Tillage and Residue Management Effects on Soil Aggregation, Soil Organic Matter Distribution and Yield in a Western Kenyan Cropping Systems with and without Soil Fauna Exclusion

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Department of Soil Quality

Wageningen, The Netherlands

By:

Tunsisa Taffe Hurisso

Supervisors: Prof. Dr. Lijbert Brussaard and Dr. Ron de Goede, Department of Soil Quality, Wageningen University, The Netherlands;
Dr. Mirjam Pulleman, CIMMYT, Mexico & Wageningen University, The Netherlands.
Dr. Bernard Vanlauwe, TSBF-CIAT, Nairobi, Kenya;
Dr. Johan Six, University of Davis, California, USA.

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Abstract

In Western Kenyan low input cropping systems, typical farming practices include soil tillage and the removal of crop residues. Such intensive cultivation and cropping has detrimental effects on the chemical, physical, and biological soil properties, especially due to decreasing soil organic matter (SOM) content and stable soil aggregation. The SOM content and soil structure of agricultural soils can be maintained through adjustment of the soil and crop management e.g. decreased soil disturbance and retention of crop residues. Besides direct positive effects of such adjusted management, also indirect effects on particularly soil structure are expected through e.g. increased populations of soil macrofauna. Macrofauna benefit from increased food availability due to residue retention and from the absence of tillage. The present research aimed to assess the effects of conventional tillage (CT) and zero tillage (ZT), both with and without residue retention on:

1. the abundance and diversity of soil macrofauna;
2. the amount and distribution of water stable soil aggregates and associated soil organic C, and the specific contribution therein of the soil macrofauna; and,
3. the crop yield with and without soil macrofauna exclusion (through the use of specific pesticides).

A field experiment was carried out in a long term tillage trial established in 2003 in Western Kenya. The treatments were tillage (CT) versus no-tillage (ZT) with and without crop residue retention in the field. Where crop residues were retained, those residues (maize stover at 2 t ha^{-1} dry weight) were incorporated into the soil in CT whereas in ZT the residues were left on the surface. Mineral fertilizer input was similar for all treatments (60 kg N ha^{-1}), P, and K). Soil samples and soil macrofauna were taken from the experimental plots using monoliths at two depths (0-15 cm and 15-30 cm). Macrofauna abundance and diversity was determined as well as water stable aggregate size distribution (4 size classes), microaggregates within macroaggregates and C and N contents of the fractions).

Three major groups of macrofauna dominated: termites, ants and earthworms (the so-called ecosystem engineers). However, macrofauna abundance was low. Aggregate isolation and C analysis showed that ZT with residue retention had higher amounts of stable macroaggregates and associated C compared to CT with residue removal at both soil depths. Regression analysis did not show a clear relation between soil fauna numbers and aggregation. Therefore, the differences in soil aggregation may primarily be explained by direct management effects, e.g. OM inputs and/or mechanical soil disturbance. The crop yield data showed that pesticide application had a positive effect on maize yield. Neither the tillage nor the residue treatment significantly affected maize yield. However, an increase in maize yield over time was observed during four cropping seasons. Our study demonstrated that ZT and residue retention and possibly also soil macrofauna can significantly improve soil aggregation and C sequestration. Therefore, due to the expected positive long-term effects of these measures on this important (physical) soil quality parameter, we conclude that ZT and residue retention in low input arable cropping systems are recommended measures to farmers, when looking at it from a sustainable soil management point of view.

Key words: Soil aggregation, zero tillage, C-sequestration, Soil macrofauna, Low input cropping systems

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Dedication

This MSc. thesis is dedicated to:

My Dad, *Taffe Hurisso Kankesso*, and my Mom, *Helisse Hosha Galcha*

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Abbreviations

CIAT	International Center for Tropical Agriculture
cPOM	Coarse Particulate Organic Matter
CIMMYT	International Maize and Wheat Improvement Center
CT	Conventional Tillage
FAO	Food and Agricultural Organization
ICRAF	International Center for Research in Agroforestry
Large M	Large Macroaggregates (>2 mm)
mM	Microaggregates (53-250 μm) within Macroaggregates (>250 μm)
Small M	Small Macroaggregates (<250 μm)
SOM	Soil Organic Matter
TSBF	Tropical Soil Biology and Fertility Institute
WSA	Water Stable Aggregates
ZT	Zero Tillage

1. Introduction

Agriculture in sub-Saharan Africa is characterized by its poor productivity. Several factors related to soil fertility limit agricultural production. Many factors, such as soil type, farmer's practices, including crop residues and mineral fertilizer management, influence crop yields. The amount of soil organic matter (SOM) is often a major constraint to sustain a high crop production (Kushwaha et al., 2001). For instance, crop yields in large parts of Kenya are low due to declining soil fertility as a result of continuous cropping and non-application of fertilizers by farmers (Ayuke et al., 2004). In addition, the soils in this area are easily compacted and are prone to erosion. As soon as the vegetation cover is removed and the land intensively cropped with annual crops, the soils physical, chemical and biological properties are readily degraded (Sanchez et al., 1997). Nevertheless, in Africa there are numerous traditional practices using organic matter to maintain soil productivity. Therefore, analyzing their limitations and improving these practices is probably much more efficient than introducing new techniques adapted to other climatic and socio-economic conditions (Roose, 1996).

In tropical areas, the fertility of cultivated soil is maintained under traditional shifting cultivation but under demographic pressure and the accompanying more intensive land use, the duration of fallow diminishes, leading to a decrease in soil fertility and plant production (Topoliantz et al., 2002). The type of land use and soil cultivation are important factors in controlling organic matter storage in soils since it affects the amount and quality of litter input, the litter decomposition rates and the process of organic matter stabilization in soils (John et al., 2005). Soil structure and soil organic matter (SOM) content are considered important indicators of soil quality in agricultural soils (Pulleman et al., 2005) and are key factors in defining management practices for sustainable land use. SOM and soil structure determine to large extent soil erodibility, workability and the availability of water and nutrients to crops (Droogers et al., 1996, 1997). Both factors are strongly affected by farm management practices and are mutually related since SOM binds mineral particles in to stable aggregates and, in turn, stable aggregates can protect SOM against rapid decomposition (Pulleman et al., 2005; Pulleman & Marinissen, 2004; Jongmans et al., 2001). Aggregates are thought to physically protect SOM, by making it less accessible for further decomposition (Bossuyt et al., 2004).

Maintenance of SOM is crucial for the sustainable management of agroecosystems because of its important effects on nutrient dynamics and soil structure (Bossuyt et al., 2002). SOM improves soil structural stability, reduces surface crusting and compaction, and increases infiltration, percolation, and water holding capacity of the soil (Tisdall et al., 1993; Stevenson, 1994). Sequestration of C in soil is also becoming increasingly important because of the concern over global warming and rising levels of atmospheric CO_2 (Bossuyt et al., 2005). Soil is estimated to be the largest terrestrial pool of C, containing 1500 Pg or twice as much as the atmosphere (Sundquist, 1993; Schlesinger, 1997).

Since the start of large scale farming in the 20th century, conventional agriculture has caused large losses of SOM from cultivated land worldwide (Pulleman et al., 2004). During the last decades Conservation agriculture systems (based on the principles of no-tillage or minimal tillage and maintenance of a permanent soil cover) has been promoted, especially in the (sub) tropics. Higher SOM losses in conventional tillage (CT) systems when compared to no-tillage (NT) systems may be attributed to (I) reduced aggregate formation in CT in comparison with NT and (II) increased decomposition due to aggregate disruption in CT (Six et al., 1999) and (III) residues mixing and aeration of the soil upon ploughing enhances microbial activity. Six et al. (1999) suggested that both the level of aggregation and aggregate turnover (i.e., rate of formation and degradation of aggregates) influences SOM dynamics. An improvement of the level of soil aggregation is thought to play an important role in reducing decomposition losses of SOM under NT (Paustian et al., 1997). Therefore, management practices, that promote maintenance and accumulation of soil C, such as NT and reduced tillage, are increasingly adopted by farmers because of the growing interest in conservation of SOM (Bossuyt et al., 2002). No-tillage management, in combination with retention of crop residues at the soil surface, can also improve yields, either directly, through increased soil water infiltration and retention, or on the longer term through improvement of a range of physical, chemical, and biological soil characteristics (Paustian et al., 1997; Hendrix et al., 1998; Govaerts et al. 2005). Yield increases as well as the reduction in labor and production (e.g. fuel) costs can be an important benefit of NT systems, and are the most important reason for farmer adoption (Wall, 2005)

1.1 **Relationship between Soil Aggregates and SOM Dynamics**

Soil organic matter can be protected from microbial attack by adsorption to clay minerals (Oades, 1984; Ladd et al., 1985) or by isolation in soil micropores (Adu and Oades, 1978; Foster, 1981). These mechanisms are responsible for the physical protection of SOM within stable macroaggregates and micro aggregates (Edwards and Brenner, 1967; Gregorich et al., 1989; Besnard et al., 1996; Six et al., 2006b).

Various explanations have been proposed for the formation of soil aggregates. According to the hierarchical model proposed by Tisdall and Oades (1982), stable micro aggregates (<250µm) are bound together to form stable macroaggregates (>250µm) with organic compounds of different origin as inter-microaggregate binding agents (Elliott, 1986; Golchin et al., 1994b). Tisdall and Oades (1982) proposed the concept that organic matter addition to soils results first in the formation of SOM associations with clay and silt particles and with microaggregates (<250µm) and that microaggregates are bound into macroaggregates for example by networks of roots or fungal hyphae that are highly responsive to management practices. Oades (1984), however, suggested that macroaggregates do not just bind existing microaggregates together, but that new microaggregates are formed preferentially within the stable macroaggregates. Mucilage produced during decomposition of organic fragments inside the macroaggregate interacts with clay, which begins to encrust the organic fragment, eventually to an extent where the degradation of the organic material is retarded (Oades, 1984). Over time, the binding agents in macroaggregates degrade resulting in a loss of macroaggregate stability and the release of stable microaggregates, which become the building blocks of the next cycle of macro aggregate formation (Six et al., 2000). Because of the nature of the binding agents involved, macroaggregates are less stable than micro aggregates (Oades, 1984; Beare et al., 1994b) and consequently more susceptible to the disruptive forces induced by cultivation (Tisdall and Oades, 1980, 1982; Bossuyt et al., 2004). Microaggregates exhibit greater stability than macroaggregates and better protect SOM against microbial decay (Tisdall and Oades, 1982; Skjemstad et al., 1990). However, the formation of microaggregates within macroaggregates is negatively related to the rate of macroaggregate turnover and, therefore, indirectly affected by management factors such as tillage and residue management (Six et al., 2000; Denef et al., 2001).

1.2 **Role of Earthworms in Soil Structure, and SOM Dynamics**

Through their feeding activities and cast production, earthworms influence both aggregate turnover and SOM dynamics (Pulleman et al., 2005). By consuming plant remains and soil, earthworms play an important role in the incorporation of organic residues into the soil matrix (Pulleman et al., 2004) and formation of biogenic soil structures (Jongmans et al., 2003). These biogenic structures include stable macroaggregates that tend to be enriched in SOM compared with non-ingested soil, because earthworms ingest large amount of organic matter, mix it with inorganic soil material, pass this mixture through their guts' and excrete it as casts (Bossuyt et al.,2004). Therefore, earthworm casts contain more water-stable macroaggregates than surrounding soil (Bossuyt et al., 2004).

In addition, earthworms can also play an important role in the formation of micro aggregates (Bossuyt et al., 2004 Pulleman et al. 2004). Shipitalo and Protz (1989) and Barois et al. (1993) discovered that the soil's existing micro-structure is destroyed in the earthworm's gut and that during transit through the gut new microaggregates are formed. Dispersed clay is brought in intimate association with mucilage–coated, decomposing organic fragments and rearrangement into newly formed microaggregates that are excreted in casts. Jongmans et al. (2001) observed the incorporation of fine organic material in an early stage of decomposition into the micro-structure within worm casts. The formation of these stable microaggregates inside earthworm casts might be important in protecting labile soil organic matter (Bossuyt et al., 2004).

The activity of earthworms in agricultural soils depends strongly on management practices such as tillage, residue inputs and placement (*i.e.* incorporated or on the surface), manure additions and fertilizer and pesticide use (Pulleman et al., 2005). Therefore, differences in earthworm activity are expected to further enhance management effects on microaggregate formation and associated SOM stabilization (Pulleman et al., 2005).

1.3 Role of Termites and Ants in Soil Structure and SOM Dynamics

The relative activity and predominance of different types of soil fauna differ in different ecological regions (Lal, 1988). Lal (1988) further stressed that termites and ants are relatively more important in soils of the arid and semi-arid tropics, although they occur virtually in wide ecological regions. Especially in the Sahel, with very long dry seasons, termites play an important role in the decomposition process (Mando, et al., 1999).

Therefore, in semi-arid and arid regions, termites influence soil properties more than earthworms (Lal, 1988). They process a substantial proportion of plant litter produced, and are a major factor in soil turnover. In some other studies, it has been reported that the presence of dry vegetal material on structurally crusted soils can trigger termite activity and thereby improves water infiltration sufficiently to activate vegetation establishment (Mando et al., 1999). However, little information is available concerning the role of termites in relation to soil structure and SOM dynamics. Despite the fact that it is generally assumed that termites and ants may influence soil structure through physical disturbance or chemical alteration of the soil, and both insects are said to be active in forming and destroying soil aggregates, research projects have rarely investigated the influence of ants and termites on soil structure (Bruyn and Conacher, 1990). They mentioned in their review paper that most studies have given greater attention to primary particle size distribution than to soil structure. Bruyn and Conacher (1990) mentioned that only Pathak and Lehri (1959) and Sheikh and Kayani (1982) examined aggregate stability. However, their study was mainly confined to mounds in comparison to adjacent soils.

The organic matter content of termite mounds directly reflects the material used in their construction and vary in amount, since the different species of termites feed upon different sources of food (Lal, 1980). However, in general, there is a higher content of organic matter in termite mounds than in control soil. In addition to redistributing organic matter, termites are responsible for altering the C:N ratio (Bruyn and Conacher, 1990).

1.4 Improved Management Practices for Sustainable Soil Use

To be able to define management systems that would improve the SOM content, soil structure and yield of low input sustainable agriculture in arid and semiarid regions, a better understanding is needed of the effects of management practices on SOM-dynamics and the interactions with soil structure and soil macrofauna (Pulleman et al., 2005). Little is known about the effects of soil macrofauna activity on the dynamics of macroaggregates and associated SOM and the formation of microaggregates within macroaggregates (Pulleman, 2005). Earthworms can play an important role in protecting carbon in the soil (Bossuyt et al., 2004) but the exact influence of their activity on the distribution and protection of C under field conditions is still poorly understood. The effects of management on the interaction between biological activity and soil structure in relation to SOM storage have largely been ignored (Pulleman and

Marinissen, 2004). Moreover, conceptual models of management effects on SOM stabilization in aggregates do not consider the effects of soil macrofauna (Pulleman et al., 2005) on the interactions between SOM and soil structure, although it is well known that earthworms through their burrowing, consumption and excretion activities significantly enhance the incorporation of SOM in to the soil and the formation of macroaggregates. The effects of termites on soil aggregation and SOM under different management practices are even less understood.

The aim of this study was, therefore, to better understand the effects of tillage and organic residue management practices, on soil physical quality (aggregation), SOM storage and the overall interaction effect on crop yields in western Kenya cropping systems. Moreover, we aimed to address specifically the effects of management-induced changes soil macrofauna abundance and diversity on the soil aggregation, SOM distribution and yield. To achieve this target, a field experiment was conducted in Maseno (Western Kenya) during the long rainy season between mid March and mid August 2006. The research project took full advantage of a conservation tillage trial at Nyabeda site that was established by TSBF in 2003.

1.5 Study Objectives

The objectives of this experiment were to assess the effects of conventional and zero tillage, both with and without residue retention on:

1. The abundance and diversity of soil macrofauna

2. The size distribution of water stable soil aggregates, the amount of microaggregates within macroaggregates, and the specific contribution therein of the soil macrofauna

3. The amount and distribution of soil organic carbon in soil aggregate fractions and the specific contribution therein of the soil macrofauna

4. The crop yield with and without soil macrofauna exclusion

1.6 Hypotheses

The working hypothesis for this study was, "No tillage and residue retention positively affect soil macroaggregation and associated C & N stabilization". This can partly be attributed to the increase in soil macrofauna abundance and diversity resulting from effects of no tillage and residue retention (Fig. 1).

Specific Hypotheses

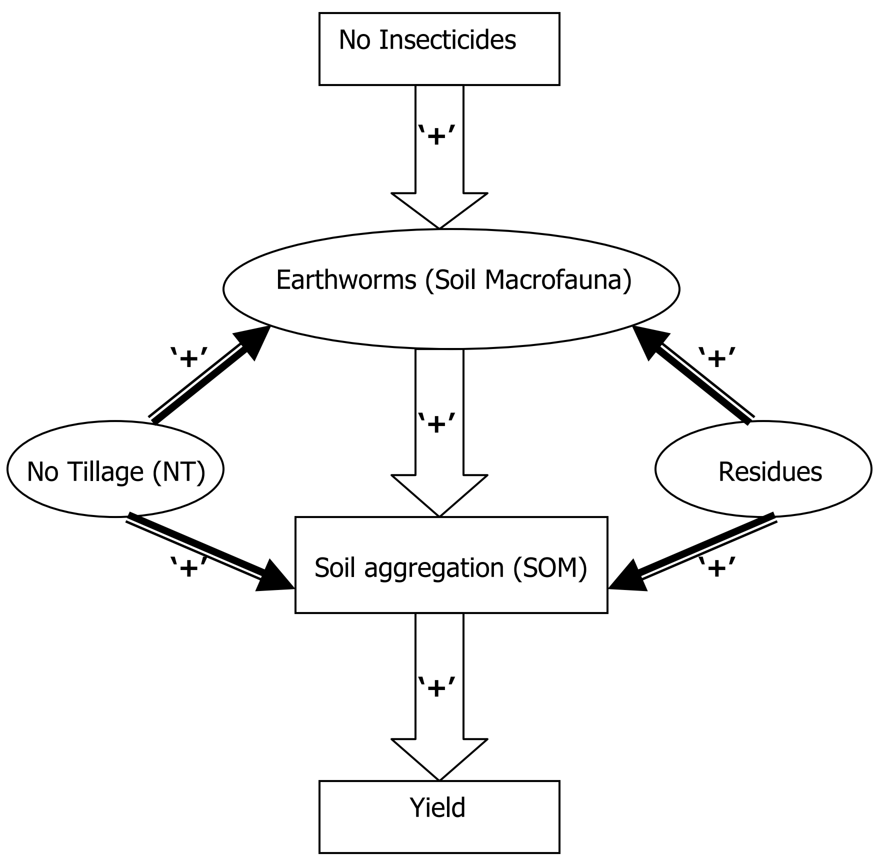
1. The absence of tillage and the retention of residues are expected to have a positive effect on the abundance and diversity of soil macrofauna. Therefore, higher numbers of different soil macrofauna groups are expected in zero tillage systems compared to conventional tillage systems when crop residues are retained (Relates to Objective 1).

