EFFECTS OF FERTILIZER-N AND ORGANIC RESOURCE MANAGEMENT ON SOIL AGGREGATES FORMATION AND CARBON CYCLING IN THE CENTRAL HIGHLANDS OF KENYA

KINYANJUI SAMUEL NJOROGE
N50/10225/06

A THESIS SUBMITTED IN PARTIAL FUFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENVIRONMENTAL STUDIES (AGROFORESTRY AND RURAL DEVELOPMENT) IN THE SCHOOL OF ENVIRONMENTAL STUDIES OF KENYATTA UNIVERSITY

May 2011
DECLARATION

This is my original work and has not been presented for a degree in any other university or any other award.

Kinyanjui Samuel Njoroge  
Dept of Environmental Sciences  
School of Environmental Studies  
Kenyatta University

Date

This thesis has been submitted with our approval as the university supervisors

Professor Daniel N. Mugendi  
Dept of Environmental Sciences  
School of Environmental Studies  
Kenyatta University

Date

Dr. Bernard Vanlauwe  
Senior Scientific officer  
Tropical Soil Biology and Fertility Institute (TSBF-CIAT)
DEDICATION

This work is dedicated to my parents Mr and Mrs. Kinyanjui who have provided everything I have needed in my academic pursuits. May God bless you abundantly.
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors Professor Daniel Mugendi of Kenyatta University and Dr. Bernard Vanlauwe of TSBF-CIAT for their efforts, dedication, advice and support throughout the study period. I also sincerely appreciate the advice and support offered by Professor Roel Merckx of Katholieke University in Leuven, Belgium, and the great input and support offered by Agnes Kavoo of TSBF-CIAT and Joses Muthamia. My gratitude also goes to the staff of TSBF-CIAT especially; Jeremiah Okeyo, Hellen Wangechi, Alice Kareri, Jacqueline Odongo, Wilson Ngului, Elias Mwangi, Boaz Waswa, Ivan Adolwa, Job Kihara, Tiberious Brian Etyang, Morris Miseda, Martin Kimanthi, Francis Njenga, Margaret Muthoni and Lukylesia Nyawira. Special mention goes to Christine Nyagaya for her help in sample preparation, and to all the students attached at TSBF led by Elizabeth Murua, Alfred Nyambane, Victor Wasike, Benjamin Kibor, Fredrick Ayuke and David Lelei. It is impossible to enumerate all the people who offered me support and advice throughout my study period. May God bless you abundantly.

Above all, I thank the Almighty God who has given me the strength to come this far.
TABLE OF CONTENTS

DECLARATION ........................................................................................................... ii
DEDICATION .............................................................................................................. iii
ACKNOWLEDGEMENTS .............................................................................................. iv
TABLE OF CONTENTS .............................................................................................. v
LIST OF TABLES ......................................................................................................... viii
LIST OF FIGURES ....................................................................................................... ix
ABBREVIATIONS AND ACRONYMS ......................................................................... x
ABSTRACT .................................................................................................................... xi

CHAPTER ONE ............................................................................................................. 1
INTRODUCTION .......................................................................................................... 1
  1.1 Background ........................................................................................................... 1
  1.2 Statement of the problem and justification .......................................................... 3
  1.3 Research hypotheses .......................................................................................... 5
  1.4 Research objectives ............................................................................................ 5
  1.5 Significance and justification of the study ........................................................... 6

CHAPTER TWO ........................................................................................................... 7
LITERATURE REVIEW ................................................................................................. 7
  2.1 Constraints to crop production in sub-Saharan Africa .......................................... 7
  2.2.1 Managing organic resources: the development of a decision support system .... 10
  2.2.2 Combined use of organic and mineral resources for soil fertility replenishment in sub-Saharan Africa ................................................................. 12
  2.3 Decomposition of organic resources ................................................................. 15
  2.3.1 Factors affecting the decomposition rate of organic resources ....................... 16
  2.3.2 Studying the decomposition pattern of organic resources ............................... 18
  2.4 Soil aggregates ................................................................................................... 19
  2.4.1 Effect of soil aggregates on soil fertility .......................................................... 21
  2.5 Organic resources and soil aggregation .............................................................. 22
  2.6 Effect of combined use of organic and mineral resources on aggregate formation 24
2.7 Role of soil organic matter in soil productivity .................................................. 25
2.8 Soil organic carbon sequestration ........................................................................ 26

CHAPTER THREE ........................................................................................................... 28
MATERIALS AND METHODS ...................................................................................... 28
3.1 Experimental sites ............................................................................................... 28
3.2 Experimental design ........................................................................................... 29
3.2.1 Materials and procedure ................................................................................ 29
3.2.2 Design of the experiment ............................................................................... 30
3.3 Soil sampling ....................................................................................................... 31
3.4 Laboratory analysis ............................................................................................ 32
3.4.1 Aggregate formation and carbon cycling ....................................................... 32
3.4.2 Aggregate separation ..................................................................................... 33
3.4.3 Soil organic matter fractionation .................................................................... 34
3.5 Statistical analyses .............................................................................................. 35

CHAPTER FOUR .......................................................................................................... 36
RESULTS AND DISCUSSION ....................................................................................... 36
4.1 General overview ............................................................................................... 36
4.2 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on aggregate proportions ........................................... 36
4.3 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on distribution of distinct SOM fractions ................. 43
4.4 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on soil carbon status .................................................. 48
4.4.1 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on carbon content of whole soils ...................... 48
4.4.2 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on carbon content of soil aggregates ............... 52
4.4.3 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on carbon content of distinct SOM fractions 58

CHAPTER FIVE ............................................................................................................. 61
CONCLUSIONS AND RECOMMENDATIONS ............................................................ 61
5.1 Conclusions ........................................................................................................61
5.2 Recommendations ............................................................................................63
REFERENCES: ........................................................................................................64
LIST OF TABLES

Table 3.1: Treatment structure for Embu and Machang’a tube experiments………………..31

Table 3.2: Chemical and physical characteristics of soils sampled in Embu and Machang’a in April 2005………………………………………………………………………………32

Table 4.1: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on proportions of soil aggregates in Embu soils ……………………37

Table 4.2: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on proportions of soil aggregates in Machang’a soils …………37

Table 4.3: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage (%) distribution of distinct SOM fractions within macroaggregates in Embu soils ……………………………………………………………44

Table 4.4: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage (%) distribution of distinct SOM fractions within macroaggregates in Machang’a soils……………………………………44

Table 4.5: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of whole soils in Embu……………………………………………………………………………………………………………………48

Table 4.6: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of whole soils in Machang’a ………………………………………………………………………………………………………………………49

Table 4.7: Effect of the amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of soil aggregates in Embu soils ……………………………………………………………………………………………………………………………53

Table 4.8: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of soil aggregates in Machang’a soils ……………………………………………………………………………………………………………………………53

Table 4.9: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of distinct SOM fractions in Embu soils…………………………………………………………………………………………………………………………58

Table 4.10: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of distinct SOM fractions in Machang’a soils ……………………………………………………………………………………………………………………………………………58
LIST OF FIGURES

Figure 2. 1: The decision support system for organic resource management (adapted from Palm et al., 2001) ..............................................................12

Figure 3. 1: A decomposition tube set up in the field ........................................30

Figure 3. 2: A section of the field layout showing the set up of decomposition tubes......31

Figure 3. 3: Complete fractionation scheme to isolate all aggregates and particulate organic matter (POM).................................................................33

Figure 3. 4: A microaggregate isolator set up on a reciprocal shaker ......................35
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support System</td>
</tr>
<tr>
<td>ISFM</td>
<td>Integrated Soil Fertility Management</td>
</tr>
<tr>
<td>Kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>M</td>
<td>Macroaggregate</td>
</tr>
<tr>
<td>Mg</td>
<td>Mega gram</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>iPOM</td>
<td>Intra Particulate Organic Matter</td>
</tr>
<tr>
<td>POM</td>
<td>Particulate Organic Matter</td>
</tr>
<tr>
<td>PROC</td>
<td>Procedure</td>
</tr>
<tr>
<td>PVC</td>
<td>Poly Vinyl Chloride</td>
</tr>
<tr>
<td>SAS</td>
<td>Statistical Analysis System</td>
</tr>
<tr>
<td>SOM</td>
<td>Soil Organic Matter</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil Organic Carbon</td>
</tr>
<tr>
<td>SSA</td>
<td>Sub-Saharan Africa</td>
</tr>
<tr>
<td>TSBF</td>
<td>Tropical Soil Biology and Fertility</td>
</tr>
</tbody>
</table>
ABSTRACT

The maintenance of proper levels of soil organic matter (SOM) has been advocated as one of the main ways of combating soil fertility decline in sub Saharan Africa (SSA). SOM levels can be increased through increased aggregate formation as soil aggregates physically protect SOM, from its loss through decomposition. The objective of this study was to investigate how the amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources affects aggregate formation and subsequent carbon (C) cycling in aggregates. The experiment was conducted in Embu and Machang’a areas of central Kenya and was based on a decomposition tube experiment that was set up in April 2005. This experiment aimed at complimenting long-term field trials started in 2002 to establish the effect of application of various combinations of organic plus mineral resources on soil nutrient status. The main variable comprised of fertilizer-N and organic resources, with the sub-treatment being soil fertility levels. Maize stover and urea fertilizer were mixed with 3.2 kg of soil and set up in decomposition tubes. The application rate was 4 ton per hectare and 120 kg per hectare for the maize stover and fertilizer respectively. Four treatments were established, namely; control (no organic resources or fertilizer-N added), sole fertilizer-N, sole stover and combined stover and fertilizer-N, with each treatment having three replicates. To determine changes in soil aggregates, soil samples obtained from the decomposition tubes were fractionated through wet sieving. SOM fractionation was also conducted to obtain the various SOM fractions. All aggregates and SOM fractions obtained were then oven dried, ground, and analyzed for C. All the data collected was analyzed with the PROC MIXED procedure of
SAS and the means separated at $p < 0.05$. Higher proportions of macroaggregates were observed for the Embu soils compared to the Machang’a ones. For both Embu and Machang’a soils, amendment of soils with sole or combined fertilizer-N and organic resources had a significant effect ($p < 0.05$) on the proportions of all aggregate class sizes. Amendment of soils of varying fertility levels with sole or combined fertilizer-N and organic resources also had a significant effect on the distribution of SOM fractions for both Embu and Machang’a soils. Significant differences in whole soils, aggregates and SOM fractions percentage carbon levels were also observed. Overall, the silt and clay fraction had higher C levels compared to the other aggregate size classes indicating higher stabilization of C within this fraction. From the results obtained from this study, the use of combined organic and mineral resources is recommended for the improvement and maintenance of soil fertility in high fertility soils. In low fertility coarse textured soils, the sole application of organic resources is recommended for the improvement and maintenance of soil fertility.
CHAPTER ONE

INTRODUCTION

1.1 Background

Sustainable food production relies heavily on the maintenance of sufficient levels of soil fertility. This can only be achieved if there is a balance between nutrient outputs and inputs (Kirchmann and Thorvaldsson, 2000). In sub Saharan Africa (SSA), this balance is hardly achieved due to the low input of nutrients whether in form of mineral fertilizers or organic inputs. This is mainly due to the high cost of fertilizers due to the liberalization of fertilizer trade and introduction of structural adjustment programs (SAP) (Ayuke et al., 2004), resulting in very low levels of fertilizer use. Current estimates for fertilizer use in Africa stand at 9 kg ha\(^{-1}\) compared to 87 kg ha\(^{-1}\) in the developed countries (Bationo et al., 2004). As for organic inputs, their successful use in soil fertility replenishment is limited by their low or imbalanced nutrient content, poor quality and the presence of other competing uses such as use as livestock feed (Palm and Rowland, 1997). With such low external input rates, soil fertility decline has persisted leading to low farm productivity and widespread hunger in the continent. Latest figures show that some 200 million people or 28% of Africa’s population are chronically hungry (Bationo et al., 2004).

