson and Ingrams, 1993). Fresh moist samples were collected for nematode and mycorrhiza spore extraction in the laboratory. Sampling was conducted 6 weeks after maize germination in both 2006 and 2007, and a second sampling was done at 12 weeks after maize germination in 2007. A total of 390 monoliths were sorted and sampled from over the two cropping seasons. Standard identification keys and manuals were used for identification of specimens to genera level. From the natural woodlands, tree densities were measured from three plots measuring 10 m x 10 m. The Shannon-Wiener index was used to calculate species dominance (Magurran 1987; 2004; Krebs 1989; Kent and Coker 1992; Townsend et al. 2003).

2.2.5 Statistical analysis

At Henderson, a completely randomized block design was applied. For each treatment, 10 monoliths were sampled. Comparisons were made broadly on conventional ploughing and conservation agriculture treatments. Among the conservation agriculture treatments different levels of soil disturbance, by animal drawn direct seeder, ripper and manually-dug basins, were considered as factors. The sites were found in two agro-ecological regions on three soil types, these were also used during comparison of results and in discussion. Within season variation was analyzed using a two time sampling data from the 2007 cropping season. Using the General Linear Model (GLM), an analysis of variance was run on fauna densities data using SigmaStat and a multiple mean comparison was run at $P < 0.05$. In order to compare conventional ploughing to conservation agriculture, orthogonal contrasts were run in SAS program. In this analysis the conservation agriculture treatments were pooled and compared to conventional ploughing treatment. In addition, box plots were used for graphical representation; showing the spread of the data, median and mean for each treatment using SigmaPlot.

2.3 Results

2.3.1 Soil fauna densities

Henderson, a sandy soil site in the sub-humid zone had the highest beetle larvae and nematode densities in the two years (Table 2.2). Total fauna density was lowest at Makwara, a sandy soil site in the semiarid zone. Makwara had no earthworms and had the least termite densities. Termite density was also highest at a sub-humid and sandy soil site, Kajengo. The sum total soil fauna groups measured across the sites were in the order, Henderson>Kajengo>Chinyanga>Makwara. Sites on sandy soils in sub-humid zone had higher fauna than one in the semi-arid zone; whereas the clayey soil site hosted less total fauna than sites in the same rainfall zone.

Table 2.2: Mean fauna densities (no. m^{-2}) on farms at Henderson, Chinyanga, Kajengo and Makwara, Zimbabwe, determined during 2006 and 2007 cropping seasons

	Henderson (no. m^{-2})	Chinyanga (no. m^{-2})	Kajengo (no. m^{-2})	Makwara (no. m^{-2})	SED
Beetle larvae	38	11	12	12	3.6
Earthworms	4	16	19	0	2.7
Nematodes*	224	132	105	105	21
Termites	85	115	198	22	14
Total fauna	315	274	334	139	

**Nematodes densities (no. per 100 g soil)*

Among the three treatments used on all sites, beetle larvae, earthworm and termite densities were least in the conventional ploughing treatment (Figure 2.1). For all the four fauna groups, nematodes included, densities in the direct seeder were consistently lower than in the ripper treatment. The ripper treatment had the highest densities for all fauna groups. All fauna groups had highest densities in the 0-10 cm soil layer (Appendix 1).

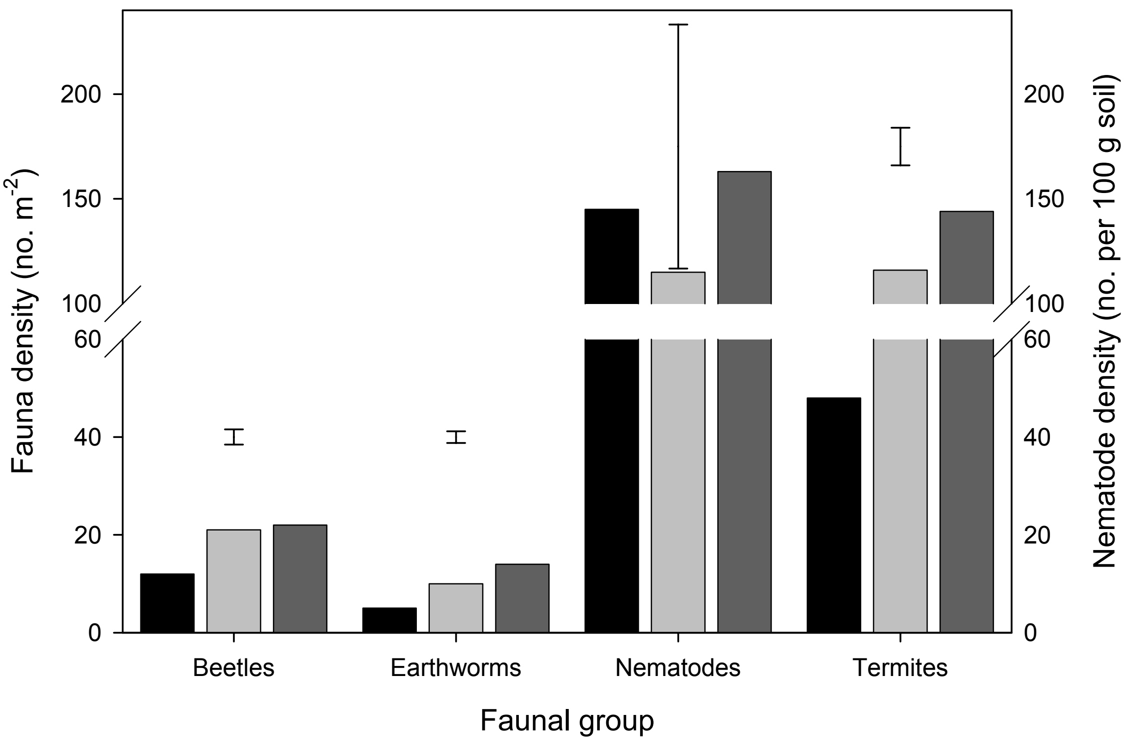


Figure 2.1: Mean fauna densities on four sites analyzed over two years (2006 and 2007) measured in conventionally ploughed (CP), direct-seeded (DS) and ripped (RR) treatments in Zimbabwe

2.3.2 Beetle larvae densities

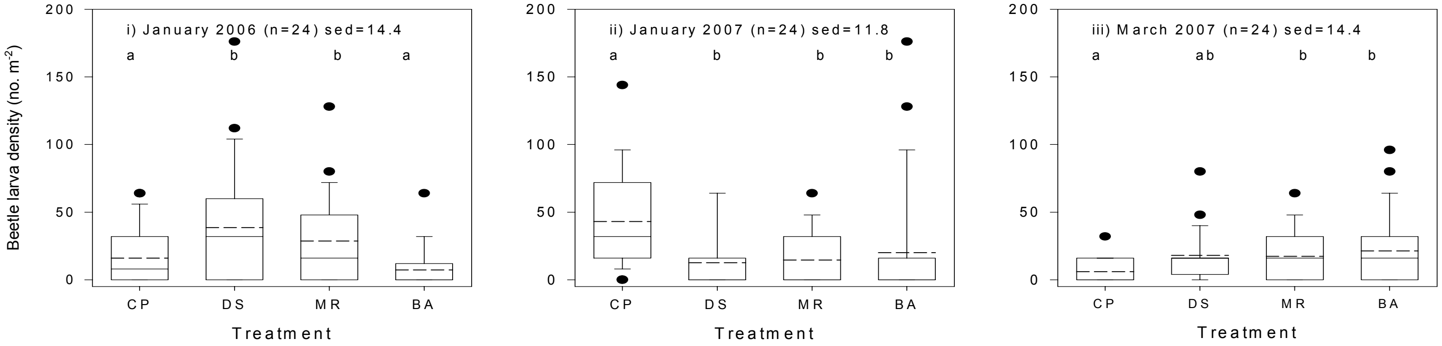
At Henderson, a site on a sandy soil in the sub-humid rainfall zone, a significant higher in beetle larvae densities ($P < 0.05$) were found in direct seeded and ripped treatments (in 2006), and in all conservation agriculture treatments in 2007 (Figure 2.2). A higher variation in densities was measured in conservation agriculture treatments relative to conventional ploughing.

Though the site at Chinyanga was on a *Chromic Luvisol*, a relatively more fertile soil compared to sandy soils, beetle larvae densities were not statistically among all treatments, although conservation agriculture treatments tended to have higher densities (Figure 2.2). On this site and all the other on-farm sites, the basin treatment was not used in the trials.

At Kajengo no difference were found among treatment except in 2006, when the ripper treatment was significantly higher than both direct seeder and conventional ploughing (Figure 2.3). Similarly at Makwara, a site in the semi-arid zone, beetle larvae densities tended to be higher on conservation agriculture treatments and, direct seeder had significantly higher density in 2007.

Even in cases where there were no treatment differences, there was a tendency for beetle larvae to respond to reduced soil disturbance in direct seeder, ripper and basins treatments. Higher variation in beetle larvae density exhibited in conservation agriculture treatment showed a short-term response to conservation agriculture and that some potions of plots under these treatments already reacted. This suggest higher potential of conservation agriculture in providing better soil conditions for soil fauna compared to conventional ploughing.

Henderson



Chinyanga

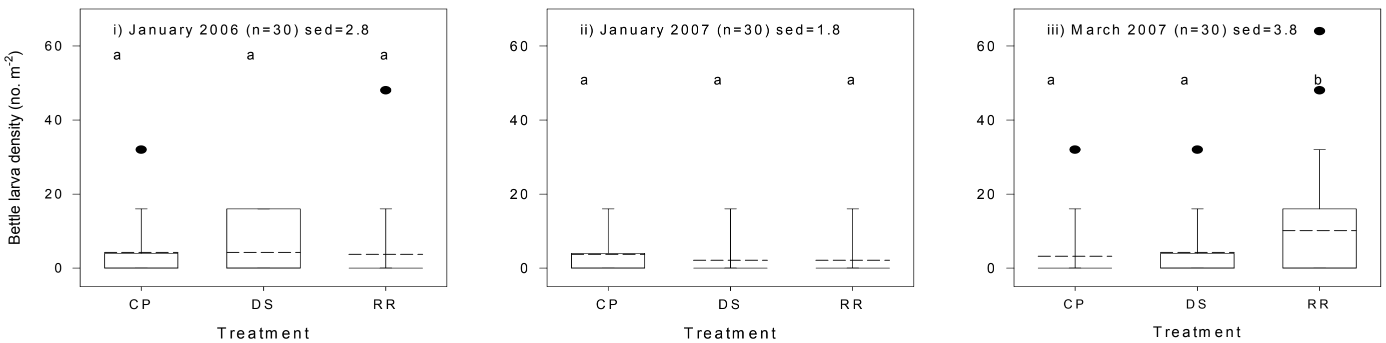
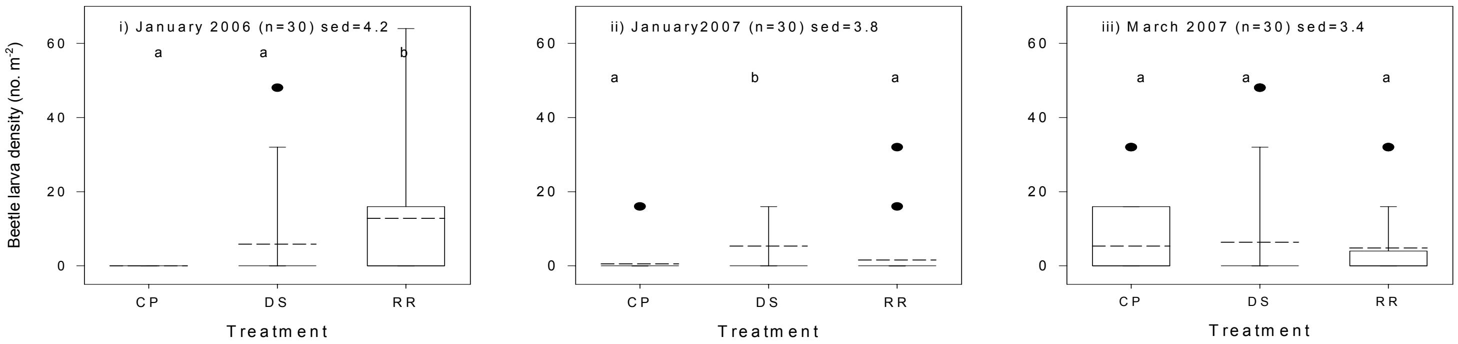


Figure 2.2: Beetle larvae densities on two farms: four treatments at Henderson and three treatments at Chinyanga in 2006 and 2007 cropping seasons. CP = conventional ploughing; DS = direct seeding; BA = basins; and MR or RR = ripping treatments. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

Kajengo



Makwara

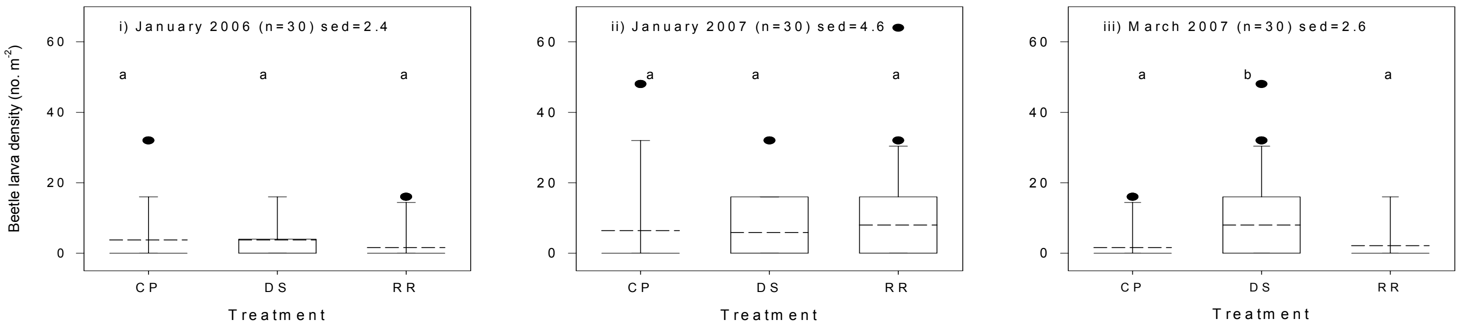


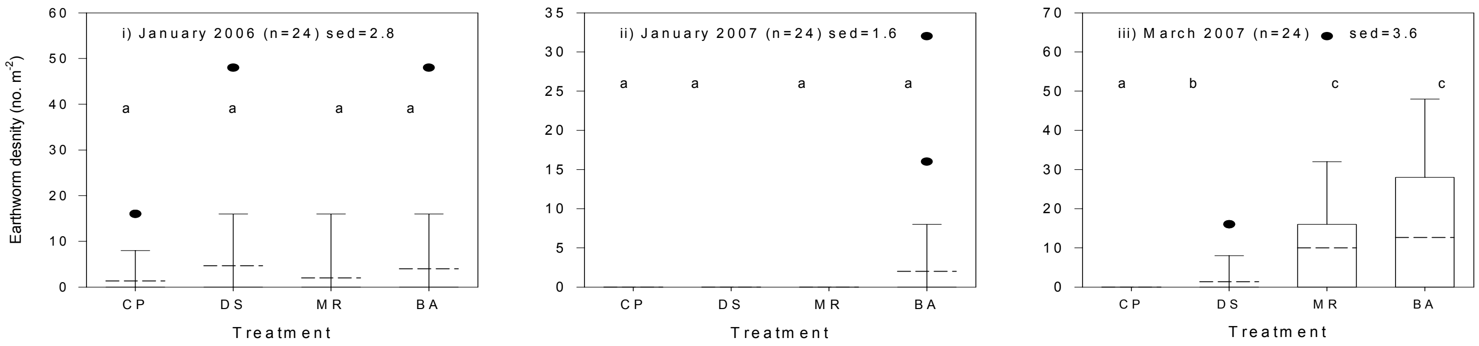
Figure 2.3: Beetle larvae densities at Kajengo and Makwara farms from three treatments conventional ploughing (CP), ripping (RR) and direct seeding (DS) treatments in 2006 ad 2007 cropping seasons. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

2.3.3 Earthworm densities

At Henderson, there were no differences in earthworm densities among treatments except later in the season in 2007; when all conservation agriculture treatments had higher densities than the conventionally ploughed treatment (Figure 2.4). Only hand hoe made basin treatment responded in earlier sampling (6 weeks after crop emergence). Variation of beetle larvae densities was higher in conservation agriculture treatments. The ripper treatment had significantly higher beetle larvae densities except in 2006 at Chinyanga. At Kajengo, ripper and direct seeder treatments had significantly higher earthworm densities except in January 2007 (Figure 2.5). No earthworms were found at Makwara in the semi-arid zone.

Though there were variations in the measured earthworm densities, either one or all conservation agriculture treatments showed higher densities and variation. This could point to the effect of minimal soil disturbance in creating a soil environment suitable for earthworms. Reduced cultivation intensity was reported to lead to increased earthworm abundance by Emmerling (2001). In the same study, a significantly higher number of burrows were also reported in treatments with minimal soil disturbance than in conventional ploughing treatment. Cultivation also causes a decrease in food supply and hence lower abundance (Lee 1985).

Henderson



Chinyanga

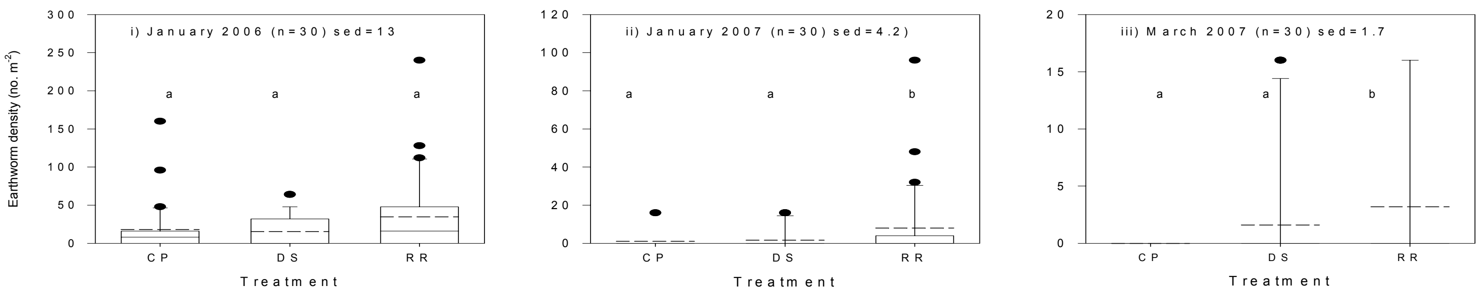


Figure 2.4: Earthworm densities on two farms: four treatments at Henderson and three treatments at Chinyanga in 2006 and 2007 cropping seasons. CP = conventional ploughing; DS = direct seeding; BA = basins; and MR or RR = ripping treatments. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

Kajengo

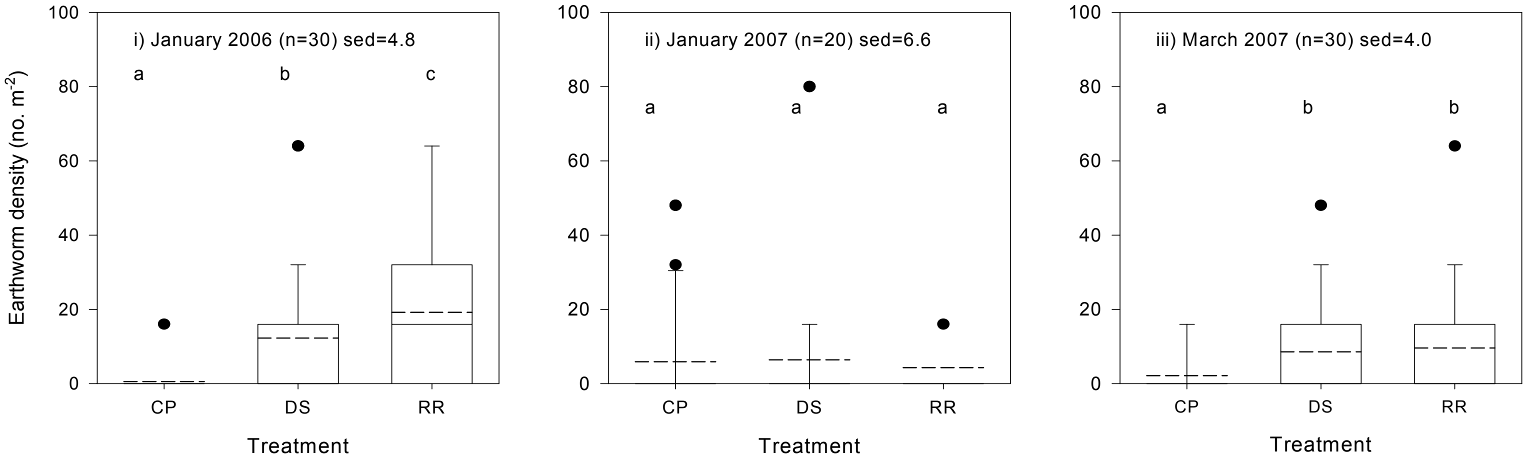


Figure 2.5: Mean earthworm densities at Kajengo from conventional ploughing (CP), ripping (RR) and direct seeding (DS) treatments measured in the 2006 and 2007 cropping seasons. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

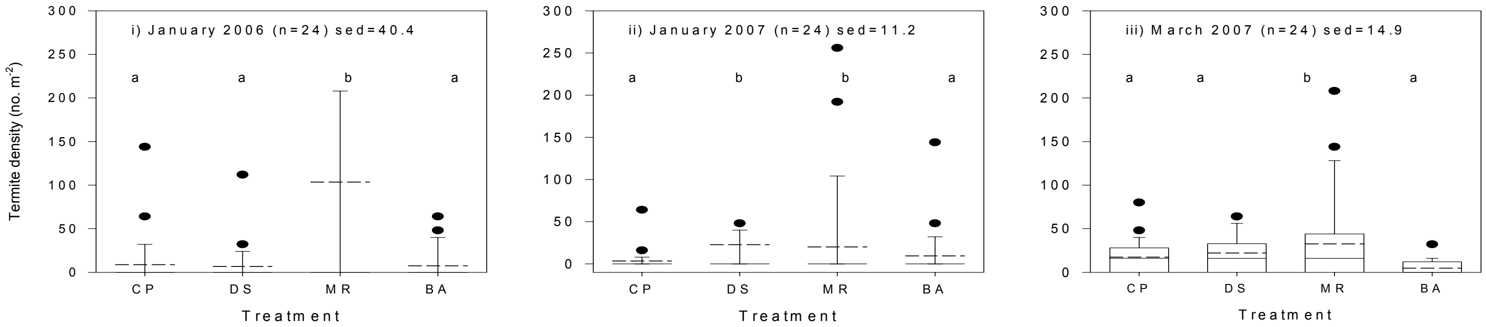
2.3.4 Termites densities

There was a consistently significantly higher termite density in Magoye ripper treatment at Henderson (Figure 2.6). The variation in densities was also highest in this treatment. Though not statistically significant, direct seeder treatment had higher termite densities except in 2006. At Chinyanga, although there were no differences among treatments, variation in termite densities tended to be higher in the conventional treatment.

There was a clear increasing trend in both termite densities and variation from conventional ploughing (least) to direct seeder (highest) at Kajengo (Figure 2.7). Direct seeder treatment was significantly higher than both ripper and conventional ploughing except in late 2007. At Makwara conservation agriculture treatments had significantly higher termite densities compared to conventional ploughing (2007). No termites measured on all treatments in 2006.