2. Conventional tillage and residue removal, in contrast to zero tillage and residue retention, leads to a decline in the amount of SOM. This results in less formation and greater disruption of water stable macroaggregates Moreover, a further reduction in soil macroaggregate formation is expected due to the reduction or elimination of soil macrofauna activity through the regular application of insecticides (Relates to Objective 2).

3. Due to slower macroaggregate turnover under zero tillage compared to conventional tillage, especially when residues are retained, we expect a higher amount of microaggregates within macroaggregates when residues are retained, and under zero tillage. These microaggregates are expected to be largely responsible for any increased C-sequestration in zero tillage systems with residue retention, compared to conventional tillage systems or residue removal (Relates to Objective 2 and 3).

4a. A higher maize yield is expected with residue retention, especially under zero tillage. This is mainly due to enhanced water and nutrient availability in such systems through residue retention. On top of this, under zero tillage with residue retention, the soil surface is better protected against erosion and slaking thereby retaining water, C and nutrients which would be lost otherwise by runoff and soil erosion (Relates to Objective 4).

4b. Any increased crop yield with residue retention and zero tillage is partly explained by the presence of a larger and more diverse macrofauna population. The soil macrofauna facilitates the incorporation of crop residues in to stable aggregates and gradual decomposition and nutrient release. Together with the positive impact on water infiltration and retention through improved soil aggregation and porosity, soil fauna is expected to contribute to improved chemical and physical soil conditions that will lead to a higher crop yield (Relates to Objective 4).



'+': Effect of Management Factors

Figure 1. *Conceptual model depicts interrelationship between management factors (tillage and residues) and soil macrofauna activity as they all together affecting soil aggregation, SOM content, and ultimately crop yield in low input farming systems.*

2. Materials and Methods

2.1 Experimental Site Description

The Nyabeda research site, in western Kenya, is located at 0° 06' N and 34° 34' E and at an altitude of 1420 m.a.s.l. The mean annual rainfall is 1800mm. The rainfall is bimodal; with the long rains from March to August, and the short rains from September to January. The soil has been classified as Ferralsol (FAO, 1990) with an average particle size distribution of 63.6 % clay, 21.1 % silt and 15.2 % sand and with a low pH range of 4.7 to 5.3 in the plow layer, 0-20 cm depth. The site was under native vegetation dominated by grasses and shrubs before it has been converted into cultivation.

2.2 Experimental Design and Management

The field work was conducted in Maseno, where this conservation tillage trial was set up in 2003 by TSBF. The experimental design consists of tillage and residue treatments in a full factorial, completely randomized block design (CRBD) in plots of 4.5 m wide and 7 m long. A '+/-Insecticide' treatment was established in 2005 as a split-plot factor. Consequently, a combination of the treatments made up a factorial experiment: conventional and zero tillage treatments are combined with '+/- Residue' and '+/- Insecticide' treatments. The treatments were replicated four times. The present study was conducted during the 2006 long rains with the following treatments using maize (Zea mays L.) hybrid as the test crop:

1. Tillage: Conventional Vs. zero tillage. In zero tillage treatment, planting rows are prepared using simple tillage tools such as shovel, hand-hoe, and fork. Manual weeding (approx. up to 5 cm deep) is performed in the whole surface of the plots. Conventional tillage consisted of manual ploughing of the whole surface to about 15 cm depth, with similar tools before planting (seedbed preparation), at planting, and after planting depending on weed occurrence.

2. Organic Residue: Where residues are retained, 2 tons ha^{-1} maize Stover are incorporated, if tilled (CT), or left on the surface with zero tillage (ZT). The choice of residue (maize stover) was based on availability in the region for potential use by farmers.

Inorganic fertilizers at: 60 Kg N ha^{-1}, P, and K using Urea, Triple Super Phosphate (TSP), and Muriate of Potash (MOP) respectively, were applied to all treatments. The conservation tillage trial consisted of continuous maize, intercropping (maize-soybean), and rotation (soybean-maize) trials. In this study, soybean-maize rotation trials were chosen to study soil aggregation, SOM, and crop yield as affected by tillage and residue treatments. In soybean phase of the rotation, maize stovers are applied only in residue treatments before soybean planting in short rains. On the other hand, in maize phase of the rotation, soybean residues are applied in all treatments before maize planting in long rains.

2.3 **Macrofauna Exclusion Experiment**

Confined 'Insecticide' subplots were established to form macrofauna-free/reduced macrofauna subplots. The +insecticide plots were treated with Endocoton, with endosulfan 35% EC as the active ingredient (NRA, 1998), at a rate of 450g a.i/ha (approx. 0.9 l/ha.) to eliminate earthworms. Similarly, the insecticide Dursban with chlorpyrifos 44.6% w/w as the active ingredient (Brooks et al., 1973) was used at a rate of 400g a.i/ha (approx. 0.8 l/ha.) to eliminate termites. The plots were protected by metal sheets to separate insecticide treated plots from untreated ones. The insecticide application was started for the first time in 2005 during the short rainy season (between October and December). Also, the insecticides were applied four times during the long rainy season where the first, second, third and last applications were carried out in May 9, 30, June 20 and July 11 respectively, in 2006. The application rates of the insecticides were based on effect levels found in the study of Quedraogo (2004). The net area of microplots used for '+insecticide' treatment was set to be 3x4.5m. For macrofauna sampling, two rows of maize plants were excluded at each side of the plots in order to minimize any possible border effect (Annex 4).

2.4 **Macrofauna Collection and Analysis**

To sample the soil macrofauna, the TSBF methodology was used (Anderson and Ingram, 1993). Soil macrofauna was sampled in the long rainy season (July 26 and 27, 2006), three weeks after the last insecticide application. There were 2x2 treatments (tillage x residue) x 4 replicates. This made 16 plots and each plot was subdivided by an insecticide treatment (+/-) which made 2x16=32 experimental units. Two monoliths were taken from each experimental unit making the total monolith sampling 64. The monoliths were subdivided in to 0-15 and 15-30 cm sub-blocks and hand-sorted. The fauna from the two monoliths that were within-plot-replicates were bulked after sorting. The macrofauna specimens were put in plastic vials separately for each depth layer. In order to minimize any disturbance to the trial, after sorting the macrofauna and taking 500g representative soil samples, the remaining soil was returned to the same plot and same depth layer as it came from. In order to indicate where exactly the monolith samples were taken, the position of the monolith sample was measured relative to a fixed point in the filed and pegs were put as a reference.

Earthworms were first killed by 50% ethanol and later placed in 4% formalin while other fauna in 70% ethanol. After extracting the monolith, four plots (2 from '+Insecticide' and 2 from '-Insecticide') were chosen to determine abundance of endogeic earthworms at >30 cm soil depth. Endogeic earthworms were measured with formalin extraction (ISO, 2001). The formalin solution (approx. 0.5%) was prepared by diluting 25 ml formalin (37%) in 5 l distilled water and 10 l was added to each monolith hole. For 30 min, all fauna emerging from the sub-soil (i.e. <30 cm soil depth) was sampled. The identification of taxonomic groups was done at the Nairobi National Museum, Nairobi, Kenya using the species collection of the Museum. The abundance of each taxon was calculated to units of number per m^2.

2.5 **Aggregate Separation Steps**

The separation of aggregates into respective size classes was carried out at two steps according to the protocol developed by Six et al. (2000) and Elliott (1986). (Annex 3)

2.5.1 **Wet Sieving of Whole Soil**

Wet sieving was used to separate size classes of water-stable-aggregates (WSA) and determine their relative contribution to total soil weight. In the field, soil samples from the monolith were broken down along natural planes of weakness into natural aggregates to let pass through an 8 mm sieve and air-dried. The air dry soil material was separated into four WSA fractions through wet-sieving as described by Elliott (1986): A representative subsample of 80g was spread evenly onto a 2000 µm sieve, immersed in distilled water, and left for 5 minutes before starting the sieving process. Then, aggregates were separated by moving the 2000 µm sieve up and down by about 3 cm with 50 repetitions in 2 minutes. The aggregates >2000 µm were collected as large macroaggregates (large M) and the same sieving procedure was repeated for the 2000-250 µm fractions (small M) with the 250 µm sieve. Then, the fraction 250-53 µm was obtained by sieving with 53 µm sieves as free microaggregates.

The aggregates remained on top of each sieve were backwashed into labeled and pre-weighed containers and oven dried at 105^0C overnight before the final weight was measured. Soil materials which passed through 53 µm were determined by taking 300 ml sub-sample from the supernatant water of the whole volume after thoroughly shaking the suspension and were dried in the same way as done for the rest of the fractions. The weights were then corrected for the size of the sub-sample as compared to the whole volume and the fractions were recorded as free silt and clay.

2.5.2 **Micro-aggregate** (53-250 µm) **Isolation**

Sub-samples from small M and large M fractions were bulked to isolate microaggregates held within macroaggregates following the method described by Six et al. (2000). First, 10g of macroaggregates was taken from oven dried large M and small M proportional to their initial weight and mixed thoroughly. Then, 5g of the mixture was scooped and used for microaggregate isolation. A device (Microaggregate Isolator) was used to completely break up macroaggregates while minimizing the break down of the released microaggregates. The macroaggregates were immersed in distilled water on top of a 250 µm mesh screen and gently shaken with 50 metal beads (diameter=4mm). Continuous and steady water flow through the device ensured that microaggregates were immediately flushed onto a 53µm sieve and not further disrupted by the metal beads. After all the macroaggregates were broken up, the sand and coarse POM remained on the 250 µm sieve were washed off and collected. The material collected on the 53 µm sieve was sieved according to Elliott (1986) to ensure that the isolated microaggregates were water stable. Silt and clay fractions (<53 µm) were obtained by sub-sampling the supernatant water after measuring the total volume and gently shaking the suspension as done in protocol-A (wet-sieving). All the fractions; sand and coarse POM (>250 μm), microaggregate within macroaggregate (250-53 μm), and silt & clay (<53 μm) from the isolation step, were dried at 105^0C overnight in the oven before the final weight measurement was taken.

2.5.3 **Summary of Isolated Soil Fractions**

In total 7 soil fractions were isolated and investigated:

Macroaggregates

A1	Large macro aggregates	(LM)	(>2000 μm)
A2	Small macro aggregates	(SM)	(250-2000 μm)
B1	Sand and course POM	(LM+SM (POM))	(>250 μm)
B2	Micro-aggregates within macroaggregates	(LM+SM (mM))	(53-250 μm)
B3	Silt and clay	(LM+SM (S+C) M)	(<53 μm)
	Free micro aggregates	(FmM)	(53-250 μm)
	Free silt and clay	(FSC)	(<53 μm)

N.B (A1 and A2 mixed together and later separated in to B1, B2 and B3)

2.6 **Other Soil Physical and Chemical Analysis**

The gravimetric soil moisture content for all plots was determined at the time of soil sampling following the procedure in the handbook of methods described by Anderson and Ingram (1993). The carbon and nitrogen for the whole soil and the seven soil fractions from wet-sieving and isolation steps, were measured using Europass Spectrometer Coupled to CHN combustion Analyzer via Finnegan's Conflo II Interface at the University of Davis, California, USA.

2.7 **Crop Yield Determination and Harvest Index**

Cob-yield, Stover-yield, and Grain-yield were measured at the time of harvest. The dry-matter yield of the test plant was measured after sun drying. The Grain-yield was measured after oven drying in order to maintain a constant grain moisture in order to avoid weight fluctuations. Grain yield was calculated from total biomass at harvest multiplied by a harvest index (Unstressed harvest index) defined as the ratio of yield to biomass for a crop without stress. Harvest indices vary based on crop/cultivar sensitivity to water stress during flowering and grain filling. Unstressed harvest index value for maize is within a range of 0.40 to 0.55.

2.8 **Statistical Analysis**

All data were tested for normal distribution and homogeneity of variances (Levene's test), and when appropriate, were log or square-root transformed for aggregate data and macrofauna abundance, respectively.

Then, all statistical tests were performed using SPSS statistical package version 12.0 (SAS institute, 1997) using a model that specified the full factorial combination of tillage and residue treatments with the insecticide treatment nested within the tillage and residue treatments. The main and interaction effects of tillage and residue treatments were tested using linear mixed models, whereas the main effect of insecticide application was tested using a nested model within the linear mixed models. Differences between the treatment groups were examined using One-Way ANOVA at a significance level (α) of $P<=0.05$; with means separation using Post Hoc Multiple Comparisons (Tukey HSD test). Linear regression analysis was performed to test for correlations between aggregate size fractions and soil-aggregate C-concentrations, and also to test correlations between soil macrofauna abundance and aggregate size fractions.

3. **Results**

3.1 **Soil Macrofauna Abundance and Diversity**

More than ten major groups of fauna were recovered from a total of 64 monolith samples taken at two soil depths (table 1). The most abundant groups of fauna recovered were termites and ants followed by 'other' soil fauna (all soil fauna except termites, ants and earthworms). When expressed on an individuals m-2 basis, 45.4% of the soil fauna were termites, 31.2% ants, 4.4% earthworms, and 2.4% spiders. The remaining macrofauna were *Isopoda, Coleoptera, Hemiptera, Chilopoda, Diplopoda/Geophilomorpha, Diplopoda/Polyzonida, Lepidoptera, and Dermaptera.* Some other specimens of smaller organisms commonly not considered as macrofauna were also found: for example, Collembola (springtails).

All the earthworm samples were juveniles and it was difficult to identify them beyond the family level. The termites belonged to the *Termitidae* family and *Macrotermitidae* sub-family. *Pseudocanthotermes sp*. was the most abundant genus from this sub-family and was found in all treatments. Moreover, some other genera *(Microtermes sp.,* and *Pseudocanthotermes militaris)* that belong to the *Microtermitidae* subfamily were recorded, but their density was low. In our study, *Formicinae* was the dominant subfamily in the ant specimens followed by *Ponerinae* and *Myrmicinae*. From these subfamilies, four genera were identified: *Technomyrmex sp.* followed by *Dorylus sp. Hypoponera sp.* and *Euponera sp.* From the spiders (Aranae/Agriopidae), only *Araneus diademata* was identified. The 'other' soil fauna could not be identified beyond the orders.

Table 1. *Soil macrofauna groups (diversity) sampled from Nyabeda, Western Kenya, following the TSBF methodology and identified in the National Museum of Nairobi, Kenya.*

Taxon and Common Name	Depth			
	0-15 cm		15-30 cm	
	'-Insecticide'	'+Insecticide'	'-Insecticide'	'+Insecticide'
Isoptera (Termites)	+++	++	+++	++
Formicidae (Ants)	+++	++	+++	++
Oligochaeta (Earthworms)	+	-	+	+
Aranae (Spiders)	++	++	++	-
Isopoda	++	++	++	+++
Coleoptera (Larvae)	+	+	+	+
Hemiptera	-	+	+	-
Chilopoda/Geophilomorph (Centipedes)	-	+	+	+
Diplopoda/Polyzonida (Millepedes)	-	+	-	-
Lepidoptera (Larvae)	-	+	-	-
Collembola (Springtails)	-	+	-	+
Dermaptera/Forficulidae (*Kaiscella spp*)	-	-	-	-

The (+++), (++) and (+) symbols indicate abundant, less abundant and rarely abundant taxon respectively. The (-) indicates the absence of the taxon from that particular depth and insecticide treatment

Table 2. *Macro fauna abundance (No. per m²) at 0-15 cm soil depth as affected by tillage, residue and insecticide treatments. Sampled three weeks after the last insecticide application was carried out. (n=4) July, 2006.*

Depth	Treatment			Earthworms		Termites		Ants		Other fauna	
	Tillage	Residue	Insecticide	**Abundance (No./m2)**							
0-15 cm	**+**	-	+	0.0(0.00)		28.0(4.00)		8.0(4.62)		24.0(10.3)	
	+	-	-	12.0(7.66)		148.0(112)		92.0(86.8)		8.0(4.62)	
	+	+	+	0.0(0.00)		44.0(44.0)		36.0(36.0)		36.0(17.7)	
	+	+	-	12.0(12.0)		108.0(55.2)		76.0(70.8)		20.0(4.00)	
	-	-	+	0.0(0.00)		28.0(16.5)		136.0(136)		0.0(0.00)	
	-	-	-	4.0(4.00)		56.0(15.3)		32.0(21.7)		4.0(4.00)	
	-	+	+	0.0(0.00)		8.0(8.00)		0.0(0.00)		24.0(19.0)	
	-	+	-	12.0(12.0)		32.0(14.6)		164.0(159)		36.0(30.9)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	0.146	0.705	0.786	0.384	0.000	1.000	3.403	**0.077**
Residue			1	0.000	1.000	1.299	0.266	0.370	0.549	4.530	**0.044***
Tillage x Residue			1	0.146	0.705	0.144	0.707	0.164	0.689	0.503	0.485
Insecticide (Tillage x Residue)			4	1.390	0.267	1.684	0.186	0.678	0.614	0.342	0.847

Values in parenthesis are standard errors. S.V=Source of variation, df=degrees of freedom, an asterisk (*) indicates a significance difference (P≤0.05). Abundances were square root transformed before statistical analysis.