In Kenya, a similar situation has been observed, where crop yields in most parts of the country are low due to declining soil fertility. This is often resulting from continuous farming and non-application of fertilizers by farmers. Low soil fertility tends to decline further as farmers remove many nutrient outputs in crops yield products, crop residues
and through losses such as leaching, and soil erosion processes (Kathuka et al., 2007). For example, in Embu district of Central Kenya as reported by Lesschen et al. (2003), nutrient balances of N, P and K were -55, -9 and -15 kg per hectare, respectively, in 1998 and in 2003, nutrient balances had decreased to -116.2, -22.1 and -31.7 per hectare for N, P and K, respectively. There is therefore an urgent need for the development of effective and affordable soil management strategies that shall adequately address the problem of soil fertility decline.

One of the ways through which smallholder farmers in SSA can replenish soil fertility in their farms is through the adoption of integrated soil fertility management (ISFM) strategies. These include among others the combined use of organic and inorganic resources. This is a feasible approach as diverse nutrient resources are usually available to resource poor farmers but are often underutilized due to lack of knowledge or other constraints such as labor (Delve, 2004). In such a system, fertilizers act as a nutrient source for plants while organic resources serve as a precursor of soil organic matter (SOM), which maintains the physical and physico-chemical components of soil fertility such as cation exchange capacity (CEC) and soil structure (Vanlauwe et al., 2002a). Organic resources also improve soil structure through increased aggregate formation, as they serve as a source of carbon compounds which play a major role in binding individual soil particles into microaggregates, and subsequently binding these microaggregates into macroaggregates (Blair et al., 2005). This is important as soil aggregation influences a range of soil properties such as aeration, water infiltration and drainage. These further influence crop establishment and growth, while also providing
habitat for soil biota (Denef et al., 2002). Increased soil aggregation also increases levels of SOM as soil aggregates physically protect SOM within their structure, thereby reducing its decomposition rate (Alvarez et al., 1998). It further reduces the loss of carbon (C) to the atmosphere as soil aggregates present in SOM form temporary C pools by stabilizing C within their structure (Six et al., 2002).

For optimal use of organic and mineral resources in soil fertility improvement, it is important to determine their applicability in agroecosystems that differ in terms of climate and soil texture. SSA is characterized by heterogeneity both in terms of climate and soil characteristics. One of the ways through which this can be achieved is by studying the decomposition patterns of organic residues as it is through this process that nutrients held within the residues are released into the soil (Palm, 1995). Although the decomposition rate of organic residues is mainly regulated by the quality of the residues (Palm, 1995), climatic conditions and soil texture have also been shown to play a key role (Meentemeyer, 1978; Becker et al., 1994; Mugendi and Nair, 1997). This can be achieved through the application of organic and mineral resources to soils differing in texture and fertility levels, in different climatic zones. Such an approach would lead to increased understanding of the short- and long-term benefits of organic and mineral resources as relates to aggregate formation and C cycling in different agroecosystems.

1.2 Statement of the problem and justification

The central highlands of Kenya are characterized by high human population that has exerted a lot of pressure on the limited land resources. This has led to increased land
fragmentation and continuous cultivation usually with minimal or no application of external nutrient inputs. This has caused continued SOM and nutrient depletion of the soil resulting in reduced crop yields. Further, the ability of the land to support other ecosystem services such as, nutrient storage and release, water holding and infiltration, root penetration among others have been compromised. The decline in farm yields has led to food insecurity and reduced farm incomes in the region, leading to increased incidences of hunger and poverty. Efforts to replenish soil fertility in these areas have mainly relied on the use of organic and mineral inputs. The success of this has however been hampered by the reduced availability of the former, and the high prices of the latter. There is therefore need for the development of a more sustainable and affordable method of soil fertility replenishment.

The combined use of organic and mineral resources is one of the ways through which farmers in this region can combat soil fertility decline. This is a feasible approach as various organic and mineral resources are available to farmers in the region though in varying quantities. The judicious use of these two nutrient sources has the ability to improve plant nutrient supply while at the same time improving SOM levels and the associated ecosystem services.

Although several studies have enumerated the various benefits associated with the combined use of organic and mineral resources, little has been done to determine the effect of soil fertility on the combined use of organic and mineral resources with regard to the decomposition of organic resources. This is important as the rate of organic
resources decomposition influences the build up of SOM, aggregate formation and consequently the stabilization of carbon within aggregates. Such a study would be of great importance as the central highlands of Kenya are characterized by heterogeneity with regard to soil fertility levels. In line with this, this study seeks to determine the effect of organic and mineral amendment on aggregate formation and C cycling to soils of varying fertility levels in the central highlands of Kenya.

1.3 Research hypotheses

This study was guided by the following hypotheses:

H1 The amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources increases aggregate formation and subsequent C protection within aggregates.

H0 The amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources does not increase aggregate formation and subsequent C protection within aggregates.

1.4 Research objectives

1. To determine the effect of the amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on aggregate formation.
2. To determine the effect of the amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on the distribution of distinct SOM fractions.

3. To determine the effect of the amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on C stabilization in soil aggregates.

1.5 Significance and justification of the study

This study demonstrates the effect of the amendment of soils of varying texture and fertility levels with sole or combined organic and mineral resources on soil aggregate formation, and subsequent C cycling within aggregates. Understanding the above processes is an important step towards the development of feasible soil management strategies based on combined organic and/or mineral resources in different agroecosystems. Such management options shall ensure improved soil structure, increased C sequestration and retention within soil aggregates, resulting in reduced CO₂ emissions, and sustained soil fertility and productivity.
CHAPTER TWO
LITERATURE REVIEW

2.1 Constraints to crop production in sub-Saharan Africa

Inadequate crop production in Africa can be attributed to soil related constraints. African soils exhibit a variety of constraints, namely: physical soil loss through erosion, nutrient deficiency, low organic matter levels, aluminum and iron toxicity, acidity, salinity and sodicity, crusting, and moisture stress (Place et al., 2003). Although some of these constraints occur naturally in tropical soils, degradation processes related to soil management exacerbate them, resulting in massive soil fertility degradation. Increased population pressure in agricultural areas has also contributed to soil fertility decline by reducing the use of traditional farming systems such as shifting cultivation and long fallow periods which allow for soil fertility to replenish and also reduce pest problems (De Groote et al., 2010). Consequently, soil fertility degradation has been described as the single most important constraint to food security in SSA (Bationo et al., 2004). As a result, SSA has been designated as one of the global hotspots for hunger in the 21st century (Rosegrant and Cline, 2003).

To counter these constraints, various soil fertility replenishment efforts such as the use of inorganic or organic resources have been put in place. However, their success has been hampered by the high costs of mineral fertilizers on one hand, and the decline in quantity and quality of organic resources applied on the other hand (Palm et al., 2001). Further, the lack of immediate benefits to farmers has affected the adoption rate of soil fertility improvement technologies such as the rotation of cereals with fast growing nitrogen
fixing herbaceous legumes such as *Crotalaria* (Versteeg et al., 1998; Ibewiro et al., 2000; De Groote et al., 2010).

In the central highlands of Kenya, declining land productivity is one of the major problems facing smallholder farmers. The decline has been associated with high population densities, deforestation (Gachane et al., 1997; Okoba and De Graaf, 2005), continuous cropping without addition of adequate fertilizer and manure (Mugwe et al., 2004), and soil erosion on the steep slopes (Mugendi et al., 1999; Mairura et al., 2008). Continuous cropping is a result of small land sizes in the area which average 1.2 ha per household, while the high cost of mineral fertilizers has limited their sufficient use by majority of the smallholder farmers (Mugendi et al., 1999; Mugwe et al., 2004). This has led to low agricultural productivity, widespread poverty and food insecurity in the region (Mugendi et al., 1999; Mairura et al., 2008).

### 2.2 Use of organic resources for soil fertility management in sub-Saharan Africa

Organic resources are widely used in soil fertility replenishment efforts in SSA. However, the success of use of organic resources varies throughout the region. This is mainly due to the heterogeneity of the region in terms of soils, climate, agricultural potential, market access, and population density (Place et al., 2003). These differences influence the types of organic resources that are technically feasible to produce, and the types of crops that will benefit from such application (Place et al., 2003). Further, the effects of these resources on soil fertility vary with cropping systems, soil types, management practices of organic materials and environmental factors (Mugwe et al., 2004).
Commonly used organic resources include: fresh, dried or composted animal manure, crop residues, green manure, and agro-industrial products such as coffee husks and forest litter (Lekasi, 2005). These resources play a key role in soil fertility management in farming systems through their short term effects on nutrient supply, and long term effects on the maintenance of soil organic matter (SOM) in soils (Palm et al., 2001).

In Kenya, use of organic resources for soil fertility replenishment efforts varies across the country. Omiti et al. (1999) found that between 86% and 91% of farmers in semiarid and semihumid areas east of Nairobi used manure, while compost was adopted by about 40% of farmers in the wetter parts of these zones, but by relatively few farmers in the more arid sites. In the more humid western highlands, Place et al. (2002) found that 70% of households used manure while 41% used compost.

Organic resources used in soil fertility improvement influence nutrient availability through the total nutrients added, by controlling the net mineralization-immobilization patterns, and by serving as a carbon (C) source for microbial activities (Palm et al., 1997). Further, these resources serve as precursors to SOM fractions, and interact with the mineral soil in complexing toxic cations (Palm et al., 1997). In addition to these direct effects on nutrient availability, research findings have also emphasized other key contributions of organic resources. These include, the provision of other macro and micro nutrients, reduction of phosphorus sorption capacity, increased carbon organic matter, reduction of soil borne pest and disease spectra in rotations, and improvement of soil
moisture status (Vanlauwe, 2002a). Compared to inorganic fertilizers, organic resources have a greater residual effect on soil fertility due to slow release of nutrients and subsequent increase in SOM (Mafongoya et al., 1998). The ability of organic resources to improve soil fertility however depends on the quality and quantity of the resources used, with the former depending on plant species, plant parts used, and their maturity (Palm et al., 2001).

Although organic resources play a major role in soil fertility replenishment efforts in SSA, their continued ability to do so is at risk due to the decline in quantity of traditional organic inputs such as crop residues and animal manures. This is mainly due to reduced production and the presence of competing uses such as use as animal feed, fuel and fiber (Palm et al., 2001). The ability of organic resources to meet crop nutrient demands over large areas is also low due to the low nutrient content of the materials, and the high labour demands for processing and application (Palm et al., 1997). As a result of this, farmers are now faced with the need to find alternative means of replenishing and maintaining soil fertility.

### 2.2.1 Managing organic resources: the development of a decision support system

Although agricultural production has for a long time depended on the use of organic inputs for soil fertility replenishment, lack of predictive guidelines for management of organic resources meant that for a long time, use of organic resources for soil fertility replenishment was primarily based on trial and error (Palm et al., 2001). In line with this, Sanchez et al. (1989) stressed the need for a predictive understanding for the management
of organic resources in tropical agroecosystems. This led to substantial progress being made in developing organic resource management knowledge, resulting in the development of the Organic Resource Database (ORD). This database contains information on organic resource quality parameters and N mineralization dynamics for almost 300 plant species found in tropical agroecosystems (Palm et al., 2001). A further analysis of the information in the ORD has led to the development of a Decision Support System (DSS) for organic resource (OR) management (Figure 2.1). The DSS recommends four classes of OR usage based on their N, polyphenol, and lignin contents, with each class having specific management options. For instance, class I (High quality ORs) with an N content of >2.5%, a lignin content of <15%, and a polyphenol content of <4% are recommended to be applied directly to the soil. Class II and III (Medium quality ORs) are proposed to be mixed with either fertilizer or class I ORs. Class IV ORs have a low N (<2.5%), and a lignin content of >15%, and are advised to be applied as surface mulch (Palm et al., 2001). Notably, two pathways of the DSS (class II and class III) advise combining OR with mineral resources (MR). This is hypothesized to yield added benefits in terms of extra yield or improved soil fertility compared to the sole application of organic resources and mineral N (Vanlauwe et al., 2002b).
2.2.2 Combined use of organic and mineral resources for soil fertility replenishment in sub-Saharan Africa