Conservation agriculture treatment showed higher termite densities variation than conventional ploughing except on a clayey soil at Chinyanga. At this site, there was a tendency for higher variation on the conventional ploughing treatment. The higher densities could be related to the mulch that was applied on all conservation agriculture treatments. In addition it could also be influenced by reduced soil disturbance on these treatments.

a) Henderson



b) Chinyanga

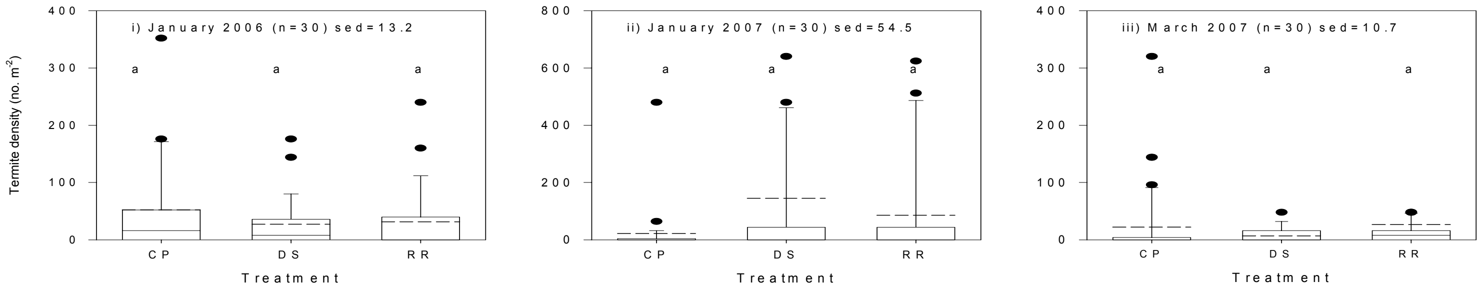
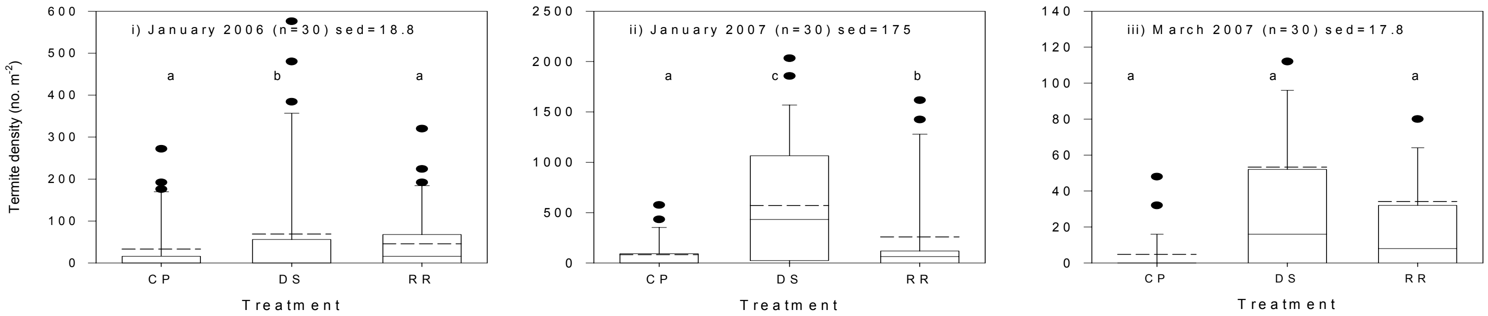


Figure 2.6: Termite densities on two farms: four treatments at Henderson and three treatments at Chinyanga in 2006 and 2007 cropping seasons. CP = conventional ploughing; DS = direct seeding; BA = basins; and MR or RR = ripping treatments. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

a) Kajengo



b) Makwara

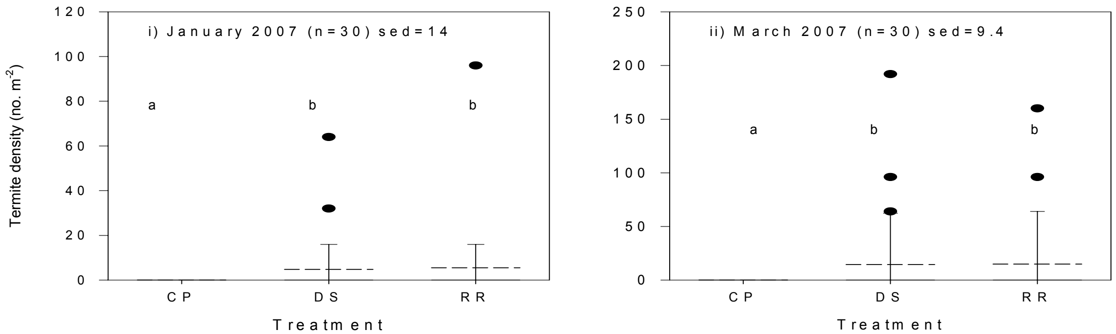


Figure 2.7: Mean termite densities from plots at Kajengo and Makwara from conventional ploughing (CP), ripping (RR) and direct seeding (DS) treatments measured in the 2006 and 2007 cropping seasons. The data was summarized in box plots where: the box represent the 25^{th} and 75^{th} percentiles, the whiskers the 10^{th} and 90^{th} percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

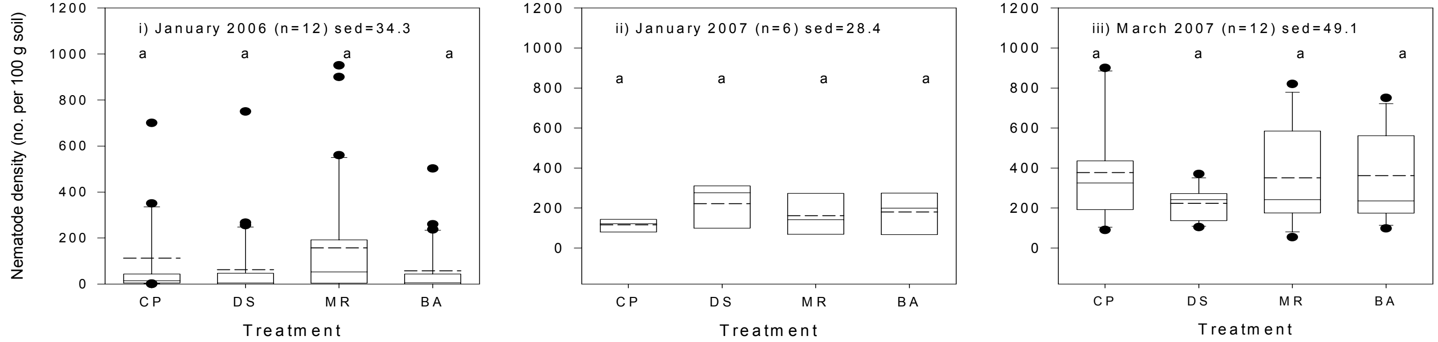
2.3.5 Nematode densities

There were no significant differences in nematode densities measured in all treatments (Figure 2.8 and 2.9). Isolated mean differences were, however, found at the different sampling dates. Nevertheless, the sites in the sub-humid zone had higher mean nematode densities than that in the semi-arid zone. The soil types did not explain the differences.

At Henderson in March 2007, the nematode densities in the basins were higher than those in conventional ploughing. All the other treatments were not significantly different. There were no significant differences between treatments in January 2007. In 2006, Magoye ripper was significantly higher than direct seeding and basins, other treatment means were similar (Figure 2.8).

At Chinyanga, there were no significant differences in either soil layers or treatments in January 2007. However, in 2006, layers showed different values, the top-soil having the highest nematode density. At Kajengo, nematode densities in direct seeding, ripping and conventional ploughing were statistically similar in January 2007 (Figure 2.9). There were no significant differences among treatments and layer depths at this site in 2006. The results from samples collected 12 weeks into the cropping season were not different from the ones collected earlier in the same season.

a) Henderson



b) Chinyanga

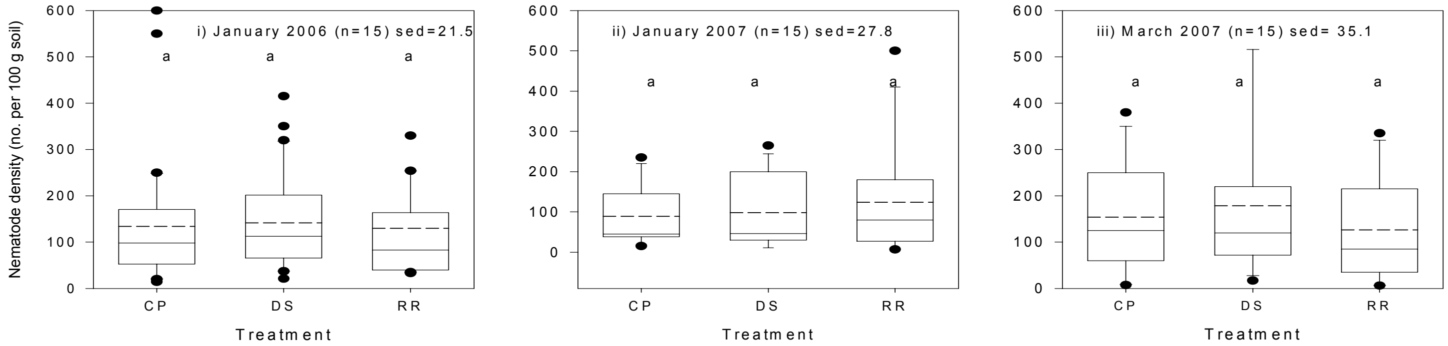


Figure 2.8: Nematode densities on two farms: four treatments at Henderson and three treatments at Chinyanga in 2006 and 2007 cropping seasons. CP = conventional ploughing; DS = direct seeding; BA = basins; and MR or RR = ripping treatments. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means (P < 0.05). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

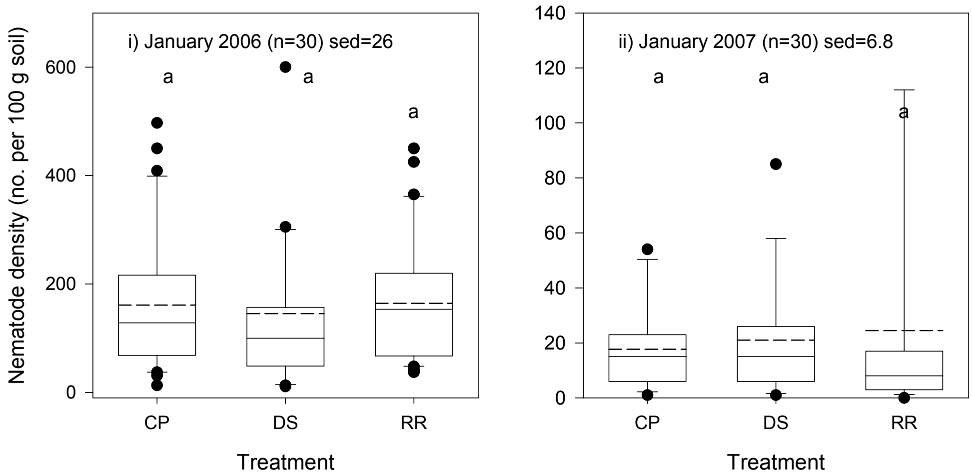


Figure 2.9: Nematode densities at Kajengo from conventional ploughing (CP), ripping (RR) and direct seeding (DS) treatments measured in the 2006 and 2007 cropping seasons. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

2.4 Discussion

2.4.1 Agro-ecological zones

Though Henderson, Chinyanga and Kajengo are situated in the same agroeoclogical zone with regard to their potential agricultural productivity, there were differences in the densities of fauna at each site. The zonation did not result in similar responses to treatments. This means that the densities of beetle larvae, earthworms, nematodes and termites were not a result of the wider geographical similarities between sites; in contrast local level factors seem to have influenced the trends much more strongly.

2.4.2 Effect of soil texture on distribution of fauna

Soil texture, in particular the clay content affected the distribution of soil fauna across the study sites. Mean earthworm densities decreased from Chinyanga to Henderson with no earthworms found at Makwara. This trend is similar to the decreasing clay content and organic matter found at these sites (Table 2.1). High clay and organic matter contents in soils increase the moisture buffering capacity.

2.4.3 Treatment effect on fauna densities

Higher densities in the mulched ripper and direct seeder treatments could result from the fact that the two treatments minimized the displacement of soil, and hence, disturbance. The effect of reduced tillage on water, organic matter and temperature also has a bearing on the survival and reproduction of soil fauna (Kladivko 2001). The minimal soil disturbance could mean that soil fauna's nesting sites (e.g. for termites) and often permanent burrows (e.g. for earthworms) are not destroyed, leading to higher densities at Henderson, Chinyanga, Kajengo and Makwara sites over the two study years. The ripping treatment showed higher mean fauna densities at Chinyanga and Kajengo further demonstrating the effect of the ripper which links the top-soil and the sub-soil horizons, and may influence moisture profiles.

Ripping has a deep-ploughing effect on the soil, which results in the breaking-up of the plough pan. On field with a long history of conventional ploughing using the mould board plough, which is the case for all the study sites, the plough pan could inhibit transportation of soil air, water and nutrients. Therefore, compared to the conventional ploughing treatment, where the soil is pulverized and the plough layer is further developed, the higher fauna densities measured in the ripper treatment could be a result of improved interaction between the top and the sub-surface layers.

The mean fauna densities were significantly different between conservation agriculture treatments with same level of residues. Whilst a number of authors have alluded to significant effect of mulch on densities of soil fauna, the results of this study show that, at least in the short term, the effects were confounded in the tillage implements used. In addition the responses were also influenced by the site differences.

Depth of sampling influenced densities, and most beetle larvae were found in the 0-10 cm soil layer. The prevalence of soil fauna in the top-soil layer on all treatments could be a result of favorable auto-ecological environmental conditions, with particular reference to rhizosphere's influence. Beetle larvae in particular were found close to maize root systems.

2.4.4 Beetles

Beetle larvae densities responded to reduced soil disturbance as reflected by the high and variable densities (Figure 2.2 and 2.3). Clark (1999) observed increased abundance of epigean ground beetles under organic systems compared to conventional systems. The lower beetle densities on the sandy soils under conventional tillage treatments e.g., at Henderson also show that tillage reduce sandy soils (Figure 2.2). This is in line with Jouquet et al. (2006), who found that the structure and distribution of the fauna were also affected by habitat disturbance. These observations are corroborated by Dangerfield (1990), who found lower abundance of beetles on cropping fields (disturbed) compared to disturbed *miombo* forest or managed eucalyptus plantations (undisturbed). Tillage can be viewed as a way of pulverizing the soil creating a poor structure on sandy soils, which is not suitable for sustained crop production (Six et al. 2004).

On the heavier textured soil at Chinyanga however, reducing tillage did not affect beetle larvae densities rather the densities were similar as in conventional ploughing treatment (Figure 2.2). This may mean that reducing tillage had a lower effect in the short term on clayey soils.

Henderson hosted more beetle larvae than other sites in the same agro-ecological zone (Table 2.2). Given relationship between beetles and trees, the flora structure adjacent to the site and landuse history could point to the higher beetle larvae densities. As suggested by Benckiser (1997), the evolution of resources at watershed or zonal level influences changes in species composition. Work of Weillbull and Ostman (2003) also demonstrated that for low-mobility beetles, the variation in population is better explained by farm level management than broader landscape heterogeneity.

The significantly higher beetle larvae densities determined in the 0-10 cm soil layer were influenced by the soil cover used in the conservation agriculture treatment. Surface mulches have been reported to cause higher soil moisture storage and temperature buffering (Acharya et al. 2005). Beetle larvae being geophagous species, they move through the soil to position themselves as close as possible to their thermal, moisture and feeding optima. With surface mulches, it can be envisaged that higher chances of bio-tillage from soil fauna occur in conservation agriculture systems than in conventional ploughing.

2.4.5 Earthworms

At Henderson there was a build-up of densities starting with a low level in 2006, with no differences in January 2006 and treatment effects becoming visible in March of 2007. Higher densities in the ripper and basins treatments at Henderson suggest a link between densities and minimal soil movement during seeding and land preparation. This is also reflected in higher earthworm densities in the ripping treatment both at Chinyanga and Kajengo. This result is similar in trend but not in magnitude to observations made by Chan (2001), who reported a reduction of earthworm abundance by a factor between 2 and 9 following tillage application under conventional ploughing systems.

The lack of earthworms at the Makwara sites could be related to the poor structure of the soil. The low clay and organic matter at this site which led to a loose structure, may not support earthworm activities. The site is on the crest of the catena, and fast soil-water drainage can also lead to relatively lower moisture residence time, deeper water table and hence unsuitable conditions for earthworms. Low organic matter in degraded soil reduces the available food sources especially for endorgenic species (Emmerling 2001). The existing higher densities and the increased densities from 2006 to 2007 in this study suggest that the soil cover and the minimum soil movement could have created favorable conditions for earthworms at the other sites. Soil water status is a major limitation to earthworm activities and distribution, since they cannot withstand prolonged periods where water potentials are lower than -0.01 MPa (Lavell and Spain 2001). However, this was only true for the sites with a clay content higher than 5 %; at Makwara, where clay content was 3 %, no earthworms were found. A low response to no-till systems was reported by Johnson-Maynard et al. (2007), who explained the trend with the short time under which the soil was under reduced tillage.

2.4.6 Termites

At Henderson, termite densities were lower under conventional ploughing than Magoye ripper and direct seeding. The higher densities in the conservation agriculture treatments were mainly a result of the residues applied as mulch in these treatments unlike on conventional ploughing. The mulch attracted termites and also provided a suitable foraging site. At Kajengo also, the termites densities were higher for ripped and direct seeded treatments compared to conventional ploughing.

Tillage affected the trends in the termite densities differently at the other sites. At Chinyanga, higher densities were found on the conventional ploughing (March 2007 and January 2006). Eggleton et al. (2002a) showed a negative correlation between the degree of disturbance of fauna habitats and species richness. On the sandy soils at Henderson and Makwara, tillage and removal of residue disturbed the habitats and also limited energy sources in conventional ploughing treatment, hence the lower termite densities. Application of surface mulches, crop or grass residues, that contain cellulose and crude protein attracted more termites, and this led to increased foraging activities at these sites on plots with minimal soil disturbance. The short-term implication of conservation agriculture practices is the provision of building blocks for a stable soil water and nutrient movement and hence soil health. However, the densities reported in this study are not comparable to the 400 per m^{-2} reported by Jones (1990).

2.4.7 Nematodes

The densities did not reflect treatment differences in nematodes meaning, in the short term, nematodes were not affected by application of conservation agriculture. Nematodes are an opportunistic faunal group (de Goede and van Dijk 1998), hence their presence across all the sites. Klavidko (2001) reported more sensitivity of larger soil organisms to tillage than smaller organisms. However, given residue retention on conservation agriculture treatments, it was expected that densities of nematodes would increase. The similarity in nematode densities could suggest that other factors limited nematode proliferation on both conservation agriculture and conventional ploughing treatments.

2.4.8 Within-season variation

The higher beetle larvae and nematode densities during the sampling in March 2007 compared to an earlier sampling in January 2007 show that there was a variation in densities within the same season. These differences could be due to the phenological developments of each species. Beetle larvae and nematodes nymphs react differently to environmental conditions such as moisture and temperature which may be related to treatment, but also to climatic factors rainfall and temperature (i.e. catchment level factors). It is difficult to assess this causality using the species densities data only.

Higher variation in densities exhibited in the ripping and direct seeding treatments nevertheless show an increased potential for soil fauna to find suitable niches to create localized structures where they can complete their life cycles. This would mean a healthier soil environment under the conservation agriculture treatments compared to the conventional treatment, where a narrow variance was measured within the season.

2.4.9 Role of fauna in agro-ecosystems

The higher densities measured under the conservation agriculture treatments imply an increase in the biomass of beetles, earthworms, nematodes and termites. As explained by Jouquet et al. (2006), the four fauna groups are elements of the belowground food web. Therefore, the high numbers increase the contribution of each species to the food web at each site.

The auto-ecological requirements of the measured soil fauna demand that they also modify the surrounding biotic and abiotic environment. Hence, the resultant biogenic structures, important for the completion of their life cycle, are yet another contribution to the soils on cropping fields. Bang et al. (2005) reported that whereas the activities of beetles affected the air permeability at 0-10 cm soil depth, they had little effect on horizons lower in the profile. With higher beetle larvae densities on mulched plots, top soil improvement is enhanced. Less soil movement under ripping and direct seeding treatments thus favor fauna nest formation in the soil and even termite galleries on the soil surface.

The distance to food source and the auto ecological requirements are important factors for soil fauna build-up. Ripping affected termites and beetle larvae, which rely on the structure of the soil to access their food sources. However, nematodes were not affected because their access to food sources is more affected by presence of soil moisture than the soil structure. In addition, nematode are associated with the rhizosphere hence their survival strategy is less prone to the influence of ripping.

2.5 Conclusions

High fauna density was measured at the Henderson site under ripper and direct seeder treatments with mulch. Even where the average densities were not higher under conservation agriculture (as in Figure 2.7), the variation of the densities was higher, pointing to the potential of conservation agriculture to improve the conditions for the soil fauna. Minimizing tillage and maintaining a soil cover increased soil fauna densities over two cropping seasons. Beetles, earthworms, nematodes and termites were concentrated in the 0-10 cm soil layer and lower densities occurred with increasing in soil depth. Ripping on heavy clay soil (Chinyanga) had a minimal effect on beetle larvae and termite densities than on sandy soil (Henderson and Kajengo). Though nematode densities did not respond to treatments in the two years of study, soil texture affected their densities. The sum all fauna densities (4 groups) was highest on sandy soils in the sub-humid zone (i.e. Henderson) and least at Makwara, a sandy soil site in the semiarid zone.

3 NEMATODE PROFILES IN CONSERVATION AGRICULTURE SYSTEMS

3.1 Introduction

Nematodes are widely distributed in agricultural land and they parasitize a range of field crops and vegetables commonly cultivated in eastern and southern Africa (PPRI 1987). Species composition and densities are largely affected by local conditions, temperature and soil type. When changing a conventional maize mono-cropping farming system to conservation agriculture system, the ratio of plant-parasitic to free-living nematodes is modified (Porazinska et al. 1999). When organic matter is applied to the soil, free-living genera tend to increase compared to plant-parasitic genera. This could be related to the fact that, two key features of conservation agriculture namely, mulching using crop residues and cereal-legume rotations, are also important cultural methods for controlling nematode infestations (FAO 2001). Further, some weeds are hosts to nematodes and lead to alteration of nematode genera present is soils. Cropping systems and organic fertilization practices improve the diversity of carbon sources for soil organisms, nematodes included. Masse (2002) reported the inhibition of species by environmental soil conditions more than host specificity on cropping lands. The potential of keeping plant parasitic nematodes low in the soil using conservation agriculture techniques has not yet been studied.

Work in Zimbabwe in the late 1970s and early 1980s, has shown that the root lesion, *Pratylenchus* spp., is the dominant nematode affecting maize fields and grasslands (PPRI 1979-80). In addition swollen roots, stunted growth and chlorosis, poor health of crops, streaked chlorosis and severe damages on maize have been reported as a result of *Scutellonema*, *Rotylenchus*, *Paralongidorus*, *Xiphinema*, *Helicotylenchus*, *Meloidogyne*, *Criconemella* nematode genera. Earlier studies reported high recoveries of soil nematodes ranging between 300 and 4000 per liter of soil.

On the other hand, the use of nematodes as an indicator of soil health has been reported since the 1960s (Luc et al. 1990). Their abundance in different environment, diverse feeding habits, and a short life cycle make them suitable bio-indicators of the state and processes in ecosystems (Porazinska et al. 1999; Yeates et al. 1993a). Nematodes play an important role in the decomposition of organic matter together with other soil fauna (Masse 2002). Their presence in the soil is influenced by type crop type, available carbon source and physical soil characteristic. The effect of nematodes on plant growth has been reported across both plant-parasitic (negative effects) and free-living nematodes (positive effects). Applying appropriate crop sequences leads to higher proportions of free-living nematodes, reduces the pathogenic effects and hence the risk of crop loss (Masse 2002). The use of organic materials and reduced tillage under conservation agriculture to reclaim degraded soils in the smallholder farming sector can modify nematode genera composition in cropping fields.

Nematodes feed on a variety of materials, their nutrition (which may vary according to development) separate saprophagous, phytophagus, predatory and parasitic groups from each other (Coleman et al. 2004). A further classification based on feeding habits was proposed by Yeates et al. (1993). Plant-parasitic nematodes are often viewed as a silent but important factor causing yield reduction. Obligate and specialized parasites rely on finding a suitable host in order to complete their life cycle (Taylor 1971). Root damage from ecto- and endoparasitic nematodes can lead to wilting, stunting, nutrient deficiencies and crop yield losses. Cultural practices of crop rotations, use of resistant cultivars, intercropping, tillage, steaming, solarization and nematicides have been advised to farmers for use in controlling nematode pressure on crops (Ettema 2002). It is not clear how effective these are in controlling parasitic groups of nematodes to levels that do not cause economic losses.

The objective of this study was to asses the changes in genera composition and densities of nematodes under conventional ploughing compared to conservation agriculture treatment; direct seeder, ripper and basins at Henderson Research Station, Chinyanga, Kajengo and Makwara, Zimbabwe, over two cropping seasons. The tested hypothesis was that in conservation agriculture treatments (with reduced tillage and residue retention), in the short, free-living nematode genera dominate the plant-parasitic ones.

3.2 Materials and methods

The study was conducted on-station at the Henderson Research Station in the Mazoe Valley and on-farm at Chinzanga, Kajengo, Makwara and Zhinya. In Zimbabwe sandy soils represents 60 % of soil that are under agriculture in Zimbabwe (Anderson et al. 1993). Three soil types were studied at Chinyanga, a heavy clay (*Chromic Luvisols),* at

Kajengo and Henderson sandy loamy (*Gleyic Luvisol)* and at Makwara and Zhinya coarse sandy soils (*Ferrali-Gleyic Arenosols*). Henderson, Chinyanga and Kajengo sites are located in agro-ecological zone II which receives an average of 800 mm of summer rainfall that occur between October and April. The Makwara and Zhinya sites (agroecological zone IV) receive an average of 650 mm annually.

Chinyanga showed the highest clay, organic matter and soil pH values (Chapter 2 Table 2.1), followed in clay content by Kajengo. The Henderson, Makwara and Zhinya soils were low in clay content. Makwara and Zhinya have similar soil textural properties, but organic carbon and soil pH were higher at Zhinya.

Moist soil samples were collected from each treatment both on-station and on-farm up to a depth of 30 cm. These were kept in a cold room below 5 ^{o}C before nematode extraction. Before extraction, soils were mixed thoroughly and passed through a 2 mm sieve to remove gravel and organic materials.

Nematode extraction from soil samples was done using the modified Bearmann filter method (Coleman et al., 2004; Luc et al., 1990; Whitehead and Hemming, 1965). Pieces of cheese-cloth and soft paper tissue were placed on the mesh covering its base. A 100 g portion of each sample was uniformly spread over the soft tissue. Water was carefully poured into a plate under the filter in order to wet the soil sample from beneath. The water level just touched the based of the mesh to avoid flooding the soil sample. The samples were left to stand for 24 hrs. After this, the mesh filter, cheesecloth, tissue and soil were removed and the nematode solution collected in containers for counting and fixing for identification. Population was expressed per 100 g of soil. Nematodes were then analyzed on Sedgwick Rafter slide at 200 x magnification enabling classification to genus level. Plant parasitic nematodes were further described at the Plant Protection Research Institute in Harare. The Shannon-Wiener diversity index and the evenness index were calculated using equations 3.1 and 3.2 (Kent and Coker 1992), for nematode genera identified for each treatment and site for comparison.