Table 3. *Macrofauna abundance (No. per m²) at 15-30 cm soil depth as affected by tillage, residue and insecticide treatments. Sampled three weeks after the last insecticide application was carried out. (n=4) July, 2006.*

Depth	Treatment			Earthworms		Termites		Ants		Other fauna	
	Tillage	Residue	Insecticide	**Abundance (No./m2)**							
15-30 cm	**+**	-	+	0.0(0.00)		20.0(15.1)		0.0(0.00)		28.0(16.5)	
	+	-	-	28.0(12.0)		8.0(4.62)		80.0(41.8)		16.0(16.0)	
	+	+	+	4.0(4.00)		24.0(15.3)		48.0(42.8)		56.0(32.3)	
	+	+	-	8.0(4.62)		36.0(21.0)		4.0(4.00)		40.0(34.8)	
	-	-	+	0.0(0.00)		192.0(151)		0.0(0.00)		36.0(13.7)	
	-	-	-	16.0(16.0)		188.0(128)		16.0(9.24)		0.0(0.00)	
	-	+	+	4.0(4.00)		32.0(32.0)		4.0(4.00)		4.0(4.00)	
	-	+	-	4.0(4.00)		80.0(36.4)		28.0(22.9)		12.0(4.00)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	2.341	0.139	1.728	0.201	0.740	0.398	0.279	0.602
Residue			1	0.146	0.705	0.432	0.517	0.082	0.777	0.279	0.602
Tillage x Residue			1	0.585	0.452	0.768	0.390	0.329	0.572	0.279	0.602
Insecticide (Tillage x Residue)			4	3.439	**0.023***	0.840	0.513	2.507	**0.069**	2.163	0.104

Values in parenthesis are standard errors. S.V=Source of variation, df=degrees of freedom, an asterisk (*) indicates a significance difference (P≤0.05). Abundances were square root transformed before statistical analysis.

Neither tillage nor the residue treatment had a significant effect on earthworm, termites, and ants' abundance at 0-15 and 15-30 cm soil depth. On the other hand, the residue effects on the abundance of 'other' soil fauna were statistically significant (P=0.044) at 0-15 cm depth. When residue was kept in the field, the mean value for 'other' soil fauna was three times bigger (29 individuals/m^2) when compared to the without residue treatment (9 individuals/m^2, Table 2). Regarding the effects of insecticide application, only at 15-30 cm soil depth, the effect of insecticide treatment on the earthworm abundance was statistically significant (P=0.023, Table 3). The number of earthworm juveniles was reduced from 12 to 2 individuals/m^2 in '-Insecticide' and '+Insecticide' treatments, respectively. There was also a marginally significant (P=0.069) insecticide effect on the abundance of ants. Insecticide application reduced the number of ants from 32 to 13 individuals/m^2 in '-Insecticide' and '+Insecticide' treatments, respectively.

3.2 **Size Distribution of Aggregates** (0-15 cm soil depth)

Table 4. *Aggregate size distribution (g dwt 100 g^{-1} soil) after wet-sieving as affected by tillage, residue and insecticide treatments at 0-15 cm soil depth. Values in parenthesis are standard errors. (n=4). July 2007.*

Treatment				Large Macroaggregates		Small Macroaggregates		Free Microaggregates		Free Silt and Clay	
Tillage	Residue	Insecticide		>2000µm		250-2000µm		53-250µm		<53µm	
+	-	+		3.7(0.68)		37.6(2.03)		43.7(2.15)		8.6(0.84)	
+	-	-		3.2(0.28)		41.2(2.55)		42.2(2.29)		8.0(0.86)	
+	+	+		6.2(1.76)		39.8(0.83)		40.4(1.36)		7.4(0.51)	
+	+	-		6.7(0.63)		38.8(2.24)		40.3(1.71)		8.9(0.58)	
-	-	+		11.2(3.25)		42.5(1.44)		33.9(3.39)		7.2(0.79)	
-	-	-		10.0(2.03)		41.8(4.07)		33.7(3.16)		10.1(2.15)	
-	+	+		8.5(0.35)		44.9(1.10)		33.8(1.07)		7.2(0.29)	
-	+	-		8.2(1.32)		43.1(1.89)		35.1(1.02)		7.6(1.11)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	21.598	**0.000***	5.437	**0.028***	23.556	**0.000***	0.085	0.773
Residue			1	2.202	0.151	0.341	0.565	0.386	0.540	0.883	0.357
Tillage x Residue			1	6.247	**0.020***	0.396	0.535	1.097	0.305	0.616	0.440
Insecticide (Tillage x Residue)			4	0.167	0.953	0.453	0.769	0.099	0.982	1.306	0.296

S.V=Source of variation, df=degrees of freedom, (+/-) symbols refer to with and without respectively, tillage, residue and insecticide treatments. An Asterisk (*) indicates a significance difference at P≤0.05. Log transformed values of large M (>2000µm) were used for statistical analysis.

In the top 15 cm soil depth, CT significantly reduced the amount of large M (>2000 µm) and small M (250-2000 µm) compared to ZT (Table 4). Consequently, larger amounts of free microaggregates (53-250 µm) were found in the CT treatments. The negative effect of tillage on large macroaggregates was somewhat reduced when residue was kept in the field, although not significantly (Fig 2). Residue application did not affect the small M and free microaggregate fractions.

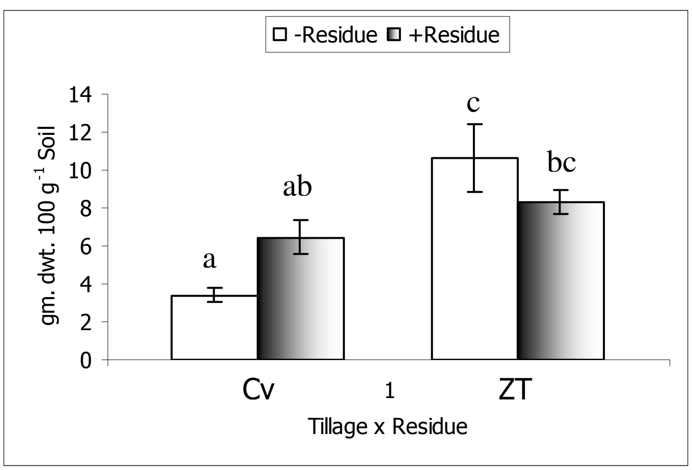


Figure 2. *Effect of tillage and residue on the fraction of large macroaggregates at 0-15 cm soil depth. Cv=conventional tillage and ZT=zero tillage. dwt=dry weight. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

3.3 **Size Distribution of Aggregates** (15-30 cm soil depth)

Table 5. *Aggregate size distribution (g dwt 100 g^{-1} soil) after wet-sieving as affected by tillage, residue and insecticide treatments at 15-30 cm soil depth. Values in parenthesis are standard errors. (n=4), July 2007.*

Treatment				Large Macroaggregates		Small Macroaggregates		Free Microaggregates		Free Silt and Clay	
Tillage	Residue	Insecticide		>2000µm		250-2000µm		53-250µm		<53µm	
+	-	+		25.8(2.23)		42.4(1.78)		23.0(2.45)		5.5(0.65)	
+	-	-		25.2(2.25)		45.1(0.86)		19.9(2.24)		4.4(0.27)	
+	+	+		19.9(2.23)		49.6(0.37)		20.7(1.89)		5.5(0.92)	
+	+	-		20.4(0.89)		46.8(0.69)		24.1(1.04)		5.0(0.43)	
-	-	+		32.3(6.00)		45.0(1.70)		16.3(3.77)		3.2(0.61)	
-	-	-		25.3(2.44)		51.0(1.40)		15.6(1.82)		2.5(0.38)	
-	+	+		27.9(3.75)		47.3(1.31)		16.1(2.58)		3.4(0.34)	
-	+	-		27.1(2.33)		45.0(1.28)		20.7(1.97)		4.3(0.55)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	6.437	**0.018***	1.653	0.211	8.364	**0.008***	20.847	**0.000***
Residue			1	2.231	0.148	2.103	0.160	1.041	0.318	2.773	0.109
Tillage x Residue			1	1.632	0.214	12.642	**0.002***	0.235	0.633	0.708	0.408
Insecticide (Tillage x Residue)			4	0.463	0.762	4.452	**0.008***	0.974	0.440	1.164	0.351

An asterisk (*) indicates a significance difference at P≤0.05. df=degrees of freedom, S.V=Source of variation, (+/-) symbols indicate with and without respectively, tillage, residue, and insecticide treatments. Log transformed values of large M (>2000µm) were used for statistical analysis.

At 15-30 cm soil depth, tillage significantly reduced the amount of large macroaggregates only (Table 5). As a consequence, tillage positively affected the amount of free microaggregates, and free silt & clay. The fractions of small macroaggregates increased when residues were maintained in conventional tillage (Fig 3). When compared without residue retention, the amount of small macroaggregates was higher in zero tillage than conventional tillage (Fig. 3).

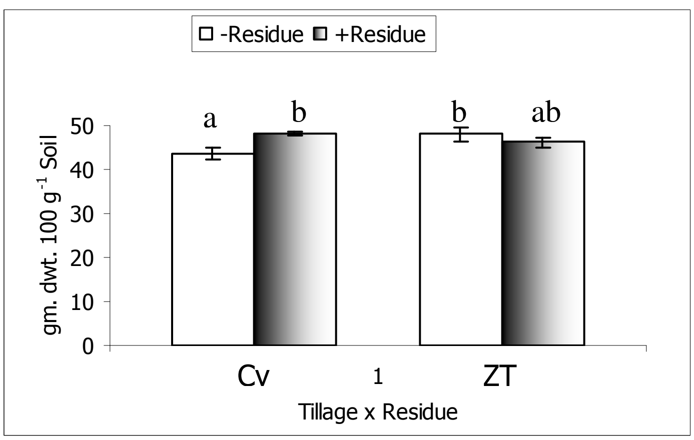


Figure 3. *Effect of tillage and residue on the fraction of Small Macroaggregates at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Treatments with different letters indicate statistically significant difference at P≤0.05.*

3.4 **Macroaggregate Composition** (0-15 cm soil depth)

Table 6. *Amount (g dwt 100 g^{-1} macroaggregates) of cPOM + coarse sand, microaggregates, and silt and clay fractions within macroaggregates (large and small aggregates combined) at 0-15 cm soil depth. (n=4) July 2007.*

Treatments				Macroaggregate		Coarse Sand + cPOM		Microaggregates		Silt and Clay	
Tillage	Residue	Insecticide		(Large M + Small M)		>250µm		53-250µm		<53µm	
				% Macroaggregate Basis							
+	-	+		28.7(2.74)		12.6(0.87)		65.7(0.99)		17.0(1.29)	
+	-	-		36.1(2.74)		8.3(2.54)		70.0(2.15)		17.5(1.26)	
+	+	+		35.8(3.64)		10.3(1.87)		66.2(1.49)		20.9(2.32)	
+	+	-		34.3(2.49)		11.2(0.49)		59.7(2.30)		26.3(1.59)	
-	-	+		44.5(4.44)		9.2(0.80)		61.7(2.40)		25.7(2.32)	
-	-	-		42.3(4.85)		9.4(0.83)		63.1(1.94)		23.8(2.17)	
-	+	+		45.0(1.45)		8.4(0.71)		64.7(1.31)		23.0(1.55)	
-	+	-		41.0(1.65)		10.3(1.65)		68.8(3.07)		18.0(1.63)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	17.514	**0.000***	1.652	0.211	0.323	0.575	2.904	0.101
Residue			1	0.248	0.623	0.035	0.853	0.036	0.851	0.685	0.416
Tillage x Residue			1	0.462	0.503	0.013	0.912	10.027	**0.004***	17.130	**0.000***
Insecticide (Tillage x Residue)			4	0.950	0.453	1.431	0.254	2.356	0.082	2.198	0.100
						% Total Soil Basis					
+	-	+				5.2(0.42)		27.1(1.88)		6.9(0.23)	
+	-	-				3.8(1.21)		30.9(1.37)		7.8(0.71)	
+	+	+				4.7(0.77)		30.5(1.72)		9.7(1.29)	
+	+	-				5.1(0.29)		27.3(2.17)		11.9(0.69)	
-	-	+				4.9(0.29)		33.1(1.06)		14.1(2.26)	
-	-	-				4.8(0.29)		32.6(2.79)		12.3(1.94)	
-	+	+				4.5(0.35)		34.6(1.33)		12.3(0.72)	
-	+	-				5.3(0.90)		35.2(1.73)		9.2(0.73)	
S.V			df			**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1			0.153	0.700	14.487	**0.001***	12.839	**0.001***
Residue			1			0.246	0.624	0.565	0.459	0.408	0.529
Tillage x Residue			1			0.132	0.719	0.758	0.393	13.512	**0.001***
Insecticide (Tillage x Residue)			4			0.828	0.520	0.968	0.443	1.803	0.161

An asterisk (*) indicates a significance difference at $P\leq0.05$. S.V=Source of variation, df=degrees of freedom. (+/-) symbols indicate with and without respectively, tillage, residue and insecticide treatments. The macroaggregates (large M + small M) are sand corrected. The numbers in the parentheses are standard errors.

At 0-15 cm depth, no significant effect of none of the factors on cPOM (coarse sand + coarse cPOM) was found. The fractions of sand corrected macroaggregates were higher in ZT compared to CT (Table 6). When expressed on a per unit macroaggregate weight basis, the fraction of microaggregates within macroaggregates was higher in CT when residues were not present (Fig. 4). In zero tillage, the fractions of microaggregates within macroaggregates had increased when residues were maintained (Fig. 4). When expressed on a whole soil weight basis, however, only the effect of tillage on microaggregates within macroaggregates was significant. The fractions of microaggregates within macroaggregates were higher in ZT compared to CT.

At 0-15 cm soil depth, residue retention increased the fractions of silt and clay (expressed on per unit macroaggregate weight basis) within macroaggregates in conventional tillage compared to without residue treatment (Fig. 5). When compared without residue retention, the fractions of silt and clay within macroaggregates were higher in zero tillage than conventional tillage (Fig. 5). When expressed on a total soil basis (Fig. 6), the results on the silt and clay fractions within macroaggregates were similar to the above described observations on per unit macroaggregate weight basis.

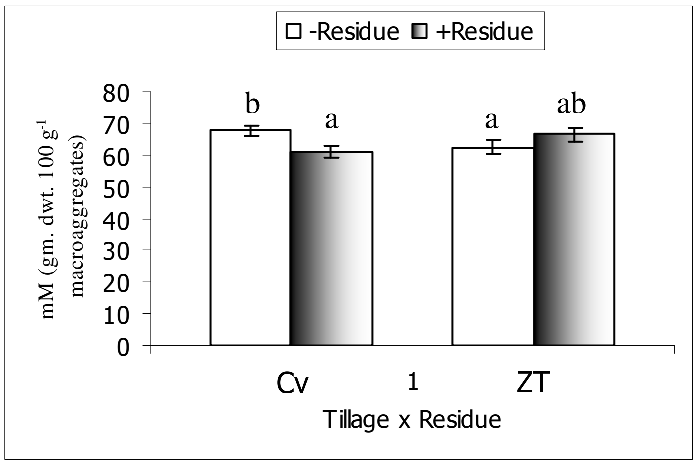


Figure 4. *Effect of tillage and residue on the fractions of microaggregates within macroaggregates (expressed on per unit macroaggregate weight basis) at 0-15 cm depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

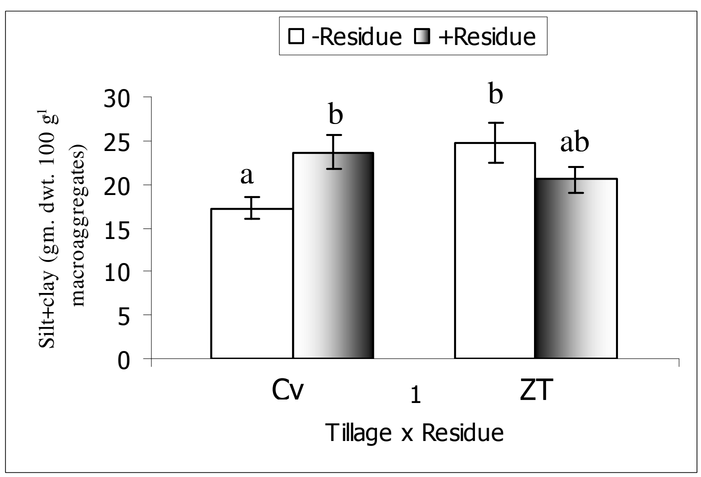


Figure 5. *Effect of tillage and residue on the fractions of silt and clay within macroaggregates (expressed on per unit macroaggregate weight basis) at 0-15 cm depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

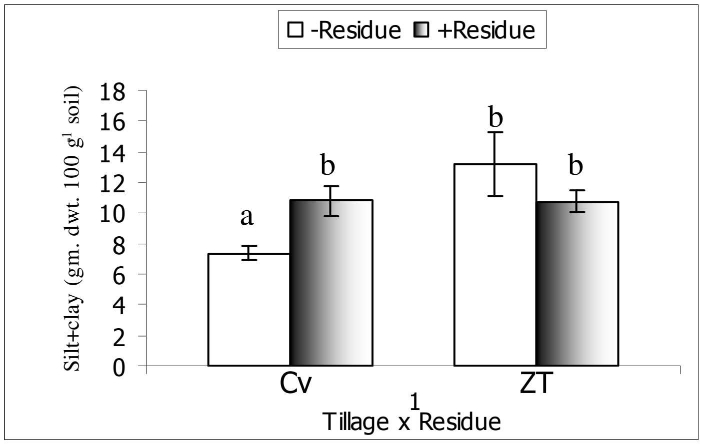


Figure 6. *Effect of tillage and residue on the fractions of silt and clay within macroaggregates (expressed on a total soil weight basis) at 0-15 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference (P≤0.05).*

3.5 **Macroaggregate Composition** (15-30 cm soil depth)

Table 7. *Amount (g dwt 100 g^{-1} macroaggregates) of cPOM + coarse sand, microaggregates, and silt and clay within macroaggregates (large and small aggregates combined) at 15-30 cm soil depth. (n=4) July 2007.*

Treatments				Macroaggregate		Coarse Sand + cPOM		Microaggregates		Silt and Clay	
Tillage	Residue	Insecticide		(Large M + Small M)		>250µm		53-250µm		<53µm	
				% Macroaggregate Basis							
+	-	+		62.5(4.05)		5.4(1.07)		59.1(1.58)		32.5(1.49)	
+	-	-		64.5(3.20)		5.8(0.91)		56.3(2.99)		35.0(3.03)	
+	+	+		64.5(2.63)		5.1(0.45)		62.2(0.73)		28.0(0.94)	
+	+	-		60.6(1.62)		6.6(0.49)		62.9(0.87)		27.4(0.94)	
-	-	+		71.4(4.74)		5.9(0.58)		23.1(2.26)		68.0(2.71)	
-	-	-		72.3(2.30)		4.0(0.35)		49.7(2.65)		42.4(2.88)	
-	+	+		70.3(3.06)		5.0(0.40)		43.2(3.37)		48.8(3.68)	
-	+	-		66.9(2.24)		5.2(1.04)		55.5(2.15)		37.1(1.89)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	10.776	**0.003***	1.788	0.194	116.939	**0.000***	117.182	**0.000***
Residue			1	0.920	0.347	0.149	0.702	31.039	**0.000***	29.230	**0.000***
Tillage x Residue			1	0.281	0.601	0.020	0.890	6.427	**0.018***	3.339	0.080
Insecticide (Tillage x Residue)			4	0.407	0.801	1.443	0.251	21.273	**0.000***	17.318	**0.000***
						% Total Soil Basis					
+	-	+				3.5(0.59)		40.1(1.80)		22.1(1.81)	
+	-	-				4.0(0.56)		39.4(0.79)		24.8(2.85)	
+	+	+				3.5(0.23)		43.4(1.18)		19.5(1.18)	
+	+	-				4.4(0.30)		42.3(0.89)		18.4(0.65)	
-	-	+				4.5(0.46)		17.6(1.19)		52.8(4.34)	
-	-	-				3.0(0.24)		37.9(2.13)		32.4(2.51)	
-	+	+				3.6(0.24)		31.6(3.12)		35.8(3.62)	
-	+	-				3.8(0.73)		39.9(0.99)		26.8(1.89)	
S.V			df			**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1			0.185	0.671	63.179	**0.000***	71.984	**0.000***
Residue			1			0.011	0.918	21.511	**0.000***	18.125	**0.000***
Tillage x Residue			1			0.223	0.641	4.285	**0.049***	3.317	0.081
Insecticide (Tillage x Residue)			4			0.932	0.138	21.136	**0.000***	9.139	**0.000***

An asterisk (*) indicates a significance difference at P≤0.05. (+/-) symbols indicate with and without respectively, tillage, residue, and insecticide treatments. S.V=source of variation, df=degrees of freedom. The macroaggregates (large M + small M) are sand corrected. The numbers in the parenthesis indicate standard errors.