The need for the combined use of organic and mineral resources for the improvement of soil fertility in SSA mainly arose as a result of the realization that there are limitations to the achievement of green revolution based solely on inorganic fertilizer use. Further it has been acknowledged that organic and inorganic inputs cannot be substituted by one another and are both required for sustainable crop production (Buresh et al., 1997; Vanlauwe et al., 2002b). This is due to the fact that inorganic or organic resources alone may not provide sufficient amounts of nutrients or may be unsuitable for alleviating specific constraints to crop growth (Sanchez and Jama, 2002). Further, there is potential for creation of added benefits through positive interactions between organic and inorganic resources in the short term, and the various roles each of these inputs play in the longterm (Place et al., 2003). Additionally, the need for integrated soil fertility management strategies in SSA has gained momentum due to mounting concerns on issues such as; rising green house gas emissions, environmental degradation, and rural
economic decline associated with modern conventional farming techniques (Angela et al., 2007). Other issues include, low levels of fertilizer application (about 9 kg ha\(^{-1}\) compared to 87 kg ha\(^{-1}\) for developed countries) (Bationo et al., 2004), and the decline in the quantity of organic matter applied in farming systems (Palm et al., 2001). These concerns have warranted a critical need for management practices that enhance land value for producers, while promoting long term agricultural sustainability and productivity (Robertson and Swinton, 2005). Alternative crop management practices, such as cover cropping, compost application and reducing or eliminating inorganic fertilizer use, have emerged as integrated and ecologically sound approaches to improving SOM levels, and supplying crops with sufficient N (Drinkwater et al., 1998). This has been confirmed by several studies with Clark et al. (1998) reporting that cropping systems that combined decreased levels of inorganic N fertilizer with organic N inputs were more efficient at storing excess N than conventional systems. Long-term studies have also shown that combinations of both organic and inorganic nutrient sources lead to enhanced nutrient availability and synchronization of nutrient release and uptake by plants (Mugendi et al., 1999; Mugwe et al., 2009)

In Kenya, reports indicate that various farmers use more than one nutrient source on their farms (Place et al., 2002). A study by Freeman and Coe (2002) found that 37% of farmers in the relatively drier zones of Kenya used both organic and inorganic resources. A further 10% were using more than one organic source but without mineral fertilizer. In the western Kenya highlands, more than two thirds of farmers using mineral resources
also use animal manure. In central Kenya, Murithi (1998) found that multiple sources of nutrients are used on a variety of crops.

In the combined use of organic and mineral resources, fertilizers act as nutrient sources for plants while organic matter serves as a precursor of SOM, which maintains the physical and physico-chemical components contributing to soil fertility such as cation exchange capacity (CEC) and soil structure (Vanlauwe et al., 2002a). The increase in SOM levels as a result of organic matter incorporation also reduces the loss of N and C through leaching and loss to the atmosphere respectively. This is due to the ability of soil aggregates present in SOM to form temporary C and N pools by stabilizing C and N within their structure (Six et al., 2002). Further benefits of combined application of organic amendments and synthetic fertilizers are in increased N synchrony through the contribution of N from both N sources in temporary distinct patterns (Palm et al., 2001), increased aggregation, and increased soil microbial populations (Hao et al., 2002). Several studies have confirmed the beneficial impacts of combined use of organic and inorganic resources. For example, in an incubation experiment with leaching tubes, Sakala et al. (2000) reported the immobilization of all the mineral-N after thoroughly mixing 50 mg ammonium-N kg\(^{-1}\) soil with 3000 mg C kg\(^{-1}\) soil of maize residues with a C:N ratio of 60. Vanlauwe et al. (2002b) reported that in a series of experiments with \(^{15}\)N labeled fertilizer (Urea and Ammonium Sulphate), and organic matter, the combined application of urea and incorporated low quality maize stover residues substantially retarded the movement of urea-N to the subsoil compared to the treatment with sole application of urea. This was most likely caused by immobilization of applied urea-N in
the SOM pool. For as at the end of the trial, 13.5% of the applied urea-N was recovered in the top 8 cm of soil compared with 3.4% in the sole treatment (Vanlauwe et al., 2002b).

The success of combined organic and inorganic resource management is however dependent on several factors. These include the availability and affordability of different types of inorganic fertilizers, the types and quantities of organic materials available, and the rates and proportions at which the two nutrient sources are combined (Palm et al., 1997).

2.3 Decomposition of organic resources

The decomposition of organic resources is the principal way through which nutrients held within organic matter are released into the soil. Understanding the decomposition and nutrient release patterns of plant materials is therefore an important first step to better management of organic inputs applied in agroforestry and other related land use systems (Palm, 1995).

Decomposition is a complex process regulated by the interactions between organisms (fauna and micro-organisms), physical environmental factors (particularly temperature and moisture) and resource quality (lignin, nitrogen, and condensed and soluble polyphenol concentrations) (Swift et al., 1979; Anderson and Ingram, 1993). There are three main processes that regulate the decomposition process namely; leaching, comminution and catabolism (Heal et al., 1997). Leaching influences decomposition by causing transport down the profile or removal from the system of labile resources in
either changed or unchanged form, while comminution influences decomposition through the physical reduction in particle size and often selective redistribution of chemically unchanged litter (Heal et al., 1997). Catabolism influences decomposition through chemical changes such as mineralization which give rise to inorganic forms and the synthesis of decomposed tissues and humus, (Heal et al., 1997).

2.3.1 Factors affecting the decomposition rate of organic resources

One of the most important factors affecting the rate of organic resource decomposition is the quality of the organic resources with regard to their chemical composition. This is mainly in terms of initial N content of the biomass, C:N ratio, lignin content, lignin:N ratio, and polyphenol and its ratios with N and lignin (Palm, 1995). All these have been shown to be important chemical qualities affecting the rate of decomposition and mineralization of organic resources, thereby determining their impact on soil fertility, especially with regard to nutrient supply and SOM formation (Palm, 1995; Mafongoya et al., 1998). High quality organic resources (high in N but low in lignin and polyphenol contents) decompose rapidly and hence release nutrients more rapidly as compared to low quality organic resources (poor in N and high in polyphenol and lignin) which decompose slowly and hence release nutrients slowly, or even initially immobilize them (Mafongoya et al., 1998). For example, a study by Mugendi et al. (1999) reported that leucaena and calliandra leafy biomass with significantly higher N concentrations and lower C:N ratio than maize roots decomposed and released N faster than maize roots over a 20-week study period.
Apart from organic resource quality, climatic conditions and soil properties also play a key role in influencing the decomposition rate of organic resources. A study by Mugendi et al. (1999) showed that rainfall and temperature were significantly correlated with the decomposition of tree biomass. This study further showed that the effect of climate on the decomposition rate of organic resources was more significant during seasons of climate variability (high variability of rainfall and temperature), with organic resource quality being a more significant factor during regular seasons when rainfall is more evenly distributed and temperature fluctuation is minimal.

Other factors that affect the rate of mineralization include soil characteristics such as texture and cultural practices such as the method of biomass application, application of mineral fertilizers, and methods employed in soil tillage (Becker et al., 1994; Mugendi and Nair, 1997). Differences in soil physical properties have also been found to indirectly affect the decomposition rate of organic matter through their effects on the types and abundance of microbial populations (Van Gestel et al., 1996), as this population is responsible for the decomposition of litter, the cycling of nutrients and the formation of SOM (Moore-Kucera and Dick, 2008). Studies have shown that communities with relatively high proportions of fungi have advantages in decomposition over communities dominated by bacteria as fungi are able to extend hyphae into the soil to extract nutrients and water (Holland and Coleman, 1987; Moore-Kucera and Dick, 2008), whereas bacteria are limited in movement. For example, a study by Ladd et al. (1995) suggested that differences in decay rates of $^{14}$C labeled biomass in soils with different physical
properties were due to the types of decomposer organisms involved in the turnover of added C.

2.3.2 Studying the decomposition pattern of organic resources

In studying the decomposition patterns of organic resources, an almost intractable problem is the need to impose methods which enable the experimental material to be identified without affecting the variables which regulate the component process (Anderson and Ingram, 1993). One of the common methods of studying the decomposition of organic matter is the use of litter bags. Enclosing litter in a mesh bag makes it possible to recover the residual experimental material and defines the conditions under which the organisms operate. However, the mesh bags and compaction of litter can create different microclimates to conditions in the unconfined litter and the incorporation of material into the soil can be affected (Anderson and Ingram, 1993). To overcome these constraints, decomposition tubes (microcosms) made of open ended polyvinyl chloride (PVC) cylinders are often used to study the decomposition patterns of organic residues as they allow for direct contact between the residues and soil, and also allow for periodic destructive sampling during the course of the study (Anderson and Ingram, 1993). Several studies have used this method to assess the decomposition of organic residues with Angers et al. (1997) using them to study the decomposition of $^{13}$C and $^{15}$N labeled wheat straw. A study by Moore-Kucera and Dick (2008) also used microcosms constructed of open-ended PVC columns to study the decomposition of $^{13}$C labeled litter.
2.4 Soil aggregates

Soil aggregates are classified into two main size groups according to their differing internal components. Particles up to approximately 250 µm are classified as microaggregates, while those greater than 250 µm are classified as macroaggregates and are bound together by oxides of iron, aluminum, polysaccharides and humic polymers (Lavelle and Spain, 2001). Soil aggregates are formed through a hierarchical order which involves the binding of small soil particles into larger sized particles (Tisdall and Oades, 1982; Jiao et al., 2006). The size of aggregates is estimated by distributing a soil sample across sieves with opening of different sizes and weighing the amount of soil on each sieve (Kemper and Rosenau, 1986; Kay and Angers, 2000). Further, the distribution of soil aggregates and their stability are important indicators of soil physical quality, reflecting the impact of land use and soil management (Castro et al., 2002).

In the aggregate hierarchy concept, it is postulated that the different binding agents (i.e., transient versus temporary versus persistent binding agents) act at different hierarchical stages of aggregation (Six et al., 2004). Free primary particles and silt sized aggregates (<20 µm) are bound together into microaggregates (20-250 µm) by persistent binding agents which include humified organic matter and polyvalent metal cation complexes. The oxides of aluminosilicates also play a role in the binding of microaggregates. These stable microaggregates, are in turn bound together into macroaggregates (>250 µm) by temporary (i.e., fungal hyphae and roots) and transient (i.e., microbial and plant derived polysaccharides) binding agents (Six et al., 2004). However, the polysaccharides are believed to mostly exert their binding capacity on a scale <50 µm within the
macroaggregates (Six et al., 2004). The macroaggregates are further stabilized through the action of microorganisms. Soil aggregates can be biologically stabilized by chemical bonding between organics and soil mineral particles, or by physical binding (Tisdall and Oades, 1982; Denef et al., 2002). Sometimes, the formation and stabilization of aggregates occurs simultaneously, but formation often precedes stabilization (Oades, 1993).

During macroaggregate stabilization, the intra-aggregate particulate organic matter (iPOM) (i.e., the fresh plant material that was incorporated in the macroaggregates during “biological” aggregate formation) is further decomposed by microorganisms into finer particulate organic matter (POM) (Six et al., 1998). This fine POM becomes increasingly encapsulated with minerals and microbial products forming new microaggregates within the macroaggregates (Six et al., 1998). This formation of microaggregates within macroaggregates has been found to be crucial for the long term sequestration of C (Six et al., 2002), as microaggregates have a greater capacity to protect C from decomposition as compared to macroaggregates (Balesdent and Gulliet, 1993). Due to this hierarchical order of aggregates and their binding agents, microaggregates stability is higher and less dependent on agricultural management as compared to macroaggregates stability (Six et al., 2004). Overall, the proportion of water-stable aggregates, as well as their total number, may increase or decrease as a function of tillage practice, soil type and clay mineralogy (Denef et al., 2001). Tillage affects aggregation by mechanical disruption of aggregates and fragmentation of roots and microbial hyphae, which are major binding agents for macroaggregates (Tisdall and Oades, 1982; Jiao et al., 2006). Tillage also
hastens SOM decomposition and reduces the soil carbon content by increasing access to SOM upon macroaggregate destruction (Balesdent et al., 2000; Jiao et al., 2006). The clay content of soils has also been found to influence soil aggregation, such that increased clay contents are often associated with increased aggregation or aggregate stability (Plante et al., 2006). In increasing soil aggregation, soil clay content indirectly affects soil C storage by occluding organic materials, making them inaccessible to degrading organisms and their enzymes (Plante et al., 2006). Other factors which may affect aggregate proportions include the number of wetting and drying cycles (Utomo and Dexter, 1982) and the application of organic inputs (Castro et al., 2002).