Diversity

$$H' = \sum_{i=1}^{s} p_i \ln p_i \tag{3.1}$$

Where s = number of genera

p_i = the proportion of the ith genus relative to the total density

ln = log base$_n$

Equitability (evenness)

$$J = \frac{H'}{H'\max} = \frac{-\sum_{i=1}^{s} p_i \ln p_i}{\ln s} \tag{3.2}$$

Where H' = Diversity

p_i = the proportion of the ith genera relative to the total density

s = number of genera

ln = log base$_n$

Statistical analysis: Using treatment as a factor an analysis of variance was run using data from each site and means were compared at $P < 0.05$. In addition box-plots were used to show in graphs, the variation of number of genera measures for plant-parasitic and free-living nematode genera at each site for each sampling time. Percentages of genera found in high numbers were also reported.

3.3 Results

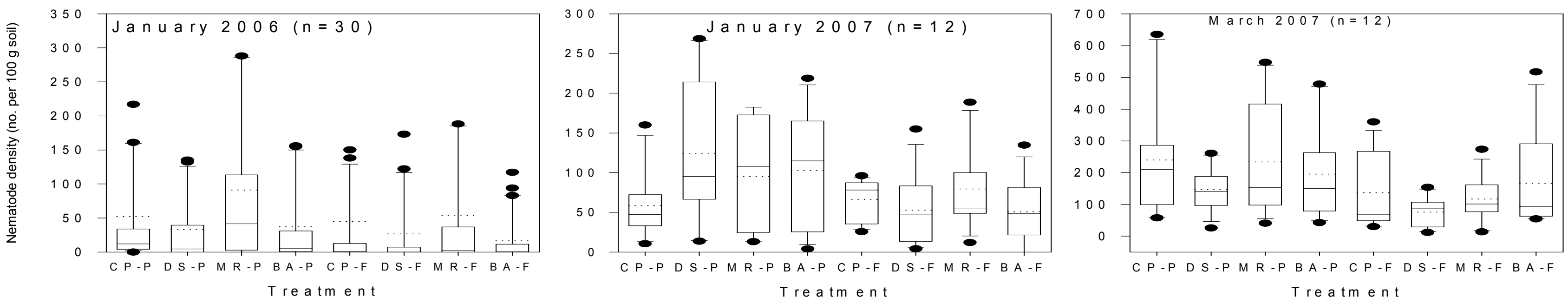
3.3.1 Nematode genera and densities

At each study site a high number of nematode genera was found though sites on sandy soils at Henderson, Kajengo and Makwara had lower numbers compared to the one on clayey soil. The highest number of genera from Henderson, Kajengo and Makwara were 22, 21 and 17, respectively, while Chinyanga had 27. Though the density ratio of plant-parasitic nematodes to the free-living genera varied at the three sampling dates, the ratio of densities of the two groups remained the same (almost equal numbers in the soil).

The range of nematode densities from Chinyanga, Kajengo and Makwara was 89-179, 16-165 and 38-179 nematodes per 100 g of soil, respectively; these ranges were narrower than the 58-378 nematode per 100 g found at Henderson. The mean nematode densities in the sandy soils were lower during early season sampling (6 weeks after maize germination) compared to 12 weeks into the cropping season. In contrast, in the clayey soils at Chinyanga, densities were higher early in the season than later. This could be due to different moisture build-up between the two soil types. In the clayey soil, an increase in a nematode-eating invertebrate fauna could also explain the lower number. Nonetheless, a build-up of the nematode communities is expected with root development as the crop grows.

Though the sites had different soil textures and were in different rainfall zones, site characteristics did not influence the distribution of nematode genera. *Helicotylenchus, Pratylenchus, Rotylenchus* and *Tylenchus* were found across all sites in higher numbers than other phyto-parasitic genera (Appendix 2). Free-living nematodes common to all sites and found in higher densities were *Rhabditis, Alaimades, Aphelenchoides* and *Dorylaimus.* At Henderson, for example, high densities of parasitic genera were found across all the four treatments: The conventional ploughing treatment had the highest density of 371 nematodes per 100 g soil, which was mainly composed of *Helicotylenchus* (19.4 %), *Pratylenchus* (17.9 %), *Rotylenchus* (9.2 %) and *Trichodorus* (7.6 %). The direct seeder treatment had the lowest nematode density, with 223 nematodes per 100 g of soil, and consisted mainly of *Pratylenchus, Rotylenchus* and *Helicotylenchus*. Only *Rotylenchus* and *Trichodorus* showed densities of more than 10 % each under basins. A non-parasitic male *Meloidogyne* genus was also found in high numbers.

a) Henderson



b) Chinyanga

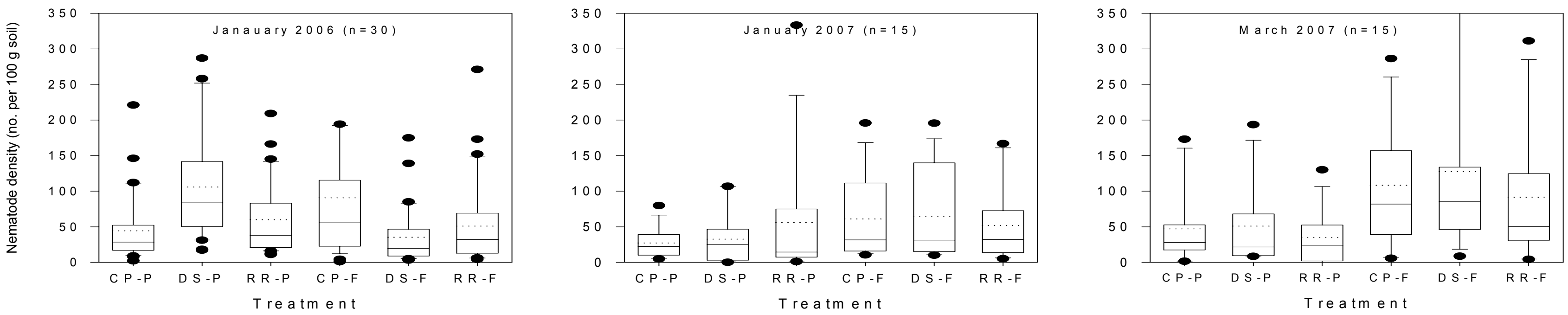
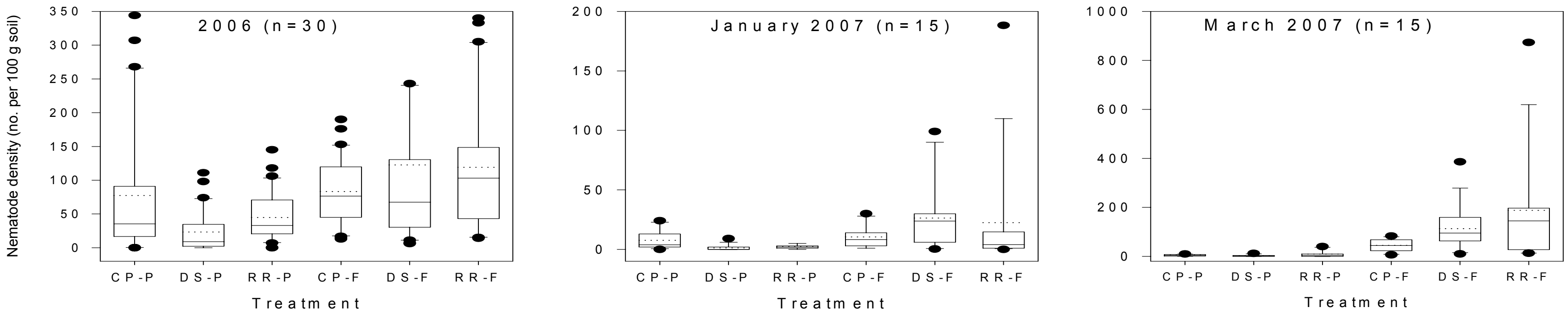


Figure 3.1: Distribution of plant-parasitic (P) and free-living (F) nematode genera at the Henderson (4 treatments) and Chinyanga (3 treatments) farms, Zimbabwe, in 2006 and 2007 cropping seasons. CP = conventional ploughing; DS = direct seeding; BA = basins; and MR or RR = ripping treatments. The data was summarized in box plots where: the box represent the 25th and 75th percentiles, the whiskers the 10th and 90th percentiles, the broken lines represents the mean and continuous lines the median. Different letters show significant statistical difference between treatment means ($P < 0.05$). In 2007 cropping season the two sampling times, (a) January (6 weeks after crop emergence) and (b) March (12 weeks after crop emergence) were representing early and late sampling.

a) Kajengo



b) Makwara

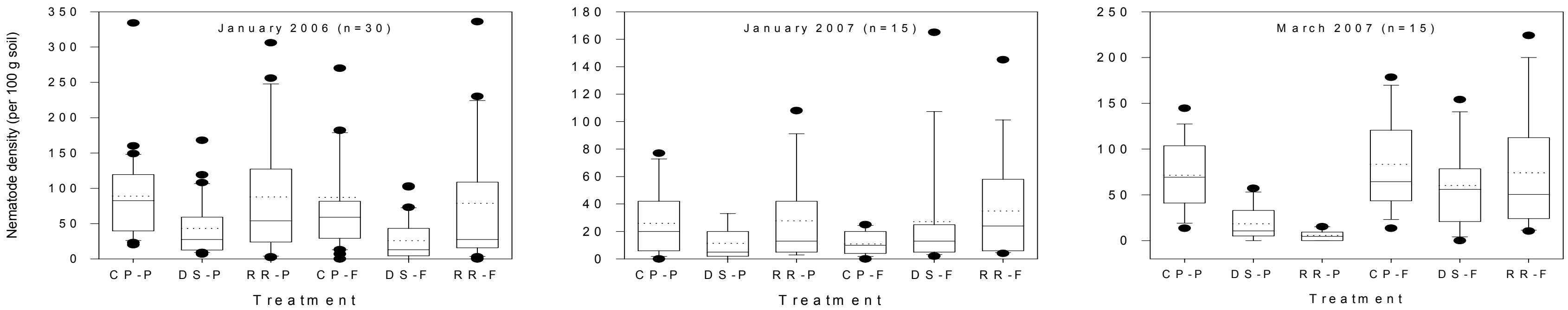


Figure 3.2: Distribution of plant parasitic (P) and non-parasitic nematode (F) genera on conventional ploughing (CP), direct seeder (DS) and ripper (RR)treatments in the 2006 and 2007 season at Kajengo and Makwara, Zimbabwe, in 2006 and 2007 cropping seasons. The data was represented in box plots where: the box and the bars represent 75 % and 90 % quartiles, respectively; the broken mean and continuous lines median, respectively. Different letters show significant statistical difference between treatment means (P < 0.05). In 2007 cropping season the two sampling times, (a) January and (b) March representing early and late sampling.

3.3.2 Nematode genera diversity

Higher diversity and evenness was calculated for the two sampling times in 2007 (6 weeks and 12 weeks into the cropping season) compared to 2006 (Table 3.2). There was a general increase in evenness in the order conventional ploughing < ripper < direct seeder < basins during the two cropping seasons. The conventional ploughing treatment showed the least evenness. At Chinyanga, there was an increase in evenness from conventional ploughing to ripper and direct seeder in 2007. However, the trend was opposite in 2006, when conventional ploughing had the highest and direct seeder the lowest evenness. At Kajengo, evenness decreased in the order conventional ploughing, ripper, direct seeder treatment in both 2006 and 2007 seasons. Higher genera evenness was measured in 2006 compared to 2007. At Makwara, genera evenness increased in the order conventional ploughing < ripping < direct seeding. However, in 2007 there was a general decline in evenness of nematode genera from conventional ploughing > ripping > direct seeding. Evenness figures calculated for 2006 were lower than for 2007. Continuous maize under semi-arid conditions led to lower nematode genera evenness in conservation agriculture treatments, whereas under sub-humid conditions evenness increased. Rotations of maize and soybean led to changes in evenness on both sandy and clay soil under sub-humid conditions.

Table 3.2: Calculated Shannon evenness indices (J) for nematode genera measured at Henderson (4 treatments), Chinyanga, Kajengo and Makwara (all 3 treatments) during the 2006 and 2007 cropping seasons

Site	Year	Conventional ploughing	Ripping	Direct seeding	Basins
Henderson	2006	1.28	1.64	1.42	1.71
	January	(3.48)	(4.32)	(3.74)	(4.52)
	2007	2.38	2.48	2.42	2.32
	January	(6.27)	(6.89)	(6.55)	(6.58)
	2007	2.35	2.21	2.41	2.76
	March	(6.91)	(6.52)	(7.22)	(8.14)
Chinyanga	2006	2.45	2.21	1.98	-
	January	(7.77)	(7.10)	(5.83)	
	2007	1.92	2.13	2.16	-
	January	(5.06)	(5.77)	(5.70)	
	2007	1.87	1.99	2.09	-
	March	(4.49)	(5.12)	(5.18)	
Kajengo	2006	2.20	2.31	1.82	-
	January	(6.54)	(7.03)	(5.35)	
	2007	1.78	1.01	1.02	-
	January	(4.68)	(3.22)	(2.35)	
	2007	1.25	1.17	0.92	-
	March	(2.43)	(2.70)	(2.11)	
Makwara	2006	1.94	2.00	2.10	-
	January	(5.48)	(5.68)	(5.68)	
	2007	2.18	2.07	1.90	-
	January	(5.42)	(5.15)	(4.72)	
	2007	2.24	1.96	2.07	-
	March	(5.74)	(4.87)	(5.14)	

Shannon diversity index (H') in parenthesis

3.4 Discussion

3.4.1 Nematode genera in relation to treatments

Consistently across the three sampling times, the observed similarity in densities of the phytoparasitic and free living nematode genera across all the treatments at Chinyanga, Henderson, Kajengo and Makwara suggest that the two groups were not affected by the treatments. However, this trend could also be a result of the short time that the treatments were applied on the study sites, thus suggesting, that in the short term parasitic genera do not increase relative to the free living groups on sandy and clayey soils. This result supports the hypothesis that conservation agriculture practices do not lead to higher risk of nematode infestation of plants. The results however do not show a reduction, in the short term, in the nematode genera parasitic to maize crops.

While the high number of parasitic genera could mean high risk of plant infestation, it also indicates the favourable soil conditions that existed for nematode proliferation at Henderson. Similar to the other sites, the parasitic genera identified at Henderson also have multiple sources of food beside plant roots. Besides their involvement in decomposition processes, microbial feeders (bacteriovores and fungivores), predacious, omnivores and entomopathogenic are important groups in maintenance soil health. This means that in soils where more food resources are available for the different tropic groups, a higher number of commonly perceived phytoparasitic may not result in higher crop damage. Thus, a certain risk of nematode attack can be deduced from the number of genera present in the soil and the potential food resources at a particular site.

Porazinska et al. (1999) reported the increase of nematode genera diversity under mulch. The lack of differences in this study between plant-parasitic and free-living nematode genera observed in different tillage and mulch treatments means that the treatments had no significant effect on the nematode dynamics over the three seasons. This result did not support our hypothesis that increased soil disturbance would modify the soil environment leading to lower nematode genera density and diversity.

Rotating cereals and legumes is one of the cultural methods of reducing nematode risk. At Chinyanga and Kajengo, the maize soybean rotation used in 2006 and 2007 did not effect any changes in the parasitic to non-parasitic ratios in the two years. This suggests that other factors were more important. This result is contrary to research results from sandy loam soils of Zimbabwe with legume and cereal rotation that have shown a decrease in *Pratylenchus* under sunnhemp and sunflower, and *Criconemella* under maize and sunhemp (PPRI 1987-88). The investigations of weed species that host *Pratylenchus*, *Meloidogyne*, *Rotylenchus* and *Paralongidorus* were not conclusive (PPRI 1984-85), and these could give a clue to the host-driven densities of nematode genera at these sites.

3.4.2 Diversity and evenness in nematode genera

The higher nematode genera evenness measured at Henderson under the conservation agriculture treatment compared to the conventional ploughing treatment shows the superiority of the former compared to the latter. In the light of phytoparasitic infection risk, higher evenness suggests that the risk of having nematodes problems is lower under CA treatments than under CP. The high evenness shows the tendency of the soil system to support a community that was not dominated by a few parasitic nematodes. In addition, the higher diversity at Henderson compared to the others is an indication of a more favorable environment where more genera could thrive. Proliferation of an evenly distributed nematode community points to a healthy soil environment at this site. This suggests that conservation agriculture treatment on sandy soils in the sub-humid zone leads to a soil environment where nematode can thrive.

At Chinyanga, rotating soybean (2007) after maize (2006) had an effect on the diversity and evenness of nematode genera. Maize crops supported genera with lower evenness under ripper and direct seeder, while soybean increased the evenness under the same treatments. This means that even if the data on the ratio of parasitic and non-parasitic nematode genera suggest no changes over the two years, rotations actually caused a shift in evenness and diversity of nematode genera. This is confirmed by the observed lower evenness and diversity calculated for maize at Kajengo in 2007 compared to soybean in 2006. Continuous maize planted at Makwara also resulted in lower evenness in the ripper and direct seeder treatments. Therefore, rotation is important and affect nematode genera diversity and evenness depending on the crop. This result is similar to reports by Mcsorley and Gallaher (1993), who found little effect of tillage on nematodes and that rotation was more important.

3.5 Conclusions

The higher fauna density and diversity at Henderson was accompanied by higher evenness under conservation agriculture compared conventional treatments. Whilst there is a risk of nematode attack on crops following short-term application of conservation agriculture, the lower densities of nematodes genera at all sites suggests it is low. In the short term, conservation agriculture treatments had no influence on the ratio of plant-parasitic to free-living nematode genera in the soil. Planting soybean after maize, on both sandy and clayey soil in the sub-humid zone, increased evenness of nematode genera.

4 EFFECT OF RESIDUE AND TILLAGE TREATMENTS ON TERMITE ACTIVITIES

4.1 Introduction

Conservation agriculture techniques have become important and appealing to farmers and agronomists mainly because of their potential support for natural soil processes that ensure sustained crop production. Applying surface mulch, direct seeding (without ploughing) and use of cereal-legume sequences are key attributes of conservation agriculture (IIRR and ACT 2005; FAO 2001). Crop residues are a food resource to soil animals and hence their application influences fauna activities. Soil fauna drives the majority of processes that enhance the quality and health of soil in crop production systems (Benckiser 1997; Doran 1997). Termites have been widely reported among studies on soil organisms because of their prevalence under diverse environmental conditions (Bignell 2000; Uys 2002). The conspicuous epigeous mounds found in cultivated and forest soils are a result of the earth-moving activities of termites (Watson 1974; Eggleton 2002; Konate 1999). However, their contributions to conservation agriculture systems in Zimbabwe have not yet been defined.

Prevalence and diversity of termites have been linked to several local and catchment level factors. The generally soft-cuticled termites cannot survive desiccation and nest-building is one activity aimed at adapting conditions to their auto-ecological requirements. Temperature, humidity and soil moisture requirements play an important role in the determination of survival rates of termites (Weibull 2003; Jouquet et al. 2006). As noted by Eggleton et al. (2002b) and Uys (2002), the savannahs of southern Africa host a diverse range of termite species because of the favorable environmental conditions. In Zimbabwe, Nyamapfene (1985) characterized termite mounds and highlighted the high soil organic matter and bases in the mound material as the major benefit of applying mound soil to crop fields which in fact is an old practice in some parts of Africa (Burnett 1948). The extent to which termites can be manipulated on cropping lands with crop residue mulch and direct seeding treatments need to be assessed.

In agro-ecosystems, termites are defined as ecosystem engineers and are responsible for modifying both biotic and abiotic soil components (Jones et al. 1994;

Ndiaye et al. 2004). Termite activities affect the physical status and soil formation processes making them important potential candidates for bio-tillage on crop fields. The tunnels they build in the soil facilitate both water and air exchange (Lal 2000). Through these activities they influence the structure of collaborative biota.

Termites feed on cellulosic plant material, and some species also have the capacity to digest lignin (Martius 1994; Uys 2002). The mechanism of digestion is either aided by symbiotic intestinal protozoa or by fungal colonies cultivated by *Termitidae* species (Collins 1989). There are reports that termites attack crops at different period during the growth cycle. However, these statements have not been substantiated by empirical data from cropping systems.

The effects of conservation agriculture and mulching on termites and the implications of termite activities on mulched cropping fields under conservation agriculture treatments compared to conventional ploughing were studied in this experiment. The specific aim was to determine whether termites are important pests to maize, and how animal traction conventional plough, direct seeder, ripper and hand-hoe-made basins affect the extent of gallery building activities.

4.2 Materials and methods

4.2.1 Study sites

The study was conducted on six sites in two different areas: Three sites (Henderson Research Station, Chinyanga and Kajengo) were in agro-ecological zone II and three sites (Chimbwa, Makwara and Zhinya) in zone IV (Chapter 1). Under the Zimbabwean classification system, agricultural potential is influenced by rainfall and soil type (Chapter 1). The two agro-ecological zones II and IV are representative of 15 % and 38 % of the total land area in Zimbabwe, respectively (Anderson et al., 1993; Nyamapfene 1991). The Henderson, Chimbwa and Zhinya sites, all sandy soils (Table 4.1), share hydromorphic soil properties due to the influence of the laterite layer at the former and lower catenal potions in a vlei margin at the latter two. On the six sites conservation agriculture had been applied since 2004. The termite activities were studied in 2006 and 2007.

Table 4.1: The site characteristics of soils (0-30 cm soil depth) from the study sites in Zimbabwe

Site	Clay (%)	Silt (%)	Fine Sand (%)	Medium Sand (%)	Course Sand (%)	Organic Carbon (%)	pH ($CaCl_2$)
Chimbwa	5	4	30	33	28	1.32	5.7
Chinyanga	39	14	27	14	7	2.00	6.3
Henderson	5	7	nd	nd	88	0.91	5.2
Kajengo	14	9	43	22	13	1.42	5.7
Makwara	6	2	28	27	39	1.02	5.3
Zhinya	4	3	37	27	29	1.60	5.9

nd = not determined

4.2.2 Treatments

Measurements were conducted on plots under conventional ploughing, direct seeding and ripping treatments. In addition, a hand-hoe-made basin treatment was monitored at Henderson. The ripper treatment at Henderson included an intercrop of maize and mucuna (Chapter 2).

4.2.3 Termite galleries

Termites build cover runways or tunnels on the soil surface on their trails that lead to the food sources. They also build similar structures on materials that they feed on, e.g., around dry maize stalks or tree branches lying on the ground. These structures, referred to here as galleries, have the function of protecting the termite individuals from desiccation during foraging activities. Termite gallery coverage was measured as an indicator of termite activities. The samples were collected during spring in 2006 before the onset of the rainy season. A quadrat of wooden frames measuring 1 m^2 was randomly placed on each plot (replicated 10 times) and the area covered by termite galleries was determined. The number of 10 cm x 10 cm polygons covered by galleries within each quadrat was counted and added together for each quadrat. These were used to calculate the average termite-gallery coverage. Gallery materials making the galleries was also collected and analyzed in the laboratory for exchangeable bases, texture, organic carbon and pH.

4.2.4 Assessing crop damage by termites

The assessment of the damage caused by termites on maize was conducted after maize maturity for two consecutive years (2006 and 2007). The extent of crop damage was measured by counting the number of maize cobs that lodged due to termite attack. Counts were made from 5 maize rows (length 20 m each) in every treatment. Damage was calculated as a percentage of the expected crop stand of 44 000 plants and 22 000 plants for the agro-ecological zones II and IV, respectively.

4.2.5 Mycorrhiza fungal spores in gallery material and the surrounding soils

The abundance of mycorrhizae was measured based on the number of fungal spores in the substrate. A total of 19 composite samples of gallery material, made from 10 sub-samples collected from each treatment, were processed. Similarly, samples of soil adjacent to the galleries in each treatment were collected. From each sample, two portions of the sample were weighed, the first one for moisture content determination and the second one for separation of spores. Spores were recovered using the modified Gerdemann and Nicholson (1963) method. To a 100 g soil sample, 500 ml of water were added and agitated in a blender for 5 minutes to remove trapped spores. The mixture was left to stand for 30 seconds to allow heavy particles to settle. The suspension was poured through a 500 µm sieve collecting spores on a chest of 250, 125 and 53 µm sieves. Addition of water and blending was repeated 3 times (until the suspension was clear). A stream of water was used to wash the colloidal particles through the respective sieves. From each sieve, the spore solution was transferred into 100 ml containers using a wash bottle making about 15-20 ml of spore solution. An equal amount of 70 % (w/v) sucrose solution was added. The solution was mixed thoroughly and centrifuged for 3 minutes at 1700 rpm (or left over-night). The supernatant was then vacuum-filtered using a Buchner funnel leaving spores on the white filter paper. Spores were counted and described for color, shape, ornamentation and light reflectance.

4.2.6 Statistical analysis

General Linear Model (GLM) techniques were used to perform analysis of variance and Tukey (0.05) was used to separate treatment means. Orthogonal contrasts were also perfomed using SAS.

4.3 Results

4.3.1 Termite galleries

Cconservation agriculture treatments led to higher gallery coverage than conventional ploughing at Henderson (on-station) except for the ripper (MR) (Figure 4.1). The area covered by termite galleries in the ripped treatment, which had a maize-mucuna intercrop was small (2 %) and similar to the CP treatment. Higher termite activities were observed on both the direct seeded (DS) (galleries covering 19 %) and the basins (BA) (covering 18 %).