No significant effect of any of the treatments was found on the amount of cPOM (coarse sand + cPOM) at 15-30 cm depth (Table 7). The fractions of macroaggregates (sand corrected) were higher in ZT compared to CT (Table 7). The fraction of microaggregates within macroaggregates decreased after insecticide application, when expressed on per unit macroaggregate basis as well as whole soil basis (Table 7). Although it was not possible to test the interactions with insecticide treatments because of the experimental layout, it appeared that the negative effect of insecticide application only occurred in the ZT, and this effect was stronger when no residues were maintained.

At 15-30 cm depth, residue retention significantly increased microaggregates within macroaggregates in zero tillage when compared to the without residue treatment (Fig. 7). The results expressed on a total soil basis for microaggregates within macroaggregates were similar to those in per unit macroaggregate weight basis (Fig. 8). Consequently, residue removal resulted in higher fractions of silt and clay within macroaggregates (expressed per unit macroaggregate weight basis) in ZT (Table 7). For the results of slit and clay within macroaggregates expressed on a whole soil basis, similar trend was found to that of per unit macroaggregate weight basis (Fig. 9).

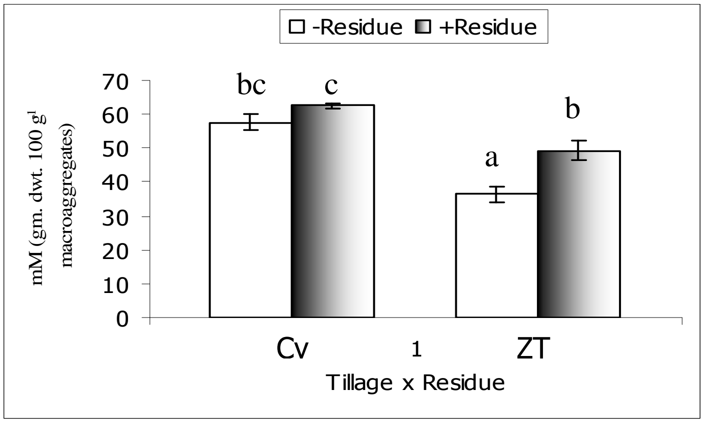


Figure 7. *Effect of tillage and residue on the fractions of microaggregates within macroaggregates (expressed on per unit macroaggregates weight basis) at 15-30 cm depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

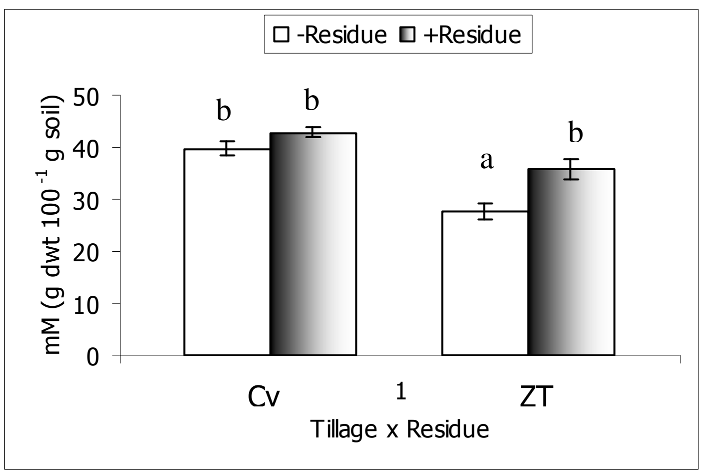


Figure 8. *Effect of tillage and residue on the fractions of microaggregates within macroaggregates (expressed on total soil basis) at 15-30 cm soil depth. Cv=conventional tillage and Zero=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

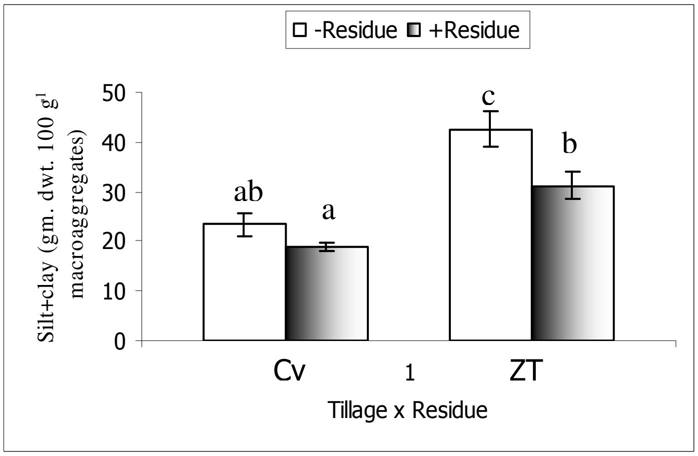


Figure 9. *Effect of tillage and residue on the fractions of silt and clay within macroaggregates (expressed on a whole soil weight basis) at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

3.6 **Relationship between Soil Macrofauna and Aggregate Size Distribution**

Only the regressions that were statistically significant are shown below:

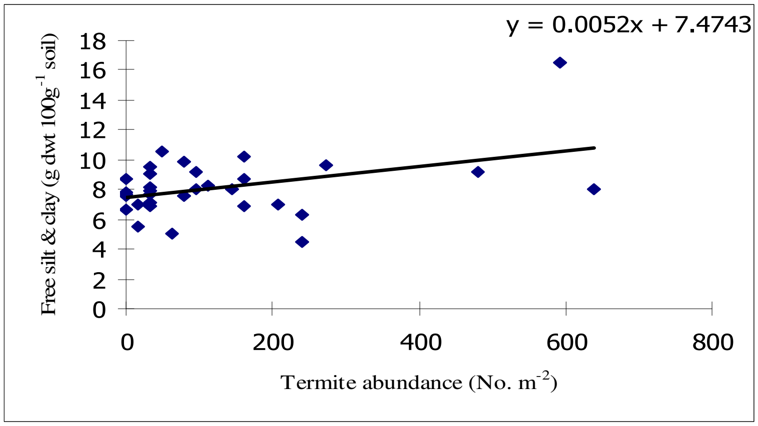


Figure 10. *Relationship between termite abundance and free silt and clay (<53µm; g dm 100 g-1 soil) at 0-15 cm soil depth under tillage, residue, and insecticide management. (r2=0.173, P=0.018, is statistically significant).*

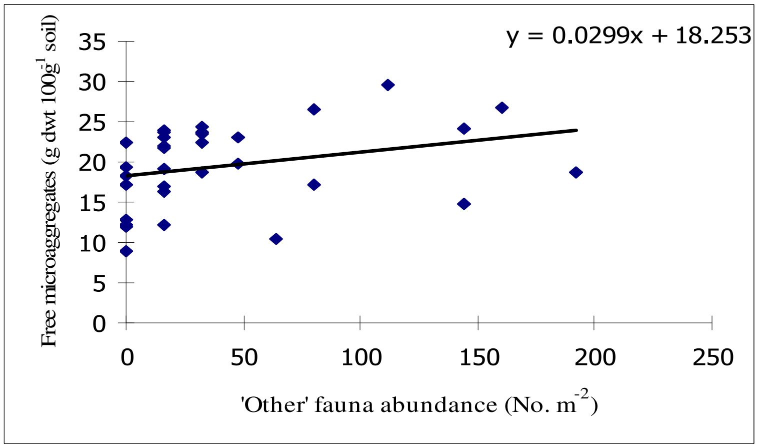


Figure 11. *Relationship between 'other' soil fauna abundance and free microaggregates (53-250µm) at 0-15 cm soil depth under tillage, residue, and insecticide management. (r2=0.094; P=0.088, marginally statistically significant).*

At 0-15 cm soil depth, termite numbers were positively related to the amount of free silt and clay fractions (Fig. 10). The abundance of 'other' soil fauna tended to have a positive relation with the quantity of free microaggregates (Fig. 11). A negative correlation was found between earthworm abundance and cPOM plus sand (Fig. 12 and Fig. 14, which might be explained by the tendency of earthworms to avoid coarse sand particles, as the cPOM by definition contains low OM when expressed in weight basis). A marginally significant, positive correlation, however, was found between earthworm abundance and the amount of microaggregates (53-250 µm) within macroaggregates (Fig. 13).

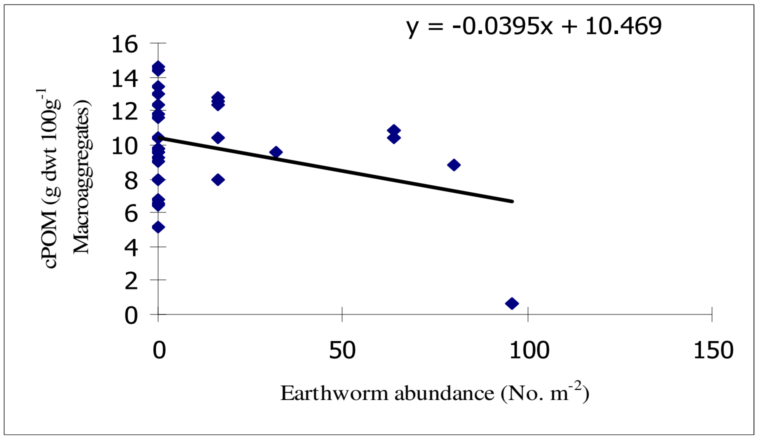


Figure 12. *Relationship between Earthworm abundance and cPOM (>250μm) at 0-15 cm soil depth under tillage, residue, and insecticide management. (r2=0.128, P=0.045, is statistically significant).*

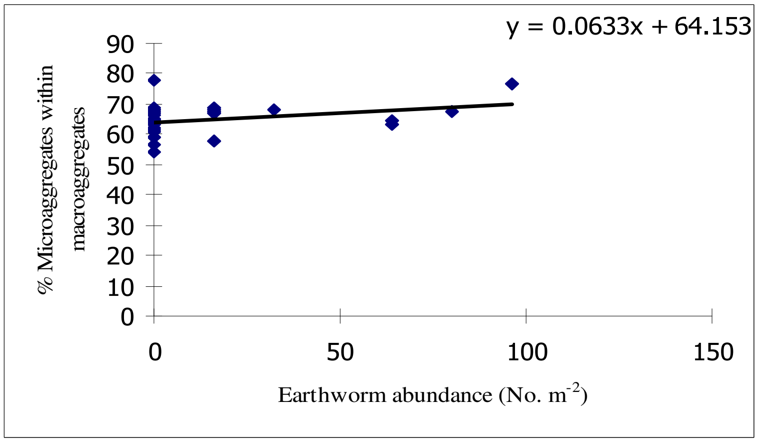


Figure 13. *Relationship between Earthworm abundance and microaggregates within macroaggregates (53-250μm) at 0-15 cm soil depth under tillage, residue, and insecticide management (r2=0.112, P=0.061, marginally statistically significant).*

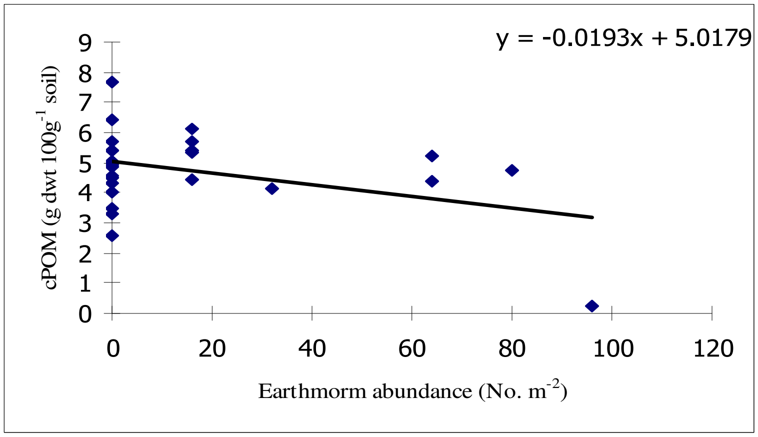


Figure 14. *Relationship between Earthworm abundance and cPOM (>250μm, per whole soil basis) at 0-15 cm soil depth under tillage, residue, and insecticide management (r2=0.1622, P=0.023, is statistically significant).*

3.7 **Soil Organic Carbon, Nitrogen and C:N ratio** (0-15 cm soil depth)

Table 8. *Effect of tillage, residue and insecticide management on the concentration of carbon and nitrogen in whole soil, and large M (>2000 µm) at 0-15 cm soil depth-after wet sieving. Numbers in brackets are standard errors. (n=4)*

Treatment				C (mg g^{-1})		N (mg g^{-1})		C : N	
Tillage	Residue	Insecticide		**Total Soil**					
+	-	+		20.4(0.47)		1.8(0.11)		12.2(0.11)	
+	-	-		20.2(0.46)		1.9(0.12)		12.1(0.05)	
+	+	+		20.4(0.41)		1.9(0.04)		11.9(0.08)	
+	+	-		19.9(0.23)		1.7(0.02)		12.1(0.09)	
-	-	+		20.2(0.21)		1.7(0.01)		12.2(0.07)	
-	-	-		20.3(0.04)		1.7(0.32)		11.9(0.17)	
-	+	+		21.1(0.51)		1.8(0.05)		12.1(0.12)	
-	+	-		21.3(0.61)		1.8(0.06)		11.9(0.13)	
S.V			df	F	P	F	P	F	P
Tillage			1	2.651	0.117	2.216	0.150	0.010	0.923
Residue			1	2.611	0.119	3.762	0.064	1.451	0.240
Tillage x Residue			1	3.846	**0.062**	2.352	0.138	0.238	0.630
Insecticide (Tillage x Residue)			4	0.198	0.937	0.388	0.815	0.841	0.513
				Large M (>2000µm)					
+	-	+		22.1(0.20)		1.8(0.04)		12.5(0.22)	
+	-	-		21.1(1.37)		1.8(0.16)		11.5(0.20)	
+	+	+		20.7(0.50)		1.8(0.05)		11.3(0.19)	
+	+	-		19.5(1.07)		1.7(0.09)		11.2(0.16)	
-	-	+		20.8(0.32)		1.8(0.04)		11.6(0.21)	
-	-	-		20.1(0.74)		1.7(0.05)		11.7(0.20)	
-	+	+		21.4(0.93)		1.8(0.08)		11.8(0.29)	
-	+	-		21.2(0.46)		1.8(0.05)		11.8(0.22)	
S.V			df	F	P	F	P	F	P
Tillage			1	0.004	0.950	0.119	0.733	0.341	0.565
Residue			1	0.339	0.566	0.034	0.856	3.936	0.059
Tillage x Residue			1	4.205	**0.051***	0.445	0.511	7.004	**0.014***
Insecticide (Tillage x Residue)			4	0.603	0.664	0.380	0.821	2.622	0.060

An (*) indicates a significance difference ($P \leq 0.05$). (+/-) symbols refer with/without respectively, tillage, residue, and insecticide treatments. S.V=source of variation. df=degrees of freedom.

At 0-15 cm soil depth, residue retention increased the C content in total soil in ZT (Table 8). Conventional tillage significantly reduced the C content in large macroaggregates even when residues were maintained (Fig. 15); where as in ZT, residue application increased the C content in large macroaggregates. A significant effect was observed of Conventional tillage –Residue + Insecticide application on the C:N ratio of macroaggregates compared to all other treatments (Table 8).

Regarding the small macroaggregates, the free microaggregates, and the free silt plus clay fractions no significant differences in C and N concentrations were observed between any of the treatments. However, a significant effects of tillage and/or residue management on the C:N ratio of those fractions occurred (Table 9). Again C:N ratios of the fractions tend to be higher when no residues are applied but more so in the conventional till treatment.