2.4.1 Effect of soil aggregates on soil fertility

One of the key ways through which soil aggregates promote soil fertility is through their effect on soil organic matter (SOM) levels. It has been proposed that soil aggregates physically protect SOM by forming a physical barrier between microorganisms and microbial enzymes, and their substrates (Alvarez et al., 1998; Krull et al., 2003; Plante et al., 2006). This increases SOM levels, as the decomposition rate of organic matter enclosed within soil aggregates is lower than the decomposition rate of organic matter located outside of soil aggregates (Angers et al., 1997). An increase in SOM levels has a positive effect on soil fertility as it is linked to soil physical, chemical, and biological properties, and is closely associated with soil productivity (Wander et al., 1994). Appropriate levels of SOM also ensure soil fertility and minimize agricultural impact on the environment through sequestration of C, reduced soil erosion, and preservation of soil biodiversity (Six et al., 2002). Soil aggregates also promote soil fertility through their
influence on microbial community structure (Hattori, 1988), oxygen diffusion (Sexstone et al., 1985), regulation of water flow, determination of nutrient adsorption and desorption (Wang et al., 2001), reduction of runoff and erosion (Barthes and Roose, 2002), and stabilization of C and N through decreased C and N mineralization (Six et al., 2002).

Although a lot of studies on soil aggregation have been conducted, the importance of soil aggregation and aggregate stability in regulating the accumulation or loss of SOM and nutrients in differently managed tropical soils is not well understood. Understanding these relationships in a broader range of soils and management conditions may be of particular importance for developing management practices for sustainable crop production systems (Ashagrie et al., 2007).

2.5 Organic resources and soil aggregation

Organic resources play a major role in aggregate formation as they serve as a source of carbon compounds, which play a critical role in binding individual soil particles into aggregates. Addition of organic matter, such as crop residues and other organic substrates to soil generally results in an increase in soil aggregate formation and stability as the residues serve as the nucleation centers for the formation of new aggregates (De Gryze et al., 2005; Bipfubusa et al., 2007). However, soil aggregate formation and stability is not only influenced by the quantity but also by the quality of organic matter inputs (Abiven et al., 2007), with the most important organic components being the polysaccharides and humic materials (Lavelle and Spain, 2001). Consequently, it has been suggested that the
improvement and maintenance of soil aggregate stability depends on the capacity of organic amendments to produce humic substances (Martens, 2000; Bipfubusa et al., 2007). In an incubation study, Annabi et al. (2007) showed a rapid effect of composted organic matter on aggregates, which they attributed to the diffusion of humic material within the aggregates, and a consequent increase in aggregate cohesion.

The incorporation of green materials leads to a flush of microbial activity and the production of such effective but ephemeral bonding agents as extra cellular polysaccharides (Chenu, 1993). If more highly decomposed materials are incorporated, the effect is lesser but longer lasting. Finally, if highly decomposed materials rich in humic compounds are incorporated, an even smaller but very long lasting stabilizing effect is obtained (Lavelle and Spain, 2001). Several studies have demonstrated the effect of organic resources on aggregate formation. Orenes et al. (2005) reported that the addition of organic matter to soil increased the number and size of water stable macro-aggregates. However, other studies have also shown that the aggregating effect of organic resources depends on the nature and rapidity of their decomposition, with those with a rapid decomposition rate showing a greater binding effect (Harris et al., 1996). High quality organic resources (high in N but low in lignin and polyphenol contents) which decompose rapidly have the highest ability to increase aggregate formation.

Generally, the large macroaggregates size class (> 2000 µm) is the fraction most influenced by the application of the organic residue (Bipfubusa et al., 2007). This is in line with the concept of aggregate hierarchy advanced by Tisdall and Oades (1982),
which states that the concentration of organic matter should increase with increasing aggregate size, and that macroaggregates should be enriched with recently added and more labile organic matter (Mikha and Rice, 2004). This has been corroborated by some studies. A study by Bipfubusa et al. (2007) reported that large macroaggregates were more enriched in the various organic matter fractions. Isotopic studies have also shown that newly added organic matter is preferentially incorporated in the stable macroaggregates (Angers and Giroux, 1996).

2.6 Effect of combined use of organic and mineral resources on aggregate formation

There is limited literature on the effect of combined organic and mineral resources on soil aggregates formation. However, a study by Harris et al. (1996) noted that nitrogen added to amendments of high carbon content decreased their long-term aggregating effectiveness. This decrease was attributed to the lower carbon:nitrogen ratio maintained in the nitrogen treated soils which favored rapid decomposition of microbially synthesized soil binding materials. Other authors have reported a positive effect of organic and inorganic resource application on aggregate formation. A study by Kavoo (2008) reported that the combination of sawdust and mineral N showed a positive interaction and resulted in an increase in large macroaggregates formation compared to the sole application of sawdust. In the same study, higher proportions of the smaller aggregate classes were observed with the addition of mineral resources (MR) to all the various classes of organic resources. This was attributed to the increased microbial activity and the consequent production of C binding agents upon the addition of mineral N as N limiting conditions have been found to limit microbial activity (Harris et al., 1996).
Combined application of organic and mineral fertilizers has also been reported to improve aggregation due to increased input of organic matter in the form of crop biomass. In a study to determine the impact of long-term application of fertilizer, manure and lime under intensive cropping, Hati et al. (2006) reported that the mean weight diameter (an index used to measure aggregation) of aggregates at 0 – 15 cm depth was highest (0.91 mm) in the NPK plus manure treatment and was significantly (p<0.05) greater than in the sole NPK treatment. The improved aggregation was attributed to the increased productivity of crops upon combined application of NPK and manure. In the long-term, they added more biomass to the soil in the form of decaying roots, litter and crop residue. Increased organic matter input, and the consequent stimulation of microbial and faunal activity favoured aggregation (Dick, 1992; Dutta et al., 2003).

2.7 Role of soil organic matter in soil productivity

Soil organic matter (SOM) content is a critical component of soil productivity. Its maintenance is critical to maintaining productivity of continuously cropped soil (Follet et al., 1987; Kipkiyai et al., 1997). One of the most important attributes of SOM is nutrient cycling through decomposition process of active fractions (Kipkiyai et al., 1997). SOM also plays a key role in regulating crop production and influencing essential soil based environmental services (Vanlauwe, 2004). The services provided by soil organic matter include nutrient supply, water availability, soil structure maintenance, and nutrient buffering. SOM also provides other crop and environmental services such as water use efficiency and carbon sequestration (Vanlauwe, 2004). In spite of the many beneficial
attributes of SOM, many agricultural systems are currently faced with changes in SOM that lead to reduced organic matter levels in soils.

Changes in SOM result from imbalances between organic inputs and losses. Declining SOM is often observed when lands are converted from natural vegetation to agriculture (Woomer et al., 1994). The maintenance of SOM is particularly difficult within smallholder cropping systems of the East African region where crop residues are regarded as an important component of livestock feed (Kipkiyai et al., 1997). As different pools of organic matter have separate functional roles within the soil (Woomer et al., 1994), one avenue towards improved land husbandry is to differentially manage SOM pools through a combination of inputs which limit SOM loss while at the same time providing plant nutrients through decomposition and mineralization processes (Brown et al., 1994). SOM levels can also be increased through activities that promote soil aggregation as soil aggregates have been found to physically protect SOM from decomposition by forming a physical barrier between microorganisms, and microbial enzymes and their substrates (Alvarez et al., 1998).

2.8 Soil organic carbon sequestration

The soil carbon (C) pool, estimated at 2500 Pg (Pg=petagram=1 \times 10^{15} g= 1 billion tons) to 1 m depth comprising of both soil organic carbon (SOC) and soil inorganic carbon (SIC) (Eswaran et al., 2000), is an important component of the global C cycle (Lal, 2006). By itself, SOC plays a crucial role in sustaining crop production and by providing essential environmental soil services. Consequently, the loss of SOC due to inappropriate land use or soil management practices can affect soil properties and lead to CO₂
emissions into the atmosphere (Razafimbelo et al., 2008), and degradation of soil and water resources (Lal, 2006). The restoration of degraded soils and ecosystems, and adoption of recommended management practices are viable options to be considered in reducing the rate of atmospheric CO$_2$ enrichment which has been linked to climate change (Lal, 2004). While reducing the risk of climate change by enrichment of atmospheric CO$_2$ concentration, SOC sequestration has numerous ancillary benefits such as the positive effect of SOC pool on soil quality, agronomic/biomass productivity, and advancing global food security (Lal, 2006).

One of the ways through which SOC can be sequestered is through soil management options that result in improved soil aggregation. Studies have shown that SOC sequestration through enhanced soil aggregation is an important strategy of judicious soil management to mitigate the increasing concentration of atmospheric CO$_2$ (Bronick and Lal, 2005). SOC associated with aggregates is protected from mineralization because it is less subjected to physical, microbial, and enzymatic degradation (Bajracharya et al., 1998). Soil aggregation also reduces the loss of SOC via erosion (Razafimbelo et al., 2008). Mineralization studies using intact versus crushed aggregates have revealed the existence of a physically protected SOC pool in the macroaggregates (Hassink et al., 1993; Beare et al., 1994). The protection of SOC in soil aggregates can therefore turn degraded soils from C sources into C sinks, resulting in increased soil fertility and reduced adverse environmental effects.
CHAPTER THREE
MATERIALS AND METHODS

3.1 Experimental sites

This study was carried out in two sites in central Kenya, namely, Embu and Machang’a. The two sites contrast in terms of rainfall, temperature and soil types as described below.

The Embu site is located in Embu district (Central Kenya), at '0° 30' S, 37° 27' E and at an altitude of 1480 m above sea level. The area has a humid climate, with the average temperature being 20°C. Rainfall is bimodal with the long rains falling between March and May, and the short rains from mid October to December. The average annual rainfall is about 1200 mm. The soil in Embu is a clay loam, (sand 32%, silt 30% and clay 38%) derived from basic volcanic rocks. The soil is classified as Humic Nitisols (FAO, 1990) and has Kaolinite as the dominant clay mineral. Subsistence mixed farming comprising of growing cash and food crops and the keeping of dairy animals is the main farming system in this area. The main cash crop grown is coffee (Coffea arabica), while the main food crop is maize (Zea mays).

The Machang’a site is located in Mbeere district. It lies at '0’47’S, 37 °40' E, and at an altitude of 1050 m above sea level. The area has a semi arid climate, and the soil is a sandy clay loam comprising of 56.5%, 12.7% and 30.8% of sand, silt and clay, respectively. It is classified as a Chromic Cambisol (Kihanda et al., 2007). The area has a mean annual temperature of 26°C, while the mean annual rainfall is 700mm. The common farming system in this area comprises of subsistence mixed farming of
food crops such as maize (*Zea mays*), beans (*Phaseolus lunatus*) and black peas (*Vigna unguiculata*).

### 3.2 Experimental design

This study was based on a decomposition tube experiment that was set up in April 2005. It aimed at complementing long-term field trials aimed at establishing the effect of application of various combinations of organic plus mineral resources on soil nutrient status.