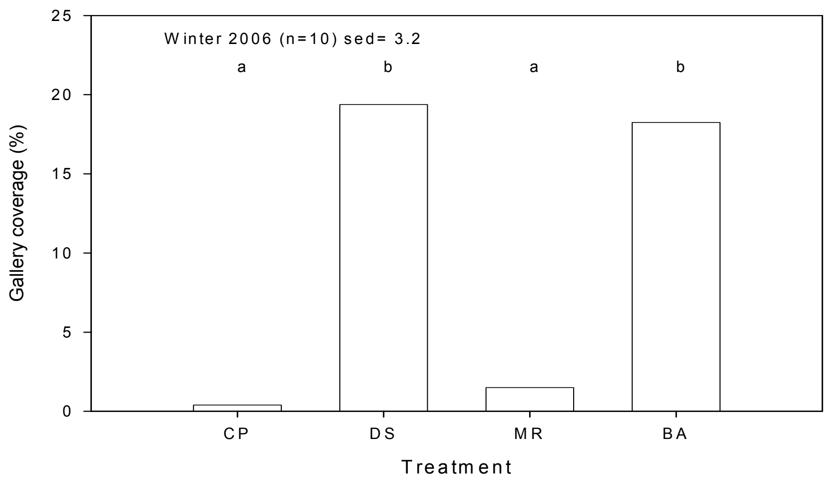


Figure 4.1: Percentage area covered by termite galleries per 1 m^2 during the winter season at Henderson from conventional ploughing (CP), direct seeding (DS), Magoye ripper (MR) and basins (BA) treatments. Different letters show significant differences ($P < 0.05$).

Whilst there were no galleries at Makwara, (see also Chapter 2; Makwara showed very low termite densities), gallery formation at Chinyanga and Kajengo was not different across treatments. However, the sites on the sandy soil in the semi-arid zone, Chimbwa and Zhinya, showed significantly higher gallery coverage on the ripper (10 %) and direct seeder (22 %) treatments (Table 4.2). Though located in contrasting rainfall zones, the highest percentage gallery coverage from the direct seeder treatment at Chimbwa was comparable to that measured at Henderson in the basins and direct seeder treatments.

Table 4.2: Mean percentage of 1 m^2 quadrant, covered by termite galleries on plots under conventional ploughing, direct seeding and ripping at Kajengo,

Chinyanga, Chimbwa and Zhinya site in Shamva and Zimuto during the winter period (n = 10 for each treatment).

	Chinyanga	Kajengo	Makwara	Chimbwa	Zhinya
Conventional ploughing	1.1	9.1	0	1.2b	0.8b
Direct seeding	5.2	2.5	0	1.7b	21.5a
Ripping	2.5	5.4	0	10.2a	1.2b
P < 0.05	ns	ns	-	*	*

*ns = no significant treatment differences, * Significant treatment difference at P<0.05, no galleries were found at Makwara*

4.3.2 Characteristics of gallery material

The results of the textural and chemical analyses of the gallery soils showed higher clay, silt and organic matter content in the gallery soil compared to the adjacent top-soil at each site (Table 4.1). However, galleries on the clayey soil at Chinyanga had lower clay, organic matter and silt contents. This is in contrast to the values for the sandy soil at Henderson, Kajengo, Makwara, Chimbwa and Zhinya. Higher CEC, calcium content and soil pH were determined for the gallery soil at all sites except Chinyanga. On sandy soil, the galleries at Henderson and Zhinya had the highest clay content and soil organic carbon percentage. This could be because termites bring-up fine soil particles to the surface to strengthen the gallery structure on the sandy soil, whereas on clay soil this might not be necessary.

4.3.3 Mycorrhiza spore density

Higher mycorrhiza spore densities were measured in the soil than in the gallery material at all sites. In both soils and gallery material, the smaller spores in the range 53 – 125 µm in diameter, were more abundant than those sized 126-250 µm and larger than 250 µm (Table 4.4). The *Chromic Lusvisol* at Chinyanga had the highest spore density for both soil and gallery material, while *Ferrali-Gleyic Arenosols* at Zhinya and Chimbwa had the lowest spore densities. At all sites, in both soil and gallery material, the skewed spore distribution towards the smallest pore diameter of 53-125 µm, could be linked to the physical protection of small-diameter spores by clay and organic mater particles. This implies that higher spore density and retention occurs in soil with improved potential productivity based on soil clay and organic matter content. The spore densities ratio of gallery material to the soil at Chimbwa and Zhinya (semi-arid zone) was higher than at sites in the sub-humid zone, suggesting that inoculation potential was higher in the drier zone.

4.3.4 Termite attack on maize

Across all sites and treatments, there were no significant termite attack on maize as measured by the number of lodged plants (Tables 4.5 and 4.6). Maize in basin and direct seeder treatments were more frequently attacked by termites than conventionally ploughed and ripped treatments. Termite attack on maize at Henderson was higher in 2007 compared to 2006 (Table 4.5). Comparing all the sites over the two years, maize at Kajengo showed the highest termite attack. This appears to related to the relatively higher termite densities observed at this site during the cropping season (Chapter 2). The results show that in the short term, residue retention on the soil surface and hence conservation agriculture does not lead to a significant increase in maize lodging as a result of termite attack.

However, this is critical for introducing conservation agriculture (farmer perceptions regarding termites as pest, cf. chapter 7), suggesting that a reassessment at a later moment may be a good measure before recommendations are given to farmers.

Table 4.3: Characteristics termite galleries materials on mulched plots at Henderson Research Station, Chinyanga, Kajengo, Chimbwa and Zhinya, Zimbabwe

Site	Clay (%)	Silt (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand (%)	pH ($CaCl_2$)	Ex Ca (cmol+ kg^{-1})	Ex Mg (cmol+ kg^{-1})	Ex K (cmol+ kg^{-1})	CEC (cmol+ kg^{-1})	Org. Carb (%)
Henderson	19.6	18.1	31.8	18.8	12.1	5.9	4.9	2.0	0.9	10.9	1.6
Chinyanga	3.0	5.0	33.0	30.0	30.0	4.7	0.3	0.1	0.1	1.6	0.9
Kajengo	11.3	11.6	32.4	24.4	21.1	5.3	2.6	1.1	0.5	6.2	1.2
Chimbwa	10.1	7.2	27.3	29.4	25.0	5.6	4.6	3.2	0.9	7.6	1.32
Zhinya	29.0	23.0	28.0	12.0	8.0	5.7	5.5	3.9	1.3	15.7	2.1

At Makwara, no termite activities hence no galleries

Table 4.4: Mean mycorrhiza spore densities (extracted from 100 g soil) in termite galleries materials and adjacent soil from Henderson Research Station, Chinyanga, Kajengo, Chimbwa and Zhinya, Zimbabwe

Spore size	Henderson		Chinyanga		Kajengo		Chimbwa		Zhinya	
	Gallery	Soil	Gallery	Soil	Gallery	Soil	Gallery	Soil	Gallery	Soil
53-125 µm	2640	9839	12800	10239	1200	9609	2404	2900	3696	3215
126-250 µm	360	1362	960	789	56	751	136	489	264	362
> 250 µm	56	188	40	74	24	68	30	17	24	19
Total	3056	11389	13800	11102	1280	10328	2570	3406	3984	3596
SED	102	220	163	306	88	167	97	121	113	148

Table 4.5: Termite attack on maize after maturity as a percentage of expected crop stands (44 000 plants per hectare at Henderson, Chinyanga and Kajengo; 22 000 plants per hectare at Chimbwa, Makwara and Zhinya), 2006, in Zimbabwe

Treatment	Henderson (%)	Chinyanga (%)	Chimbwa (%)	Makwara (%)	Zhinya (%)
Conventional ploughing	0.5	4.1	2.0	0.8	1.2
	(0.6)	(1.6)	(1.7)	(0.4)	(1.7)
Direct seeder	0.17	3.0	1.0	0.4	0.8
	(1.5)	(2.0)	(1.3)	(0.7)	(1.3)
Ripper	0.15	2.7	1.3	0.6	1.1
	(2.0)	(1.9)	(1.4)	(0.4)	(1.4)
Basins	0.23	-	-	-	-
	(0.3)				

Standard deviations of the mean in parenthesis; Kajengo site was under soybean in 2006

Table 4.6: Termite attack on maize after maturity as a percentage of expected crop stands (44 000 plants per hectare for Henderson, Chinyanga and Kajengo; 22 000 plants per hectare at Chimbwa, Makwara and Zhinya), 2007, Zimbabwe

Treatment	Henderson (%)	Chimbwa (%)	Kajengo (%)	Makwara (%)	Zhinya (%)
Conventional plough	1.5	1.3	8.0	4.0	1.3
	(1.3)	(1.6)	(6.4)	(4.0)	(1.8)
Direct seeder	3.6	0.8	6.0	0.8	2.0
	(1.5)	(0.3)	(1.8)	(0.4)	(1.6)
Ripper	2.8	1.5	4.0	0.6	1.4
	(1.9)	(1.0)	(2.2)	(0.6)	(2.0)
Basins	4.2	-	-	-	-
	(4.4)				

Standard deviations of the mean in parenthesis; Chinyanga was under soybean in 2007

4.4 Discussion

4.4.1 Termite galleries

The higher gallery coverage measured in conservation agriculture treatments showed higher termite foraging than in conventional ploughing (Figure 4.1). Mulch attracted termites and hence more galleries were built on treatments with minimal soil disturbance. Mando et al. (1997) reported increased termite activity leading to improved water infiltration rates and storage following increased termite abundance on mulched plots. In the same study, termites were regarded as useful biological agents controlling and correcting soil crusting problems in the Sahel region.

The constituents of gallery material make it a suitable soil ameliorant. The high clay, silt, organic matter and bases have the potential of increasing fertility of sandy soil. This result corroborate work by Watson (1974 and 1976) and Nyamapfene (1985) who explained the importance of termitaria as a fertility input for resource constrained smallholder farmers. Amelung et al. (2002) and Konate et al. (1999) also found termites nest significantly enriched in soil organic matter compared to surrounding soils. However, our results show that the light textured sandy soils had galleries better enriched with clay, silt and organic matter than the heavier texture clayey soils.

Though built to meet termite auto-ecological needs (Jouquet et al. 2005), galleries are an important input on sandy soils. This observation is in line with the propositions on the extended phenotype engineers' preferences of modifying the habitat to suit their. The difference in the constituents of biogenic structures resulting from termite activities is important information, which supports endeavours to manipulate soil animals for the benefit of soil productivity. Termite activities were, therefore, more beneficial on sandy soil both in the semi-arid and sub-humid rainfall zones.

4.4.2 Mycorrhiza fungal spores

The higher mycorrhizal fungal spore counts at Chinyanga suggest a relationship between soil type and spore density. The clayey soil, which has higher inherent potential production, could be suitable increased media for fungal spore growth. Though the densities of mycorrhiza spores in the gallery material were consistently lower than in the surrounding soil, their presence indicates that termites inoculate the foraging sites with mycorrhizae. On the semi-arid sites in Chimbwa and Zhinya, spore density in gallery materials was comparable to that in the soil. This suggests that potential inoculation is higher on semi-arid sites. Given the importance of mycorrhiza in the cropping system, this observation supports the modification of collaborative fauna communities by termites. Soil fauna has a high potential role in mycorrhizae inoculation as demonstrated by termites in this study. Similarly, Lee (1995) reported vesicular-abuscular mycorrhizae spores and propagules contained in earthworm casts on deep tillage treatments. The combination of high spore density, high clay and organic carbon content in gallery material relative to the soil makes gallery building an important avenue of sandy soil reclamation. On sites in semi-arid zones and also sandy soil in general, this means that the importance of mycorrhiza as a morphological adaptation of crops to nutrient and water limitation could be enhanced through termite activities.

4.4.3 Termites as maize pest

Maize attacks by termites after harvest in the 2006 cropping season there was low. Both on-station and on-farm results show a similarly low percentages of maize stalks attacked by termites. Reports on termite attack on maize are based on conventional ploughing practices, where crop residues are removed during land preparation. The results of this study show little damage through termite attack both in the conventional (with no residue incorporation) and conservation agriculture treatments. This is in agreement with observations by Uys (2002), which suggests where dry residues (food) are available low termite attack on the live plant will occur; suggesting that maize can be attacked after maturity especially when dry. Lavell and Spain (2001) explained termite preference of dry residues to living and fresh plant materials. However some genera under food limited conditions attack fresh plants. The observed insignificant termite attack on maize in this study is in line with work reported by Sileshi et al. (2005). In their study on the effect of incorporating leguminous litter on infertile soils, increase termite attack on maize was reported on conventionally ploughed plots compared to improved fallows. Further they also reported less than 5 % lodging as a result of attack on improved fallow treatments.

Attack of crops is in line with awareness of the farmers regarding the role of termites under conventional ploughing systems. It is important to note, however, that the reported farmers' experiences followed residue incorporation at land preparation.

This could suggest that different termite feeding habits are involved when residues are incorporated and when applied as surface mulch. Incorporation could encourage the build-up of soil feeding termites, whereas the litter foragers can act on the mulches. This would suggest that data on termite attack in systems where organic materials are ploughed under and data from no-till systems need to be analyzed separately, as cross comparison could lead to unclear conclusions. With little evidence of maize attack following two years of conservation agriculture compared with conventional ploughing, indications are that in the short term the mulch provides alternative energy sources for termites and are fed on by these before they attack the maize plants. Uys (2002) supports this by suggesting that attack on live plants mostly occurs under limited alternative food conditions for fungus-growing termites, which is the case when residues are removed and/or incorporated. The incidence and severity of termite attack is driven by factors like existing termite population, availability of residues for food and host susceptibility (Kirton 1999). There are also reports that termites attack diseased, water or nutrient stressed crops. Further data is needed to deduce the extent of attack and the associated economic damage.

4.4.4 Ecological significance of termite galleries

Termite galleries can be viewed as important re-fertilization avenues in the soil. Thus termites act as collaborators in the use of mulches as soil fertility amendments. Besides the physical ecological role, the termites potentially inoculate the soil with *Termitomyces* fungi. This activity supports the increasingly important distribution of beneficial microbiota species throughout the soil horizons. As suggested by Jouquet et al. (2005) the function of inoculating the soil with diverse microbes is of importance to the soil health. Results from (Aanen 2002) showed how symmetrical symbiosis between *Macrotermitinae* termites and *Termitomyces* fungi enabled termites to occupy and utilize differential food niches. In the *Miombo* ecoregion, *Odontotermes transvaalensis* and *Termitomyces* species are important symbionts (WWF 2002). Gallery building also involves the organo-mineral complex formation that stabilizes the soil and the surface mulches, hence protecting the soil from erosion agents.

Supporting the process of nutrient recycling through gallery construction was a beneficial termite activity on the farms. Fungus-cultivating termite genera often transport organic materials to the base of their nests, and the by-products of the feeding through fungus combs are brought up for gallery construction (Abe et al. 2000). Jones (1990) also reported the role of fungus-growing termites in regional soil forming processes. Brossard et al. (2006) reported higher clay and organic matter contents from nest than in the surrounding area, noting that the total weight and hence the short-term contribution of the structures was low. Thus, the overall contribution is important when viewed over time. Termites contribute to pedogenesis through galleries construction, which is important for the regeneration of fertility on degraded sandy soils.

4.5 Conclusions

From the results, the following conclusions can be drawn:

- Termite attack on maize was too low to lead to economic losses.
- Gallery construction by termites was influenced by conservation agriculture treatment and soil type.
- Presence of mycorrhizal fungal spores in galleries means termites inoculated the soil surface with spores.
- Galleries contribute clay, silt and organic matter to sandy soils.
- Termites are important in the bio-recycling of fine mineral matter and organic matter.

5 MULCH RESIDUE DECOMPOSITION DURING DRY WINTER AND WET SUMMER SEASONS

5.1 Introduction

Organic-based farming systems have the potential for improving the stability of crop production on degraded soils in Sub-Saharan Africa. Currently, the widely used conventional farming practices do not return residues to the soil surface, since most of these are burnt, fed to animals or used for construction purposes. Soil cover maintenance throughout a cropping cycle is one of the important attributes of Conservation Agriculture (CA), and so are direct seeding and rotations. Mulching is particularly important on weakly structured soils on smallholder farms, where rainfall events are characterized by high-intensity short duration storms (Anderson et al. 1993). Erosion and degradation have greatly reduced the potential soil productivity.

The rather ancient practice of using live and or dead plant materials to cover the soil helps to protect the soil from degradation. So-called mulch, consisting of plant residues can be defined as materials specifically introduced to the soil-air interface to manage soil and water and thus create a favourable environment for plant growth (Lal, 2002). Mulching is an ecological approach to reduce degradation and to increase environmental quality and nutrient cycling (Acharya 2005). Under the unimodal rainfall pattern experienced in southern Africa, soil cover is important at the onset of the rains and during the crop growing summer and the dry winter seasons.

In areas of southern Africa where CA has been introduced, maize stover and grass cut from velds are candidates for use as soil cover in maize-based crop production systems. Live soil covers include a range of green manures such as *Mucuna* and *Crotalaria* species, which are adapted to the tropical conditions (Prasifka et al. 2006). Maize residues have multiple uses on the farm (Chapter 7), and their appropriate management is warranted under conservation agriculture. World estimates of crop residue production show that maize residues come third after wheat and rice (Lal 2002). Often, biomass for use as soil cover is reduced by lower production potentials in smallholder farms and competing alternative uses. Nevertheless, residue management directly influences decomposition rates and in-directly soil fauna activities and land productivity (Coleman et al. 2004)

By definition, conservation agriculture plots must have a sufficient soil cover at any one given time (FAO 1979; IIRR and ACT 2005). Over time, effectiveness of mulches applied by farmers is dependent on the amount initially applied and how fast this is reduced by biological agents (consumed by soil animals), and lost through physical forces of erosion (wind and water). The decomposition of mulch is related to soil fauna and microbial activities, which are governed by extrinsic and intrinsic factors (Heal et al. 1997). Ritter (2005) observed higher rates of decomposition when soil contact with the organic materials was increased by burying materials. Work done using litterbags of different mesh sizes by Martius et al. (2004) demonstrated the role of different faunal groupings (macro-, meso- and microfauna), in the decomposition process. Residue management thus directly influences decomposition rates and indirectly soil fauna activities and land productivity (Coleman et al. 2004). Variable rates of decomposition of residues incorporated during land preparation have been reported by scientists and farmers (Chikowo 2004; Musvoto 2000). Interactions of climate, soil biota and substrate quality have been pointed to as drivers of decomposition of litter (Heal et al. 1997).

In short, knowledge of residue dynamics on cropping fields is important, as these affect other agronomic factors such as water and organisms, and could limit the size of land under conservation agriculture. In this study, therefore, rates of soil cover loss were determined. Litterbags with large mesh size (5 mm) were used to investigate the rate of decomposition resulting from macro-, meso- and microfauna activities in maize stover mulch on the soil surface. The aim of this study was to determine the relative rate of loss of surface-applied maize residues on conventionally ploughed and conservation agriculture plots during the cold dry winter and wet hot summer rainfall season.

5.2 Materials and methods

The study was conducted at Henderson Research Station, Shamva (Chinyanga and Kajengo) and Zimuto (Makwara and Zhinya) (see Chapter 1). The hot wet summer and cold dry winters characterize the Zimbabwean annual climate. A unimodal rainfall pattern, which is the major characteristic of the summer season, supports the dry-land agriculture on smallholder farms. Cropping cycle starts in October-November (summer) ending in April, covering an effective period of 5 months. The winter in June, July and early part of August comes after a short autumn season. The short spring is between September and October.

5.2.1 Litter bag experiment

Coarse polythene bags of 30 cm x 30 cm with a mesh size of 5 mm were used. For each treatment at each site, 16 bags containing 50 g of maize residues were installed at the onset of both the summer and winter experiments. A total of 512 bags was used at 5 sites and these were sampled destructively at 4-week intervals for processing in the laboratory (Anderson and Ingram 1996). At each retrieval date, 4 replicate bags were collected from each treatment at each site. Weight losses were measured after the litter has been oven-dried at 65 ^{o}C. To account for mass from the inorganic soil contamination following termite galleries, ash content of the remaining litter was determined following combustion in a muffle furnace at 550 ^{o}C for 6 hrs. The weight loss was calculated from the difference between ash corrected initial residue weight and the final litter weight from the bags (ash corrected). Decomposition rates were calculated from the figures taken over the duration of the experiment. Negative exponential regression was fitted through the data using the “two parameter single exponential decay” fitting procedure of Sigma plot software. The decay coefficient k was determined from the regression $y = a.e^{-kx}$, where x is the time of exposure in days, y is the remaining percentage weight. A, the y-axis coefficient, is the initial weight corresponding to 100 % residue weight (Kurzatkowski et al 2004).

The initial and subsequent ash content was determined at 500 ^{o}C, lignin and cellulose were measured using the ADF method as outlined by Anderson and Ingram (1993). Partial micro-Kjedahl digestion was used to determine the crude protein contents of the litter (Van Camp and Dierckx 2004).

5.3 Results

5.3.1 Chemical characteristics of maize litter

The chemical characterization of maize litter showed higher crude protein, calcium and phosphorus content in the residues from Makwara and Zhinya compared to those from Henderson, Chinyanga and Kajengo (Table 5.1).

Table 5.1: Chemical characteristics of maize litter used in the decomposition experiment at Henderson, Chinyanga, Kajengo, Makwara and Zhinya, Zimbabwe

Site	Lignin (%)	Cellulose (%)	Crude Protein (%)	C:N	Calcium (%)	Phosphorus (%)
Henderson	20.24	28.51	1.95	51	0.12	0.07
Chinyanga Kajengo	18.90	28.90	1.33	53	0.23	0.06
Makwara Zhinya	19.13	25.50	2.93	52	0.51	0.39

5.3.2 Weight losses

Winter

On conventionally ploughed treatments, winter decomposition rates were lower on sites in the sub-humid rainfall zone Henderson and Chinyanga compared to the semi-arid sties Makwara and Zhinya. During the winter period the highest residue losses were measured at Henderson under basins(8 %), at Zhinya 10 % under direct seeder, at Kajengo 12 % (conventional plough), Chinyanga 16 % (direct seeder) and Makwara 20 % (ripper). Our data suggests that, to the contrary, fauna was active and decomposing litter during the winter season.

The litter decomposition pattern in the conventionally ploughed treatments at the semi-arid sites did not fit the negative exponential model. Rather the pattern was characterized by significant litter loss in the first 28 days followed by minimal losses thereafter, producing an L-shaped graph for the decomposition pattern. A similar trend was observed on the clayey soil sites in the sub-humid rainfall zone. This could be related to a change in climatic factors that influence fauna activities and decomposition, e.g., soil moisture temperature.

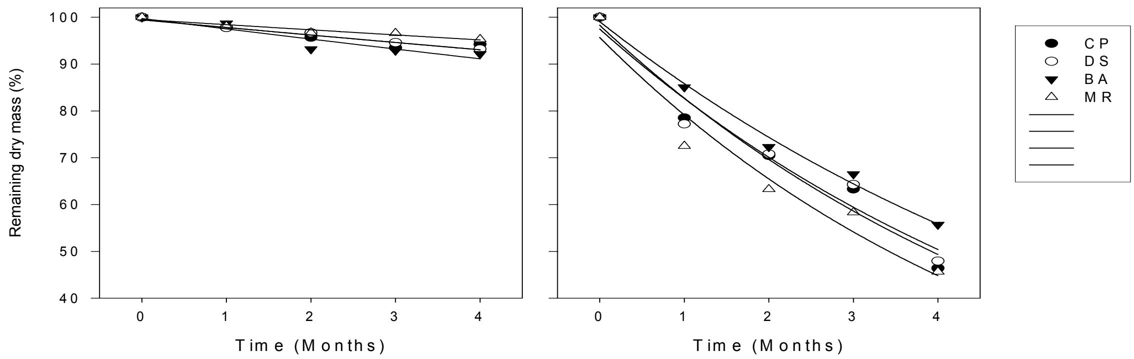
The conventional ploughing treatment had relatively lower decomposition rates compared to conservation agriculture treatments during the winter except at Zhinya. At Henderson, the rates of decomposition were similar for all treatments with the exception of the ripper treatment, where rates were lower. Similarly, this result was observed in these treatments when termite galleries were measured at the end of the winter (Chapter 4).

Summer

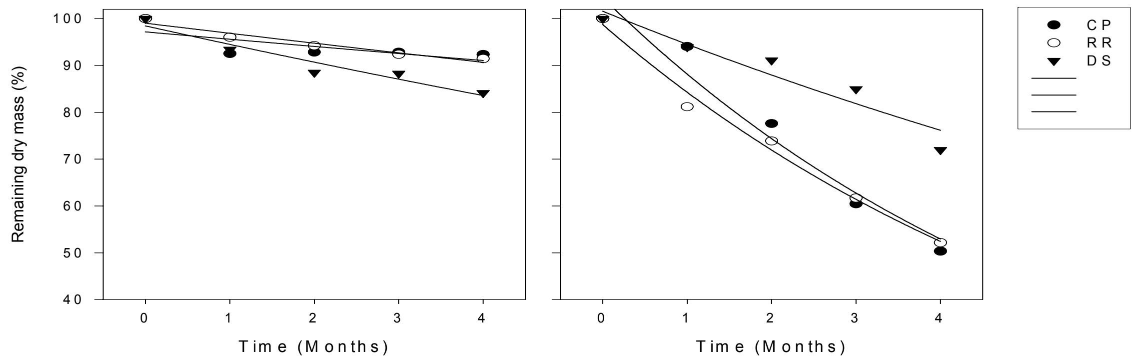
During the summer, the decomposition rate constants (*K*) in conventional ploughing treatments were 10-fold the values measured in winter at Henderson, Chinyanga and Makwara. At Kajengo and Zhinya, the decomposition rates were also higher for the summer period compared to winter, showing a similar trend. In summer, the losses ranged from 45 % under direct seeder at Zhinya, 50 % at Kajengo under direct seeder, 50 % at Chinyanga under conventional plough and ripper, and up to 65 % at Makwara under the conventionally ploughed treatment.