Table 9. *Effect of tillage, residue and insecticide management on the concentration of carbon and nitrogen in small M (250-2000 µm), free microaggregates (53-250 µm), and free Silt & Clay (<53 µm)-after wet sieving at 0-15 cm soil depth. Numbers in brackets are standard errors. (n=4)*

Treatment				C (mg g^{-1})		N (mg g^{-1})		C : N	
Tillage	Residue	Insecticide		**Small M (250-2000µm)**					
+	-	+		18.8(0.62)		1.5(0.04)		12.3(0.14)	
+	-	-		19.6(1.08)		1.6(0.11)		12.1(0.24)	
+	+	+		19.3(0.47)		1.7(0.04)		11.6(0.08)	
+	+	-		19.2(0.45)		1.6(0.05)		11.7(0.15)	
-	-	+		19.6(0.56)		1.7(0.04)		12.1(0.15)	
-	-	-		19.8(0.45)		1.6(0.03)		12.0(0.17)	
-	+	+		20.2(0.90)		1.6(0.05)		12.3(0.14)	
-	+	-		20.1(0.68)		1.7(0.06)		12.1(0.11)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	1.917	0.179	0.545	0.468	2.365	0.137
Residue			1	0.147	0.705	1.276	0.270	3.503	0.074
Tillage x Residue			1	0.081	0.778	0.686	0.416	7.548	**0.011***
Insecticide (Tillage x Residue)			4	0.172	0.860	0.553	0.699	0.516	0.725
				Free Microaggregates (53-250µm)					
+	-	+		21.4(0.93)		1.8(0.07)		11.9(0.04)	
+	-	-		20.4(0.67)		1.8(0.07)		11.8(0.22)	
+	+	+		20.7(0.33)		1.8(0.06)		11.3(0.16)	
+	+	-		20.8(0.10)		1.8)0.02)		11.6(0.15)	
-	-	+		21.0(0.44)		1.7(0.01)		12.2(0.22)	
-	-	-		21.2(0.29)		1.8(0.02)		11.9(0.07)	
-	+	+		21.5(0.32)		1.9(0.02)		11.6(0.10)	
-	+	-		21.6(0.43)		1.9(0.02)		11.6(0.11)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	2.080	0.162	0.248	0.623	2.143	0.156
Residue			1	0.140	0.712	6.193	0.020	12.343	**0.002***
Tillage x Residue			1	0.796	0.381	0.688	0.415	0.000	1.000
Insecticide (Tillage x Residue)			4	0.470	0.757	0.468	0.759	0.986	0.434
				Free Silt & Clay (<53µm)					
+	-	+		23.3(0.16)		2.1(0.03)		11.2(0.22)	
+	-	-		24.2(0.57)		2.1(0.09)		11.4(0.27)	
+	+	+		23.8(0.80)		2.3(0.12)		10.3(0.23)	
+	+	-		22.5(0.58)		2.1(0.06)		10.7(0.19)	
-	-	+		23.9(0.65)		2.2(0.04)		10.9(0.10)	
-	-	-		24.5(1.08)		2.2(0.04)		11.1(0.46)	
-	+	+		24.0(0.48)		2.3(0.07)		10.5(0.37)	
-	+	-		23.2(0.45)		2.2(0.09)		10.9(0.48)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	1.031	0.320	0.585	0.452	0.016	0.902
Residue			1	1.775	0.195	1.830	0.189	7.045	**0.014***
Tillage x Residue			1	0.002	0.967	0.585	0.452	0.826	0.372
Insecticide (Tillage x Residue)			4	1.073	0.392	1.318	0.292	0.385	0.817

An (*) indicates a significance difference ($P \leq 0.05$). (+/-) symbols refer with/without respectively, tillage, residue, and insecticide treatments. S.V=source of variation. df=degrees of freedom.

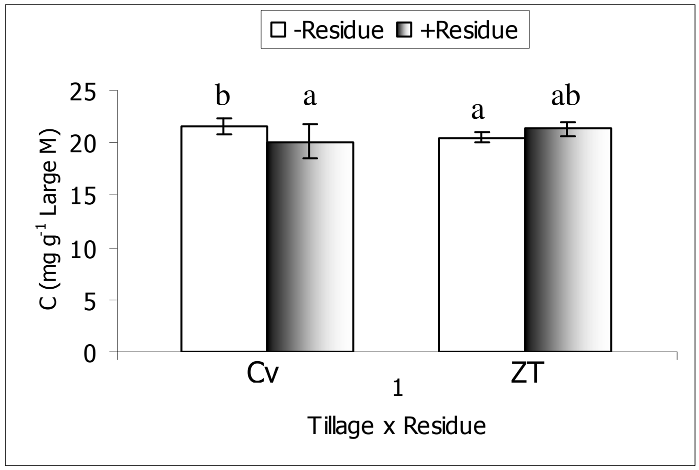


Figure 15. *Effect of tillage and residue on Carbon concentration in large M at 0-15 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

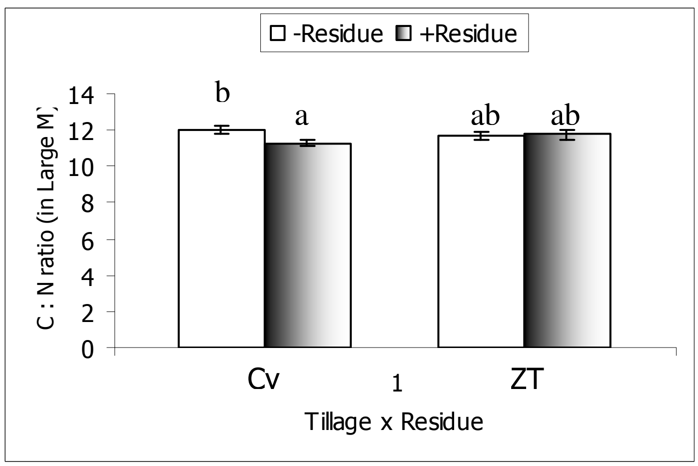


Figure 16. *Effect of tillage, residue, and insecticide management on C: N ratio in large M at 0-15 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

Table 10. *Effect of tillage, residue and insecticide management on the concentration of carbon and nitrogen in cPOM (>250 µm), microaggregates (53-250 µm), and Silt & Clay (<53 µm) within macroaggregates at 0-15 cm soil depth-after isolation. Numbers in brackets are standard errors. (n=4)*

Treatment				C (mg g^{-1})		N (mg g^{-1})		C : N	
Tillage	Residue	Insecticide		**cPOM (>250µm)**					
+	-	+		12.76(2.28)		0.89(0.23)		14.98(1.07)	
+	-	-		19.21(4.79)		1.60(0.48)		13.00(1.34)	
+	+	+		17.16(2.66)		1.42(0.27)		12.53(0.79)	
+	+	-		17.34(2.68)		1.44(0.24)		12.15(0.25)	
-	-	+		13.04(2.50)		0.74(0.07)		17.16(1.65)	
-	-	-		8.93(0.19)		0.62(0.02)		14.51(0.67)	
-	+	+		13.61(2.02)		0.86(0.08)		16.59(3.66)	
-	+	-		11.74(1.11)		0.86(0.11)		13.94(0.65)	
S.V			df	F	P	F	P	F	P
Tillage			1	6.782	**0.016***	10.867	**0.003***	5.441	**0.028***
Residue			1	0.646	0.429	2.649	0.117	1.934	0.117
Tillage x Residue			1	0.013	0.909	0.004	0.951	0.163	0.690
Insecticide (Tillage x Residue)			4	1.147	0.359	0.928	0.464	0.967	0.444
				Microaggregates (53-250µm) within macroaggregates					
+	-	+		17.83(3.02)		1.48(0.29)		12.44(0.67)	
+	-	-		21.32(1.26)		1.70(0.06)		12.53(0.44)	
+	+	+		27.93(2.87)		2.42(0.23)		11.52(0.25)	
+	+	-		18.60(3.30)		1.58(0.35)		12.51(1.14)	
-	-	+		19.51(0.24)		1.71(0.01)		11.43(0.08)	
-	-	-		19.78(0.57)		1.78(0.05)		11.13(0.16)	
-	+	+		20.90(0.31)		1.90(0.04)		11.03(0.10)	
-	+	-		21.12(0.85)		1.92(0.16)		11.14(0.51)	
S.V			df	F	P	F	P	F	P
Tillage			1	0.001	0.973	0.628	0.436	9.324	**0.005***
Residue			1	1.589	0.220	1.494	0.233	1.036	0.319
Tillage x Residue			1	0.196	0.662	0.221	0.642	0.397	0.535
Insecticide (Tillage x Residue)			4	2.232	0.096	1.813	0.159	0.402	0.805
				Silt + Clay (<53µm) within macroaggregates					
+	-	+		31.58(1.12)		2.73(0.05)		11.62(0.60)	
+	-	-		18.08(5.37)		1.51(0.57)		13.27(1.20)	
+	+	+		22.35(6.57)		1.68(0.54)		13.84(0.73)	
+	+	-		11.51(1.66)		0.86(0.13)		13.51(0.36)	
-	-	+		29.78(1.65)		2.98(0.22)		10.04(0.30)	
-	-	-		29.87(1.45)		2.74(0.08)		10.89(0.38)	
-	+	+		30.50(1.36)		2.79(0.05)		10.92(0.32)	
-	+	-		33.75(3.43)		3.05(0.22)		11.04(0.65)	
S.V			df	F	P	F	P	F	P
Tillage			1	19.009	**0.000***	25.802	**0.000***	27.798	**0.000***
Residue			1	2.135	0.157	3.166	0.088	4.414	**0.046***
Tillage x Residue			1	4.013	0.057	3.698	0.066	0.454	0.507
Insecticide (Tillage x Residue)			4	3.229	**0.030***	2.886	**0.044***	0.957	0.449

An (*) indicates a significance difference (P≤0.05). (+/-) symbols refer with/without respectively, tillage, residue, and insecticide treatment. S.V=source of variation. df=degrees of freedom.

No significant effect of any of the management factors on the concentration of C in microaggregates within macroaggregates was found at 0-15 cm soil depth, only the effect of tillage on the C:N ratio in microaggregates within macroaggregates was statistically significant (P=0.005). The C:N ratio was lower in ZT compared to CT (Table 10). Zero tillage had significantly increased the C and N contents in the fractions of silt and clay within macroaggregates. The increase in C and N contents was more pronounced when crop residues were maintained (Table 10).

3.8 **Soil Organic Carbon, Nitrogen and C:N ratio** (15-30 cm soil depth)

Table 11. *Effect of tillage, residue and insecticide management on the concentration of carbon and nitrogen in whole soil, and large M (>2000 µm) at 15-30 cm soil depth-after wet sieving. Numbers in brackets are standard errors. (n=4)*

Treatment				C (mg g^{-1})		N (mg g^{-1})		C : N	
Tillage	Residue	Insecticide		**Total Soil**					
+	-	+		18.5(1.12)		1.6(0.08)		11.5(0.20)	
+	-	-		18.4(0.87)		1.6(0.06)		11.5(0.16)	
+	+	+		16.9(0.61)		1.6(0.03)		10.9(0.23)	
+	+	-		18.1(0.53)		1.6(0.02)		11.4(0.23)	
-	-	+		17.6(0.49)		1.5(0.01)		11.7(0.32)	
-	-	-		16.1(0.70)		1.5(0.05)		10.9(0.11)	
-	+	+		18.4(0.65)		1.6(0.05)		11.5(0.09)	
-	+	-		18.4(0.42)		1.6(0.03)		11.4(0.20)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	0.545	0.468	1.561	0.224	0.133	0.718
Residue			1	0.420	0.523	1.661	0.210	0.370	0.549
Tillage x Residue			1	6.213	**0.020***	6.343	**0.019***	2.180	0.153
Insecticide (Tillage x Residue)			4	0.862	0.501	0.147	0.962	2.542	0.066
				Large M (>2000µm)					
+	-	+		18.0(0.57)		1.5(0.02)		11.9(0.24)	
+	-	-		18.3(0.65)		1.6(0.04)		11.3(0.24)	
+	+	+		16.1(0.15)		1.5(0.02)		10.7(0.07)	
+	+	-		17.9(0.65)		1.6(0.04)		11.4(0.16)	
-	-	+		16.9(1.18)		1.5(0.12)		11.5(0.56)	
-	-	-		16.1(0.88)		1.5(0.06)		10.8(0.32)	
-	+	+		17.9(0.74)		1.5(0.07)		11.6(0.21)	
-	+	-		17.7(0.30)		1.6(0.03)		11.5(0.24)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	0.641	0.431	0.637	0.433	0.001	0.971
Residue			1	0.018	0.895	0.088	0.769	0.083	0.776
Tillage x Residue			1	5.718	**0.025***	1.034	0.319	5.506	**0.028***
Insecticide (Tillage x Residue)			4	1.158	0.354	0.749	0.569	2.074	0.116

An (*) indicates a significance difference (P≤0.05). (+/-) symbols refer with/without respectively, tillage, residue, and insecticide treatments. S.V=source of variation. df=degrees of freedom.

At 15-30 cm soil depth, the carbon and nitrogen content in total soil was higher in ZT when residues were maintained (Fig. 17). The same trend was found in the carbon concentration in small and large macroaggregates as well as free microaggregates. When compared between CT and ZT with residue retention, the C:N ratio in small macroaggregates was lower in CT (Fig. 18).

Table 12**.** *Effect of tillage, residue and insecticide management on the concentration of carbon and nitrogen in small M (>2000 µm), free microaggregates (53-250 µm), and free Silt & Clay (<53 µm) at 15-30 cm soil depth- after wet sieving. Numbers in brackets are standard errors. (n=4)*

Treatment				C (mg g^{-1})		N (mg g^{-1})		C : N	
Tillage	Residue	Insecticide		**Small M (250-2000µm)**					
+	-	+		19.3(0.85)		1.6(0.05)		11.89(0.21)	
+	-	-		18.5(1.09)		1.6(0.08)		11.50(0.11)	
+	+	+		17.0(0.30)		1.57(0.03)		10.87(0.10)	
+	+	-		17.9(0.77)		1.59(0.01)		11.24(0.15)	
-	-	+		16.8(0.57)		1.51(0.05)		11.18(0.09)	
-	-	-		15.9(0.91)		1.43(0.05)		11.12(0.25)	
-	+	+		17.9(0.78)		1.53(0.07)		11.72(0.09)	
-	+	-		20.7(2.65)		1.54(0.04)		13.60(2.07)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	0.570	0.458	7.388	**0.012***	0.761	0.392
Residue			1	0.807	0.378	0.159	0.694	0.509	0.482
Tillage x Residue			1	8.060	**0.009***	1.777	0.195	5.289	**0.030***
Insecticide (Tillage x Residue)			4	0.941	0.457	0.319	0.862	0.774	0.553
				Free Microaggregates (53-250µm)					
+	-	+		20.55(0.45)		1.70(0.02)		12.11(0.17)	
+	-	-		19.09(1.21)		1.66(0.09)		11.50(0.15)	
+	+	+		18.38(0.62)		1.64(0.04)		11.19(0.21)	
+	+	-		19.28(0.26)		1.70(0.04)		11.38(0.17)	
-	-	+		18.35(0.44)		1.64(0.04)		11.19(0.03)	
-	-	-		17.27(0.95)		1.57(0.05)		11.01(0.25)	
-	+	+		19.10(0.73)		1.65(0.05)		11.58(0.24)	
-	+	-		19.58(0.70)		1.66(0.05)		11.85(0.46)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	2.102	0.160	1.478	0.236	1.231	0.278
Residue			1	0.263	0.612	0.292	0.594	0.092	0.765
Tillage x Residue			1	6.084	**0.021***	0.657	0.425	11.075	**0.003***
Insecticide (Tillage x Residue)			4	1.037	0.409	0.469	0.758	1.068	0.394
				Free silt + Clay (<53µm)					
+	-	+		24.57(0.39)		2.35(0.08)		10.48(0.39)	
+	-	-		24.00(0.74)		2.31(0.02)		10.41(0.26)	
+	+	+		24.47(0.67)		2.37(0.10)		10.36(0.47)	
+	+	-		25.76(2.54)		2.35(0.10)		10.95(0.80)	
-	-	+		26.54(1.73)		2.64(0.21)		10.16(0.66)	
-	-	-		25.98(1.49)		2.71(0.19)		9.75(0.93)	
-	+	+		25.80(1.49)		2.55(0.12)		10.12(0.28)	
-	+	-		25.25(1.21)		2.22(0.11)		11.51(0.92)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	1.378	0.252	3.979	0.058	0.130	0.721
Residue			1	0.002	0.965	2.025	0.168	1.391	0.250
Tillage x Residue			1	0.590	0.450	3.062	0.093	0.501	0.486
Insecticide (Tillage x Residue)			4	0.157	0.958	0.884	0.488	0.747	0.569

An (*) indicates a significance difference (P≤0.05). (+/-) symbols refer with/without respectively, tillage, residue, and insecticide treatments. S.V=source of variation. df=degrees of freedom.