#### 3.2.1 Materials and procedure

The decomposition tubes were made of poly vinyl chloride (PVC) as shown in figure 3.1, with a diameter of 10 cm and a length of 35 cm. All the tubes had an iron mesh at the base to prevent soil movement from the tubes. The tubes were also covered with an iron mesh at the top to prevent entry of any substances such as litter. The organic and inorganic resources were mixed with 3.2 kg of soil and placed into the decomposition tubes which were then placed in holes measuring 15 cm in diameter and 30 cm in depth. The organic resources were in the form of maize stover applied at a rate of 4 ton per hectare, while the mineral resources were in the form urea applied at a rate of 120 kg per hectare (Table 3.1). The organic resources were hand incorporated while the fertilizer was incorporated in liquid form during the set up of the experiment.
3.2.2 Design of the experiment

The experiment was set up as a randomized complete block design. Soils of varying fertility levels; low, medium, and high fertility were obtained from farms around the experimental sites, incorporated with sole or combined organic and mineral resources, and set up in decomposition tubes in the respective sites as shown in Figure 3.2. The experiment comprised of four treatments namely, control (no stover or fertilizer-N applied), sole stover, sole fertilizer, and stover plus fertilizer. Each treatment had three replicates, amounting to a total of 36 tubes per site.
Table 3.1: Treatment structure for Embu and Machang’a tube experiments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Quantity of organic resources applied (t ha(^{-1}))</th>
<th>Quantity of inorganic resources applied (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fertilizer-N</td>
<td>0</td>
<td>120</td>
</tr>
<tr>
<td>Maize stover</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Fertilizer-N plus maize stover</td>
<td>4</td>
<td>120</td>
</tr>
</tbody>
</table>

3.3 Soil sampling

Soil sampling for the baseline study was conducted at the onset of the experiment in 2005. Soil samples were collected from farms near each of the two sites and chemical and physical soil characterization conducted. Based on the results of the soil characterization, soils were classified as low, medium and high fertility. The physical and chemical characteristics of these soils are presented in Table 3.2.

Soil sampling from the decomposition tubes was conducted in December 2006. The soil was sieved through an 8 mm sieve, and sub samples of approximately 2 kg obtained for SOM fractionation. The soil was then packed, air dried and stored at room temperature in readiness for physical fractionation through wet sieving.
Table 3.2: Chemical and physical characteristics of soils sampled in Machang’a and Embu in April 2005

<table>
<thead>
<tr>
<th>Site</th>
<th>Fertility</th>
<th>% C</th>
<th>% N</th>
<th>C:N</th>
<th>P ppm</th>
<th>PH</th>
<th>EX K (cmol/kg)</th>
<th>EX Ca (cmol/kg)</th>
<th>EX Mg (cmol/kg)</th>
<th>EX Na (cmol/kg)</th>
<th>CEC (cmol/kg)</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machang’a</td>
<td>Low</td>
<td>0.33</td>
<td>0.03</td>
<td>11:1</td>
<td>4.0</td>
<td>6.60</td>
<td>0.90</td>
<td>8.01</td>
<td>2.25</td>
<td>0.12</td>
<td>13.5</td>
<td>75.1</td>
<td>10.0</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.44</td>
<td>0.04</td>
<td>11:1</td>
<td>4.5</td>
<td>5.84</td>
<td>2.44</td>
<td>12.85</td>
<td>3.51</td>
<td>0.25</td>
<td>25.5</td>
<td>75.1</td>
<td>14.9</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.92</td>
<td>0.08</td>
<td>12:1</td>
<td>5.65</td>
<td>7.12</td>
<td>2.02</td>
<td>18.13</td>
<td>4.44</td>
<td>0.12</td>
<td>26.0</td>
<td>81.1</td>
<td>10.0</td>
<td>8.9</td>
</tr>
<tr>
<td>Embu</td>
<td>Low</td>
<td>1.58</td>
<td>0.17</td>
<td>9:1</td>
<td>1.0</td>
<td>6.48</td>
<td>0.37</td>
<td>2.09</td>
<td>0.70</td>
<td>0.83</td>
<td>4.0</td>
<td>17.2</td>
<td>30.0</td>
<td>52.8</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>2.77</td>
<td>0.26</td>
<td>11:1</td>
<td>4.5</td>
<td>6.92</td>
<td>0.68</td>
<td>6.01</td>
<td>1.03</td>
<td>0.59</td>
<td>8.5</td>
<td>17.1</td>
<td>16.0</td>
<td>66.9</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>3.41</td>
<td>0.33</td>
<td>11:1</td>
<td>3.0</td>
<td>6.50</td>
<td>0.92</td>
<td>8.28</td>
<td>2.63</td>
<td>0.11</td>
<td>14.0</td>
<td>15.2</td>
<td>16.0</td>
<td>68.8</td>
</tr>
</tbody>
</table>

3.4 Laboratory analysis

3.4.1 Aggregate formation and carbon cycling

To determine the effect of fertilizer-N and organic resources incorporation on aggregate formation and C cycling, soil samples taken from the field and from the decomposition tubes were analyzed using physical fractionation methods (Elliot, 1986) into the various fractions shown below (Fig, 3.3).
3.4.2 Aggregate separation

Soil samples were separated into four aggregate size fractions through wet sieving into large macroaggregates (>2000 µm), small macroaggregates (250 µm-2000 µm), microaggregates (53–250 µm), and silt + clay associated particles (<53 µm) (Elliot, 1986). An 80 g sub-sample of soil was evenly spread over a 2 mm sieve submerged in 1 cm of deionised water for 5 minutes. The soil was subsequently sieved for 2 minutes by manually moving the sieve up and down 50 times during a 2 minute period. Soil remaining on the sieve was backwashed into a pre-weighed beaker for drying, while the soil and water that passed through the sieve was transferred to a 250 µm sieve and the sieving procedure repeated. This was again done using the 53 µm sieve. To
subsample the silt and clay fraction, a bottle based method was used to obtain a 250 ml subsample. The four aggregate fractions were oven dried at 105°C and weighed. All fractions were then pulverized and analyzed for C.

3.4.3 Soil organic matter fractionation

To obtain the SOM fractions, subsamples from the small and large macroaggregates were taken to isolate the microaggregates held within macroaggregates following the method described by Six et al. (2000b). A microaggregate isolator, (Figure 3.4) was used to completely break up macroaggregates while minimizing the breakdown of microaggregates. This method was adapted for each soil to allow for complete dispersion of the macroaggregates without disrupting the microaggregates within macroaggregates.

For Embu soils, 5 g subsamples were soaked overnight in 50 ml of deionised water. The following day, the subsamples were immersed in deionised water on top of a 250 µm mesh screen and gently shaken on a reciprocal shaker with 50 glass beads (4 mm diameter) for 5 minutes at 250 rpm. A continuous and steady flow of water through the device was maintained to ensure that microaggregates were immediately flushed into a 53 µm sieve and not further disrupted by the glass beads. Microaggregates collected on the 53 µm sieve were further sieved according to Elliot (1986) to ensure that the microaggregates collected were water stable.

Three fractions were obtained; coarse particulate organic matter (> 250 µm), microaggregates within macroaggregates (53-250 µm), and silt and clay (< 53 µm). The fractions were then oven dried at 105°C, weighed, pulverized and analyzed for C.
For the Machang’a samples, a different protocol was adopted as macroaggregates from sandy soils are less stable. A 15 g sub-sample of macroaggregates was used for the isolation process. These sub-samples were soaked in deionised water for 20 minutes and then shaken for 3 minutes at 150 rpm.

Figure 3. 4: A microaggregate isolator set up on a reciprocal shaker

3.5 Statistical analyses

Data collected from this study was analyzed using the SAS PROC MIXED procedure. The means were then separated at p <0.05 and the standard error of difference (SED) of the means used to compare the responses between sole and combined application of fertilizer-N and organic resources.
CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 General overview

This chapter presents the results of the study. It is divided into three sub-sections. The first section discusses the effect of the amendment of soils with fertilizer-N and organic resources on soil aggregates proportions. The second section discusses the effect of these amendments on the distribution of distinct SOM fractions within macroaggregates. Finally, the third and last sub-section discusses the effect of these amendments on the carbon contents of whole soils (un sieved soil), aggregates, and SOM fractions.

4.2 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on aggregate proportions

Soil aggregates play an integral part in soil fertility due to the many vital functions they provide. For this study, soils were separated into four aggregate size classes namely large macroaggregates (>2000 µm), small macroaggregates (250 – 2000 µm) microaggregates (53-250 µm), and silt and clay (<53 µm) through wet sieving. In the Embu site (Table 4.1), higher proportions of small macroaggregates (250-2000 µm) were observed across all amendments compared to the other aggregate size classes. For the Machang’a site (Table 4.2), the highest proportion of aggregates was observed in the microaggregates (53-250 µm) size class.

In the Embu site (Table 4.1), the proportions of large macroaggregates (>2000 µm) for all amendments of low fertility soils with fertilizer-N and organic resources were significantly different (p<0.05) to the proportion observed for the control.
Table 4.1: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on proportions of soil aggregates in Embu soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Control</th>
<th>Fertilizer N</th>
<th>Stover</th>
<th>Stover + Fertilizer N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Aggregate size class proportions (%)</td>
<td>&gt;2000 µm</td>
<td>250-2000 µm</td>
<td>53-250 µm</td>
<td>&lt;53 µm</td>
</tr>
<tr>
<td>Control</td>
<td>6.62</td>
<td>64.71</td>
<td>21.55</td>
<td>3.69</td>
</tr>
<tr>
<td></td>
<td>5.04</td>
<td>59.88</td>
<td>26.31</td>
<td>3.98</td>
</tr>
<tr>
<td></td>
<td>12.10</td>
<td>63.00</td>
<td>17.11</td>
<td>2.09</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>9.50</td>
<td>62.00</td>
<td>20.35</td>
<td>3.36</td>
</tr>
<tr>
<td></td>
<td>4.23</td>
<td>61.56</td>
<td>25.71</td>
<td>4.47</td>
</tr>
<tr>
<td></td>
<td>16.46</td>
<td>61.00</td>
<td>15.21</td>
<td>1.79</td>
</tr>
<tr>
<td>Stover</td>
<td>7.57</td>
<td>61.90</td>
<td>23.74</td>
<td>3.70</td>
</tr>
<tr>
<td></td>
<td>4.90</td>
<td>61.08</td>
<td>25.41</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>13.67</td>
<td>64.23</td>
<td>15.57</td>
<td>2.14</td>
</tr>
<tr>
<td>Stover + Fertilizer N</td>
<td>8.40</td>
<td>67.16</td>
<td>18.29</td>
<td>3.10</td>
</tr>
<tr>
<td></td>
<td>7.25</td>
<td>63.47</td>
<td>21.44</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>13.41</td>
<td>64.09</td>
<td>15.60</td>
<td>2.01</td>
</tr>
<tr>
<td>SED</td>
<td>0.77*</td>
<td>0.77*</td>
<td>1.23*</td>
<td>1.23*</td>
</tr>
<tr>
<td></td>
<td>0.77*</td>
<td>0.77</td>
<td>1.23*</td>
<td>0.89*</td>
</tr>
<tr>
<td></td>
<td>0.77*</td>
<td>1.23*</td>
<td>0.89*</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>1.23*</td>
<td>0.89</td>
<td>0.89</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>1.23*</td>
<td>0.28</td>
<td>0.28*</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>0.28</td>
<td>0.28*</td>
<td>0.28</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; **SED**=Difference between treatments is statistically significant at *p*<0.05

Table 4.2: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on proportions of soil aggregates in Machang’a soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Control</th>
<th>Fertilizer N</th>
<th>Stover</th>
<th>Stover + Fertilizer N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Aggregate size class proportions (%)</td>
<td>&gt;2000 µm</td>
<td>250-2000 µm</td>
<td>53-250 µm</td>
<td>&lt;53 µm</td>
</tr>
<tr>
<td>Control</td>
<td>0.90</td>
<td>36.19</td>
<td>56.45</td>
<td>5.03</td>
</tr>
<tr>
<td></td>
<td>1.27</td>
<td>20.21</td>
<td>70.99</td>
<td>6.86</td>
</tr>
<tr>
<td></td>
<td>15.34</td>
<td>30.27</td>
<td>44.41</td>
<td>4.73</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>2.39</td>
<td>36.80</td>
<td>52.80</td>
<td>5.72</td>
</tr>
<tr>
<td></td>
<td>1.02</td>
<td>19.78</td>
<td>70.34</td>
<td>7.49</td>
</tr>
<tr>
<td></td>
<td>15.11</td>
<td>32.19</td>
<td>45.45</td>
<td>5.74</td>
</tr>
<tr>
<td>Stover</td>
<td>4.57</td>
<td>34.33</td>
<td>54.95</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td>2.94</td>
<td>19.26</td>
<td>66.99</td>
<td>8.57</td>
</tr>
<tr>
<td></td>
<td>16.65</td>
<td>33.80</td>
<td>43.72</td>
<td>3.89</td>
</tr>
<tr>
<td>Stover + Fertilizer N</td>
<td>1.18</td>
<td>35.22</td>
<td>57.35</td>
<td>5.05</td>
</tr>
<tr>
<td></td>
<td>3.01</td>
<td>19.43</td>
<td>69.40</td>
<td>6.77</td>
</tr>
<tr>
<td></td>
<td>16.51</td>
<td>30.88</td>
<td>45.84</td>
<td>5.13</td>
</tr>
<tr>
<td>SED</td>
<td>0.56*</td>
<td>0.83</td>
<td>1.00*</td>
<td>0.40*</td>
</tr>
<tr>
<td></td>
<td>0.56*</td>
<td>0.83</td>
<td>1.00*</td>
<td>0.40*</td>
</tr>
<tr>
<td></td>
<td>0.56*</td>
<td>0.83*</td>
<td>1.00*</td>
<td>0.40*</td>
</tr>
<tr>
<td></td>
<td>0.83</td>
<td>0.40</td>
<td>0.40*</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>0.83*</td>
<td>0.40</td>
<td>0.40*</td>
<td>0.40</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; **SED**=Difference between treatments is statistically significant at *p*<0.05
This was in the order, sole fertilizer-N > stover plus fertilizer-N > sole stover. For the amendments involving medium fertility soil, only the combined stover and fertilizer-N treatment had a significant effect (p<0.05) on proportions of large macroaggregates with regard to the control. Proportions of large macroaggregates for all amendments of high fertility soils with fertilizer-N and organic resources were significantly different (p<0.05) to the control. For these treatments, the sole fertilizer-N treatment had the highest proportion (16.46%) of large macroaggregates.