During the summer, decomposition was higher under conservation agriculture treatments to than under conventional ploughing except at Chinyanga and Makwara. At these two sites, both direct seeder and ripper had lower decomposition rates than conventional ploughing and direct seeder.

a) Henderson



b) Chinyanga



a) Kajengo

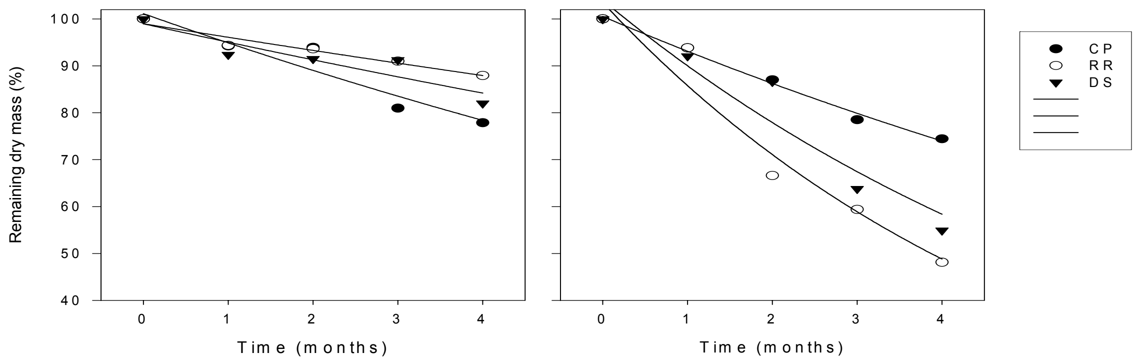
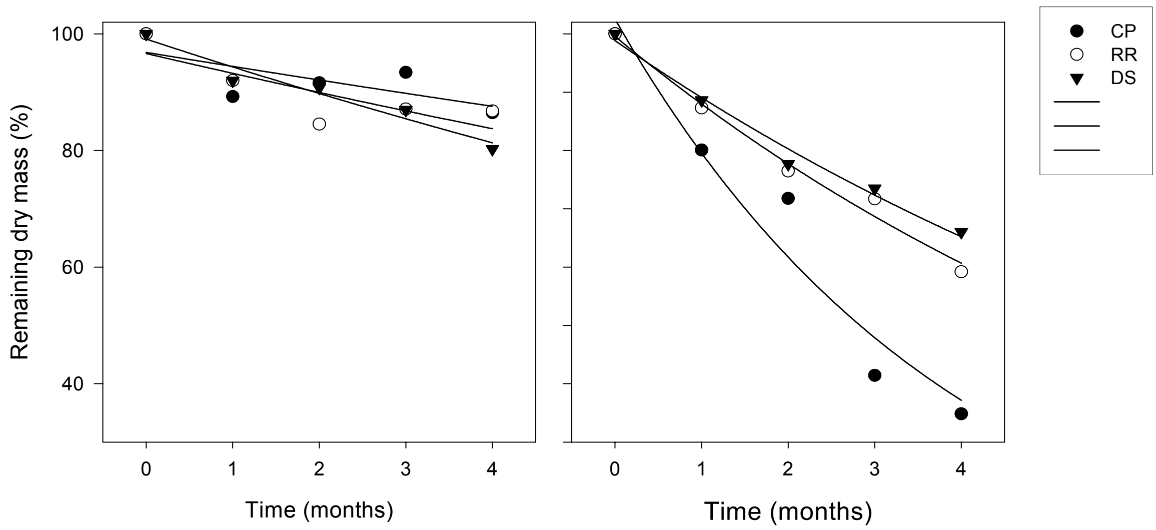


Figure 5.1: Litter losses from decomposition experiment at (a) Henderson Research station (b) Chinyanga and (c) Kajengo during winter and spring (2006) and summer (2007) on conventionally ploughed plots (CP), direct seeded (DS), ripper (RR/MR) and basin (BA) treatments

a) Makwara



b) Zhinya

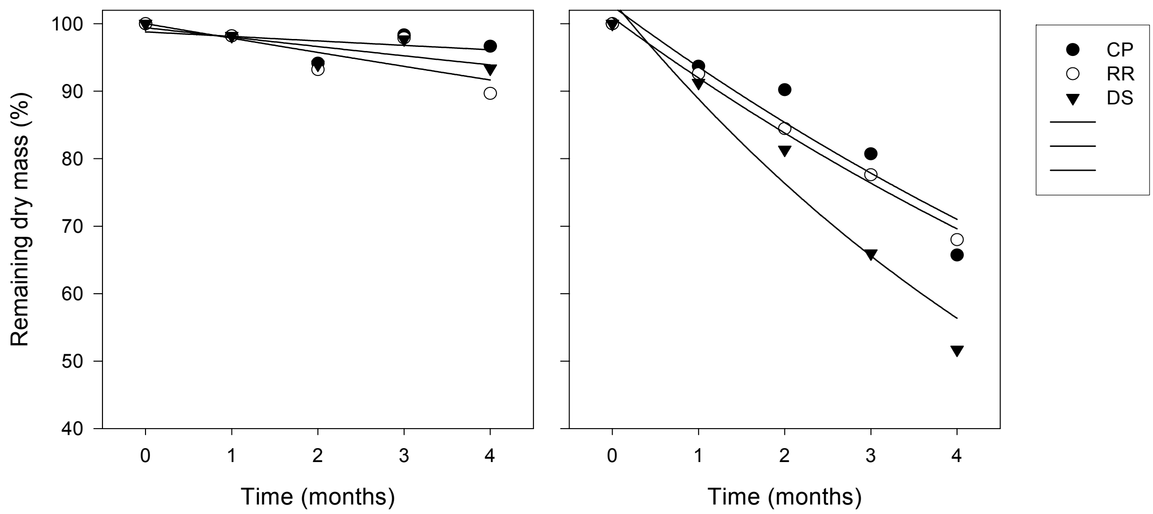


Figure 5.2: Litter losses from decomposition experiment at (a) Makwara and (b) Zhinya during winter and spring (2006) and summer (2007) on conventionally ploughed plots (CP), direct seeded (DS) and ripper (RR) treatments.

Table 5.2: Decomposition rate constants (*K*) in conventional (CP), direct seeder (DS), Magoye ripper (MR) and basins (BA) treatments at Henderson for winter and spring (2006), and summer and autumn (2007).

Treatment	*K* (month)	*K* (day)	R^2	P (0.05)	*K* (month)	*K* (day)	R^2	P (0.05)
	----------------Winter and spring-----------				-----------Summer and autumn----------			
Conventional plough (CP)	0.017	0.001	0.708	0.016	0.172	0.006	0.997	0.003
Direct seeder (DS)	0.017	0.001	0.820	0.035	0.165	0.006	0.996	0.005
Ripper (MR)	0.011	0.001	0.967	0.008	0.190	0.006	0.994	0.006
Basins (BA)	0.017	0.002	0.849	0.027	0.143	0.005	0.995	0.001

Table 5.3: Decomposition rate constant (*K*) in conventional (CP), ripper (RR) and direct seeder (DS) treatments at Chinyanga for winter and spring (2006), and summer and autumn (2007).

Treatment	*K* (month)	*K* (day)	R^2	P (0.05)	*K* (month)	*K* (day)	R^2	P (0.05)
	-------------Winter and spring----------				----------Summer and autumn----------			
Conventional plough (CP)	0.016	0.001	0.999	0.164	0.170	0.006	0.999	0.005
Direct seeder (DS)	0.041	0.002	0.999	0.008	0.072	0.003	0.998	0.012
Ripper (RR)	0.022	0.001	0.999	0.058	0.158	0.006	0.999	0.001

Table 5.4: Decomposition rate constant (*K*) in conventional (CP), ripper (RR) and direct seeder (DS) treatments at Kajengo in Shamva for winter and spring (2006), and summer and autumn (2007).

Treatment	*K* (month)	*K* (day)	R^2	P (0.05)	*K* (month)	*K* (day)	R^2	P (0.05)
	-----------Winter and spring----------				----------Summer and autumn----------			
Conventional plough (CP)	0.030	0.001	0.988	0.449	0.077	0.003	0.999	0.001
Direct seeder (DS)	0.380	0.002	0.998	0.061	0.144	0.005	0.994	0.012
Ripper (RR)	0.029	0.001	0.999	0.005	0.188	0.007	0.994	0.005

Table 5.5: Decomposition rate constant (*K*) in conventional (CP), ripper (RR) and direct seeder (DS) treatments at Makwara in Zimuto for winter and spring (2006), and summer and autumn (2007).

Treatment	*K* (month)	*K* (day)	R^2	P (0.05)	*K* (month)	*K* (day)	R^2	P (0.05)
	-----------Winter and spring--------				----------Summer and autumn------------			
Conventional plough (CP)	0.025	0.001	0.998	0.176	0.254	0.009	0.989	0.007
Direct seeder (DS)	0.049	0.002	0.999	0.005	0.104	0.004	0.999	0.001
Ripper (RR)	0.036	0.001	0.998	0.092	0.124	0.004	0.999	0.001

Table 5.6: Decomposition rate constant (*K*) in conventional (CP), ripper (RR) and direct seeder (DS) treatments at Zhinya for winter and spring (2006), and summer and autumn (2007).

Treatment	*K* (month)	*K* (day)	R^2	P (0.05)	*K* (month)	*K* (day)	R^2	P (0.05)
		Winter and spring				Summer and autumn		
Conventional plough (CP)	0.068	0.001	0.999	0.418	0.092	0.003	0.997	0.013
Direct seeder (DS)	0.014	0.001	0.999	0.134	0.152	0.005	0.997	0.004
Ripper (RR)	0.022	0.001	0.999	0.012	0.093	0.003	0.999	0.001

5.4 Discussion

5.4.1 Litter losses

Higher decomposition rates were measured in the summer/autumn than in the winter/spring seasons. Temperature and moisture are the two main factors that could explain the differences (Chapter 1). Rainfall hence lower soil moisture led to reduced litter decomposition. Previous studies have shown the link between habitat moisture and fauna activities and hence decomposition. Higher soil temperature caused increased litter decomposition in earlier studies (Ritter 2005). However, it is not clear whether temperature and moisture explain the 10-fold increase between winter and summer decomposition rates (Tables 5.2-5.6)

The variation in litter loss is not related to the litter quality at each site. High decomposition rates were observed at Makwara in summer compared to other sites where all sites received residues with similar chemical characteristics (Table 5.1). The observed biomass losses were probably a result of physical rather than chemico-biological transformation of the litter. Chemical characteristics, which are known to influence decomposition in buried litter bags, do not explain the variation in rate of surface residues loss (Heal et al. 1997). This observation is contrary to work by Musvoto et al. (2000) who, using buried miombo and *Mangifera indigo* litter of different quality, showed exponential decay for both lignin and cellulose. Chikowo (2004) also found a similar relationship for agroforestry materials in Zimbabwe.

Comminution of surface-applied residues by macrofauna could explain why decomposition did not conform to the expected patterns considering the initial chemical characteristics. Couteanx et al. (1991) and Seastedt (1984) showed that the effect of macrofauna involvement in substrate decomposition led to different decomposition rates and patterns. Given the dominance of termites at these sites (Chapter 2), foraging and hence comminution could be the main avenue through which litter loss took place (Winsome 2005). The dietary preferences of termites (ligno-cellulosic materials), as defined by (Trancello and Lenthold 2000), suggest that maize litter attracted the termites leading to high decomposition.

Termites are involved in the primary decomposition process of cutting down large pieces of organic materials. In addition, termites built galleries around the litter, which was evidence of foraging (Chapter 4). Hunter et al. (2003) reported the influence of macroinvetebrates and local site conditions to the overall decomposition of litter. In other studies, Seastedt (1984b) suggested an equation describing litter breakdown showing the importance of soil fauna in the decomposition of low quality litter.

5.4.2 Decomposition on different treatments

The application of tillage and residue management systems on-farm demonstrates the importance of three factors that influence decomposition rates of surface mulch: (a) seasonal effects, (b) soil type, and (c) catenal effects. These influence the decomposition of litter and indirectly the fauna activities. Coleman et al. (2004) showed the influence of soil water conditions on soil biological activities and indirectly the decomposition of litter. The effect of contrasting soil types was demonstrated between on a *Chromic Luvisol* and on a *Gleyic Luvisol* at Chinyanga and Kajengo respectively, both in the same agroecology. In summer the CP treatment at Chinyanga showed higher decomposition than that at Kajengo. This shows a differential effect of conventionally ploughing a clay soil, which improves the soil environment and hence locomotion of organisms, thus leading to higher decomposition. Conversely, minimal tillage application on a sandy loam soil at Kajengo provide a favorable environment for the development of fauna, leading to higher decomposition in DS and SS treatments. On a clayey soil at Chinyanga, minimal disturbance restricted fauna activities, leading to lower rates of decomposition on DS and SS treatments. This corroborates findings by Martius (2004), who reported microclimate of a site, among other factors, as an important determinant of decomposition of plant litter. Coleman et al. (2004) identified the influence of edaphic factors on microclimate as an important regulator of the decomposition process. Furthermore, earthworms and termites have been reported to be important decomposers of maize litter and other low quality straw during the early stages of the decomposition process (Kurzatkowski et al. 2004; Martius et al. 2004; Tian et al. 1995) The current results also suggest that mulching during the winter on clayey soil was effective in keeping conditions favorable for soil organisms, whereas tillage improved the soil environment during the summer. This demonstrates the seasonal effect of temperature and moisture in winter (cool to cold) and summer (warm to hot) in Zimbabwe. Mclnerney and Bolger (2000) reported on the importance of moisture in influencing the decomposition of surface-applied and soil-buried litter.

The Makwara farm stood on high ground whereas Zhinya was on the lower catenal position. Higher decomposition under CP at Makwara during the summer was a result of the combination of high temperature and moisture. In contrast at Zhinya, restricted drainage because of its lower catenal position could have kept the moisture in the profile longer, hence reducing fauna activities. Mulch improved the soil in the CA treatments and could have buffered temperature fluctuations. In line with our hypothesis, on higher decomposition rate was obtained under CP in Zimuto during the summer period. The combination of high temperatures, low biomass per unit area and longer mid-season dry periods promotes higher decomposition and mass loss. In Shamva, sandy soil with lower potential exhibited higher decomposition. This indicates that the actual breakdown and decomposition is a function of more than one factor and the interaction of biota, substrate quality and climate as reported in literature (Coleman et al. 2004; Gonzalez and Seastedt 2001; Heal et al. 1997). Whilst decomposition patterns fitted the negative exponential model, variation between treatments and sites was high. Patchy foraging of macrofauna could explain the differences. Since termites dominated the fauna on the farms (Chapter 2), the patch foraging habits could have influenced the decomposition rates. Kurzatkowski et al. (2004) reported similar variable decomposition rates resulting from macrofauna activities.

5.4.3 Management of residues

On bare soil, wind and water erosion are the significant agents of physical mulch degradation. Mulch reduces the raindrop action on soils at the onset of the summer rainfall season. The decomposition rates measured suggest careful management of soil cover during both winter and summer. There is a link between residue management, decomposition rate, and soil fauna, which is influenced by soil disturbance. Although winter losses are lower than summer losses, there is need to ensure that enough mulch is still available at the end of the winter before the rains start. The higher losses during summer also require that enough residues remain on the soil surface after the summer cropping season. This suggests change in the farmers' practice of either removing or leaving residues to waste away during the winter season. In the short term, annual addition of residues may be necessary to maintain a high soil cover. Decomposition of these residues is dictated by the residue quality, physico-chemical environment, and decomposer community at each site (Heal et al. 1997; Gonzalez and Seastdt 2001; Swift et al. 1979).

5.5 Conclusions

Residue losses resulting from fauna activities are substantial, especially during the summer season. Mass loss was more pronounced on sandy soil in the semi-arid zone than on clayey soil in the sub-humid rainfall zone. Macrofauna communities dominated by termites are the main agent of decomposition of surface mulches under conservation agriculture (chapters 2 and 4).

6 WEED COMPOSITION ON CONSERVATION AGRICULTURE PLOTS ON DIFFERENT SOILS IN ZIMBABWE

6.1 Introduction

Weed control has been of concern throughout the history of agriculture and even with the popularization of herbicides it has remained inadequate (Lamarca 1996). Weeds compete vigorously with crops for nutrients, light, space and moisture. Under extreme infestations, crops are choked by weeds leading to reduced grain and non-grain biomass yields (Oldreive 1993; Makanganise 1999; Vogel 1994). Reduction of yields ranges from small percentages to total crop failure as a consequence of aggressive weed competition (Rambakudzibga et al. 2002). Currently, the weed management practices used by farmers do not target reduction of the weed seed banks in the soil but rather perpetuate them by turning the soil continuously.

There are a considerable number of interactions between weeds and other crop production factors. Twomlow (1997) reported that the weeding regimes and frequency considerably affected the moisture profiles of sandy soils. The commonly reported weed *Striga asiatica,* for example, is found on most low nitrogen soil and has drastic effects on maize yields. Weeds are reportedly hosts to pests and in particular some nematode genera that are parasites to crops. Lesion nematode densities have been reported to be related to presence of weeds on fields where maize is grown (Swarup and Soma-Moss 1990). These interactions could lower crop production if a long-term weed control mechanism is not put in place.

The labour demand during weed control on farms is high. Weeding accounts for about 60 % of the time smallholder farmers spend on the land (FAO 2001). Mechanical and manual methods are commonly used by farmers. On average, farmers apply two or three weed control operations in one crop growing season. Under conventional ploughing systems, effective weed control in the first 4 weeks after maize emergence could lead to a better crop yield (Rambakudzibga et al. 2002). Despite recommendations for a weed management plan on the farms, farmers still struggle to overcome weed pressure on their crops. Under conservation agriculture systems, when no early-season mechanical weed removal is exercised, a greater weed control challenge is envisaged. With labor shortages at farm level caused mainly by migration and HIV/AIDS, strategic initiatives of labor saving weed control need to be explored. With the introduction of conservation agriculture, effective, labour saving and weed-seed-bank-targeted approaches are required.

In southern Africa, tillage is mostly viewed as an accessible mechanical way of controlling weeds on the fields. The use of the animal-drawn moldboard plough and the three-tine cultivator has been accepted as an efficient way of mechanically controlling early weeds by most smallholder farmers (Chatizwa et al. 1998; Emmerling 2001). Farmer surveys have shown that among farm implements, the majority of farmers own single furrow ploughs (80 %), cultivators (20 %), riggers or rippers (5 %), and several hand hoes (Ellis-Jones and Mudhara 1995). The socio-economic circumstances of farmers often determine the adoption and adaptation of suggested methods.

A weed control management regime constituting of (a) timely control to reduce competition with crops (b) late weed control to prevent seed setting is appropriate under conservation agriculture to lower the problem of weed pressure over time. Under conservation agriculture, direct seeding without ploughing and the maintenance of soil cover also help to controll the development of weeds at the onset of the rainy season. Compared to conventional ploughing systems, conservation agriculture can result in a shift in the distribution of weeds.

The short-comings of relying on 100 % mechanical weed control methods are mainly to do with ever increasing costs of weed suppression and the increase in soil weed-seed banks over time. Use of the mould board plough in conventional ploughing systems facilitates both the burying of weed seeds and the exposure of seed buried in the soil in previous season. Work by Mabasa et al. (1990) has shown that seed viability of common weeds ranges from 1-25 years. On the other hand, nonavailability, high cost, crop damage, poisoning of personnel applying the chemicals, and negative environmental effects are some of the reasons why herbicide use is lower compared to the mechanical methods of weed controll.

To advance an effective control of weeds, the response of species to current as well as new farming systems needs to be ascertained. Weed densities and species were studied at four sites under conventional ploughing (CP) and conservation agriculture (CA) treatments on two soil types in two agro-ecological zones of Zimbabwe. The aim of the study was to assess short-term effects of a combination of mechanical and chemical weed control practices on weed densities and species during the winter season.

6.2 Materials and methods

The study was conducted at Henderson Research Station, Chinyanga, Kajengo, Makwara and Zhinya. At these sites, conventional ploughing and conservation agriculture treatments were applied between 2004 and 2007. Prior to being put under these treatments, the sites were under conventional farming (Chapter 1). The sites were located in sub-humid and semi-arid conditions and on two soil types, i.e., sandy and clayey (Table 2.1).

6.2.1 Treatments

In all seasons, shallow hand weeding was applied three times during the cropping season. All plots at Henderson were sprayed with glyphosate herbicide at a rate of 3 l ha^{-1} in the first season. In subsequent seasons, three shallow manual weedings were applied on all plots. Targeted herbicide application on spots where *Richardia scabra* and *Cynodon dactlylon* weeds were problematic was done using a weed wiper on CA treatments. Prior to seeding, glyphosate was applied on all CA treatments in 2005 but none was applied in 2006. Late weed control was practiced in the two study years at Henderson Research Station. In the first season, wheat straw (about 2.5 -3.0 t ha^{-1}) was imported from a neighboring field and distributed on all plots. In the second season, a combination of wheat straw and maize stover amounting to 1.5-2.0 t ha^{-1} was used as soil cover. In the third season, all the maize stover was retained, which amounted to 2.8 - 3.0 t ha^{-1}.

In 2005, maize residues ranging from 4.9 t ha^{-1} to 6.1 t ha^{-1} were applied at Chinyanga and Kajengo. Three shallow hand-hoe weedings were applied in each year at each site. Glyphosate was applied before seeding each season.

At Makwara and Zhinya, weed management constituted a glyphosate application before seeding at a rate of 2.5 l ha^{-1} and three shallow hand-hoe weedings during the cropping season. At Makwara, maize residues were imported, and between 2.5 and 3 t ha^{-1} were applied. However, this amount was supplemented by grass cut from the veld. In 2005, the two sites received about 0.7 t ha^{-1} of maize stover generated insitu.

Measurements were made at four treatments at Henderson Research Station, i.e., conventional moldboard ploughing (CP), direct seeding using an animal traction seeder (DS), hand-hoe-made basins (BA), and direct seeding rip lines (MR) made by a ripper without furrow openers. On-farm at Chinyanga, Kajengo, Makwara and Zhinya three treatments were used, i.e., conventional ploughing (CP), direct seeding using an animal traction seeder (DS), and seeding using an animal traction ripper (RR). The treatments were applied in the 2006 and 2007 agricultural season under rainfed conditions.

At Henderson, all treatments were under maize except for the ripper treatment (MR), which had a maize-mucuna intercrop in 2006 and maize-crotalaria in 2007. At Chinyanga and Kajengo, a maize-soybean rotation was applied. On the former, soybean came after maize and on the latter the reverse. The plots at Makwara and Zhinya had continuous maize planted throughout the study period.

Measurement of weeds was conducted over the years 2006 and 2007. Weed species and densities were measured using the quadrat method. A 1 m^2 wooden quadrat was used as the unit of measurement, and four randomly selected replicates were measured for each treatment.

6.2.2 Data analysis

Using GLM techniques, an analysis of variance (ANOVA) was run using SIGMASTAT, and a multiple mean comparison was used to compare the treatment effects. Means were separated by Tukey (0.05) following an ANOVA. In addition, Shannon Wiener diversity indices were calculated to compare weed diversity and evenness across the sites.

6.3 Results

6.3.1 Weed species

A wide range of weed species was found at the study sites. The loest number of species were measured in the semi-arid zone at Zhinya, where only 7 species were found on the site over the two years.

The weed densities minly comprised the following 26 species found in different combinations at each site: *Amaranthus hybridus* L., *Ageratum conyzoides* L., *Bidens pilosa* L., *Chromolaena odorata* (L.) King and Robinson, *Cissampelos* *mucronata* A. Rich., *Commelina benghalensis* L., *Conyza albida* (Retz.) E.H. Walker, *Conyza bonarienses* (L.) Cronq., *Conyza spinosus* , *Convolvulus arvensis* L., *Cynodon dactylon* (L.) Pers., *Cyperus albida* L., *Eleusine indica* (L.) Gaertn, *Eragrostis sp.*(Jacq.) Nees., *Galinsoga parviflora* Cav., *Helichrysum argyrosphyllum* DC., *Hibiscus meeusei* Exell., *Indigofera viciodes, Leucas martinicensis* L., *Melinis repens* (Wild.) C.E. Hubbard, *Mycandar benghalensis, Oldenlandia herbacea* (L.) Robx., *Ruvavashuro, Ruvachiru*[1] and *Richardia scabra* L.. Weed species were identified from Drummond (1984), Skerman and Riveros (1990), and Makanganise and Mabasa (1999).

6.3.2 Weed densities

Significant differences in means occurred across sites in both 2006 and 2007 ($P < 0.05$). Henderson had a significantly lower mean weed density than all other sites except Makwara. Chinyanga had lower weed density than Kajengo, but was not different from Makwara and Zhinya. Highest densities were found at Kajengo and were higher than at Makwara the same as the mean calculated for Zhinya. Makwara sites had lower weed densities than Zhinya. Mean weed densities were in the order Kajengo > Zhinya > Chinyanga > Makwara > Henderson in 2006. In the same year, the RR treatment had a higher mean weed density than both CP and DS across all sites. There was no difference between DS and CP treatments.

In 2007, Henderson had a lower mean weed density than Chinyanga, Kajengo, Makwara and Zhinya. In addition Chinyanga, which was not different from Kajengo and Zhinya, had a higher mean weed density than Makwara. Kajengo was higher than Makwara but not different from Zhinya. Mean weed densities measured at Makwara were lower than at Zhinya. Zhinya had the highest mean weed density. The order was as follows: Zhinya > Kajengo > Chinyanga > Makwara > Henderson. There were no statistical differences among treatments in 2007.

At Henderson Research station there was a decline in weed density between the 2006 and 2007 winter seasons in all treatments except for the direct seeded (DS) treatment, where higher mean weed density was measured in 2007 (Table 6.1 and 6.2). In both years, *Richardia scabra* was the dominant weed and in 2006 and 2007, *Conyza borariensis* and *Cissampela mucronata* respectively, accounted for a significant proportion. The *Richardia scabra* proportion of density decreased significantly on the basins (BA) and Magoye ripper (MR) treatments and increased on the conventional ploughing (CP) and direct seeded treatments. Significantly higher densities ($P < 0.05$) were measured for CP compared to the other treatments in 2006 and 2007. In addition, the BA treatment had a mean weed density equal to that of the MR treatment in 2007.