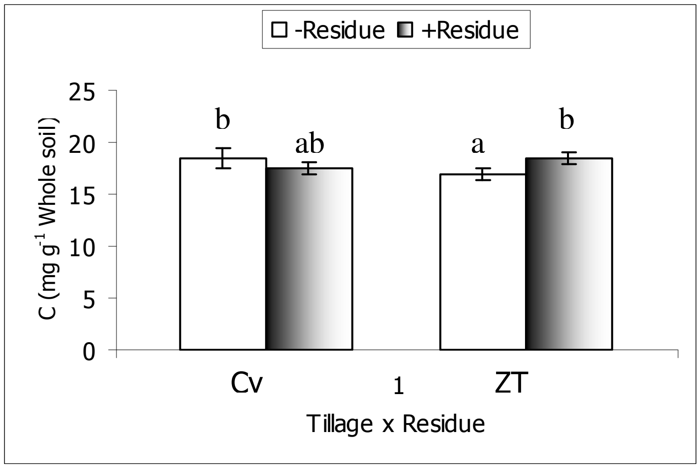


Figure 17. *Effect of tillage and residue on the fraction of Carbon in total soil at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors.*

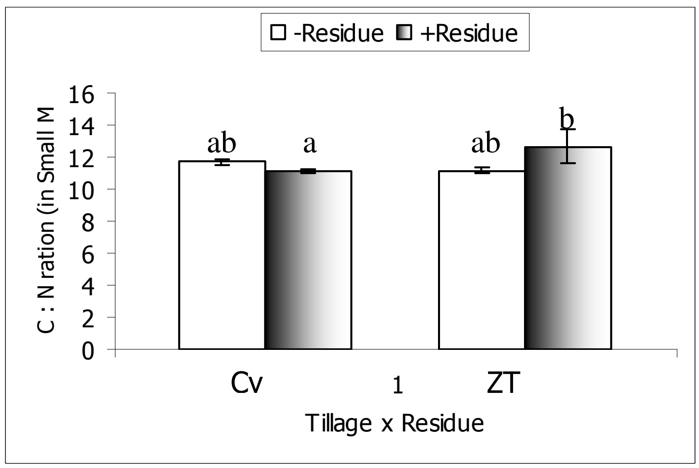


Figure 18. *Effect of tillage, residue, and insecticide management on C:N ratio in small macroaggregates at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

Table 13**.** *Effect of tillage, residue and insecticide management on the concentration of carbon and nitrogen in cPOM (>250µm), microaggregates (53-250µm), and Silt & Clay (<53µm) within macroaggregates at 15-30 cm soil depth-after isolation. Numbers in brackets are standard errors. (n=4)*

Treatment				C (mg g^{-1})		N (mg g^{-1})		C : N	
Tillage	Residue	Insecticide		**cPOM (>250µm)**					
+	-	-		11.53(1.78)		0.54(0.05)		22.24(3.99)	
+	-	+		12.14(3.61)		0.54(0.05)		21.97(5.16)	
+	+	-		15.98(1.56)		1.31(0.27)		13.90(2.79)	
+	+	+		10.84(1.49)		0.54(0.07)		21.27(4.12)	
-	-	-		15.02(2.40)		1.31(0.27)		12.18(1.30)	
-	-	+		17.11(1.10)		1.59(0.10)		10.79(0.17)	
-	+	-		10.04(0.25)		0.60(0.06)		17.07(1.53)	
-	+	+		10.15(0.78)		0.70(0.06)		14.68(1.11)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	0.297	0.591	11.052	**0.003***	9.243	**0.006***
Residue			1	2.123	0.158	2.638	0.118	0.108	0.745
Tillage x Residue			1	9.283	**0.006***	26.566	**0.000***	7.205	**0.013***
Insecticide (Tillage x Residue)			4	1.216	0.330	3.813	**0.015***	1.147	0.359
				Microaggregates (53-250µm) within macroaggregates					
+	-	-		19.41(1.95)		1.54(0.06)		12.61(1.17)	
+	-	+		17.22(0.67)		1.51(0.06)		11.38(0.16)	
+	+	-		24.39(0.80)		2.15(0.07)		11.35(0.24)	
+	+	+		15.20(1.08)		1.44(0.10)		10.57(0.16)	
-	-	-		14.82(1.90)		1.38(0.22)		10.96(0.55)	
-	-	+		18.23(0.86)		1.63(0.11)		11.23(0.28)	
-	+	-		16.59(0.67)		1.50(0.04)		11.08(0.29)	
-	+	+		17.18(0.77)		1.54(0.06)		11.18(0.16)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	7.725	**0.010***	4.133	**0.053***	1.210	0.282
Residue			1	1.186	0.287	3.659	0.059	2.308	0.142
Tillage x Residue			1	0.436	0.515	3.153	0.088	2.308	0.142
Insecticide (Tillage x Residue)			4	8.858	**0.000***	6.722	**0.001***	1.068	0.394
				Silt+Clay (<53µm) within macroaggregates					
+	-	-		25.49(3.00)		2.11(0.06)		12.08(1.33)	
+	-	+		25.18(2.21)		2.11(0.05)		11.90(0.83)	
+	+	-		16.59(4.04)		1.34(0.43)		13.71(1.40)	
+	+	+		22.01(1.78)		1.90(0.13)		11.55(0.28)	
-	-	-		17.16(1.27)		1.42(0.28)		13.93(3.40)	
-	-	+		11.15(1.63)		0.63(0.08)		18.52(3.62)	
-	+	-		18.66(1.30)		2.07(0.16)		9.05(0.18)	
-	+	+		20.49(0.99)		1.98(0.06)		10.34(0.35)	
S.V			df	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	8.747	**0.007***	5.038	**0.034***	0.016	0.901
Residue			1	0.049	0.828	3.438	0.076	5.886	**0.023***
Tillage x Residue			1	13.784	**0.001***	25.012	**0.000***	9.666	**0.005***
Insecticide (Tillage x Residue)			4	2.638	0.059	3.859	**0.015***	1.283	0.304

An (*) indicates a significance difference (P≤0.05). (+/-) symbols refer with/without respectively, tillage, residue, and insecticide treatments. S.V=source of variation. df=degrees of freedom.

At 15-30 cm depth, the C and N concentration in cPOM was higher in ZT even when no crop residues were retained (Fig. 19); Where as in CT, the C and N content of cPOM increased when residues were maintained. Consequently, residue retention had lowered the C:N ratio in cPOM in the conventional tillage (Fig. 20).

At 15-30 cm soil depth, residue retention had increased the concentration of carbon and nitrogen in the fractions of silt and clay within macroaggregates in zero tillage (Fig. 21 and Fig. 22). Consequently, the C: N ratio in silt and clay within macroaggregates was lower in ZT treatments where crop residues were maintained (Fig. 23); where as in CT the C:N ratio did not differ between residue treatments.

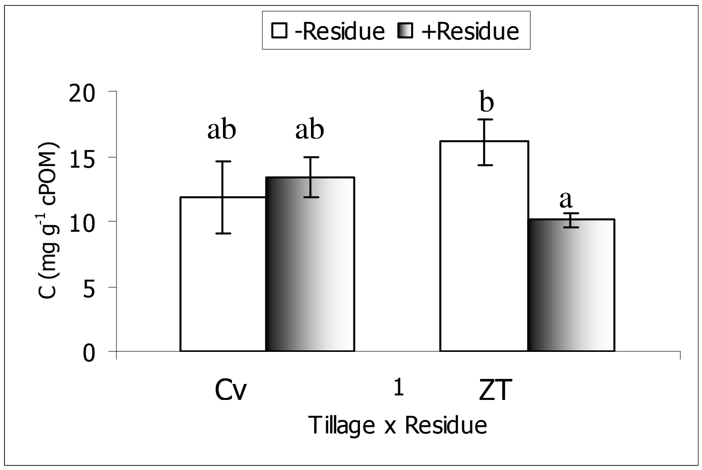


Figure 19. *Effect of tillage and residue on the fraction of Carbon in cPOM at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

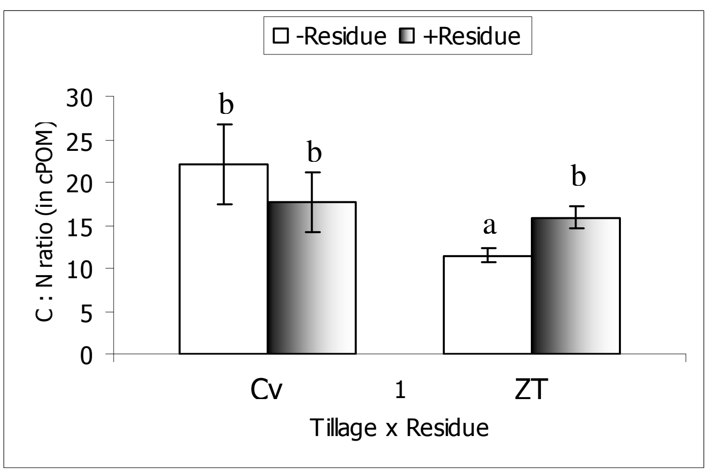


Figure 20. *Effect of tillage, residue, and insecticide management on C:N ratio in cPOM at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

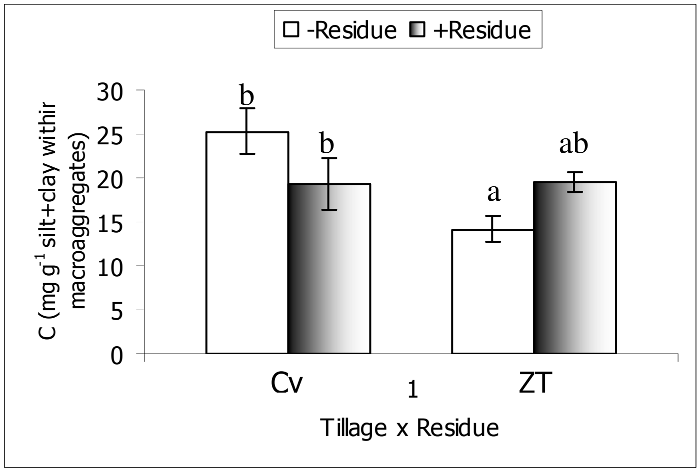


Figure 21. *Effect of tillage and, residue, on the fraction of Carbon in silt and clay within Macroaggregates at 15-30 cm soil depth. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

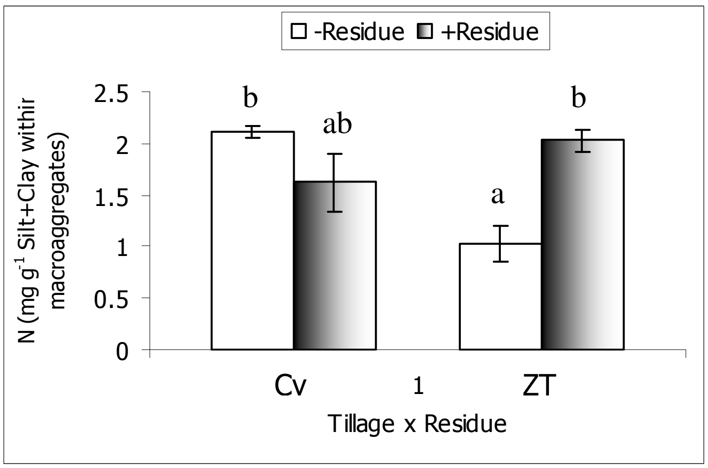


Figure 22. *Effect of tillage and residue, on the fraction of N in silt and clay within Macroaggregates at 15-30 cm soil depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

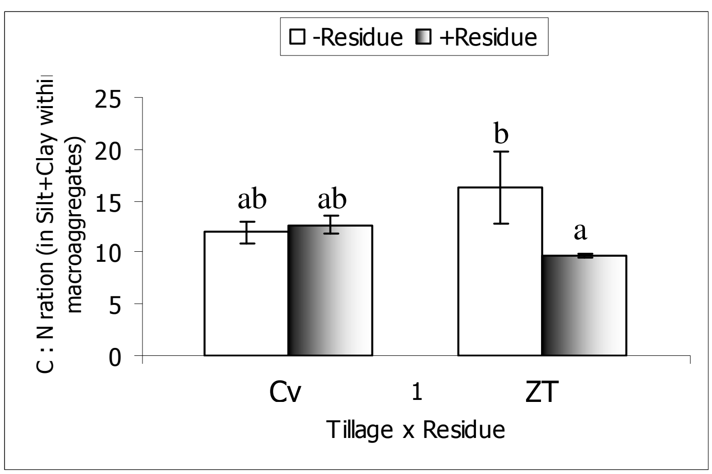


Figure 23. *Effect of tillage, residue, and insecticide management on C:N ratio in silt and clay within macroaggregates at 15-30 cm depth. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

3.9 **Distribution of Soil Carbon in Aggregate Fractions**

Table 14. *Amount and distribution of Carbon in aggregates at 0-15 cm and 15-30 cm soil depth as affected by tillage and residue management and insecticide application. Numbers in Brackets indicate standard errors. (n=4) January 2007.*

Treatment				Total soil		Large M (>2000 µm)		Small M (250-2000 µm)		Free microaggregates (53-250 µm)		Free silt & clay (<53 µm)	
Depth	Tillage	Residue	Insecticide	C (mg/100g soil)									
0-15 cm	+	-	+	2035(52.2)		75(15.3)		766(52.2)		887(37.2)		176(19.9)	
	+	-	-	2011(46.2)		64(5.5)		825(36.2)		851(62.1)		161(16.5)	
	+	+	+	2035(38.2)		126(68.3)		811(25.9)		822(34.7)		152(10.9)	
	+	+	-	1989(18.6)		133(12.1)		773(51.1)		801(30.0)		178(10.4)	
	-	-	+	2014(16.6)		225(64.1)		855(23.5)		683(72.1)		146(16.8)	
	-	-	-	2012(39.4)		201(40.2)		843(95.1)		678(65.3)		201(37.9)	
	-	+	+	2114(50.2)		180(9.3)		951(42.3)		714(13.7)		153(7.5)	
	-	+	-	2129(61.8)		176(30.6)		914(21.5)		747(37.7)		162(26.2)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	2.649	0.117	17.715	**0.000***	7.775	**0.010***	15.743	**0.001***	0.004	0.950
Residue			1	2.601	0.120	0.317	0.579	1.324	0.261	0.011	0.918	0.446	0.511
Tillage x Residue			1	3.836	**0.062**	4.301	**0.049***	1.589	0.220	2.497	0.127	0.181	0.574
Insecticide (Tillage x Residue)			4	0.197	0.938	0.090	0.985	0.336	0.851	0.156	0.958	1.223	0.327
				C (mg/100g soil)									
15-30 cm	+	-	+	1848(112)		469(48.0)		779(36.1)		430(62.0)		103(15.5)	
	+	-	-	1845(86.6)		461(33.7)		830(10.0)		373(58.8)		82(8.5)	
	+	+	+	1699(61.3)		337(33.1)		842(25.6)		353(41.4)		95(17.5)	
	+	+	-	1810(53.2)		369(9.7)		846(30.7)		435(14.3)		92(10.3)	
	-	-	+	1759(48.7)		563(94.9)		794(46.5)		289(70.9)		57(11.6)	
	-	-	-	1611(70.1)		410(52.5)		820(19.2)		250(29.5)		40(6.5)	
	-	+	+	1841(64.7)		512(66.5)		871(39.5)		299(55.6)		63(8.0)	
	-	+	-	1843(42.4)		500(48.5)		828(10.0)		381(37.7)		79(12.1)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	0.542	0.469	5.246	**0.031***	0.027	0.871	7.038	**0.014***	15.875	**0.001***
Residue			1	0.420	0.523	1.480	0.236	3.336	0.080	0.814	0.376	2.027	0.167
Tillage x Residue			1	6.213	**0.020***	3.019	0.095	0.004	0.953	1.239	0.277	1.674	0.208
Insecticide (Tillage x Residue)			4	0.859	0.503	1.068	0.394	0.619	0.653	0.922	0.467	0.935	0.460

An asterisk (*) indicates a significance difference at P≤0.05. (+/-) symbols refer with and without respectively, tillage, residue, and insecticide treatments. S.V=Source of variation and df=degrees of freedom. The carbon content is expressed per relative weight of aggregate fractions.

At 0-15 cm soil depth, CT significantly reduced the fraction of carbon present in large M (Table 14). The negative effects of tillage on the fraction of carbon present in large M disappeared when residues were maintained (Fig. 25). When compared between CT and ZT both without residues, there was 67% more Carbon present as large macroaggregates occluded C in ZT (Fig. 25). The effect of tillage on carbon present in small macroaggregates was only significant at 0-15 cm soil depth. Carbon present in small macroaggregates was higher in ZT than CT. Consequently, higher amounts of carbon were associated with the free microaggregate fraction in CT at both depth layers. Similarly, more C present as part of the free silt and clay fractions was found in CT; however, the tillage effect was only significant at 15-30 cm depth.

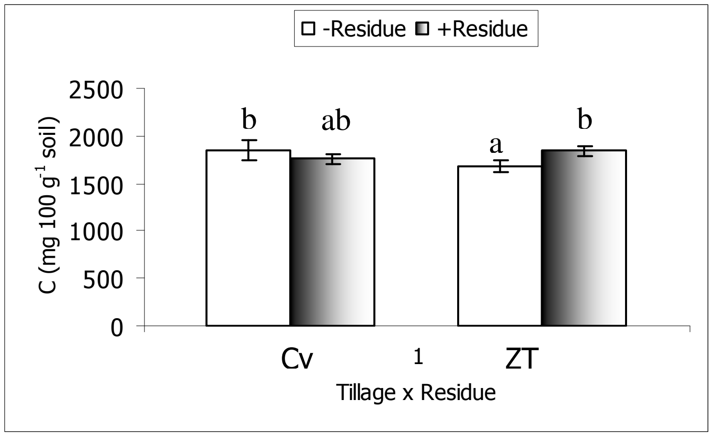


Figure 24. *Fraction of Carbon in total soil at 15-30 cm soil depth as affected by tillage and residue. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

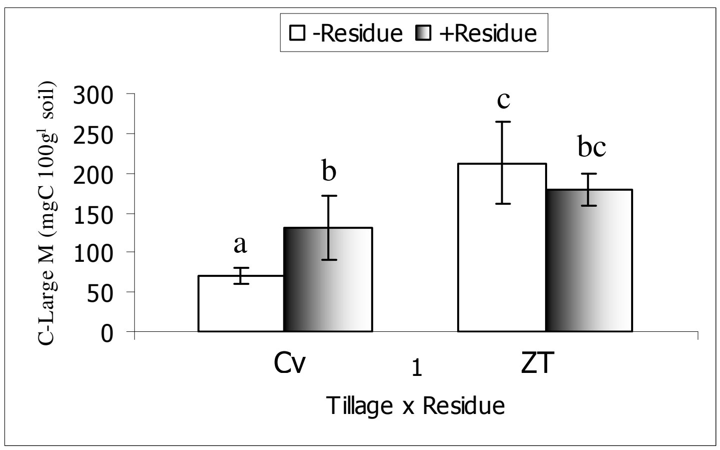


Figure 25. *Fractions of Carbon in large macroaggregates at 0-15 cm soil depth as affected by tillage and residue. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

3.10 **Soil Carbon Associated with Fractions Isolated from Macroaggregates**

Table 15. *Amount and distribution of Carbon in cPOM plus sand, microaggregates, and silt and clay within macroaggregates at 0-15 cm and 15-30 cm soil depth, as affected by tillage and residue management and insecticide application. Numbers in Brackets indicate standard errors. (n=4) January 2007.*

Depth	Treatment Tillage	Treatment Residue	Treatment Insecticide	Macroaggregates (Large M + small M)		Coarse POM >250µm		Microaggregates within macroaggregates		Silt & clay within macroaggregates	
				C (mg 100 g^{-1} soil)		C (mg/100g Macroaggregates)					
0-15 cm	+	-	+	842(61.9)		106(10.4)		554(46.4)		141(7.2)	
	+	-	-	889(35.5)		75(23.8)		621(17.2)		156(12.8)	
	+	+	+	937(41.9)		95(15.8)		620(30.2)		198(27.4)	
	+	+	-	906(53.2)		101(6.2)		543(47.9)		237(13.5)	
	-	-	+	1079(68.3)		98(6.7)		661(17.4)		282(43.6)	
	-	-	-	1044(102)		97(7.3)		659(66.3)		246(24.5)	
	-	+	+	1131(45.9)		95(8.5)		733(43.4)		259(14.1)	
	-	+	-	1090(23.5)		112(17.9)		751(46.3)		196(15.9)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	21.722	**0.000***	0.387	0.540	15.156	**0.001***	15.299	**0.001***
Residue			1	1.627	0.214	0.548	0.467	1.633	0.214	1.006	0.326
Tillage x Residue			1	0.008	0.930	0.005	0.944	2.126	0.158	10.915	**0.003***
Insecticide (Tillage x Residue)			4	0.227	0.921	0.873	0.494	0.751	0.567	1.722	0.178
				C (mg 100 g^{-1} soil)		C (mg/100g Macroaggregates)					
15-30 cm	+	-	+	1248(69.6)		67(13.6)		735(23.9)		408(40.4)	
	+	-	-	1291(37.4)		75(12.7)		727(42.5)		451(38.3)	
	+	+	+	1179(33.9)		60(4.6)		734(24.4)		330(14.8)	
	+	+	-	1215(28.3)		80(6.7)		765(26.9)		332(8.1)	
	-	-	+	1357(63.9)		79(6.3)		309(16.5)		927(72.4)	
	-	-	-	1229(64.9)		49(5.3)		608(31.2)		524(52.3)	
	-	+	+	1383(47.3)		68(3.8)		597(46.2)		676(64.0)	
	-	+	-	1328(44.2)		70(15.2)		735(22.4)		494(34.9)	
S.V			**df**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Tillage			1	6.388	**0.018***	0.339	0.566	66.862	**0.000***	72.496	**0.000***
Residue			1	0.019	0.891	0.057	0.813	26.894	**0.000***	13.703	**0.001***
Tillage x Residue			1	3.521	0.073	0.195	0.663	18.755	**0.000***	0.417	0.525
Insecticide (Tillage x Residue)			4	1.077	0.390	1.861	0.150	14.479	**0.000***	11.827	**0.000***

An asterisk (*) indicates a significance difference at P≤0.05. (+/-) symbols refer with and without respectively, tillage, residue, and insecticide treatments. S.V=Source of variation and df=degrees of freedom. The Carbon content is expressed per relative weight of fractions inside macroaggregates as obtained from isolation step.

None of the treatments affected carbon concentrations in cPOM (coarse sand + cPOM) at either soil depth. The fraction of total soil carbon associated with macroaggregates (after sand correction) was higher in ZT than CT (Table 15). Similarly, higher amount of carbon in microaggregates as well as silt and clay within macroaggregates was found in Zero tillage. In conventional tillage, residue retention increased the amount of carbon present in silt and clay within macroaggregates (Fig. 26). For example, there was 32% more carbon in silt and clay within macroaggregates in CT due to residue retention at 0-15 cm soil depth (Fig. 26).

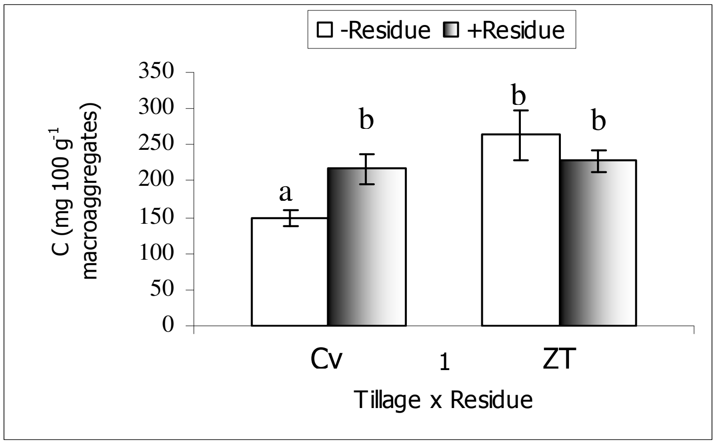


Figure 26. *Fractions of Carbon in silt and clay within macroaggregates at 0-15 cm soil depth as affected by tillage and residue. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

At 15-30 cm soil depth, residue retention increased the fraction of carbon associated with the microaggregates within macroaggregates in ZT (Fig. 27). In contrast, insecticide application reduced the fraction of carbon in microaggregates within macroaggregates by 33% in zero tillage when compared to without insecticide treatments (Table 15). Although it was not possible to test interaction with insecticide treatment due to the experimental layout, it appeared that the negative effect of insecticide application only occurred in ZT, and this effect was stronger when no residues were present.

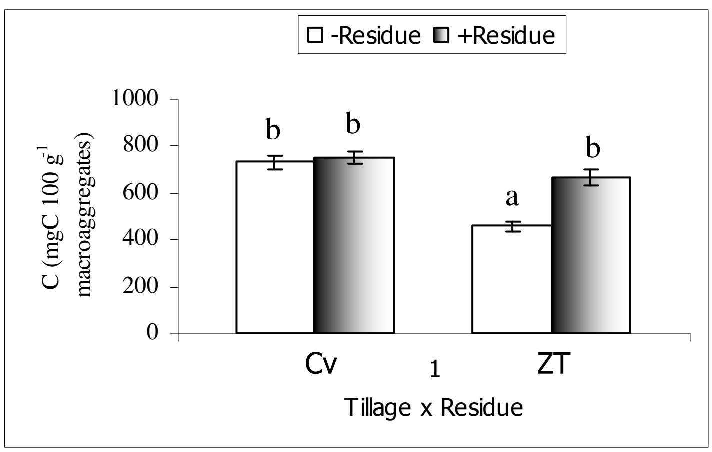


Figure 27. *Fractions of Carbon in microaggregates within macroaggregates at 15-30 cm soil depth as affected by tillage and residue. Cv=conventional tillage and ZT=zero tillage. Bars indicate standard errors. Different letters indicate statistically significant difference at P≤0.05.*

3.11 **Maize Yield and Harvest Index**

Table 16. *Maize total biomass production and grain yield as affected by tillage, residue, and insecticide treatments. Values in parenthesis are standard errors. (n=4) August 2006.*

Treatment				Total Biomas		HI		Grain Yield	
Tillage	Residue	Insecticide		(ton/ha)		(-)		(ton/ha)	
+	-	+		13.1(0.99)		0.43(0.04)		5.7(0.72)	
+	-	-		8.3(0.59)		0.47(0.03)		3.9(0.39)	
+	+	+		10.5(1.38)		0.48(0.03)		5.0(0.69)	
+	+	-		9.1(0.88)		0.46(0.03)		4.1(0.28)	
-	-	+		12.3(0.57)		0.48(0.02)		5.9(0.46)	
-	-	-		8.1(0.53)		0.44(0.03)		3.5(0.20)	
-	+	+		12.2(1.41)		0.45(0.06)		5.3(0.61)	
-	+	-		7.8(0.51)		0.44(0.03)		3.4(0.42)	
S.V			df	F	P	F	P	F	P
Tillage			1	0.041	0.842	0.188	0.668	0.194	0.663
Residue			1	0.671	0.421	0.016	0.899	0.599	0.446
Tillage x Residue			1	0.284	0.599	0.475	0.497	0.037	0.850
Insecticide (Tillage x Residue)			4	9.149	**0.000***	0.347	0.843	6.516	**0.001***

S.V=source of variation, (+/-) symbols refer to with and without respectively, tillage, residue, and insecticide treatments, df=degrees of freedom, HI=Harvest Index, and an asterisk (*) indicates statistically significant difference at P≤0.05.

The maize yield was not affected significantly by tillage nor residue management. A highly statistically significant (P=0.000, Table 16) difference was found, however, between mean yields (total biomass and grain yield) due to insecticide application. The yield was higher in '+Insecticide' than '-insecticide' treatments. However, none of the treatments resulted in differences in the harvest index. There was statistically significant difference in total yield between cropping seasons (Table 17).

Table 17. *Maize yield (Total biomass and Grain yield). In four consecutive long rainy seasons as affected by tillage and residue management. Values in brackets are standard errors.*

Treatment			Grain Yield (ton/ha)							
Tillage	Residue		2003		2004		2005		2006	
+	-		2.8(0.70)		4.9(0.60)		6.3(0.20)		4.8(0.50)	
+	+		3.2(0.20)		5.3(1.10)		6.1(0.40)		4.6(0.38)	
-	-		3.0(0.30)		4.1(1.10)		4.8(1.70)		4.7(0.51)	
-	+		2.7(0.60)		4.7(0.80)		6.2(0.60)		4.4(0.49)	
S.V		df	F	P	F	P	F	P	F	P
Tillage		1	0.32	0.57	3.64	0.08	1.85	0.20	0.11	0.74
Residue		1	0.04	0.83	2.41	0.14	1.33	0.27	0.34	0.57
Tillage x Residue		1	1.33	0.27	0.04	0.82	3.02	0.11	0.02	0.89
Total Biomass (ton/ha)			$6.8(0.90)^{a}$		$11.9(2.40)^{b}$		$11.2(1.60)^{b}$		$10.2(0.86)^{b}$	

S.V=Source of variation. df=degrees of freedom. (+/-) symbols indicate with and without respectively, tillage and residue treatments. Different letters indicate a significant difference at P≤0.05.

4. Discussion

Tillage, Residue, and Insecticide Management Effects on Soil Macrofauna

Earthworms

All the earthworm specimens were juveniles. This might be because of the time of sampling, which was towards the end of the rainy season when in most cases earthworms are present in the form of cocoons and juveniles. The densities of earthworms were not affected by the tillage and the residue treatments. Nevertheless, insecticide application considerably reduced the number of earthworms in both depth layers, although this reduction was only significant at 15-30 cm depth probably due to high spatial variability of earthworm numbers. The average density of earthworm juveniles was 12 individuals m^{-2} when no insecticides were applied. In Central Kenya, at 15-30 cm depth, a density of 27 earthworms m^{-2} at Embu was reported to be low (A. Ponce-Mendoza, in prep.). Thus, the earthworm numbers from our study were even lower than the abundance in central Kenya. A survey of earthworms in East Africa some years ago showed that most of the earthworms were small, and not very abundant, except where there was a lot of organic matter present or added (Personal communication George Brown). We, therefore, suggest further research on earthworm abundance and diversity to find out factors responsible for this low earthworm population.

Termites

Termite activity can play a significant role in improving the physical properties of compacted soils, such as those in the Sahel (Lal, 1988) and their activity depends on climate, soil, vegetation and land use. However, in our study, the tillage and the residue treatment effects on the abundance of termites were not statistically significant at either depth (0-15 cm and 15-30 cm). Tian et al. (1993) reported that the effects of mulch on termite populations indicate that termites prefer plant residues with low nutritional quality, which decomposes slowly and have a larger effect on the micro-climate. Therefore, the reason why we did not see residue effects on termite densities could be attributed to the quality of the residue applied .Before planting of the maize phase of the rotation, soybean residues are retained in all plots, irrespective of tillage and residue treatment and no additional maize residues are applied. Soybean residues are of high quality and expected to decompose quickly without benefiting termites. Pesticides effectively reduced termite numbers at 0-15 cm depth, but not at 15-30 cm depth. This could be due to that the pesticides applied to remove/reduce termite population might not be enough to be effective over the whole depth. It is recommended that soil macrofauna sampling should be carried out earlier in the season (6-8 weeks after planting)

Ants

Ants are abundant and ecologically dominant faunal group in arid and semi-arid soils (Morton and Davidson, 1988). The subfamilies *Myrmicinae* and *Formicinae* are the largest and most dominant in African habitats (Bolton, 1985; Marsh, 1986; Lindsey and Skinner, 2001). In this study, the tillage and the residue treatments did not affect the population of ants. Nevertheless, insecticide application reduced the number of ants in most, though not all, treatments. For example, a density of 32 and 13 ants m^2 were found in '-Insecticide' and '+Insecticide' treatments respectively. In Central Kenya, densities of approx. 20 ants m^{-2} at Embu and 15 ants m^{-2} at Machanga site were found in a soil without residue retention and no insecticide application (control soil) (unpublished data, A. Ponce-Mendoza). When we compare the number of ants in our study from '-Insecticide' treatment with the numbers in central Kenya, the abundances in western Kenya were low. The low numbers in western Kenya could be due to the severe drought in previous years.

'Other' Soil Macrofauna

At 0-15 cm depth, the residue treatments affected the densities of 'other' soil fauna (all the different groups determined in the site except earthworms, termites, ants, and spiders). Persistent to our hypothesis, the density of 'other' soil fauna was three times higher in the plots where residues were retained, irrespective of tillage treatment. From another study, with maize stover application, approx. 90 individuals' m^2 were found at Machanga sites, Central Kenya (A. Ponce-Mendoza, unpublished data). The densities found in our study were quite low when compared to the densities found in Central Kenya. This might be due to the influence of severe drought in previous years in western Kenya. The soil macrofauna could be still recovering from the drought impact. The pesticides used less clearly affected the densities of other macrofauna, besides termites, ants and earthworms.

Tillage and Residue Effects on Macroaggregates

We hypothesized that long-term CT and residue removal, in contrast to ZT and residue retention, leads to a decline in the amount of SOM and a reduction of water stable macroaggregates. At 0-15 cm depth, consistent with our hypothesis, CT negatively affected the amount of large and small macroaggregates compared to ZT. However, the negative effect of tillage largely disappeared when residues were maintained in the field (Table 4 and Fig. 2). The increased macroaggregation in zero tillage without residue could be the result of less soil disturbance. Other authors have found that aggregate stability was increased under reduced tillage compared to conventionally tilled, cultivated systems (Elliott, 1986; Cambardella and Elliott, 1994; Beare et al., 1994a,b; Jastrow et al., 1996; Six et al., 1998). Tisdall and Oades (1982), and Elliott (1986) reported that macroaggregate stability responds rapidly to changes in both tillage type and organic inputs. However, in our experiment, the residue retention did not significantly affect the amount of stable macroaggregates at 0-15 cm depth.

More large macroaggregates were found at 15-30 cm depth than at 0-15 cm depth for both tillage systems. Because soil texture data for 15-30 cm depth are lacking we are not sure whether this is related to a sudden change in clay content. Otherwise it may be explained by the absence of disruptive forces from tillage (hand-hoeing to 15 cm depth) and rainfall impact at greater depth, although increasing macroaggregation with depth contrasts with results generally found Six et al. (2001). When looking at the effect of management at 15-30 cm soil depth, there was a statistically significant increase in the amount of large macroaggregates in zero tillage, irrespective of residue management. .

Tillage and Residue Effects on Microaggregates (53-250 µm) within Macroaggregates

The hypothesis of a higher total amount of microaggregates within macroaggregates in ZT when residue was retained is not consistent with our macroaggregate composition data (Table 6, at 0-15 cm. depth). In zero tillage residue retention did not differ from that of without residue treatment. When residues are absent, the fraction of microaggregates within macroaggregates was higher in CT compared to ZT. On the other hand, the fraction of microaggregates within macroaggregates was higher in zero tillage (when expressed in total soil basis) compared to conventional tillage (Table 6). Supporting this, Beare et al. (1994a), Gale et al. (2000) and Six et al. (1999a, 2000) reported that if macroaggregates are not disturbed (as under no tillage/natural ecosystem) residues that are encapsulated inside these aggregates decompose and fragment into finer organic matter that gradually becomes encrusted with clay particles and microbial products forming microaggregates within macroaggregates. However, in our study the higher total number of mM is explained by the larger amounts of stable macroaggregates under ZT rather than a higher concentration of microaggregates within macroaggregates.

At 15-30 cm depth, the tillage and the residue treatment effects on microaggregates within macroaggregates were statistically significant (when expressed on per unit macroaggregate weight basis as well as a whole soil basis). Consistent with our hypothesis, residue retention increased the fraction of microaggregates within macroaggregates, but only under ZT (Figure 7). When comparing CT and ZT, however, the concentration of microaggregates within macroaggregates was significantly higher in CT, which contrasts with our hypothesis. However, when the amount of mM is expressed on a total soil basis, the difference between CT and ZT is somewhat reduced (Figure 8). This was probably the result of a higher amount of macroaggregates in ZT due to slower rate of macroaggregate turnover.

The fraction of microaggregates within macroaggregates decreased after insecticide application by 37% at 15-30 cm soil depth. Although it was not possible to test the interaction with insecticide due to the experimental layout (insecticide treatment was nested within tillage and residue treatment), it suggested that the negative effect of insecticide application occurred only in ZT, and this effect was stronger when residues were removed from the field. The (-,-,+) treatment was very much lower than all other treatments (Table 7). From the results of our study it is difficult to explain this observation and whether it is related to reduced earthworm activity in that treatment or whether a direct effect of the chemicals on soil aggregation under the specific condition of zero tillage without residue retention at 15-30 cm depth.

Regression analysis did not show a clear relation between soil fauna numbers and aggregation. Therefore, the differences in soil aggregation may primarily be explained by direct management effects, e.g. OM inputs and/or mechanical soil disturbance. The regression coefficient (R^2) for the statistically significant correlations was small indicating that only a very small amount of the variation in aggregate fractions would be explained by the soil fauna. The observation that we have got a minimal relationship between the soil fauna and the aggregate fractions could be due to the low density of soil macrofauna, at least at the time of sampling. Therefore, we suggest that the relationship should be further investigated as to what would happen at higher macrofaunal densities.

Tillage and Residue Effects on Soil Organic Carbon

There was an indication that total soil carbon, at least in 15-30 cm depth layer, was positively affected due to residue retention, but only in zero tillage (Table 11 and Figure 17 and 24). On the other hand, the concentration of total soil carbon in the top soil was far higher than the concentration at deeper soil layer (15-30 cm), which is may be due to differences in soil bulk density. However, carbon data were not corrected for possible differences in sand and soil bulk density between tillage types and depth.

Carbon inside Macroaggregates

At 0-15 cm soil depth, our results showed that the fractions of soil carbon present in large macroaggregates was lower in conventional tillage when compared to zero tillage. Since the carbon data showed (Table 14) is expressed on a total soil basis, the higher fraction of carbon in large macroaggregates was perhaps due to the more macroaggregates in ZT at that depth. The lower carbon content in large macroaggregates in conventional tillage was probably a result of high organic matter decomposition enhanced by disruption of aggregates through tillage (Hassink, 1995). The negative effects of conventional tillage on the distribution of carbon disappeared when crop residues were maintained (Figure 25). At 15-30 cm soil depth, there was a similar trend of results on the distribution of carbon in large macroaggregates to those at 0-15 cm soil depth. But at this depth, the fraction of carbon in large macroaggregates was higher compared to carbon in large macroaggregates at the upper depth (Table 14).

At 0-15 cm soil depth, the fraction of carbon present in small macroaggregates was higher in zero tillage compared to conventional tillage (Table 14). The work done by Paustian et al. (2000) and Six et al. (2000) showed that an increase in aggregation is concomitant with increase in organic carbon in no-till systems. At 15-30 cm soil depth, the tillage and the residue treatments did not affect the amount of carbon associated with small macroaggregates.

Carbon inside Microaggregates within Macroaggregates

We hypothesized that microaggregates within macroaggregates are expected to be largely responsible for any increased C-sequestration in ZT especially when residues are maintained, due to a higher total amount of microaggregates contained within macroaggregates compared to CT or residue removal. At 0-15 cm soil depth, consistent with our hypothesis, a higher fraction of Carbon in microaggregates within macroaggregates was found in ZT compared to CT (Table 15). This could be a result of the higher fraction of microaggregates within macroaggregates in ZT in that depth.

At 15-30 cm depth, the distribution of Carbon in microaggregates within macroaggregates was lower in zero tillage compared to conventional tillage (Table 15). When crop residues were maintained, the fraction of Carbon in microaggregates within macroaggregates had increased by 31% in zero tillage because crop residue retention and zero tillage had a positive effect on total amounts of stable macroaggregates. On the other hand, the higher fraction of Carbon in microaggregates within macroaggregates present in conventional tillage at 15-30 cm depth was probably a result of organic matter (residues) distribution from upper soil to lower horizon caused by mixing through tillage (Etana et al., 1999). In zero tillage, the effect of insecticide application on the distribution of microaggregates within macroaggregates (and thus associated C) was statistically significant. There was a strong reduction in the fractions of microaggregates within macroaggregates, and thus in the fraction of total soil C retained in those mM when insecticides were applied in zero tillage, especially in the case of residue removal (Table 15).

Effects of Management on Maize Yield

A higher maize yield can be expected under ZT with residue retention due to enhanced water, and possibly nutrient availability in such systems compared to CT systems (Edwards et al., 1992; Quedraogo, 2004). Govaerts et al. (2005) reported that highest maize yield was obtained where maize and wheat were rotated in ZT with residue fully kept on the filed. The work done by Govaerts et al. (2005) showed that although higher maize yield was obtained with residue retention in both CT and ZT systems, residue retention was crucial to ZT practice and resulted in a higher yields than CT. Moisture availability is another important reason for the higher yields under ZT plus residues in semi-arid tropical regions and can also play a role in humid tropical areas at least in dry years. Duration of experiment when yield differences between tillage and residue treatments become visible is an important factor to be considered. For example, Fisher et al. (2002) found no significant tillage effect on maize yield in sub-humid tropical highlands of Mexico in an experiment conducted for three years. Supporting this, Govaerts (2005) reported that it can take some time –roughly 5 years-before the full benefits of ZT with residue retention become evident. On the other hand, one of the principal reasons farmers till their soil is to control weeds, and therefore as tillage is obviated in ZT, weed control becomes extremely important factor that could cause yield decline (Wall, 2005). Moreover, insect pests are yield limiting factors in tropical agro-ecosystems. For example, in South Africa, termites are considered as pest organisms in maize crops (Barrios et al., 1998; Eicher, 1995; Lal, 1998).

Taking the above mentioned factors in to consideration, the effects of management in relation to results of the current season maize yield data in comparison to data from the previous years of the same experiment (rotation) are discussed here below:

Tillage and Residue Management Effects on Maize Yield

The present conservation tillage trial runs for about seven consecutive seasons starting in 2003. Nevertheless, none of the management effects ever resulted in significant maize yield differences, when considered the yield data from Maize-soybean rotation trial. As to why tillage and residue managements have not yet caused yield differences, it was probably due to the soybean residues applied to all the treatments before maize planting, which makes N immobilization less likely. Moreover, no difference in soil cover is expected between treatments in maize phase of the rotation since all the treatments received soybean residues. Consequently, any beneficial effects of ZT on moisture availability are more expected during soybean phase of the rotation where maize stovers are applied only in residue treatments. However, residue retention (if maize stover) should be combined with mineral nitrogen and phosphorous fertilizers to avoid nutrient limitation in zero tillage (Vanlauwe et al., 2001). Therefore, it would be important to look also at data in the 0 or low fertilizer treatments of the trial and evaluate the effects of tillage and residue treatments on yield differences. On the other hand, from the cropping seasons perspective, there was a significant increase in maize yield between the starting year of the conservation tillage trial and the subsequent cropping seasons/years (Table 16). When the duration of the conservation tillage trial in Nyabeda site is compared to other similar research projects, it can take some time before any benefits from zero tillage as well as residue retention become visible. So, we suggest that the conservation tillage trial is worth continuing for additional years to prove the long-term sustainability of the tillage-residue management system.

Effects of Insecticide Applications on Maize Yield

In contrast to our hypothesis, insecticide application had increased maize yield (both total biomass and grain yield). We expected a higher maize yield in the '-insecticide' treatments where the soil macrofauna can facilitates the incorporation of crop residues in to stable aggregates and gradual decomposition and nutrient release. Together with the positive impact on water infiltration and retention through improved soil aggregation and porosity, soil macrofauna were expected to contribute to improved chemical and physical soil conditions that will lead to a higher crop yield but our result proved otherwise. Maize yield data from the current year experiment showed that there was a 31% yield increase in '+insecticide' treatment compared to '-insecticide' treatment. Therefore, the yield increase may be the result of elimination/reduction of soil fauna (particularly termites and ants, through insecticide application), which would otherwise become a pest to the crop. We suggest a further research on the specificity/effectiveness of the pesticides on target organisms. We also suggest that data on pest incidence should be measured and studied in order to investigate the severity of damage caused by insects on the crop yield.

Effects of Moisture Accumulation (in '+Insecticide' Plots) on Maize Yield

We also attributed the yield increase to soil moisture accumulation in the confined insecticide treated microplots. The metal sheets used to separate pesticide treated plots from untreated ones could have accumulated rain water and increased moisture availability, especially at dry times in the season. Supporting this, the plant density appeared to be higher in the confined '+insecticide' treatments, which maybe due to enhanced moisture availability at germination. However, regarding the potential effect of the metal sheets on soil water dynamics in the microplots, the harvest indices (HI) for dry matter was similar for the with (0.46) and without (0.45) insecticide treatments, indicating that there was no moisture stress during grain filling (Unstressed harvest index values for maize, 0.4-0.55). To better understand the effect of insecticides on yield, we suggest further research to investigate the effect of insecticides on the yield without metal sheets (to avoid any temporal ponding of water in the microplots), and soil moisture measurements should be taken at different stages of crop growth.

4. **Conclusions**

Our results, generally, provide a basis to support the development of zero/minimum tillage and residue retention for better aggregation and carbon sequestration. If farmers opt to practicing the traditional way of conventional tillage, then, from a soil quality perspective, it would be preferable to maintain crop residues in the field. Tillage caused a significant disruption of macroaggregates compared to zero tillage, but only in the top 15 cm depth of the soil. The negative effects of tillage on aggregate disruption largely disappeared when crop residues were maintained in the field. Through the adoption of zero tillage, it was proved that macroaggregation was positively affected as it had been indicated in our macroaggregate data (Table 3 and 4). These macroaggregates were found containing more soil carbon indicating that SOM is better protected against decomposition due to reduced soil disturbance in zero tillage. On the other hand, as zero tillage had involved some soil disturbance (top 5 cm) because of manual weeding, the beneficial effects of zero tillage on macroaggregates and carbon concentrations might have been reduced. Thus, we suggest further study on macroaggregation and associated carbon under zero tillage without such soil disturbance as can be caused by manual weeding. There is an indication that the total soil carbon was positively affected due to residue retention, though it was apparent only in zero tillage. Our study demonstrated that the total soil carbon decreased from topsoil to deeper soil layer (15-30 cm) both in conventional and zero tillage treatments.

Our results revealed that the fractions of macroaggregates were higher at 15-30 cm soil depth, irrespective of tillage treatment, when compared to macroaggregate fractions at 0-15 cm depth. Moreover, residue retention results in higher microaggregation inside macroaggregates than without residues, as was shown by the 20-30% increase of these fractions in zero tillage in the subsoil layer. Thus, the increased amount of macroaggregation at 15-30 cm soil depth, suggest that the rate of macroaggregates turnover was slower at 15-30 cm possibly due to the type of tillage tools, which can hardly cause soil disturbance beyond 15 cm. The decrease in the fractions of microaggregates within macroaggregates and associated carbon after insecticide application in zero tillage needs further investigation to know whether the decrease was due to reduced macrofauna (particularly earthworms), or it was a direct result of insecticide application in a complex interaction with tillage and residues. Our macroaggregate composition data, generally, shows a decreasing trend of microaggregates within macroaggregates from topsoil to subsurface soil irrespective of tillage types.

Tillage and residue management have not caused yield differences in this conservation tillage trial, for the 4 year maize crops since the start of the trial, so no indications of improvement of soil fertility during 4 years of ZT and/or residue retention are apparent. On the other hand, any direct benefits of ZT on soil moisture retention and subsequently on yield could not be tested since all treatments were amended with (rapidly decomposable) soybean residues only before planting of the maize. More research is required to elucidate the reason for the considerable increase in maize yield upon insecticide application found for all treatments.

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6. **Appendix**

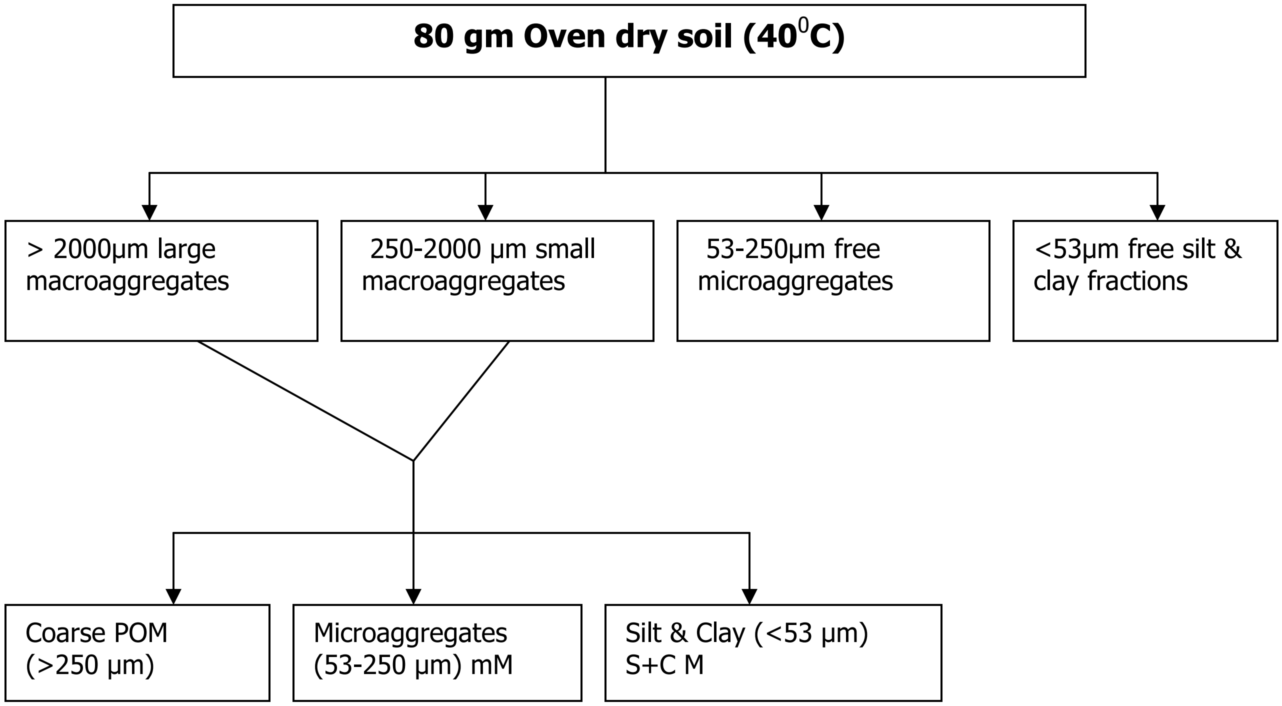
Annex 1: The Treatment Structure of the Field Experiment

Factors	Number of levels	Description of levels
Site	1	Nyabeda
Residue type/quality	1	Soybean
Residue quantity	1	2 ton/ha
N-application	1	60 Kg/ha
P-application	1	60 Kg/ha
K-application	1	60 Kg/ha
Crop presence	1	Maize
Insecticide	2*	With (+) & Without (-)
Cropping pattern	1	Soybean-maize Rotation
Residue amendment	2	Retained (+) & Not-retained (-)
Tillage practice/operation	2	Conservation and Conventional
Sampling time	1	July 26 & 27, 2006
Replicates	4	
Total	32	

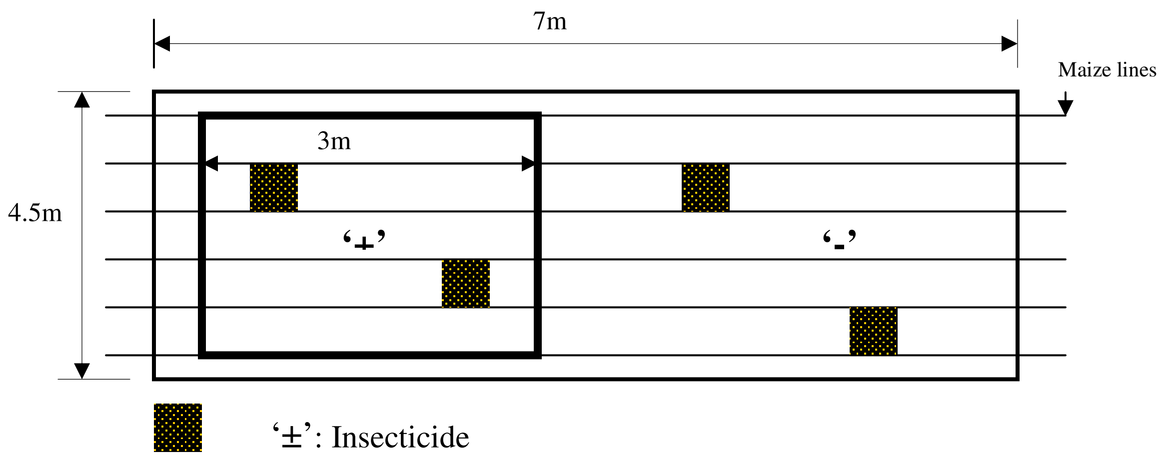
* Nested within the residue and tillage treatments

Rep-1		Rep-2		Rep-3		Rep-4	
101T3(90N)	102T3(0N)	201T10(60N) L	202T10(0N) L	301T5 L	302T5 I	401T9(90N)	402T9(0N)
104T3(60N)	103T3(30N)	204T10(60N) C	203T10(0N) C	304T5 I	303T5 C	404T9(60N)	403T9(30N)
105T1(60N) L	106T1(0N) L	205T12(90N)	206T12(0N)	305T4(60N) L	306T4(0N) L	405T8 L	406T8 I
108T1(60N) C	107T1(0N) C	208T12(60N)	207T12(30N)	308T4(60N) C	307T4(0N) C	408T8 I	407T8 C
109T2 L	110T2 I	209T11 L	210T11 I	309T6(90N)	310T6(0N)	409T7(60N) L	410T7(0N) L
112T2 I	111T2 C	212T11 I	211T11 C	312T6(60N)	311T6(30N)	412T7(60N) C	411T7(0N) C
113T4(60N) L	114T4(0N) L	213T9(90N)	214T9(0N)	313T2 L	314T2 I	413T11 L	414T11 I
116T4(60N) C	115T4(0N) C	216T9(60N)	215T9(30N)	316T2 I	315T2 C	416T11 I	415T11 C
117T6(90N)	118T6(0N)	217T7(60N) L	218T7(0N) L	317T3(90N)	318T3(0N)	417T10(60N) L	418T10(0N) L
120T6(60N)	119T6(30N)	220T7(60N) C	219T7(0N) C	320T3(60N)	319T3(30N)	420T10(60N) C	419T10(0N) C
121T5 L	122T5 I	221T8 L	222T8 I	321T1(60N) L	322T1(0N) L	421T12(90N)	422T12(0N)
124T5 I	123T5 C	224T8 I	223T8 C	324T1(60N) C	323T1(0N) C	424T12(60N)	423T12(30N)
125T8 L	126T8 I	225T6(90N)	226T6(0N)	325T10(60N) L	326T10(0N) L	425T1(60N) L	426T1(0N) L
128T8 I	127T8 C	228T6(60N)	227T6(30N)	328T10(60N)C	327T10(0N)C	428T1(60N) C	427T1(0N) C
129T9(90N)	130T9(0N)	229T4(60N) L	230T4(0N) L	329T11 L	330T11 I	429T2 L	430T2 I
132T9(60N)	131T9(30N)	232T4(60N) C	231T4(0N) C	332T11 I	331T11 C	432T2 I	431T2 C
133T7(60N) L	134T7(0N) L	233T5 L	234T5 I	333T12(90N)	334T12(0N)	433T3(90N)	434T3(0N)
136T7(60N) C	135T7(0N) C	236T5 I	235T5 C	336T12(60N)	335T12(30N)	436T3(60N)	435T3(30N)
137T12(90N)	138T12(0N)	237T1(60N) L	238T1(0N) L	337T8 L	338T8 I	437T6(90N)	438T6(0N)
140T12(60N)	139T12(30N)	240T1(60N) C	239T1(0N) C	340T8 I	339T8 C	440T6(60N)	439T6(30N)
141T11 L	142T11 I	241T3(90N)	242T3(0N)	341T7(60N) L	342T7(0N) L	441T4(60N) L	442T4(0N) L
144T11 I	143T11 C	244T3(60N)	243T3(30N)	344T7(60N) C	343T7(0N) C	444T4(60N) C	443T4(0N) C
145T10(60N)	146T10(0N) L	245T2 L	246T2 I	345T9(90N)	346T9(0N)	445T5 L	446T5 I
148T10(60N)	147T10(0N) C	248T2 I	247T2 C	348T9(60N)	347T9(30N)	448T5 I	447T5 C

Annex 2: *Experimental plot Layout of conservation tillage trial at Nyabeda research site, Maseno. The highlighted experimental plots indicate the ones used for this study. Numbers preceding letters indicate plot no. in the filed. T1=conservation tillage '-Residue', T4=conservation tillage 'Residue', T7=conventional tillage '-Residue', T10=conventional tillage '+Residue'. C=cereal (Maize), L=Legume (Soybean), I=intercrop, and N=Nitrogen*



Annex 3: *Complete fractionation scheme to isolate all aggregate and particulate organic material (POM) fractions to determine aggregate and POM C and N dynamics across the continuum of ecosystems*



Annex 4: *Sketch of the plot and the location of monolith sampling*