In the Machang’a site (Table 4.2), the amendment of low fertility soil with sole fertilizer and sole stover had significant effects (p<0.05) on the proportions of large macroaggregates as compared to the control treatment. Overall for these amendments, the sole stover treatment had the highest proportion (4.57%) of large macroaggregates. For the medium fertility soils, the sole stover and combined stover and fertilizer-N treatments had significant effects on the proportions of large macroaggregates as compared to the control treatment. For these treatments, the combined stover and fertilizer-N treatment had the highest proportion (3.01%) of large macroaggregates. A similar trend was observed for the high fertility soil where the proportions of large macroaggregates in both the sole stover and combined stover and fertilizer-N treatments were significantly different from those of the control. For these treatments, the sole stover treatment had the highest proportion (16.65%) of large macroaggregates.

In the small macroaggregates size class (250-2000 µm), the amendment of low fertility soil in the Embu site with combined stover and fertilizer-N had a significant effect on the
proportions of small macroaggregates (Table 4.1) with regard to the control treatment. This treatment accounted for the highest proportion of small macroaggregates (67.16%). With regard to the medium fertility soil, both the sole fertilizer-N and combined stover and fertilizer-N treatments had significant effects on the proportions of small macroaggregates. For these amendments, the combined stover and fertilizer-N treatment had the highest proportion (63.37%) of small macroaggregates. For the treatments involving high fertility soil, only the sole stover treatment had a significant effect on the proportion of small macroaggregates. In the Machang’a site, the effect of amendment of low fertility soil with fertilizer-N and organic resources on proportions of small macroaggregates were only significant for the sole fertilizer-N treatment. This treatment accounted for the highest (36.80%) proportion of small macroaggregates. For the amendments involving medium fertility soil, no treatment was significantly different from the control. With regard to high fertility soil, both the sole stover and the sole fertilizer-N treatments had significant effects on the proportions of small macroaggregates as compared to the control treatment. Overall for these treatments, the sole stover treatment had the highest proportion (33.80%) of small macroaggregates.

In the microaggregates size class (53 - 250 µm), the amendment of low fertility soils in Embu with sole fertilizer-N and combined stover and fertilizer-N had a significant negative effect in that it resulted in lower levels of microaggregates compared to the control treatment (Table 4.1). In the medium fertility Embu soils, all amendments involving fertilizer-N and organic resources resulted in reduced levels of microaggregates. A similar trend was observed in the high fertility soils. For the
Machang’a site, all amendments of soils with sole stover had a significant negative effect on proportions of microaggregates.

The differences in aggregate composition observed between the Embu and Machang’a soils could be due to the higher clay content in the Embu soils as compared to the Machang’a ones (Table 3.2). Several studies have shown that soil texture influences aggregation (Chaney and Swift, 1984; Plante et al., 2006) such that increased clay contents are associated with increased aggregation or aggregate stability. Bartoli et al. (1992) found that water-stable aggregates were correlated with aggregate strength, which correlated well with clay content. More recently, a study by De Gryze et al. (2005) found that the amount of water stable aggregates >2000 µm in a natural ecosystem decreased in the order: silty clay loam > silt loam > sandy loam. This is also in agreement with a study by Barthes and Roose (2002) who reported that an increase in coarse sands caused simultaneous decreases in clay plus fine silts and aggregate fractions.

The higher proportions of large macroaggregates observed in the sole fertilizer-N or combined stover and fertilizer-N amendments in the Embu soils (Table 4.1) indicate increased macroaggregate formation upon the amendment of these soils with fertilizer-N. This could be due to increased N levels which resulted in an increase in microbial activity as N limiting conditions have been found to be low in microbial activity (Harris et al., 1996). Studies have also associated addition of mineral N with increased microbial activity and the subsequent release of C-rich binding compounds resulting in higher formation of large macroaggregates (Six et al., 2000a; Dutta et al., 2003). This is also
supported by a study conducted by Kavoo (2008) who reported a higher initial formation of large macroaggregates upon the amendment of sawdust with mineral N fertilizer for soils in Embu.

For the Machang’a site (Table 4.2), the significant effects observed with the amendments involving sole stover and combined stover and fertilizer-N on the proportions of large macroaggregates indicate increased macroaggregate formation. This could be due to the addition of maize stover as the addition of organic matter such as crop residues and other organic substances to soil has been found to generally increase aggregation (Bipfubusa et al., 2007). This is supported by a study by Sodhi et al. (2009) who reported an increase in the proportions of macroaggregates and a subsequent decrease in the proportions of microaggregates upon the amendment of soil with rice compost. Bronick and Lal (2005) also reported increased aggregation and aggregate stability upon amendments of soils with corn residues. Studies have also shown that the large macroaggregates fractions are highly responsive to organic residue addition in soil (Bipfubusa et al., 2007). Increased formation of macroaggregates upon the addition of organic resources has been attributed to the organic resources serving as nucleation sites for the growth of fungi and bacteria (Jastrow, 1996; Puget et al., 1996; De Gryze et al., 2005). The fungal hyphae then initiate macroaggregate formation by enmeshing fine particles into macroaggregates (Tisdall and Oades, 1982). With time, the microbial (fungal and bacteria) exudates, produced as a result of decomposition of plant residues form binding agents that further stabilize macroaggregates (Six et al., 2002). The formation of macroaggregates around organic residues has further been confirmed by studies using $^{13}$C natural abundance in fields.
These studies have consistently shown that macroaggregates are formed around newly incorporated organic residues (Puget et al., 1996; Six et al., 1998). De Gryze et al. (2005) also reported a linear increase in aggregate formation with increasing amounts of low quality residues (low in N but high in lignin) added.

The significant negative effect on the proportions of microaggregates for all amendments involving high fertility soils in the Embu site could be due to increased binding of microaggregates into macroaggregates upon amendment of soils with fertilizer-N and organic resources. According to the hierarchical concept of aggregate formation, macroaggregates are formed by the binding together of smaller aggregates such as stable microaggregates (Tisdall and Oades, 1982; Balesdent et al., 2000). Six et al. (1999) suggested that the addition of new residues in a no till management system promoted organic matter stabilization through the binding of primary soil particles and old microaggregates into new macroaggregates. Further, fragmented crop residue (particulate organic matter) has been found to form the nuclei for new microaggregates that can be bound together by transient and labile organic matter to form new macroaggregates (Golchin et al., 1994; Olchin et al., 2008). This causes an increase in proportions of macroaggregates, followed by a subsequent decrease in microaggregate proportions. The results indicate that macroaggregate formation and stabilization was higher in higher fertility soils and is in line with the higher proportions of macroaggregates observed for the Embu high fertility soils.
4.3 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on distribution of distinct SOM fractions

The proportions of functional soil organic matter fractions; i.e., coarse particulate organic matter (cPOM), microaggregates within macroaggregates (mM) and silt and clay (s+c) were determined through isolation from macroaggregates. For the Embu site (Table 4.3), higher proportions of microaggregates within macroaggregates were observed across all amendments, as compared to the other SOM fractions. The scenario was different for the Machang’a site (Table 4.4) where higher proportions of cPOM fractions were observed across all amendments, as compared to the other SOM fractions.

In the Embu site, all amendments of low fertility soil with sole and combined application of fertilizer-N and organic resources had a significant effect on the distribution of cPOM fractions compared to the control (Table 4.3). The sole fertilizer-N treatment accounted for the highest proportion of cPOM fractions (9%). Amendment of medium fertility soils with fertilizer-N and organic resources had no significant effect on the distribution of cPOM fractions. A similar trend was observed in the high fertility soil. Overall, cPOM fractions ranged between 2.60% and 9.00%, 0.73% and 1.00%, and 0.73% and 1.33% for the low, medium and high fertility soils respectively.
Table 4.3: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage (%) distribution of distinct SOM fractions within macroaggregates in Embu soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>cPOM</th>
<th>mM</th>
<th>S&amp;C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Control</td>
<td>2.60</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>9.00</td>
<td>0.93</td>
<td>0.86</td>
</tr>
<tr>
<td>Stover</td>
<td>7.00</td>
<td>0.93</td>
<td>0.73</td>
</tr>
<tr>
<td>Stover + Fertilizer N</td>
<td>4.93</td>
<td>0.73</td>
<td>1.33</td>
</tr>
<tr>
<td>SED</td>
<td>0.45*</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

*SED = Standard error of difference of means; SED*=Difference between treatments is statistically significant at p<0.05

Table 4.4: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage (%) distribution of distinct SOM fractions within macroaggregates in Machang’a soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>cPOM</th>
<th>mM</th>
<th>S&amp;C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Control</td>
<td>69.76</td>
<td>68.11</td>
<td>71.54</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>67.61</td>
<td>65.50</td>
<td>70.70</td>
</tr>
<tr>
<td>Stover</td>
<td>68.60</td>
<td>71.89</td>
<td>71.30</td>
</tr>
<tr>
<td>Stover + Fertilizer N</td>
<td>74.51</td>
<td>67.67</td>
<td>68.83</td>
</tr>
<tr>
<td>SED</td>
<td>2.25*</td>
<td>2.25*</td>
<td>2.25</td>
</tr>
</tbody>
</table>

*SED = Standard error of difference of means; SED*=Difference between treatments is statistically significant at p<0.05
In the Machang’a low fertility soils, the proportion of cPOM fractions in the combined stover and fertilizer-N treatment was significantly different to that of the control (Table, 4.4). This treatment accounted for the highest proportion (74.51%) of cPOM fractions among all amendments. For the medium fertility soil, only the sole stover treatment had a significant effect on the proportions of cPOM fractions with regard to the control. A similar trend was observed in the high fertility soil. Overall, cPOM fractions ranged between 67.61% and 74.51%, 65.50% and 71.89%, and 68.83% and 71.54% for the treatments involving low, medium and high fertility soil levels respectively.