There was a reduction in weed densities in the conventional ploughing treatment between 2006 and 2007 on the sites located in the sub-humid zone, Chinyanga, Henderson and Kajengo whereas an increase was recorded in the semi-arid area. However, the ripper and direct seeder treatments had less weeds regardless of the soil texture on the sites. Relatively higher densities were measured on the clayey soil at Chinyanga compared to the sites on sandy soil. Though located on sandy soils, Kajengo however, was an exception and had higher mean weed densities for the two years compared to all the other sites.

Richardia scabra and *C. dactylon* were the most abundant weeds in both years on the semi-arid sites (Table 6.3-6.10). On the wetter sites, *R. scabra* density was higher for both the sandy and clayey soils. In addition, the Kajengo and Chinyanga sites though on contrasting soil types, sandy and clayey, respectively, had higher densities of *G. parvilora*. The weed species identified at Henderson Research Station were more comparable to those at Zhinya, though the two sites are in contrasting rainfall zones. A weed legume *Indigofera viciodes* was amongst the weeds found at Henderson and Chinyanga.

Table 6.1: Mean weed densities at Henderson (4 treatments); Chinyanga, Kajengo, Makwara and Zhinya (3 treatments), Zimbabwe during winter 2006

Site	Conventional ploughing (CP)	Direct seeding (DS)	Ripper (MR/RR)	Basins (BA)	P<0.05
Henderson	36582	3535	8477	7559	sig.
Chinyanga	125038	162038	171863	-	ns
Kajengo	198500	296025	472500	-	sig.
Makwara	13225	31313	273550	-	sig.
Zhinya	49488	158275	484094	-	sig.

Table 6.2: Mean weed densities at Henderson (4 treatments), Chinyanga, Kajengo, Makwara and Zhinya (3 treatments), Zimbabwe during winter 2007.

Site	Conventional ploughing (CP)	Direct seeding (DS)	Ripper (MR/RR)	Basins (BA)	P<0.05
Henderson	10941	4981	3497	6023	sig.
Chinyanga	42500	52000	53750	-	ns
Kajengo	41750	68250	43250	-	sig.
Makwara	30000	28500	16000	-	sig.
Zhinya	72750	60000	58000	-	ns

sig = significantly different; ns = not significantly different

Table 6.3: Mean weed species density in conventional ploughing, direct seeding, ripping and basin treatments measured after maize harvest in 2006 at Henderson, Zimbabwe.

Treatment	Conventional ploughing	Direct seeding	Ripper	Basins
Richardia scabra	21758 (59.5)	996 (28.2)	2813 (33.2)	1250 (16.5)
Conyza borariensis	8457 (23.1)	137 (3.9)	4043 (47.7)	293 (3.9)
Cynodon dactylon	2852 (7.8)	0	352 (4.1)	117 (1.6)
Cissampelas mucronata	1250 (3.4)	0	332 (3.9)	156 (2.1)
Indigofera viciodes	918 (2.5)	293 (8.3)	78 (0.9)	0
Helicochrysum argyrosphaerum	664 (1.8)	742 (21.0)	78 (0.9)	1914 (25.3)
Oldenlandia herbacea	352 (1.0)	39 (1.1)	313 (3.7)	20 (0.3)
Commelina bengalensis	117 (0.3)	605 (17.1)	156 (1.8)	137 (1.8)
Chromolaena odorata	0	0	0	313
Helicochrysum spp.	0	605 (17.1)	20 (0.2)	3086 (40.8)
Other	215 (0.6)	117 (3.3)	293 (3.5)	273 (3.6)

Percentage contribution of each species to treatment means in parenthesis

Table 6.4: Mean weed species density in conventional ploughing, direct seeding, ripping and basins treatments measured after maize harvest in 2007 at Henderson, Zimbabwe.

Treatment	Conventional ploughing	Direct seeding	Ripper	Basins
Richardia scabra	6833 (62)	2460 (49)	2322 (66)	3586 (60)
Cissampelas mucronata	1276 (12)	0	65 (2)	135 (2)
Conyza spinosus	891 (8)	371 (7)	69 (2)	453 (8)
Ageratum conzoides	864 (8)	461 (9)	54 (2)	328 (5)
Eragrostis	378 (3)	328 (7)	148 (4)	95 (2)
Oldenlandia herbacea	292 (3)	211 (4)	106 (3)	345 (6)
Cynodon dactylon	123 (1)	16 (0)	108 (3)	0
Indigofera viciodes	111 (1)	73 (1)	32 (1)	38 (1)
Conyza albida	43 (0)	225 (5)	38 (1)	20 (0)
Bidens pilosa	35 (0)	107 (2)	22 (1)	75 (1)
Mycandra bengalensis	6 (0)	0	4 (0)	84 (1)
Other	23 (0)	387 (8)	44 (1)	30 (0)

Percentage contribution of each species to treatment means in parenthesis

Table 6.5: Mean weed species density in conventional plough (CP), direct seeder (DS) and ripper (RR) treatments measured after maize harvest in at Chinyanga, Zimbabwe in 2006

Treatment	Conventional ploughing	Direct seeding	Ripper
Richardia scabra	67188 (54)	23438 (14)	23213 (14)
Cynodon dactylon	28125 (22)	30950 (19)	20000 (12)
Galinsoga parviflora	28000 (22)	79775 (49)	97750 (57)
Bidens pilosa	1225 (1)	13750 (8)	13838 (8)
Indigofera viciodes	250 (0)	1500 (1)	1125 (1)
Tall derere	0 (0)	12188 (8)	15000 (9)
Other	250 (0)	438 (0)	938 (1)

Percentage contribution of each species to treatment means in parenthesis

Table 6.6: Mean weed species density in conventional plough (CP), direct seeder (DS) and ripper (RR) treatments measured after maize harvest in at Chinyanga, Zimbabwe 2007

Treatment	Conventional ploughing	Direct seeding	Ripper
Galinsoga parviflora	18750 (44)	17000 (33)	25000 (47)
Richardia scabra	10750 (25)	12000 (23)	12250 (23)
Bidens pilosa	4500 (11)	3000 (6)	4250 (8)
Melinis repens	2500 (6)	6000 (12)	3500 (7)
Commelina benghalensis	1750 (4)	3000 (6)	1750 (3)
Leucas martinicensis	1750 (4)	4000 (8)	3500 (7)
Amaranthus hybridus	1250 (3)	4000 (8)	1500 (3)
Acanthospermum hispidum	1250 (3)	3000 (6)	1000 (2)
Other	0 (0)	0 (0)	1000 (2)

Percentage contribution of each species to treatment means in parenthesis

Table 6.7: Mean weed species density in conventional plough (CP), direct seeder (DS) and ripper (RR) treatments measured after maize harvest in at Kajengo, Zimbabwe in 2006

Treatment	Conventional ploughing	Direct seeding	Ripper
Galinsoga parviflora	80625 (41)	34125 (12)	116250 (25)
Yellow flower	61250 (3)	77525 (4)	210375 (2)
Richardia scabra	43750 (22)	39375 (13)	76125 (16)
Ruvavashuro [1] *	5500 (3)	12250 (8)	10750 (2)
Chromolaena odorata	5250 (3)	60000 (20)	1500 (0)
Cynodon dactylon	625 (0)	27750 (9)	27500 (6)
Other	1500 (1)	45000 (015	30000 (6)

*Percentage contribution of each species to treatment means in parenthesis, *not identified, [1] could not be identified using the available weed keys*

Table 6.8: Mean weed species density in conventional plough (CP), direct seeder and (DS) ripper (RR) treatments measured after maize harvest in, in 2007 at Kajengo, Zimbabwe

Treatment	Conventional ploughing	Direct seeding	Ripper
Galinsoga parviflora	20750 (50)	19250 (28)	12000 (28)
Leucas martinicensis	8750 (21)	16750 (25)	10750 (25)
Ruvachuru [1] *	4250 (10)	4250 (6)	12750 (29)
Commelina benghalensis	3500 (8)	0 (0)	750 (2)
Richardia scabra	2000 (5)	15500 (23)	3750 (9)
Bidens pilosa	1250 (3)	0 (0)	750 (2)
Eragrostis spp.	750 (2)	6750 (10)	1750 (4)
Ageratum conzoides	500 (1)	750 (1)	500 (1)
Amaranthus hybridus	0 (0)	500 (1)	250 (1)
Other	0 (0)	4500 (7)	0 (0)

*Percentage contribution of each species to treatment means in parenthesis, *not identified, [1] could not be identified using the available weed keys*

Table 6.9: Mean weed species density in conventional plough (CP), ripper (RR) and direct seeder (DS) treatments measured after maize harvest in at Makwara, Zimbabwe in 2006 and 2007

Treatment	Conventional ploughing		Ripper		Direct seeding	
	2006	2007	2006	2007	2006	2007
Cynodon dactylon	5250 (39.7)	7750 (26)	48250 (17.6)	3500 (22)	9688 (30.9)	9250 (32.5)
Richardia scabra	5250 (39.7)	17750 (59)	90988 (33.3)	8000 (50)	9313 (29.7)	10500 (36.8)
Cissampelas mucronata	2100 (15.9)	0	28375 (10.4)	0	8750 (27.9)	0
Oldenlandia herbacea	625 (4.7)	0	105938 (38.7)	0	3536 (11.4)	0
Bidens pilosa	0	1250 (4)	0	750 (5)	0	1750 (6.1)
Elucine indiga	0	500 (2)	0	1750 (11)	0	1500 (5.3)
Hibiscus meeusei	0	1750 (6)	0	750 (5)	0	2750 (9.6)
Melinis repens	0	0	0	500 (3)	0	1250 (4.4)
Vernonina poskeana	0	750 (3)	0	750 (5)	0	1500 (5.3)
Other	0	250 (1)	0	0	0	0

Percentage contribution of each species to treatment means in parenthesis

Table 6.10: Mean weed species density in conventional ploughing, ripper (RR) and direct seeder (DS) treatments measured after maize harvest at Zhinya, Zimbabwe in 2006 and 2007

Treatment	Conventional ploughing		Ripper		Direct seeding	
	2006	2007	2006	2007	2006	2007
Oldenlandia herbacea	16813 (34.0)	13750 (19)	197500 (40.8)	7500 (13)	58063 (36.7)	7750 (13)
Richardia scabra	12238 (24.7)	19750 (27)	124063 (25.6)	37500 (65)	51188 (32.3)	46250 (77)
Cynodon dactylon	4875 (9.9)	10000 (14)	5750 (1.2)	4250 (7)	6125 (3.9)	3500 (6.0)
Cissampelas mucronata	2750 (5.6)	0	33438 (6.9)	0	17088 (10.8)	0
Conyza borareinsis	938 (1.9)	0	96844 (20)	0	19813 (12.5)	0
Elucine indiga	0	1750 (2)	0	3250 (6)	0	1000 (2.0)
Hibiscus meeusei	0	24750 (34)	0	3250 (6)	0	500 (1.0)
Melinis repens	0	2250 (3)	0	1250 (2)	0	750 (1)
Other	11875 (24.0)	500 (1)	26500 (5.5)	1000 (2)	6000 (3.8)	250 (0)

Percentage contribution of each species to treatment means in parenthesis

6.3.3 Weed evenness as measured by Shannon-Wiener index

At Henderson, though conventional ploughing had higher mean weed density, weeds had the least evenness in both years (Table 6.11). This means that the total counts were dominated only by a few weed species. Evenness increased from 2006 into 2007 under the same treatment. Direct seeder maintained higher evenness than other treatments over the two year. Except at Zhinya, all sites had higher weed species evenness in 2007 compared to 2006. At Henderson, Chinyanga and Makwara lower weed evenness was calculated on the conventional ploughing treatment compared to other treatments. At Chinyanga, where not weed density differences were not significant, higher evenness was measured for the direct seeding and ripping treatments in 2006. In 2007, the direct seeding treatment had higher species evenness. On the conventional ploughing treatment a marked difference in evenness was observed only on sites with more clay content (Chinyanga and Kajengo).

An increase in weed evenness suggests that the proportional contribution of each weed species to the mean density of the treatment also increases. However, higher diversity of weed species does not always lead to higher evenness. At Kajengo for example a higher number of species in 2007 lead to a higher evenness compared to 2006 (Table 6.7).

Table 6.11: Shannon evenness indices (*J*) for weed species at Henderson Chinyanga, Kajengo, Makwara and Zhinya, Zimbabwe, in 2006 and 2007.

Site	Year	Conventional ploughing	Direct seeding	Ripping	Basins
Henderson	2006	1.21 (2.65)	1.71 (3.56)	1.33 (3.07)	1.53 (3.53)
	2007	1.32 (3.38)	1.79 (4.30)	1.39 (3.56)	1.46 (3.63)
Chinyanga	2006	0.88 (1.57)	1.35 (2.63)	1.34 (2.60)	-
	2007	1.61 (3.35)	1.86 (3.86)	1.63 (3.58)	-
Kajengo	2006	1.16 (2.25)	1.82 (3.55)	1.39 (2.70)	-
	2007	1.51 (3.14)	1.60 (3.33)	1.49 (3.22)	-
Makwara	2006	1.19 (1.66)	1.34 (1.85)	1.31 (1.82)	-
	2007	1.20 (2.34)	1.61 (3.13)	1.53 (2.97)	-
Zhinga	2006	1.48 (2.66)	1.49 (2.67)	1.40 (2.51)	-
	2007	1.44 (2.80)	0.98 (1.90)	1.39 (2.70)	-

Shannon diversity index (H') in parenthesis

6.4 Discussion

6.4.1 Distribution of weed species

Across all the five sites, *Richardia scabra, Cynodon dactylon* and *Galinsoga praviflora* were the dominant weeds. Whilst *R. scabra* was found throughout, high densities of *G. parviflora* were restricted to Chinyanga and Kajengo, with only a few plants at Henderson. This result is a refinement to previous research in Zimbabwe, which has shown that *C. dactylon, R. scabra, Cyprus esculentus* and *Elucine indiga* are dominant and persistent on common sandy and red clayey soil types (Twomlow 1997).

Earlier studies show high prevalence of parasistic weed species such as *Striga asiatica* on low fertility plots (Chatizwa and Vorage 2000). However, the results in this study show none such species. This was rather unexpected given the low soil fertility status in the smallholder farming areas.

6.4.2 Treatment effects on weeds

The overall density reduction at all sites over the two years could be a result of the different weed management strategies applied on each site. However, these interact often with climatic factors. The application of a combination of an early chemical weed control (before seeding) and three shallow hand-hoe manual weedings per cropping season could also account for the observed lower densities after crop harvest. In particular, the application of late weed control and targeted follow-up on *R. scabra* and C. *datcylon* hot spots only used at Henderson Research Station could have led to lower weed densities. The benefits of such an approach accrue when the timing of crop growth and development are utilized for the successful capturing of resources by plants (Ghersa 2000).

In line with our hypothesis, mean weed densities were related to the soil textures of the sites (Table 2.1). More weeds were measured on clayey soils (Chinyanga) compared to light-textured sandy soils. However, this did not apply to Kajengo. The 14 % clay content of the soil at Kajengo could be the reason why weed densities were higher than on sandy soils. This suggests that clay particles in the soils could affect seeding of weeds. There were, however, no marked differences in the dominant weed species between sites on soils of different texture.

Comparing two sites in the same agroecological zone under similar weed management, a higher treatment response was observed at Kajengo (sandy loam), leading to differences in treatment means compared to Chinyanga (clayey). Similarly, treatment effects were statistically significant and different on other light-textured soils at Makwara and Zhinya.

In the two years, the high mean weed densities at Kajengo and Zhinya were also related to the higher soil organic matter content measured at these sites. This is particularly evident when mean weed densities at Makwara with lower soil organic matter are compared to those at Zhinya, both sites being in the semi-arid zone. High clay and organic matter on sandy soils increase the potential fertility of the soil. The results would imply that the agroecological factors had less effect on the mean weed densities than to the soils and weed management practices. High clay content and organic matter on sandy soils are indicators of high fertility. The presence of higher weed densities confirms the competition the crops on these fields will be subjected to, hence the need to weed control.

At Chinyanga and Kajengo, maize and soybean were rotated, which was different from the continuous maize system at the other sites. While the mean weed densities were not affected by soybean and maize at Chinyanga and Kajengo, the weed species dominancy and hence evenness was affected. There was a switch from *Ruvachuru* following soybean to *G. parviflora* after maize at Kajengo. However at Chinyanga, Richardia scabra dominance after maize was replaced by *G. parviflora* after soybean. This shows the effect of cropping sequences on weed species. Work on *Striga* has shown that use of legume in sequences with cereals, other organic materials and mineral fertilizers that supply nitrogen can result in its reduction (Riches et al. 2001).

Ripping through the plough layer affected the weed density at some sites. At Chinyanga and Kajengo, higher mean weed densities were calculated in the ripping treatment in the two years. Compared to the other sites, Chinyanga and Kajengo, which had high clay-content soils, showed stronger responses of weeds to the ripping treatment, suggesting an interaction between high clay in the soil and the weed. The deep ploughing across the plough pan could have exposed some weed seed from the subsurface leading to higher germination rates later. In addition, ripping could have increased access of the weeds to subsoil moisture and thus higher densities. A similar effect of the ripping treatment was evident at Makwara and Zhinya in 2006.

At Henderson, a significantly higher weed density was measured in the conventional ploughing treatment compared to the other treatments. The conventional ploughing treatment had a similar effect at Makwara and Zhinya after the 2007 maize crop. Turning the soil using the mould-board plough both exposes and buries weed seeds. Though mechanical weed control reduces the already established weeds, it creates physical soil conditions ideal for seeds on the surface to germinate. Weed infestation increases with mixing of the soil (Lamarca 1996). However, this result is contrary to observations by Vogel (2004), who noted that reduced tillage techniques were quickly affected by the incidence of weed and required more labor to control compared to the clean tillage practices.

Residue cover application was part of the conservation agriculture treatments on all sites. The variation in response to applied residues show that these apparently had no effect on weeds. Higher weed densities on the ripping treatment with crop residues and on conventional ploughing with no residues show the minimal effect residue cover had on mean weed densities over the two years.

Among the minority weeds in the study, the presence of *Cyprus esculentus* at Henderson and Zhinya confirmed water table fluctuations during the rainy season at these sites. At Henderson, temporal water logging conditions resulted from the laterite layer found in the profile beyond 30 cm depth. At Zhinya, the presence of the weed confirms the lower catenal position of this site on a vlei margin. *Cyprus esculentus* was reportedly abundant in the vlei margin and vlei catenal positions. Other weeds found on CA plots were *Gisekia pharnaceoides* (L.) (Aizoaceae family), *Bidens pilosa* (L.) and *Conyza sumatrensis* (both belonging to the Compositae family) (Chatizwa et al. 1998). Another similarity was the presence of *Oldenlandia herbacea* at the two sites.

An increase in the weed species evenness was calculated for sites in both the sub-humid and semi-arid areas except for Zhinya (located in the semi-arid zone). Whilst this could indicate a reduction in one or a few species dominating the weed densities at a particular site, the values did not show sharp increases. However, the reduction in evenness calculated at Zhinya could be due to the relatively increased *R. scabra* densities. *Richardia scabra* has been reported to spread fast, taking advantage of space and of the reduced competition from other weeds.

While this study reports weed densities and how it reflects on management of weed biomass to reduce competitions effects on crops; the management of weed-seed banks in the soil remains an important goal for the future work. Through knowledge of factors that control weed phenology, and of the site-specific influence of soil hydric and thermal properties on seed dormancy is important in shifting from managing weed populations to weed management (Ghersa 2000). In addition, weed management strategies can become a component of the whole cropping system on farms.

6.4.3 Weed nematode interactions

Weeds host some nematode genera that are parasites to crops such as maize and other cereals. Previous studies have shown that *Cynodon dactylon*, *Eleusine* sp., and *Eragrostis* sp. are potential hosts of *Pratylenchus* genera (Hunt 1998). *Eragrostis* species have also been reported to host nematodes from the *Rotylenchus* genera. These relationships suggest that there are possibilities of controlling nematodes through improved weed management practices. Though nematode risk from this study was low (Chapter 2 and 3), future work focusing on the prevalence of weed genera that support plant-parasitic nematodes is important. This could build on previous work: Mabasa (1995) suggested effective control of *Cynodon dactylon* and other common weeds by judicious use of herbicides and post-harvest tillage.

6.5 Conclusions

From the results of this study the following conclusion can be drawn:

- *Richardia scabra, Galinsoga parviflora, Cynodon datylon* and *Elusine indiga* were dominant weeds during 2006 and 2007.
- On conservation agriculture treatments, residues had less effect on mean weed density and species evenness than tillage over the two years.
- Combinations of chemical control, hand weeding and late weed control substantially reduce weed after crop harvesting.
- Soil texture affected weed densities; more clay and organic matter content were related to higher densities.

7 FARMERS' PERCEPTIONS ON SOIL FAUNA IN RELATION TO CROP RESIDUE MANAGEMENT ON SMALLHOLDER FARMS IN ZIMBABWE

7.1 Introduction

Soil fauna on farm land is part of the high biodiversity in natural and managed environments. Pivotal roles of fauna that are beneficial to farm families include organic matter decomposition, bioturbation, suppression of soil borne diseases, nutrient cycling, and provision of environmental services such as bioremediation of pollution and mitigation of greenhouse gas emissions (Tondoh et al. 2001; Collins et al. 1989; Bignell et al. 2000). Ecologically, benefits range from contribution to nutrient turnover, to participation in the food web, and habitat modification (Uys 2002).

Besides the ecological roles of termites and beetles there are socio-economic benefits associated with these animals for smallholder farmers. Different termite castes (workers and alates) and mature beetles are food for the farm families in southern Africa. The nutritional benefits of consuming termite alates far exceed, for example, that of consuming similar amount of groundnut (Logan 1992). Farmers derive financial benefits from the sale of roasted termite alates and soldiers and mature beetles.

The insects derive energy from organic matter on the farms. This includes crop residues and other vegetation and animal remains. Under low input agriculture systems, crop residues are an important source of nutrients. The decomposition process, which is central to the mineralization of nutrient elements, is facilitated by soil organisms (Heal et al. 1997). Hence, on cropping lands there should be a close link between soil fauna and residue management.

Farmers are aware of the ecological interactions among several groups of insects on the farm. This is the more so when these have a bearing on the growth and overall yield levels of the commonly grown crops. Given the importance of residue cover as one of the pillars of conservation agriculture, the perception of farmers were examined in this study. The idea was to provide key information for (1) their current knowledge, and (2) identifying knowledge gaps with regards to a better management of conservation agriculture systems. The aim was to understand how the current knowledge of fauna on the farm was linked to residue utilization by farmers.

7.2 Materials and methods

The study was conducted in two smallholder farming areas, Shamva and Zimuto in Zimbabwe, under, respectively, sub-humid and semi-arid climates. Both areas are part of the open *miombo* savanna vegetation which covers a large part of eastern and southern Africa.

Land ownership in these two areas is the communal tenure system characteristic of smallholder farming areas in Zimbabwe. People in Zimuto have been farming since the 1960s. In Shamva, farmers settled for farming in the mid1980s and most of the farm families came from the Mt. Darwin area. In the two areas, mixed farming is practiced, and crops and livestock are managed together by each individual household. Indigenous cattle breeds are dominant in both areas. Maize is the main staple crop in Shamva and Zimuto; the addition farmers grow cash crops, small grains and legumes in loose rotation of varying order. The cropping and livestock enterprises have a strong impact on the ecology of the fauna in these areas.

Participatory rural appraisal (PRA) techniques were used to generate data from four groups, i.e., two each from Shamva and Zimuto. Focus groups discussions were used in soliciting information on the influence of the level of knowledge of insects on the farmers' way of residue use. Ranking, scoring and seasonal calendars of prevalence of soil insects were used to analyze the periodicity of fauna activities (Chambers 1994). The meetings began with introductions and identification of rapporteurs and facilitators. The brainstorming sessions raised issues ranging from general farming experiences, types of crops grown and related insects and pests, livestock production, the climatic variations in relation to cropping cycles, and the interaction of residue use and fauna on the farms. Ample discussion time was then allowed for each of the thematic subtopics; diagrammatic representation was one of the key tools of capturing and illustrating linkages among components of the farming systems (Pretty et al. 1995; Bellon 2001). At the end of each meeting, written up material was used to summarize key results of the discussion against a check-list of questions (Appendix 3).

The focus groups were composed of male and female farmers. Though the target was to have gender-balanced groups (50:50 ratio of female to male farmers), the gender ratio of participants varied. However, the variations did not deviate significantly.

The average number of participants for each group was 8, ranging from 7 to 13. Participants were drawn from farm families that had farming experience in the particular area. The majority of surveyed farmers were members of groups taking part in the on-farm demonstrations in the CIMMYT's conservation agriculture project.

7.3 Results

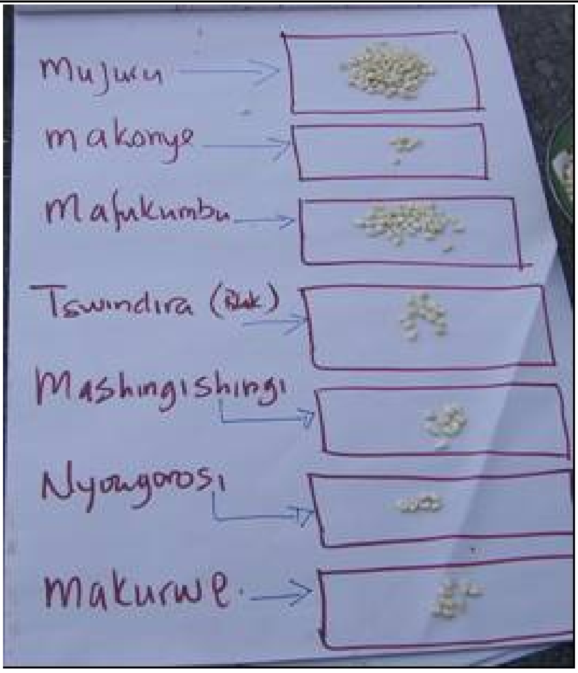
7.3.1 Fauna species in agro-ecosystems

Insects belonging to six orders were listed by farmers from both the sub-humid Shamva and semi-arid Zimuto farming areas. The orders Coleoptera, Hymenoptera, Isoptera, Lepidoptera, Opisthophora and Orthoptera (beetles, ants, termites, cutworms, earthworms and crickets, respectively) were identified. The farmers reported termites and ants as the dominant fauna on the farms throughout the whole year (Tables 7.1a – 7.1d). In addition, farmers reported high densities of aphids, termites and other insect pests on stressed crops during mid-season dry spells. This suggests synchronized pest attack and pest succession on weak crops. Earthworms were discussed as an important fauna group in Shamva, where soils are heavier (Tables 7.1a and 7.1b) but not in Zimuto, where soils are sandy and rainfall is lower (Tables 7.1c and 7.1d). Farmers from both areas experienced some problems with cutworms, though it was indicated that their prevalence was lower than for other insects. Though the two study areas were in different agro-ecological zones, a similar list of insects at order level was produced in both areas. This could be a result of the influence of the open *miombo* savanna vegetation and eco-region which the two share.

Cultivated crops provide food which attracts insects to the fields (Table 7.2). Further, farmers also noted that tillage operations disturbed the habitat of the soil fauna resulting in variation in densities. However, the distribution of species was related to the climatic conditions and soil types in the specific area. Farmers described numerous groups of insects both beneficial and pests.

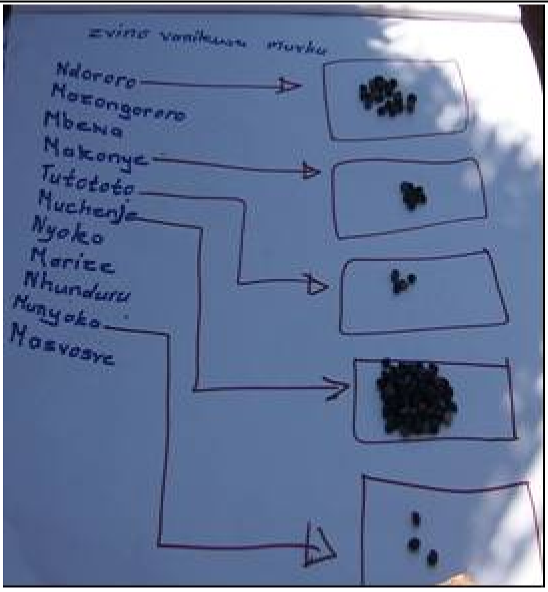
Table 7.1a: Ranking of the most common and important soil fauna by farmers at Shamva (group 1), Zimbabwe, using beads

Name of soil animal	Local name	Score (no. of beads)	Rank
Termites (Isoptera)			1
Cutworms (Lepidoptera)			
Ants[1] (Hymenoptera)			6
Ants[2] (Hymenoptera)			2
Ants[3] (Hymenoptera)			3
Earthworms (Opisthophora)			4
			7
Crickets[4] (Orthoptera)			
			5



1. Relatively large brown that soil heaps at the foot of crops and some trees, 2. Small black ants, 3. Large black ants which move in a big swam with soldiers that defend the community through biting and at the same time producing a strong-scented warning pheromone. These ants are known to feed on termites, 4. Large cricket species Gryllus bimaculatus that form soil heaps at the opening of their burrows. Some farm families collect these for food.

Table 7.1b: Ranking of the most common and important soil fauna by farmers at Shamva (group 2), Zimbabwe, using beads

Name of soil animal	Local name	Score (no. of beads)	Rank
Crickets[1] (Orthoptera)			2
Cutworms (Lepidoptera)			
Beetles (Coleoptera)			3
Termites (Isoptera)			
Earthworms (Opisthophora)			
			1
			5

1. Small black crickets that are also known for their sharp noise especially during the wet period. Unlike Gryllus bimaculatus, these are not edible.

Table 7.1c: Ranking of the most common and important soil animals by farmers at Zimuto (group 1), Zimbabwe, using beads

Name of soil animal	Local name	Score (no. of beads)	Rank
Termite (Isoptera)			1
Crickets[1] (Orthoptera)			2
Mice (Rodentia)			5
Cutworms (Lepidoptera)			2
Ants (Hymenoptera)			4
Millipedes (Diplopoda)			6

1. *Gryllus bimaculatus*

Table 7.1d: Ranking of the most common and important soil animals by 4 sub-groups of farmers at Zimuto (group 2), Zimbabwe, using beads

	Group 1	Group 2	Score	Rank	Group 3	Group 4	Score	Rank
Ants (Hymenoptera)	4	2	6	5	2	2	4	5
Crickets[1] (Orthoptera)	6	5	11	3	19	7	26	3
Cutworms (Lepidoptera)	6	16	22	2	8	4	12	4
Mice (Rodentia)	3	4	7	4	24	8	32	1
Millipedes (Diplopoda)	2	1	3	6	1	1	2	6
Termites (Isoptera)	8	11	19	1	10	20	30	2

[1] *Gryllus bimaculatus*

Farmers grouped termites into two main types, namely the soldier and worker termites. Soldier termites are found in two forms (1) the large dark brown headed and (2) the small pale-brown headed type. Two activities were associated with the worker termites. Firstly, the building by smaller bodied castes of galleries in the fields and outside and secondly, the collection by large worker castes of residues particularly grass from the veld; especially at the end of the dry season. Gallery building by termites was prevalent on clayey soils while little construction work was observed on sandy.

The presence of white grubs (beetle larvae), earthworms and cutworms were also reported by farmers in both Shamva and Zimuto. All three were linked to moist soils, and thus their presence followed the soil moisture profile during the rainy season. In addition to soil moisture, white grubs were closely associated with decomposing matter and therefore were commonly found around cattle kraals, composts and manure heaps. In Zimuto farmers reported two grub types, one in manure/cattle dung and another in the field. The grub found in the dung dies during the drying period and has black or white mandibles, whereas the grub found in fields has brownish mandibles. Earthworms are found in wet areas with higher clay content and rarely on up-land fields on coarse sands, except when there is decomposing organic matter. They are found mostly in grey-colored clayey soils. However cutworms are found on field crops, cereals and vegetables and are frequently pests causing damage to crops. Several ant species were also reported by farmers and these were linked to different soil types. Common species were reportedly found on poorly structured sandy soils and these build large galleries below ground. It was also highlighted by farmers that low termite activity was evident in areas with high ant density.

7.3.2 Factors affecting prevalence

Soil fauna density and diversity is largely affected by biophysical site characteristics and management factors. Within a location where environmental factors are similar, management factors that vary across farms determine species densities. Farmers identified temperature, in particular occurrence of warm days, water and soil moisture, and soil types as the major biophysical factors that affected prevalence of soil fauna. An increase in pests was reported during mid-season drought periods on cropping lands, which indicates the influence of temperature on fauna densities.

Soil moisture, resulting from regular rainfall during the wet season, is important for organisms and is a soil conditioner influencing morbidity. Farmers were aware that most faunal life cycles revolve around the availability of water and soil moisture for their completion. The level of soil moisture was an important attribute of the soil as a habitat of soil fauna. Most soil fauna responded to the soil moisture levels. The activities of beetle, earthworms, worms, termites, ants and millipedes are influenced by soil moisture. Termites are subdued by high rainfall and high levels of soil moisture, whereas densities increase during seasonal dry spells. Within wetlands (*matororo*), low termite densities are found but higher densities of earthworms, beetles and crickets.

The heavier soil types in Shamva hosted more fauna than the light-textured soils in Zimuto. Within the same location, densities of a particular insect on a heavy or light soil varied depending on species. Earthworms were found on heavy wet soils at the lower catenal positions, whereas termites and white grubs were found on higher ground where the soils are light textured.

The management of organic matter/materials and weed control were identified as factors that caused changes in prevalence of soil fauna. Farmers use grass, crop residues, composts and animal manures for maintaining soil fertility. Maize residues attract termites, while groundnut residues lead to an increase in white grubs. The application of decomposing organic manures to crop fields led to an increase in white grubs, *pongwe,* ants, termites and sometimes cutworms. Higher densities were related to high organic material content in the soil. Availability of tree or crop residues on the soil surface influenced the movements of termites, beetles, mice and other animals. Some of the residues decomposed fast because of the activities of soil fauna. Where weed biomass is utilized as a carbon source by soil fauna, more weeds lead to increased numbers. Crickets, worker-termites and mice are examples of animals that are influenced by the availability of weeds. The application of surface residues was also associated with increased cricket (*ndororo*) infestation. When combined with winter ploughing, increased insect activity early in the growing season was reported to result in a higher number of crop pest attacks early in the season.

7.3.3 Roles of insects

Farmers perceived three roles that insects play on the farm: (1) they can be pests on crops, (2) they can be conditioners of the soil, and (3) some insects prey on crop pests. It was noted that all three roles were related to the rainfall and cropping patterns.

Several crops were commonly cultivated in the area, i.e., cotton, maize, tobacco, groundnuts, cowpeas, beans and soybean. Farmers noted that each crop hosted several pests and intensity of infestation varied with seasons and rainfall patterns. There was no proper distinction between pest and that the insects in general, the main reason given was that observations were mainly on the dynamics of harmful organisms than on non-pests because of the economic loss the latter are associated with. Among the crops, maize, groundnuts, bambara groundnuts and vegetables were the most susceptible to insect and soil borne pest attack. In most cases, the pests affect the underground parts of the crops, which could mildly stress the crop, thus reducing the quality of tubers and roots or causing crops to wilt and die off.

Table 7.2: Interactions between crops and soil animals as perceived by farmers in Shamva and Zimuto, Zimbabwe, across different seasons in a year.

Crop	Scientific name	Ants	Aphids	Cut-worms	Beetle larvae	Earth-worms	*Cylas bruneus* (Pongwe)	Phono-ptons	Termites
Cereals									
Maize	*Zea mays* L.	z	z/s	z/s	z	z	z/s	z	z
Sorghum	*Sorghum bicolor* (L.) Moench.		z		z				z/s
Finger millet	*Eleusine coracan* (L.) Gaertn	z	z						z
Pearl millet	*Pennisetum americanum* (L.) Leeke.		z						
Rice	*Oryza sativa*	z		z	z				
Wheat	*Tricum aestivum* L.	z							
Oil/Protein									
Groundnut	*Arachis hypogaea* L.	z	z/s	z	z	z	z/s	z	z
Bambara	*Vigna subterranean* (L.) Verdc.	z	z/s	z	z	z	z/s	z	z
Cowpea	*Vigna unguiculata* (L.) Walp		z/s	z		z		z	
Beans	*Phaseolus vulgaris* L.						z/s		
Fibre									
Cotton	*Gossypium hirsutum* L.		z/s						
Vegetables									
Rape	*Brassica napus* L.		Z						z
Cabbage	*Brassica capitata* L.		z						z
Pumpkins	xxx		z						
Tubers									
Sweet potato	*Ipomea batatas* (L.) Poir					z	z/s		z
Potatoes	*Solanum tuberosum*						z/s		
Sugar									
Sweet sorghum	xxxx	z/s			z				
Sugarcane	*Saccharum offinarum* L.	z/s			z				

S and Z represent presence of an insect in Shamva and Zimuto, respectively

7.3.4 Beneficial effects of termites in the field

Fauna in agro-ecosystems is part of the local food webs, and relationships exist between crops and insects Table 7.2. Farmers demonstrated the functions of such webs when they described the interactive relationships between termites, which act as alternative food for birds (*nyerere, hanga*). In addition, ants feed on termites and aphids (Table 7.3). Farmers also pointed out that fauna drives the organic matter decomposition process. Other ecological roles of soil fauna discussed by the farmers include improving soil fertility through faunal building activities, modification of soil to enhance conditions for diverse fauna habitats, comminution of residues, increasing soil organic matter, improving porosity in soils, and reducing hard-pan effects on crops (Table 7.3). Further the communities in Zimuto noted cash injection into household economies from the sale of termite alates and mature beetles. Fauna were received not only as pests, but also as playing positive roles that were an important contribution to the ecosystem. These range from modifying the soil environment to the benefit of crops to preying and hence reducing densities of other crop pests.

Table 7.3: Roles of individual fauna groups on smallholder farms in Zimbabwe as perceived by farmers

Insect	Activities related to fauna roles in agro-ecosystems
Ants	Feed on aphids and improve soil porosity
Beetle larvae	Highly associated with decomposing organic materials in cases where there is insufficient organic materials, they could attack crops
Earthworms	Move-about in the soil without harming crops
Millipedes	Do not feed on crops
Crickets	Does not feed on or disturb crops
Termites	Improve fertility of soil; cut residues into smaller pieces

Crickets, mature beetles, termite soldiers and alates, and white ants (tsambarafuta) are edible, often used as relish by some farm families and are an important source of protein.

7.3.5 Crop damage by insects

Soil animal are sometimes pests on common crops (Table 7.4). Farmer noted that prevalence insects that cause crop damage were monitored throughout the whole growing season. This is done in order to take corrective action before crop losses occur. Pests damage leaves, flowers, roots or below-ground tubers/storage organs of crops. Whilst none of the faunal groups was reported as a major pest on maize causing yield losses, termites, beetle larvae, cricket, and *pongwe* were said to lead to yield reduction and poor quality grain and/or tubers (Table 7.4).

Interactions between crops and soil fauna are both positive and negative. The majority of insects such as termites and beetle larvae are not typical pests with a life cycle directly linked to crop growth. Unlike aphids that depend on the leafy crop growth, termites and beetle larvae can complete their life cycles on dead organic material. However, farmers perceived that they were pests on most of the crops.

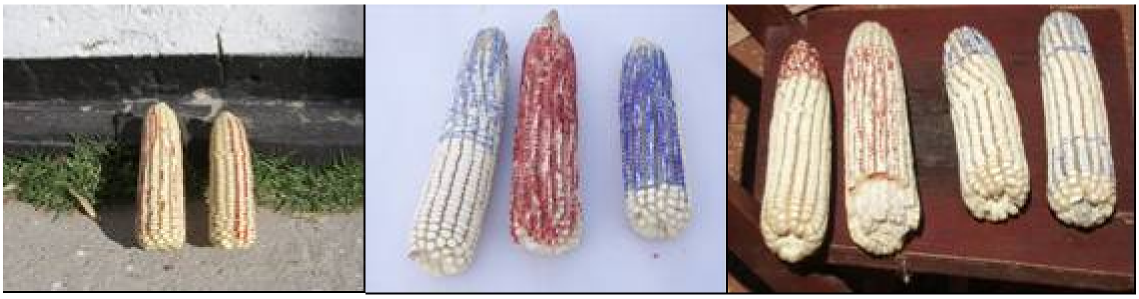


Figure 7.1: Illustrations by farmers showing the points of maize cobs that are usually damaged during termite attack after maize maturity

Table 7.4: Pests found on farms in Shamva and Zimuto, Zimbabwe, the crop parts they attack and the phenological stage most affected

Insect	Crops affected	Description of effect	Growth stage
Ants	Cereals	Chew crop leaves	All stages
Aphids	Vegetables, cereals, oil and protein crops, cotton	Attack leaves of stressed crops causing damage and reduced growth	All stages
Cutworms	Maize and other cereals, cotton, vegetables	Cut stalks or leaves of young plants; cut flowers on cotton	Young and maturing crops
Cylas bruneus (Pongwe)	Groundnut; sweet potatoes; potatoes	Graze the outer skin and layers of epidermis forming channel around the kennels and tubers; penetrate tubers causing them to rot.	After flowering
Termites	Cereals, vegetables, oil/protein plants	Cut young and mature plants stems just above the ground; attack maize cobs after maturity	Early growth and after maize maturity
White grubs	Maize	Cut and eat roots of plants during the first 4 weeks of growth	Early growth period

7.3.6 Sources of information

The Department Agricultural Research and Extension Services (AREX) is the major source of farming information (Table 7.5). The department has personnel representation at ward level in all districts across Zimbabwe. AREX officers organize training meetings and workshops on different aspects covering topics on crop and livestock production. It is important to note that there is a master-farmer training run in each ward that is covered over three years. These courses however are for few enterprising farmers. Development and research of non-governmental organizations (NGOs) also play an important role in both Shamva and Zimuto. Also included in this bracket are private companies that promote particular crops, for example, cotton or soybean. Major points of information during interaction with different organizations are on germplasm, pest control on crops and dietary improvements for livestock.

Table 7.5: Major sources of crop-livestock information in order of the diversity and effectiveness of institutional source

Site	Gender	1st	2nd	3rd	4th	5th
Shamva	M	Extension officers	DAPP[1]	Family members	Cotton companies	School
	F	Family members	Extension officers	Church	School	
Zimuto	M	Extension officers	Makoholi[2]	Family members	Other farmers	
	F	School	Family members	Extension officers		

M = Male farmers, F = Female farmers, [1] DAPP = Development Aid from People to People is a developmental NGO based in Shamva smallholder farming area, [2] Makoholi is a national agricultural research station close to Zimuto

Whilst extension dominates as the source of information pertaining farming, NGOs are also important. Both in Shamva and Zimuto, the passing on of farming information across generations from elderly family members remains an important part of knowledge storage and transfer. Traditional sources of information are important in dissemination of information as shown by the result from this study. However, they present challenges in that they sometimes provide only a narrow information base. Whereas diversity in sources of information theoretically provides flexibility among farmers, in practice only a single or at best a few sources influence the practices farmers get involved in.

7.4 Discussion

7.4.1 Soil fauna on farms

Farmers related prevalence of fauna from 6 orders to mainly climate and soil factors in both study sites, which is supported by scientific findings (Lavelle and Spain 2001). The similarity of insects community composition in the two studied areas which differ in rainfall and temperature means that the described fauna groups transcend the agro-ecological boundaries. Farmers did not mention tillage as one of the factors that influence fauna densities on the farm. This could either be due to lower fauna presence prior to the onset of the rains, or a result of closer monitoring during the crop growing period compared to other times. Nevertheless, the results of this study show that tillage constitutes an important factor in soil fauna densities on the farm (Chapter 2). Within-genera knowledge of fauna was demonstrated when farmers described the two species of termites commonly found on their farms. This observation was important in that it presented scope to work with farmers in exploring fauna on the farm.

7.4.2 Residue utilization

In mixed cropping systems, livestock and crop subsystems are interdependent and they influence how residues are used by farmers. In both Shamva and Zimuto, farmers reported maize residues to be the most important residues generated annually from the fields as by. Most of the residues are put away in different kinds of storage facilities for use as supplementary feeding during the cold dry winter season (Figure 7.3), which corroborate the importance of maize stover as supplementary cattle feed. The most common structure is built using poles above the or close to the cattle kraal (Figure 7.2). From these structures cattle are fed within the kraal and the remains get mixed with dung through stamping by the cattle. This practice was reinforced by information farmers received on livestock rearing training programs, which include discussions on feed formulation through mixtures of stover and urea to improve the nutrition and palatability of hay (Francis and Sibanda 2001). Nevertheless, the main source of feed for cattle is grass from the velds and associated vegetation. Feeding of livestock and use of residues to reduce muddy conditions within cattle kraals lead to increased manure production. Manure has been reported as a key link between the livestock and cropping subsystems on the farms, and Murwira et al. (1995) reported manure as a key soil fertility resource on smallholder farms in Zimbabwe.

Figure 7.2: Structures used by farmers for storing maize and other crop residues for supplementary livestock feeding

Under the communal land ownership system, pastures are shared across several villages (Rukuni 2006). During the non-cropping season, cattle graze freely on the fields. Hence, stover remaining on the fields is browsed in-situ after the grain harvest. After removal of cobs, the stover is frequently left in heaps at particular points on the field where the livestock then browse.

Residues are also used for construction of structures for keeping small livestock on the farm. They form an important component of roofing material in combination with grass as thatching material. For the resource-constrained farmers, crop residues are also sources of fuel for food preparation in the homestead.

Crop residues are furthermore used by farmers for making compost for use on niches with lower nutrient status than the rest of the field (Figure 7.3). In addition, residues can be used for making composts, which are applied in vegetable gardens. Mulching around citrus and other fruit trees is practiced in order to improve moisture storage. However, several factors influence utilization of residues for soil fertility among them number of livestock owned, his age, number of years in school, and extension services (Nhamo et al. 2002). At each farm a combination of factors dictates the level of utilization. The isolated discussions on observations of fauna in relation to residue use showed that farmers considered the two separately. Experience-based knowledge of the relations between residue use soil fauna activities on cropping lands was limited in both the sub-humid and semi-arid areas.

7.4.3 Termites and residue management

Farmers reported that termites affected maize-cotton sequences most, but also maize-groundnut sequences and other crop combinations. They observed that incorporation of the remains of the stover often formed 'hot spots' frequented by termites as these present a major food resource. Termite attack on maize growing on such spots has also been reported by (Logan 1992). Termite behavior after exhausting the maize stalks remains unknown. The range of attack by termites around these hot spots was also not clear.

Compared to sandy soils, heavier red clays hosted more termites according to the farmers. Where crop residues were heaped, there was evidence of termite activities in the form of termite galleries, and attack on maize was reported. Where there were termite mounds within the field, more termite activities were observed.

Whilst appearance of fauna on fields was often a direct result of applying decomposed manures and fresh organic residues, the rates reported by farmers were too low o establish a clear relationship. Farmers did not see any link between fauna activities and pest incidence. This suggests that the current practices of crop residues application (timing and quantities) did not overload fields with residues and sudden pest incidence. As farmers generally applied only low quality residue which decompose slowly the fauna response may be slow so that farmers did not perceive any link between decomposition and soil fauna. This, however, is in contrast to farmers' knowledge of the role of residues in building up soil fertility.

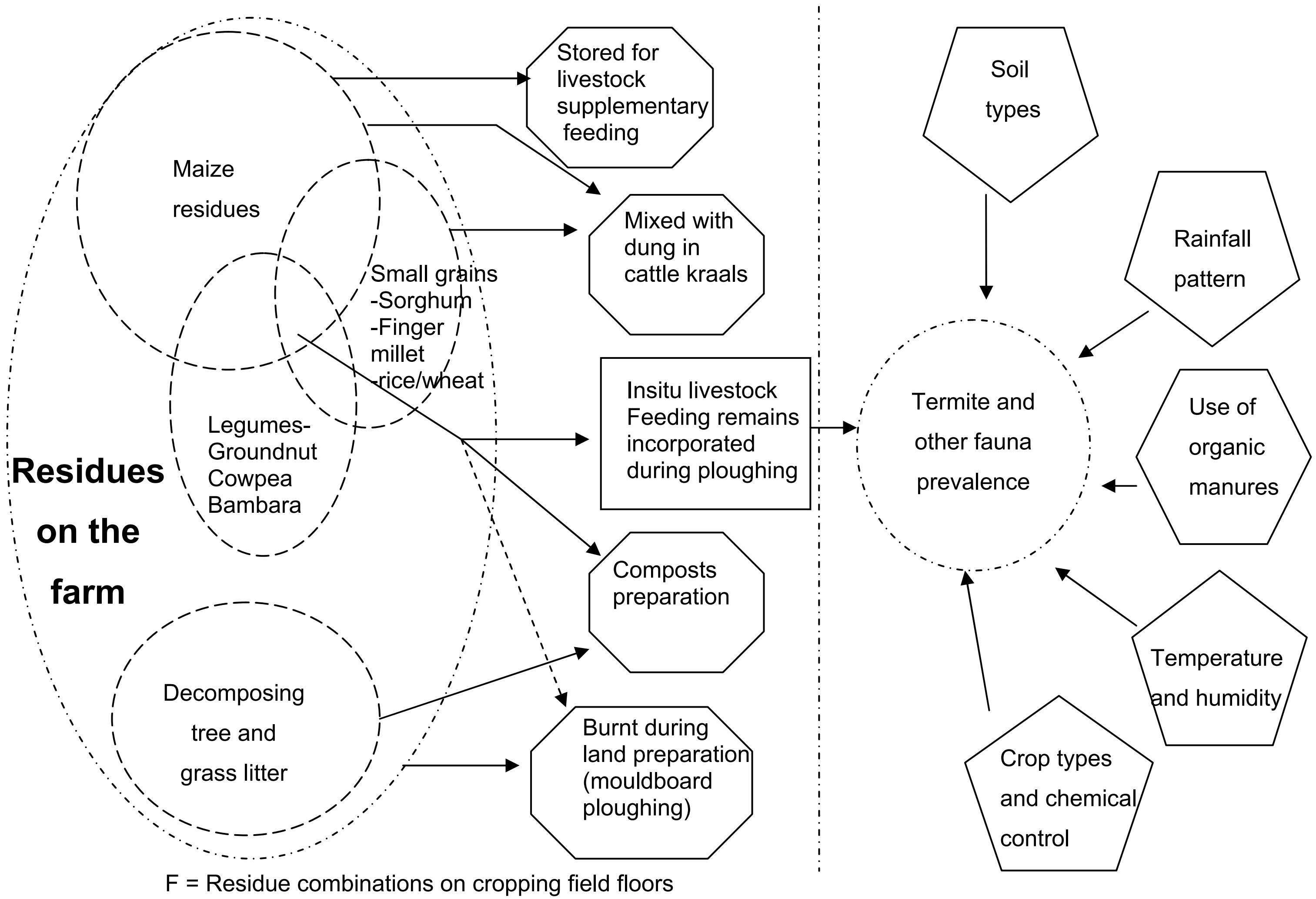


Figure 7.3: Residue use flow-chart representing scenarios of farms in Shamva and Zimuto, Zimbabwe

7.4.4 Estimated losses

Termite attack on crops was reported to take place during early growth stages and later after crop maturity where crop residues were not applied. On fields where there were active termite mounds, or in the case of fields surrounded by a large number of active mounds, higher losses were reported. Without termite control losses ranged from 20 kg ha^{-1} of grain to up to 250 kg ha^{-1}. Farmers noted that losses occur mostly through reduced grain quality as part of the grain is damaged by the termites. After maize maturity, farmers reported lodging of the maize plant, exposing and attacking the cob as the order which termites followed whenever crops were attacked. Termites preferred the grain cobs to leaf matter at maize maturity.