The higher proportions of cPOM fractions observed for the Machang’a soils as compared to the Embu ones could be due to differences in texture. Studies have shown that the proportion of mass associated with the coarse (>250 µm) sand plus POM fractions decreases with increasing clay content (Plante et al., 2006). With regard to the mM fractions, the higher proportions observed for the Embu soils indicate that formation and stabilization of macroaggregates in these soils is higher than in the Machang’a soils. Studies have shown that it is through the formation and subsequent stabilization of macroaggregates that microaggregates are formed within macroaggregates (Puget et al., 1996; Six et al., 2004). During macroaggregate stabilization, the intra-aggregate particulate organic matter POM (i.e., the fresh plant material that was incorporated in the macroaggregates during “biological” aggregate formation) is further decomposed by microorganisms and fragments into finer POM (Six et al., 1998). This fine POM then becomes increasingly encapsulated with minerals and microbial products forming new microaggregates within the macroaggregates (Six et al., 1998). These microaggregates
are later released upon the breakdown of macroaggregates, and may be subsequently reincorporated into new aggregates. This is corroborated by the higher proportions of macroaggregates observed for the Embu soils as compared to the Machang’a soils (Table 4.1). The lower formation and stabilization rates of macroaggregates in the Machang’a soils compared to the Embu soils can be attributed to differences in texture as this influences the turnover rate of organic matter (Six et al., 2002). It is known that in coarse-textured soils of arid and semi arid regions such as those of Machang’a, there exists a rapid turnover of organic matter (Quiroga et al., 1999; Hevia et al., 2003), and that only a low amount of fresh organic residues will contribute to humified soil organic matter which is essential for soil aggregation. Under these conditions, most of plant and animal residues incorporated in the soil will be mineralized (Gregorich et al., 1994).

The higher proportions of cPOM fractions observed in the low fertility soils compared to higher fertility soils at the Embu site could mean that there was an accumulation of POM. This could probably be due to slow decomposition rate in these soils as this has been found to cause decreases in POM size (Guggenberger et al., 1999). The low decomposition rate exhibited in this soil could be due to the low microbial activity usually associated with low fertility soils (Kolbl et al., 2006). In their studies, Scolter et al. (2003) and Sehy et al. (2003) reported a direct relationship between soil fertility and the decomposition of organic residues.

The significant effect on mM proportions for the amendment of low fertility soil with sole fertilizer-N, and amendment of medium and high fertility soils with sole fertilizer-N
and combined stover and fertilizer-N in the Embu site indicates increased macroaggregate formation and stability. This can be attributed to the addition of fertilizer-N which increased soil N levels resulting in a subsequent rise in microbial activity and hence improved aggregate formation and stabilization, and the subsequent formation of microaggregates within macroaggregates (Harris et al. 1996; Six et al., 2000a). The formation of microaggregates within macroaggregates upon the stabilization of macroaggregates has been found to be crucial for the long term sequestration of C (Six et al., 2002), as microaggregates have a greater capacity to protect C from decomposition as compared to macroaggregates (Balesdent et al., 1993).
4.4 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on soil carbon status

In the following subsections, the carbon content of whole soil, aggregate size fractions and SOM fractions isolated from macroaggregates is presented and discussed.

4.4.1 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on carbon content of whole soils

The incorporation of fertilizer-N and organic resources in soils resulted in changes in soil C status of whole soils in both Embu and Machang’a (Tables 4.5 and 4.6). At both sites, %C levels of soils increased with increasing fertility. Overall, soils at the Embu site had higher %C levels compared to those for Machang’a. At the Embu site, no treatment had a significant effect on %C levels of whole soils for all soil fertility levels (Table 4.5). However, for all fertility levels, the combined stover and fertilizer-N treatments had the highest %C levels.

Table 4.5: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of whole soils in Embu

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.71</td>
<td>2.89</td>
<td>3.13</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>1.59</td>
<td>2.94</td>
<td>3.16</td>
</tr>
<tr>
<td>Stover</td>
<td>1.73</td>
<td>2.87</td>
<td>3.13</td>
</tr>
<tr>
<td>Stover + Fertilizer N</td>
<td>1.74</td>
<td>2.96</td>
<td>3.20</td>
</tr>
<tr>
<td><strong>SED</strong></td>
<td><strong>0.14</strong></td>
<td><strong>0.14</strong></td>
<td><strong>0.14</strong></td>
</tr>
</tbody>
</table>

*SED = Standard error of difference of means*
Table 4.6: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of whole soils in Machang’a

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.26</td>
<td>0.27</td>
<td>0.61</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>0.17</td>
<td>0.30</td>
<td>0.64</td>
</tr>
<tr>
<td>Stover</td>
<td>0.28</td>
<td>0.31</td>
<td>0.62</td>
</tr>
<tr>
<td>Stover + Fertilizer N</td>
<td>0.24</td>
<td>0.22</td>
<td>0.66</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; SED* = Difference between treatments is statistically significant at p<0.05

In the Machang’a site (Table 4.6), amendment of low fertility soils with sole stover had a significant (p<0.05) effect on the %C level of whole soil compared to the control treatment. For the medium fertility soils, whole soil %C levels of both the sole fertilizer-N and sole stover treatments were significantly different from that of the control. For these treatments, the sole stover treatment had the highest whole soil C level (0.31%). For the high fertility soils, whole soil %C levels of both the sole fertilizer-N and the combined stover and fertilizer-N treatments were significantly different from that of the control. For these treatments, the combined stover and fertilizer-N treatment had the highest whole soil C level (0.66%).

The higher whole soil C levels observed for the Embu soils as compared to the Machang’a ones could be due to the higher proportions of clay content observed for the Embu soils compared to the Machang’a ones (Table 3.2). Studies have shown that soil texture is a key variable affecting soil C, as a result of electrostatic binding between negatively charged clay surfaces and organic colloids via cation bridges (Paustian et al., 2003; Barthes and Roose, 2002). Comparing similar tropical soils with different clay
mineralogy, Wattel-Koekkoek and Burman (2004) found that the effective cation capacity of the clays can explain differences in the mean residence of OM. In a study over a range of tropical soils, Feller and Tessier (1996) also confirmed that due to the sorption of fine organic constituents to fine mineral particles, C amount in the fine fraction increases with the proportion of fine primary particles. The relationship between clay concentration and SOC content is sufficiently strong that SOM models such as Century (Parton, 1996) and RothC (Jenkinson, 1990) assume that SOM decomposition decreases as clay concentration increases, such that if all factors are equal, SOC accumulates faster as soil clay content increases (McLauchlan, 2006).

The lower whole soil C levels observed for the Machang’a soils also explains the lower proportions of macroaggregates observed for these soils. A study by Castro et al. (2002) reported that a soil that is low in organic carbon will be poorly aggregated since the weight and the content of organic carbon in the >2000 µm size class is lower than the weight and the content of organic carbon of other aggregate size classes.

The higher whole soil C levels observed for all Embu soils with combined stover and fertilizer-N amendments as compared to the sole application of stover is in line with a study by Kavoo (2008). This study reported that the combined application of tithonia and mineral fertilizer-N had a higher concentration of C (35.8 g C kg⁻¹ whole soil) compared to the sole application of tithonia (31.8 g C kg⁻¹ whole soil) for soils in Embu. Hati et al. (2006) also reported a significant effect of fertilizer-N and organic manure application on the soil organic carbon levels up to a depth of 0.30 m, with the SOC content in the 0 -
0.15 m layer being the highest (6.5 g kg\(^{-1}\)) in the fertilizer-N plus manure treatment. These higher levels of percent C could be as a result of increased rate of decomposition of maize stover and the subsequent release of carbon compounds in the presence of mineral fertilizer. Studies have shown that addition of mineral-N increases the decomposition rate of organic resources. Jenkinson and Rayner (1985) reported that the addition of mineral-N increased the decomposition rate of wheat straw by satisfying the N requirements of microorganisms. Berg and Matzner (1997) also reported that in the early stages of plant decomposition, mineral-N inputs stimulate hydrolysis of soluble C compounds and nonlignified holocellulose. During the decomposition of organic resources, plant material fragments or particulate organic matter (POM) gradually become encrusted with clay particles and microbial products to form the core of stable microaggregates (Six et al., 2004), resulting in an increase in whole soil C. The formation of microaggregates has been found to be crucial for the storage and stabilization of soil C in the long term through the incorporation of new C into microaggregates (Jastrow and Miller, 1998; Six et al., 1998; Gale et al., 2000). This incorporation of new C into free microaggregates is an important factor contributing to C sequestration (Skjemstad et al., 1990), since C contained in free microaggregates has a slower turnover than C in macroaggregates (Jastrow, 1996). These results indicate potential changes in soil C storage that could become more important over time because small short-term differences in decomposition with mineral-N input can add up to large differences in the long-term storage of SOM (Agren et al., 2001).

The significant effect of the amendment of low and medium fertility Machang’a soil with sole stover on whole soil C could be due to a buildup of SOC upon the application of
This is in line with findings by Angela et al. (2007) who reported that the amount of SOC sequestered in an organic system (5.70 Mg SOC ha\(^{-1}\)) was greater than the SOC sequestered by a conventional and low input systems (570 and -340 kg SOC ha\(^{-1}\), respectively). Harris et al. (1996) also suggested that the addition of class III organic resources leads to intermediate aggregate formation and breakdown resulting in C accumulation. Studies by Paustian et al. (2000) and Waswa et al. (2007) further reported that increases in soil carbon inputs is one of the ways through which soil C stocks can be increased. The addition of organic matter to soils results in higher soil C levels through their occlusion within soil aggregates when new aggregates form around the organic matter (Plante and Mcgill, 2002). Increased occlusion increases C sequestration because of the decrease in mineralization in the occluded state due to increased interaction of the organic matter with reactive surfaces (Plante and Mcgill, 2002).

### 4.4.2 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on carbon content of soil aggregates

The amendment of soils with fertilizer-N and organic resources had varying effects on the carbon content of soil aggregates (Tables 4.7 and 4.8). Overall, soil aggregates from the Embu soils had higher %C levels compared to those from the Machang’a soils. In the large macroaggregates obtained from Embu soils (Table 4.7), only the amendment of low fertility soil with sole stover treatment had a significant effect on %C levels of large
Table 4.7: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of soil aggregates in Embu soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>&gt;2000 µm</th>
<th>250-2000 µm</th>
<th>53-250 µm</th>
<th>&lt;53 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>3.04</td>
<td>3.12</td>
<td>1.61</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>1.02</td>
<td>2.83</td>
<td>3.18</td>
<td>1.53</td>
</tr>
<tr>
<td>Stover</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>1.53</td>
<td>2.93</td>
<td>2.97</td>
<td>1.62</td>
</tr>
<tr>
<td>Stover, Fertilizer N</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>1.19</td>
<td>2.99</td>
<td>3.01</td>
<td>1.56</td>
</tr>
<tr>
<td>SED</td>
<td>0.24*</td>
<td>0.24</td>
<td>0.24</td>
<td>0.61</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; SED*=Difference between treatments is statistically significant at p<0.05

Table 4.8: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of soil aggregates in Machang’a soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>&gt;2000 µm</th>
<th>250-2000 µm</th>
<th>53-250 µm</th>
<th>&lt;53 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.35</td>
<td>0.25</td>
<td>0.28</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>0.47</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Stover</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>0.52</td>
<td>1.67</td>
<td>0.22</td>
<td>0.23</td>
</tr>
<tr>
<td>Stover, Fertilizer N</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>0.52</td>
<td>0.34</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>SED</td>
<td>0.37</td>
<td>0.37*</td>
<td>0.37*</td>
<td>0.08</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; SED*=Difference between treatments is statistically significant at p<0.05
macroaggregates as compared to the control treatment. For the large macroaggregates obtained from Machang’a soils (Table 4.8), only the amendment of medium fertility soil with sole stover had a significant effect on the %C levels of large macroaggregates compared to the control treatment. For this soil, this amendment accounted for the highest %C (1.67) level of macroaggregates.

In the small macroaggregates (250-2000 µm) size class, amendments of Embu soils with fertilizer-N and organic resources had no significant effect on %C levels. For the Machang’a site, amendments of low fertility soil with fertilizer–N and organic resources had no significant effect on %C levels of small macroaggregates. However, in the medium fertility soil, the %C level of small macroaggregates in the sole stover treatment was significantly different (p<0.05) to that of the control. In the high fertility Machang’a soils, only the sole fertilizer-N treatment had a significant effect on the %C levels of small macroaggregates.

In the Embu low fertility soil (Table 4.7), the %C level of microaggregates (53 – 250 µm) in the combined stover and fertilizer-N treatment was significantly different (p<0.05) from that of the control treatment. For the medium fertility soils, only the sole fertilizer-N treatment had a significant effect on the %C level of microaggregates. Amendment of high fertility soil with fertilizer-N and organic resources had no significant effect on the %C level of microaggregates. For the Machang’a soils (Table 4.8), only the amendment of high fertility soil with sole fertilizer-N had a significant effect on the %C level of microaggregates as compared to the control treatment. For both Embu and Machang’a
soils, the silt and clay size class had the highest %C level compared to the other size classes. On average for all soil fertility levels, the silt and clay size class (<53 µm) had higher %C contents compared to the other aggregates size classes for both the Embu and Machang’a sites.