Though farmers reported some fauna as pests, the discussions showed the economic importance of these to the whole production process to be low. The relative reduction in total yield following a pest attack was more in cash crops, such as cotton and vegetables, and less in cereals such as maize and sorghum. Logan (1992) highlighted the perception by farmers of termites as pests, but also reported termites as an important resource for farmers in Africa. Measurements of termite attack done during this study (Chapter 4) also confirm that the yield losses are low and not economically significant. While the diets of termites include live and dead vegetation and wood, dung and fungus, their reported preference of dead grass, fallen leaves and small branches (Traniello and Leuthold 2000) could explain the low termite attacks on maize plants.

7.4.5 Methods of pest control

Farmers use both traditional and modern methods of pest control. Removal of remaining crop residues from the fields mainly by burning was a common practice perceived as a measure to control above all termites and white grubs. Burning of grass around the field was also practiced to reduce potential pest activities of other soil fauna. In addition, farmers incorporated the residues during land preparation as a method of removing any remaining un-burnt crop residues from the previous cropping season from the fields.

Table 7.6: Percentages of farmers using different pest control methods in smallholder farming areas of Zimbabwe

Method of control	Shamva	Zimuto	Utilization	Major limitation
Chemical spraying	85 %	60 %	High	Cost of chemicals
Herbal control	40 %	45 %	Medium	Knowledge
Manual killing	40 %	30 %	Medium	Labour
River sand	5 %	20 %	Low	Effectiveness
Weeding	60 %	55 %	High	Labour
Winter ploughing	30 %	50 %	Low	Soil moisture
Wood ash	25 %	30 %	Low	Effectiveness

More farmers used chemical pest control methods in Shamva, with its higher production potential, than in Zimuto. Farmers on the heavier soils in Shamva had more experience with the use of chemical pest control on crops such as cotton, whereas in Zimuto their knowledge was derived from the growing of vegetables in gardens on the *vlei* margins. Cutworms, stalk borers and aphids were target pests controlled by this method. With lower density pest, manual killing of the pest was commonly practiced in both areas. This was achieved mainly by setting up traps and digging out the pests from their subsurface nests. White grubs, termites, especially the queens, mice, crickets and cutworms were manually removed and killed.

Discussions on weed control and management indicated that some weeds hosted pests and that controlling them led to reduced pest incidences. In addition to controlling weeds hand hoeing also disturbed the termite galleries on the soil surface, thus reducing their expansion. Though farmers mentioned the application of dry grass as bait for termites, the method was not widely used. Winter ploughing also reduced termite attack on crops.

7.4.6 Knowledge gaps between conventional and conservation agriculture

The traditional methods of pest control shows potential for applying it in the integrated pest management. Except for the use of ash and a few scented herbs, the knowledge of traditional methods has not been sufficiently supported for widespread use by farm families. Importance of traditional and conventional wisdom passed on through generations was reported in both Shamva and Zimuto, where practices such as the use of river sand to control cutworms and wood ash against termites, were still being used. Farmers also used local herbs containing particular scents that deter insects to reduce pest pressure, e.g., *Zumbani*. Seasonal application of such control methods could help in the development of sustainable soil management, especially if the applications are targeted at identified peak problematic periods such as the mid season droughts. An in-depth knowledge of traditional methods of pest control was observed; however the use of these was reportedly low, as farmers seemed to rely more on chemical control methods for reducing infestation.

The limited application of mulch around fruit trees show that there is potential to build on such knowledge. Incorporation of residues into the soil increases the rate of decomposition through more favourable conditions for soil fauna. When organic matter content in the soil is low the insects could attack the crops. How insects responded to incorporation of residues could not be evaluated during these discussions. In low production areas, e.g. Zimuto, the low biomass produced could be the main reason why low fauna densities were associated with residues. Control of termites and pests was a higher priority in the sub-humid zone in Shamva compared to Zimuto.

Knowledge gaps between conventional ploughing practices and conservation agriculture need to be addressed in order to improve adoption and adaptation, otherwise a mismatch between current practices of conventional farming and the introduced conservation agriculture techniques will result in only minimal improvement in residue management. The switch from conventional to conservation agriculture practices requires an investment in information.

7.4.7 Knowledge of fauna

Farmers expressed some knowledge of the relationships between worker termites and alates, which they know as usually flying for nest building after the first rains each year. They acknowledged that these share the same mother, i.e., the queen. Farmers described the similarities between the bodies of the castes. The expression of fauna knowledge by farmers on the key functionalities of the cropping systems was an important base for building more knowledge. However, viewing insects as pests could lead to biodiversity losses, as these will be killed by pesticides. Where broad-based pesticides are used, chemical control has a detrimental bearing on the functional roles ecosystems are supposed to perform. Given that 85 % and 60 % of farmers interviewed in Shamva and Zimuto, respectively, used chemical control methods (Table 7.6), the understanding of pest control needs to be placed in the context of improved fauna diversity on the farms.

7.4.8 Periodicity of termite prevalence

Termites are found throughout the whole year, with densities peaking during warm and moist periods, the lowest numbers occurring during high rainfall periods and during the cold and dry winter. Broadly, the rainfall patterns of Shamva and Zimuto are similar with slight temporal differences. In Shamva, termite biomass increases during October after the first rains reducing with more frequent rainfall events in November and December. Termite activity starts earlier in Zimuto, as around September residual moisture from the wetlands provide soil moisture. The densities decease again with rainfall until December. In both areas, January has low average rainfall, and mid-season droughts are common and thus during this period termite activity is high. Densities of termites in the field drop between February and March, peaking again in April through to May. During this time, maize is mature and termite attack on cobs intensifies. For maize, early logging of mature plants and termites attack on the cob and feeding on the grain was reported. In some cases, the whole cob is eaten while in some cases half the grain was cut which reduced cob quality.

During the dry winter months from May to August, termites also bring up moisture to the surface, leading to higher decomposition of organic matter. Attacks on wooden structures increase both in the field and around the homestead. Termites were concentrated in warm areas, heaped materials and in mounds. Under the current management system, maintaining moisture during the peak attack period of January and March of each year could reduce prevalence and hence pests. Under conservation agriculture, the proper use of mulches presents an opportunity for keeping higher soil moisture levels than those under conventional farming. Use of residue cover could also provide termites and other fauna with abundant food and lead them away from crops.

Seasonality reported by farmers was consistent with measurements in this study, which found lower densities of termites in March compared to January in the 2007 season (Chapter 4).

7.5 Conclusions

- The majority of farmers perceived termites as pests on maize under conventional ploughing systems.
- There is limited application of traditional methods of deterring pests and reducing pressure of infestation compared to chemical pest control.
- Current residue utilization on the farms is driven more by supplementary livestock feeding during the dry winter period than knowledge on soil fauna.
- Residues remaining on the fields are cleared before the onset of the rains to allow smooth passage of tillage implements for seedbed preparation and planting.

8 SUMMARY AND RECOMMENDATIONS

8.1 Introduction

The determination of fauna densities (Chapter 2) was used as a basis for assessing their contribution to soil health under conservation agriculture (CA) systems. A conventional ploughing (CP) treatment was used as the reference point in this study. These assessments are shortterm, as they were carried out in the same years of implementation of conservation agriculture.

8.2 Fauna communities

Macrofauna, i.e., termites and beetle larvae in this study, responded to the application of CA better than the meso-fauna group (represented here by nematodes). Invariably, the responses to the short term application of CA did not provide a sharp contrast between the two farming systems in terms of the role fauna groups contribute to soil health, but some of the results show significant differences (the CA treatments having higher fauna densities than the CP), and some insignificant trends can be seen. Also, the CA treatments frequently resulted in higher variation in the density data of the various sample replications, showing higher potential for soils under these treatments to build up which may not have met the actual soil fauna increases at all sampled sites as the reaction was low. Further, there was evidence from the residue decomposition experiments (Chapter 5) that fauna contributes to decomposition; an important process in nutrient cycling in terrestrial ecosystems. Ripping through the plough pan, a layer formed from long term use of the moldboard plough, resulted in fauna increases relative to the CP on sandy soils.

The slow buildup of earthworms on CA treatments was an important result which is consistent with the assumption that favorable conditions for earthworms were built up. This is in line with results from long-term studies (Lal 1988).

Meso-fauna (nematodes) did not respond to short term changes in farming systems as indicated by the lack of differences between treatments at all sites. The free-living and phyto-parasitic nematode genera also showed a similar lack of change over the short time.

Whilst species are important in explaining some of the activities exhibited by termites for example, this study does not present data on changes in species during 2006 and 2007. As the system develops, identification of species fauna groups will provide valuable information for further analysis. A larger part of the literature on termites in the tropics, though, is largely on studies in forests and other natural vegetation systems (WWF 2002) and less is reported on cropping fields (see also Bignell and Eggleton 2000). It will be useful to link the work on species in cropping systems to the natural vegetation of the sites.

High variability of termites and beetle larvae was noted especially under conservation agriculture treatments as compared to the narrow ranges under CP. This can be interpreted as the occurrence of a heterogeneous soil environment with more nesting sites for soil fauna in these treatments. There was, however, higher variability, which could not be accounted for between densities measured on on-farm compared to on-station. Patchy management of soil fertility and concentrating resources to maximize yield output from organic amendments on the small farms are some of the explanations of the high variability. However, the historical effects should be overshadowed by CA treatment effects in the medium to long term.

The high fauna abundance shown at Henderson (chapter 2) as an indicator of how habitable the site and in particular the direct seeded treatments were for the fauna communities. In addition, the high diversity and evenness also measured on ripper and direct seeder treatments indicate the high potential and ecological quality of conservation agriculture compared to conventional farming practices. The lower evenness calculated for nematodes on the conventional ploughing treatment, for example, could indicate habitat stress in these treatments. As explained by Magurran (1987; 2004), more diverse and equitable species are indicative of disturbance and pollution. The conservation agriculture treatment increased heterogeneity, and hence more micro-sites and micro-habitats were available to accommodate more fauna.

The results show the importance of cropping systems and their influence on soil fauna diversity. The higher fauna densities observed under ripper and direct seeder treatments also conform to the theory on paradox of intermediate disturbance and moderate productivity. Under this theory, the habitat created with some soil disturbance (basins, ripper and direct seeder) is better than that with extreme disturbance, in this case the conventional treatment. This support the hypothesis that more soil fauna and better soil health is associated with the CA practices compared to CP.

8.3 Farmer perceptions

The relatively higher termite densities found (Chapter 2) corroborate perceptions by farmers on fauna on the farm (Chapter 7). However, contrary to what farmers indicated in interviews (Chapter 7), there was only low termite attack on maize at crop maturity (Chapter 4), even with increased termite densities. This message needs to be passsed on to the farmers through participatory learning exercises such as mid-season field visits. In addition, this will also allow for future monitoring and discussions over the behavior of termites as pests on farmers' fields.

8.4 Biomass and soil fauna

The several uses of crop residues reported by the farmers (Chapter 7) and the illustrations of current residue flow (Figure 7.2) on the farm need to be analyzed in the light of the developments in cropping systems. The efficiency with which residues are used could be ascertained neither in this study nor in literature. However de Leeuw (1997) proposed that the future allocation in response to cropping systems, diversity and enhanced quality of residues could determine demand and supply. In the same light, the reported uses by farmers do not suggest a lower probability of crop residue allocation for cropping systems such as conservation agriculture. The opportunities of mulch use by farmers to address soil, insects and weed management problems are high. The practices can be influenced by interaction of factors such as production and retention of sufficient quantities and complementary crop growing practices (Erenstein 2003).

While this study shows the effects of rotations on weed evenness, methods of weed control need to be tested further on farmer's fields. Current practices based on mechanical weed control can also be substituted by either one or a combination of biological, chemical or ecological methods (Skesman and Riveros 1990). Solutions to the problems in controlling couch grass rhizomes, which are more difficult to deal with especially on sandy soils where they develop deep root systems, need to be explored. There was an apparent reduction of total soil fauna densities with the increase in *R. scabra*. Reduced fauna densities indicated low potential of soil under which *R. scabra* thrives by efficiently utilizing the low soil nutrient and water. Given that R. scabra has shown protracted germination periods that cover most of the growing season (Mabasa 1993), it is worth investigating methods of controlling such weeds. This will conserve both nutrients and moisture for the benefit of crops and fauna.

There was an improvement in crop yields in 2007. The direct seeding treatment had higher crop biomass yields compared to both the ripper and conventional ploughing treatments (Table 8.1). This was an improvement, as in 2006 the conventional ploughing treatment showed higher yields. This result together with the findings on fauna densities shows the potential for an increase in soil health on conservation agriculture over time.

Table 8.1: Maize total biomass yield (kg ha^{-1}) at Henderson, Chinyanga, Kajengo, Makwara, Zhinya and Chimbwa, Zimbabwe, obtained in 2006 and 2007 cropping seasons from conventional ploughing (CP), ripper (RR), direct seeder (DS) and basin (BA) treatments.

	Henderson	Chinyanga	Kajengo	Makwara	Zhinya	Chimbwa
			2006 cropping season			
CP	6325	9365	2060s	948	-	2698
RR	5365	10201	1941s	1405	-	2769
DS	5654	8014	1171s	2033	-	2698
BA	5463	-	-	-	-	-
			2007 cropping season			
CP	8381	4986s	7627	725	3421	2281
RR	7435	4912s	6874	3503	3174	1372
DS	9278	7627s	11777	3855	3759	1319
BA	9802	-	-	-	-	-

S = soybean yields, Source: CIMMYT Conservation Agriculture Project Reports

8.5 Role of soil fauna in soil health

A lot is known about soil health and the importance of soil fauna in its development (Coleman et al. 2004). The practical indices of measuring this contribution are relatively few (Doran and Safley 1997), often the contribution of fauna in decomposition and primary productivity are followed. However, in this study, the extent of termite gallery coverage on cropping fields following application of conservation agriculture was proposed and used to estimate the benefits accruing over a short time. This was done in conjunction with the termite density data measured on the same sites (Chapter 2). The termite gallery building process on feeding sites is not well documented, and hence this method needs further testing. Clay and soil organic matter found in gallery material are important to soil fertility build-up; this makes gallery construction a beneficial contribution to soil health in the long term. Other works have also shown that physical soil attribute such as bulky density and porosity, following bio-turbation activities, are useful indicators of soil development in relation to fauna activities (Mando 1997).

While diversity change as measured by Shannon-Wiener indices is an important attribute of the soil system, understanding the interaction among the individual fauna groups is critical for improving the management of resources on the farms. The individual activities add up and contribute to the overall soil quality (Bengtsson 1998). In this study, interaction of termites and mycorrhizal spores is a case in point that demonstrates collaboration of fauna groups. The observations show three key roles that the selected soil fauna groups had in improving soil health: (1) increased fauna biomass and hence the expansion of the food web, (2) higher activity leading to more biogenic structures containing important ameliorants in the form of clay, silt and organic matter, and (3) inoculation of the soil surface with mycorrhiza spores and maintenance an even nematode genera distribution between parasitic and non-parasitic groups. All the fauna groups participated in decomposition, a key process in soils and their development (Acharya 2005; Franzluebbers 2002).

8.6 Summary

From a combination of the on-station and on-farm experiments, farmer perceptions gathered through interview this thesis aimed at defining the role of soil fauna in the soil health improvement under short term conservation agriculture practices relative to conventional ploughing. The following question and answers were matched based on the data and observations in the preceding chapters:

Did conservation agriculture treatments significantly increase densities and diversity of termites, beetle larvae, nematodes and earthworm in sandy soils in the short term? Yes: in the case of macrofauna, beetle larvae and termites, though densities had high variability. No: in the case of nematodes and earthworms.

Did surface residue decomposition rates during both summer and winter allow for a relative increase in soil cover over time on directly seeded plots? Yes, high rates were measured for summer compared to winter season. The rates allowed residue carryover into the next cropping season.

How did weed densities and species change in the short term following management strategies targeted at the soil weed-seed bank? Densities changed but the short term data could not explain these and the lack of species differences.

How does knowledge on soil fauna farmers have explain the current residue utilization practices? Knowledge of soil fauna does not influence residue use rather the need for supplementary livestock feed does.

Did soil fauna contribute to soil health? Yes, higher densities meant increased participation in the food web, gallery materials provided clay and organic matter on the soil surface, and contained mycorrhiza spores. Higher decomposition rates and crop yields also reflected improved soil health in conservation agriculture treatments.

8.7 Recommendations

In order to assess longterm changes in soil health, a combination of biological, chemical and physical soil indices are required. Long term studies on changes in species are an important way of monitoring the ecology of cropping systems, for exmple, the role of termites in soil pedogenesis through the gallery building activities needs to be explored further. The composition of biogenic structures of termites are species specific (Amelung et al. 2002), and there is a need to study the relationships between species and gallery materials.

Termite attack on maize, which can changes over time, needs to be monitored. Current result conform to the previous finding that termites prefer dry materials to live crops for food. This finding needs to be shared with farmers during exchange visits and green shows.

Within-season variation shown in the data from 2007 suggests that two or three sampling events are needed to explore diversity and richness. The sampling method used in this study was robust enough to capture the variations across treatments. However, to capture changes in beetle larvae and termite species, a combination of monoliths and survey methods would be appropriate both on the plots and in the surrounding natural forests.

Conservation agriculture treatments showed potential for increasing soil health. There is need to explore how crop residues, one of the important pillars, are used on the farms. Current residue use practices do not show a clear link to soil health improvement. In addition, crop rotations are also important in conservation agriculture systems, and how they interact with different faunal groups warrants further studies.

The findings on weeds are important in the light of saving labour and managing parasitic nematodes. The changes and interaction on sandy and clayey soils are not yet clear. Further, weed management options are required for different farmers.

Soil health is an integrating concept, and future work would benefit from other soil-related measurements, e.g., moisture dynamics, soil temperature, and soil physical parameters.

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10 APPENDICES

Appendix 1: Fauna densities (no. m^{-2}) measured at different soil depths at Henderson, Chinyanga, Kajengo, Makwara and Zhinya, Zimbabwe, in 2006 and 2007 cropping seasons

		Henderson	Chinyanga	Kajengo	Makwara
January 2006					
Beetles	0-10 cm	60.8	9.1	16.6	6.4
	10-20 cm	20.0	2.7	1.6	2.2
	20-30 cm	14.0	0.6	0.5	0.6
Earthworms	0-10 cm	7.5	39.0	22.4	0
	10-20 cm	1.0	24.0	6.9	0
	20-30 cm	0.5	5.3	2.7	0
Nematodes	0-10 cm	143.5	225.0	9.1	217
	10-20 cm	104	103.0	2.7	103
	20-30 cm	44.7	78.8	0	91.7
Termites	0-10 cm	72.0	36.8	64.6	0
	10-20 cm	11.5	43.8	69.4	0
	20-30 cm	11.0	30.4	13.9	0
January 2007					
Beetles	0-10 cm	23.3	9.3	13.8	13.8
	10-20 cm	56.0	9.3	3.1	28.0
	20-30 cm	35.3	5.3	6.2	19.6
Earthworms	0-10 cm	4	8.4	34.7	0
	10-20 cm	1	8.9	13.3	0
	20-30 cm	0	15.6	5.3	0
Nematodes	0-10 cm	178	183	32.6	50.1
	10-20 cm	177	84.8	15.8	44.3
	20-30 cm	123	42.9	20.6	43.4
Termites	0-10 cm	20.7	264	811	7.1
	10-20 cm	90.0	383	357	4.0
	20-30 cm	22.7	157	580	101
March 2007					
Beetles	0-10 cm	60.7	20.0	16.9	9.8
	10-20 cm	33.3	19.1	12.4	11.6
	20-30 cm	44.0	12.9	17.8	12.4
Earthworms	0-10 cm	25.3	5.3	18.2	0
	10-20 cm	12.0	5.3	16.4	0
	20-30 cm	16.0	3.1	24.0	0
Nematodes	0-10 cm	377	274	132	104
	10-20 cm	348	112	145	119
	20-30 cm	260	74	85.4	91.5
Termites	0-10 cm	105.3	60.0	60.9	17.8
	10-20 cm	73.3	67.5	39.6	53.3
	20-30 cm	64.0	22.7	169.8	15.1

Appendix 2: Nematode genera found at Henderson, Chinyanga, Kajengo and Makwara, Zimbabwe, during 2006 and 2007 cropping seasons

	Henderson	Chinyanga	Kajengo	Makwara
Alaimades	P	P	P	P
Aphelenchoides	P	-	-	P
Bastidae	P	-	-	-
Bunonematidae	P	-	-	-
Cephalobidae	P	P	P	P
Criconematidae	P	-	-	-
Diplogasteridae	P	-	P	-
Dolicodorus	P	-	-	-
Dorylaimus	P	P	P	P
Helicotylenchus	P	P	P	P
Hetedera	P	-	P	-
Histimanella	P	-	-	-
Hoplolaimus	P	-	-	-
Giant nematode	P	-	-	-
Longidorus	P	-	P	-
Meloidogyne	P	P	-	P
Mononchus	P	-	-	-
Paratylenchus	P	-	-	-
Pratylenchus	P	P	P	P
Prismatolidae	P	-	-	-
Radophilus	P	-	-	P
Rhabditis	P	P	P	-
Rotylenchus	P	P	P	P
Tylenchus	P	P	P	P
Tylenchorhyruch us	P	-	-	-
Xiphinema	P	-	-	-

P= Present

Appendix 3: Questions used during participatory rural appraisal (PRA) to guide discussions with farmers on the relationship between fauna and crop residue utilization on the farms.

Fauna	Residues	Interactions
Which fauna groups are present on the farm?	Which residues do you use on the farm (type, state and source)?	Which crops are most susceptible to pests?
What are some of the roles of the different fauna?	How are crop residues used on the farm?	Estimate the potential losses on grain and non-grain biomass following pest attack.
Are there factors that determine densities of these fauna on the farm?	Is the use of residues related in any way to the fauna prevalence on the farm?	Are there known practices for controlling pests?
Which groups are most prevalent?		
Distinguish beneficial from non-beneficial organisms.		

ACKNOWLEDGEMENTS

Firstly, I thank BMZ for funding the work under the collaborative project "Promotion of widespread adoption of Conservation Agriculture in East and Southern Africa", jointly executed by CIMMYT, Centre for Development Research (ZEF) and University of Hohenheim. I also thank DAAD for providing a short-term scholarship through ZEF, which enabled me to complete my thesis work. My sincere thanks go to my mentors. I enjoyed thesis supervision by PD. Dr. Christopher Martius and Professor Dr. Dieter Wittmann, both at the University of Bonn. Field work was made more exciting under the supervision of Dr. Christian Thierfelder and Dr. Patrick Wall, who are based at CIMMYT in Zimbabwe. I would also want thank Prof. Dr. Heiner Goldbach for chairing the defense committee.

Colleagues I worked together with at CIMMYT deserve to be mentioned: Mr. Sign Phiri, Dr. Augustine Langyintuo (all CIMMYT staff), Lewis Machida, Dayne, Pretty Chingombe (fellow students), for their encouragement and support. The Zimuto team assisted in a big way during data collection in southern Zimbabwe. In particular, I would like to mention Themba and "*bhudhi Oga*" for assisting with the digging of soil monoliths and with weed counts. Farmers who participated in the PRAs in Shamva and Zimuto deserve special mention, and many thanks go to them. The Chairman, Chief Technician (Mr. Gerald Ashley), technicians (Mr. Alferi and Mr. Hatidani) from the Biological Sciences Department in the University of Zimbabwe, helped a great deal to complete analyses. Termite taxonomy work was assisted by a visit to ARC laboratories in South Africa where Dr. Vivienne Uys hosted me; I would like to thank her. At ZEF, assistance from Mrs. R. Zabel, Dr. G. Manske (Bonn International Graduate School for Development Research at ZEF), Ms. Margaret Jend (ZEF C) is acknowledged. John Kasina commented on my work and assisted with ideas on the arrangement and layout of the thesis. To him my message is "Kasina, you are not a grandfather at all, but a friend indeed". During thesis writing I shared an office with Alexander Tupitsa, Hong Chin Goh and Lisa Oberkircher, they made the office environment bearable. However, during the times when the house was full, I was in the minority and my vote counted to nothing. The ladies would not entertain my appeals for "one man two votes", even up to today! Hong Ching helped me a lot during the 10/12 miscommunication. I sincerely thank Makarius Mdemu for listening to the dry-runs, eventually they became moist!

Philosophy time was enjoyable during short breaks from long hours in the office both at CIMMYT and at ZEF. I would like to remember the endless discussions with colleagues, Shephard Siziba, Rene Capote Fuentes, and Franklin Simtowe. The Makoka family supported me during my last period of stay in Bonn, many thanks. Thanks also to colleagues in the 'ZEF Batch 2005' for keeping the stress levels normal, "you are all good crooks". I would also like to acknowledge support from my friends Mr and Mrs. Chingombe, Mr. and Mrs. Sibanda, Mr and Mrs. Mugumbate and Dr. and Mrs. Tagwirei. Dr. Tagwirei inspired and encouraged me; I can now explain our 'phylogeny'.

Finally, I would like to thank my parents for sending me to school. Sincere thanks go to Shylet (*informatics*), Julius *(broken bones*), Mrs. Kokera, Taka, Farai and my elder brothers who supported me in one way or another. Most importantly, I would like to thank my wife, Pauline Paidamoyo for the support and encouragement during the whole time I was working towards completing this work. To my son, Simbarashe Anthony (*tonaldo*) and daughter Makanaka Alyssandra (*mk*), well you have been a source of great encouragement to me, so I thank you very much.