The significant effect of the stover treatment on the %C levels of large macroaggregates in Embu and Machang’a, and the small macroaggregates in Machang’a indicates a C build up in macroaggregates upon organic residue application. This could be due to higher formation of macroaggregates upon the application of stover, as the decomposition of organic residues has been shown to increase aggregation and aggregate stability (Tisdall and Oades, 1982; Bronick and Lal, 2005). This is in agreement with a study by Bipfubusa et al. (2007) who reported an increase in the C content of large and small macroaggregates upon the amendment of soils with both paper mill sludge and paper mill sludge compost. Studies elsewhere have also suggested that macroaggregates are stabilized mainly by carbohydrate-rich root or plant debris occluded within aggregates (Golchin et al., 1994). A study by Angers and Giroux (1996) provided further evidence that slake resistant macroaggregates are stabilized by recently deposited residues, while Jastrow (1996) suggested that the intra-macroaggregate particulate organic matter (POM) is an important agent that facilitates the binding of microaggregates into macroaggregates. Increased aggregation results in an increase in the C level of macroaggregates as aggregates are known to physically protect C (Jastrow et al., 1996 and Puget et al., 1996). Studies have shown that aggregates contain labile C that is physically protected from microbial decomposition (Amelung and Zech, 1999;
McLauchlan, 2006). The protection of C in macroaggregates contributes to C retention in soils by slowing its mineralization rate, resulting in a net gain in soil C (Mikha and Rice, 2004).

The significant effect on %C levels of microaggregates observed for the amendment of both medium fertility Embu soil and high fertility Machang’a soil with sole fertilizer-N could be due to increased turnover of macroaggregates and the subsequent release of microaggregates. This increase in turnover rate could be as a result of increased decomposition of C compounds binding macroaggregates upon the addition of sole fertilizer-N. Upon the application of fertilizer-N without a C source, microorganisms have been found to decompose the C-rich binding agents, resulting in C losses (Angela et al., 2007). As the binding agents in macroaggregates degrade, macroaggregate stability is lost resulting in the release of stable microaggregates (Six et al., 2000b). This causes a transfer of carbon from macroaggregates into microaggregates upon the breakdown of the macroaggregates (Jastrow, 1996, Six et al., 1998, Gale et al., 2000), resulting in increased C levels of microaggregates.

The higher %C levels observed for the silt and clay size class (53 – 250 µm) as compared to the other aggregate size classes for both the Embu and Machang’a soils could be due to the transfer of carbon compounds into this fraction. This is in line with findings by Jastrow (1996) and Kavoo (2008). Their findings indicated that there occurs a direct transfer of some plant compounds into the silt and clay fractions, primarily through breakdown, leaching, comminution and selective microbial degradation (Mikutta et al.,
Other studies have also shown that the silt and clay fractions have the ability to biochemically and chemically protect organic C bound to them, thereby protecting it from microbial decomposition (Sleutel et al., 2006; Fonte et al., 2007). It has also been reported that the silt and clay fractions have a higher C stabilization capacity compared to other fractions (Six et al., 2002). The stabilization of C by association with silt and clay particles has been found to be one of the ways through which organic C is preserved (Six et al., 2002). A study by Balabane and Plante (2004) hypothesized that silt-size aggregates are sites where physically protected OM can mature and interact with specific adsorption sites on mineral surfaces. Data by Virto et al. (2008) showed that almost half of the total soil organic C was stored in these aggregates. The higher stabilization of C in silt and clay particles could be due to the greater biological activity associated with clay-sized particles which is reflected in the larger content of microbially derived products in clay than in >2 µm separates (Christensen, 1992). Clay also maintains the largest concentrations of OM, suggesting that the microbial activity provides more microbial metabolites and residues (including cell wall materials) that become stabilized and accumulate in clay (Hedges & Oades, 1997; Kaiser et al., 1998). Stabilization of C in the silt and clay fraction plays an important role in the buildup of soil carbon as it is one of the main ways through which organic C is preserved (Six et al., 2002; McLauchan, 2006).
4.4.3 Effect of amendment of soils of varying texture and fertility levels with fertilizer-N and organic resources on carbon content of distinct SOM fractions

The following section presents the results obtained by analyzing the carbon contents of SOM fractions [(coarse particulate organic matter (cPOM), microaggregates within macroaggregates (mM) and silt and clay (s+c)]. For the Embu soils, the cPOM fractions had generally higher %C levels than the other SOM fractions (Table 4.9), whereas for the Machang’a soils, the silt and clay fractions had the highest %C levels compared to other SOM fractions (Table 4.10).

4.9: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of distinct SOM fractions in Embu soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>cPOM (%)</th>
<th>mM (%)</th>
<th>S&amp;С (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Low 1.27</td>
<td>Medium 8.25</td>
<td>High 10.47</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>Low 0.78</td>
<td>Medium 5.78</td>
<td>High 11.26</td>
</tr>
<tr>
<td>Stover</td>
<td>Low 0.78</td>
<td>Medium 5.62</td>
<td>High 7.56</td>
</tr>
<tr>
<td>Stover + Fert N</td>
<td>Low 0.68</td>
<td>Medium 5.59</td>
<td>High 6.58</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; SED* = Difference between treatments is statistically significant at p<0.05

4.10: Effect of amendment of soils of varying fertility levels with fertilizer-N and organic resources on percentage carbon content of distinct SOM fractions in Machang’a soils

<table>
<thead>
<tr>
<th>Treatments</th>
<th>cPOM (%)</th>
<th>mM (%)</th>
<th>S&amp;С (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Low 0.21</td>
<td>Medium 0.20</td>
<td>High 0.27</td>
</tr>
<tr>
<td>Fertilizer N</td>
<td>Low 0.17</td>
<td>Medium 0.21</td>
<td>High 0.23</td>
</tr>
<tr>
<td>Stover</td>
<td>Low 0.15</td>
<td>Medium 0.21</td>
<td>High 0.26</td>
</tr>
<tr>
<td>Stover + Fert N</td>
<td>Low 0.13</td>
<td>Medium 0.16</td>
<td>High 0.29</td>
</tr>
</tbody>
</table>

SED = Standard error of difference of means; SED* = Difference between treatments is statistically significant at p<0.05
In the Embu site, incorporation of fertilizer-N and organic resources in low fertility Embu soils had no significant effect (p<0.05) on the %C level of cPOM fractions with regard to the control (Table 4.9). A similar trend was observed for both the medium and high fertility soils. Overall, a general increase in cPOM %C levels with increasing soil fertility was observed in this site. No significant effects on cPOM %C levels were observed for the incorporation of fertilizer-N and organic resources in Machang’a soils. However, as observed in the Embu soils, %C levels of cPOM fractions increased with increasing soil fertility. Overall, cPOM fractions from the Embu soils ranged between 0.68% and 11.26% and were higher than those from the Machang’a site which ranged between 0.13% and 0.29%.

With regard to microaggregates within macroaggregates fractions, it was observed that for the amendments involving low fertility Embu soil (Table 4.9), only the sole stover treatment had a significant effect (p<0.05) on %C levels. For the medium fertility soil, all amendments involving fertilizer-N and organic resources had a significant effect on %C levels of mM fractions as compared to the control treatment. For these treatments, the effect on %C levels of mM fractions was in the order sole fertilizer-N > sole stover > stover plus fertilizer-N > control. Incorporation of sole or combined organic and mineral resources in Embu high fertility soils had no significant effect on %C levels of mM fractions.

For the Machang’a low fertility soils (Table 4.10) the carbon contents of mM fractions revealed that only the sole fertilizer-N treatment had a significant effect on the %C levels
of mM fractions. Whereas with medium fertility soil no treatment had a significant effect on %C levels of mM fractions with regard to the control. For the treatments involving high fertility soils, only the sole stover treatment had a significant on %C levels of mM fractions. Overall, the %C levels of mM fractions for Embu soils were higher than for those of Machang’a soils.

The higher %C level of cPOM fractions for Embu soils as compared to Machang’a soils indicates increased macroaggregates formation for these soils. Studies have shown that macroaggregates form around POM (Six et al., 1998; Olchin et al., 2006). This causes a buildup in cPOM C as intra aggregate POM is less susceptible to decomposition than free POM in the soil matrix (Six et al., 1999; Olchin et al., 2006). This is due in part to the physical and chemical protection that aggregates provide. This is in agreement with the higher proportions of macroaggregates observed for the Embu soils as compared to the Machang’a ones.

The significant effect on %C levels of mM fractions observed for the sole stover treatment in the low and high fertility Embu soils indicates a transfer of C from macroaggregates into the mM fraction. This could be due to the decomposition of organic residues from maize stover input. This has been shown to result in macroaggregate stabilization, which is associated with the formation of microaggregates within macroaggregates resulting in subsequent C transfer (Denef et al., 2002; Jiao et al., 2006). This is important with regard to soil C sequestration as microaggregates have a higher ability to protect C as compared to macroaggregates.
CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results indicated that the amendment of soils of varying texture and fertility levels with sole or combined fertilizer-N and organic resources significantly affects the formation and distribution of aggregates. For the Embu soils, both the sole application of fertilizer-N and the combined application of fertilizer-N and maize stover had significant effects on the formation of macroaggregates. This indicates an increase in aggregation upon the application of fertilizer-N either solely, or in combination with stover. For the Machang’a soils, both the sole application of stover and the combined stover and fertilizer-N application had significant effects on macroaggregates formation. Soils in Embu had higher proportions of macroaggregates compared to those in Machang’a. This indicates that soil texture has an effect on aggregate proportions. For both Embu and Machang’a soils, high fertility soils had higher proportions of large macroaggregates compared to soils of lower fertility levels. This is an indication that soil fertility also contributes to the build up of aggregation.

Amendment of Embu soils of all fertility levels with combined stover and fertilizer-N had significant negative effects on the proportions of microaggregates. This resulted in lower proportions of microaggregates for these amendments and increased macroaggregate formation. For the Machang’a soil, the sole stover treatment had a significant negative effect on the proportions of microaggregates for all soil fertility levels. This indicates that
for the Embu soils which are higher in fertility, the combined application of fertilizer-N and organic resources resulted in higher macroaggregation, while for lower fertility Machang’a soils, higher macroaggregation resulted from sole application of organic resources. This is beneficial as the formation and stabilization of macroaggregates improves soil structure and also results in increased C sequestration through C stabilization within aggregates. Increases in whole soil C levels were observed for all soil fertility levels in Embu upon amendment with combined stover and fertilizer-N. For the Machang’a soils, all treatments with sole stover resulted in increased whole soil C. The continued application of combined organic and mineral resources in high fertility soils, and the sole application organic resources in lower fertility soils has the ability of improving soil C status.

For both the Embu and Machang’a soils, treatment of soils with sole or combined organic and mineral resources significantly affected the C concentrations of aggregates across all size classes. For all amendments, the silt and clay fraction had higher levels of C compared to the other aggregate size classes. This illustrates the importance of this size class in C sequestration due to its ability to stabilize C.

For Embu soil, amendment with combined stover and fertilizer-N resulted in reduced cPOM %C levels, but with a slight increase in mM %C levels across all soil fertility levels. A similar observation was made for the amendment of high fertility Machang’a soil with sole stover. This shows that inherent soil fertility together with use of organic
and fertilizer-N applications have an effect on the formation and stabilization of macroaggregates in soils.

5.2 Recommendations

From the results obtained in this study, the following recommendations are proposed;

(i) To achieve maximum benefits with regard to soil aggregation, the application of organic resources either solely or in combination with mineral-N fertilizer is recommended.

(ii) For the long term build up of SOM the combined application of organic and mineral resources is recommended for higher fertility soils, while for lower fertility soils, the sole application of organic resources is recommended.

(iii) Further research should also be conducted to confirm and consolidate the findings of this study.
REFERENCES:


