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SOIL ORGANIC MATTER STATUS UNDER DIFFERENT AGROFORESTRY MANAGEMENT PRACTICES IN THREE SELECTED SITES IN KENYA

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Declaration

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Dedication

This work is dedicated to my beloved parents Mr. Joel Waswa and Mrs. Helen O. Waswa, brothers and sisters and to my beloved family Ruth Kangai and Cedrick Waswa for their sacrifice, patience and support throughout my education.

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Abstract

Soil organic matter (SOM) plays an important role in ensuring a healthy soil status. This study was designed to evaluate the influence of organic resource management on SOM-related soil properties in the Kabete, Maseno and the Embu experiments in Kenya. The choice of these experiments was based on the different organic resources applied, their lifespan as well as their unique ecological locations that characterize most smallholder farming areas in Kenya. Soil samples were collected from these experiments before the long rains season of 2002 and prepared for analyses. Soils were analyzed for inorganic nitrogen, total carbon, nitrogen, carbon mineralization, bulk density and soil moisture retention. In addition, SOM aggregate and size fractionation, potassium permanganate oxidation and the carbon isotope labeling techniques were used to determine the quality of the various SOM fractions formed. All the data collected was subjected to analyses of variance (ANOVA) and the means separated at $P \leq 0.05$. Mineral N was significantly different ($P \leq 0.05$) across the treatments in HI Embu and PM1 Maseno experiments and tended to be higher in organic treatments as compared to the control and the fertilizer treatments. N1 Kabete experiment had the lowest C, N and ^{13}C values pointing to the young age of this experiment as well as the low quantity of the organic residues applied. On the other hand, HI Embu experiment had high soil C values of over 2.0% indicating a positive effect of continued application of organic residues. Potassium permanganate oxidizable carbon was significantly different for N1 Kabete and PM1 Maseno experiments and tended to vary according to the differences in organic resource management regimes in these experiments.

The bulk density was not significantly affected by organic residue management regimes at any of the sites. Soil moisture retention trends were more defined in the older PM1 Maseno as compared to the younger N1 Kabete and HI Embu experiments. Aggregate mineral fraction (MF) size distribution were dominated by macroaggregates (250-500 µm and >500 µm) in the three experiments. HI Embu experiment had higher aggregate light fraction (LF) proportions as compared to N1 Kabete and PM1 Maseno experiments indicating the beneficial effects of continued organic residue application. Similarly, higher proportions of aggregate LF C and N were observed in macroaggregate fractions for the three experiments with organic treatments having higher proportions of both aggregate MF and LF C and N. The δ^{13}C signatures of the macroaggregates (>250 µm) LF were more negative as compared to the δ^{13}C values in the microaggregate (53-250 µm) LF. This pointed to C contribution to the most recently incorporated organic matter from C3 organic resources being applied. The results thus indicated that studies on soil physical properties require prolonged experimentation for the effects among the treatments to be isolated. Application of organic residues tended to improve SOM and related soil chemical properties thus justifying the need for continued application of organics to improve soil status.

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List of acronyms

ANCA:	Automated Nitrogen and Carbon Analyser
ANOVA:	Analysis of Variance
CEC:	Cation Exchange capacity
CIAT:	International Centre for Tropical Agriculture
FAO:	Food Agriculture Organization
ICRAF:	International centre for Research in Agroforestry
ISFM:	Integrated Soil Fertility Management
KARI:	Kenya Agriculture Research Institute
KU:	Kenyatta University
NARL:	National Agriculture Research laboratories
PDB:	Pee De Belemnite
RCBD:	Randomized Complete Block Design
RRC:	Regional research Centre
SOM:	Soil Organic Matter
TSBF:	Tropical Soil Biology and Fertility
UNESCO:	United Nations Educational, Scientific and Cultural Organization (UNESCO)
WAC:	World Agroforestry Centre (ICRAF)

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Soil organic matter (SOM) is an important component of soils that contributes to its fertility. SOM encompasses plant, animal and microbial residues in all stages of decay and a diversity of heterogeneous organic substances intimately associated with inorganic soil components (Christensen, 1992). This term, therefore, designates a highly complex pool that includes numerous carbonaceous compounds (Buyanovzky *et al.*, 1994) that form a biochemical continuum from cellular fractions of higher plants, microbial and animal origin, through low and medium molecular weight humus compounds whose structure has yet to be characterized (Anderson and Ingram, 1993).

Concentrations of SOM range from 0.2% in desert soils to over 80% in peat soils (Smith, 1994). In temperate regions, SOM ranges between 0.45% and 10%; with the humid soils averaging 3-4% and semi-arid soils 1-3% (Smith and Elliot, 1990). Even in soils with relatively low concentrations of SOM, this complex substance has a major influence on both chemical and physical properties of the soil (Smith, 1994).

SOM components are in continuous turnover (Woomer *et al.*, 1994) due to the complex interactions of biological, chemical and physical processes in the soil. Changes in land use and management practices also influence the amount and rate of SOM losses and gains (Guggenberger *et al.*, 1994; 1995). Native soils have their

SOM content usually in a state of dynamic equilibrium where organic matter losses are balanced by organic matter inputs. Cultivation of soils however alters this equilibrium by increasing SOM losses due to the exposure of aggregate-protected organic matter to microbial decomposition (Beare *et al.*, 1994). In view of the important role of SOM in supplying nutrients, buffering nutrients and water and maintaining soil structure (Woomer *et al.*, 1994), considerable attention has been directed towards the identification of agricultural practices that maintain adequate SOM contents in the soil (Barrios *et al.*, 1996).

Addition of fresh organic matter into the soil is one possible way to manage the size and quality of the SOM pool. Although most of the organic resources show limited increases in crop growth, they increase the soil organic carbon status (Vanlauwe *et al.*, 2001) and have a positive impact on the environmental service functions of the soil resource. As observed by Vanlauwe (2004), SOM is not only a major regulator of the various processes underlying the supply of nutrients and the creation of a favourable environment for plant growth such as nutrient supply, water availability, soil structure maintenance, nutrient buffering and other miscellaneous roles such as sorption but also regulates various processes governing the creation of soil-based environmental services such as water use efficiency, carbon sequestration and clean water supply through reduced ammonia losses. However, residue quality tends to modify the residue decomposition process (Vanlauwe *et al.*, 1996; Mafongoya *et al.*, 1997a; b) and may be an important factor in regulating the impact of fresh organic matter on the various SOM fractions. The rate of biomass decomposition hence the amount of SOM content of the soil is related to a number of plant (litter)-quality indices such as the organic resource nitrogen (N), carbon (C), lignin and polyphenol contents and their ratios (Jama and Nair, 1996; Mafongoya *et al.*, 1997a; b).

The distribution of SOM within the functional pools is an important consideration in developing a better understanding of soil organic matter in ecosystems (Swift, 1986, Parton *et al.*, 1989; Jenkinson, 1990). Focus has now shifted towards using soil size and density fractionation techniques which have shown promise for physically dividing soil into SOM pools differing in composition and biological functions (Christensen, 1992). In addition, the carbon-13 isotope technique has also emerged as a tracer for studying shifts in carbon in the soil. Whereas models have been developed to predict SOM dynamics, they (models) have been inadequate in isolating and quantifying some of the functional pools of SOM, particularly the slow pool consisting of materials of yet unknown physical and chemical properties (Woomer *et al.*, 1994; Hassink, 1995). Lacking also is adequate information on the effects of the different qualities of organic resources on the nature and dynamics of the resultant SOM under different management practices and soil types. This study, therefore, set out to assess the effects of the quality and duration of organic resource application on the composition and quality of SOM formed as well as the effect of this SOM on other soil physical, chemical and biological properties. By exploring the above conditions in experiments that have different lifespans and which are in different ecological zones, the study would provide a better basis for comparisons of the effects of organic residues on SOM pools.

1.2 Statement of the problem

The fertility of any soil is central to the sustainability of both natural and managed ecosystems because it is the medium from which terrestrial production emanates (Scholes *et al.*, 1994). SOM plays an important role in maintaining soil structure, water-holding capacity, microbial biomass and soil fauna, and in nutrient cycling and its decline with cropping is a major factor affecting sustainability of cropping systems (Buyanovzky *et al.*, 1994). Nutrient capital has gradually been depleted by crop harvest removals, leaching and soil erosion to the extent to which soil fertility replenishment has been recommended as a necessary investment in natural resource capital.

Studies indicate that soil physical, chemical and biological properties can sustainably be improved through the improvement of SOM. Practices such as alley cropping and biomass transfer offer the potential of doing this through the cycling of organic matter back to the soil. The major obstacle hindering the efficacy of these strategies is the lack of adequate understanding on the effects of the different organic resource qualities on the nature of the resultant SOM. Soil organic carbon analyses carried out on whole soil (WS) samples do not give a clear impression of the status of the soil since this is obscured by the high background carbon levels. This therefore calls for the need to explore the SOM fractions. Considering that information on the active pools of the SOM is still scanty, it is difficult to optimize decisions on the use of the qualities of SOM that contribute to higher nutrient recovery. This study therefore, sought to increase understanding on the effects of organic resources on the nature of the SOM formed and to identify the roles played by the various components of SOM in nutrient supply as well as other soil properties.

1.3 Research questions

The study pursued the following research questions:

1. How do the different soil organic matter fractions compare after application of organic inputs of different qualities/quantities?
2. To what extent are the other SOM-related soil physical, chemical and biological properties influenced by the quality/quantity of the organic resources applied to the soil?

1.4 Objectives of the study

The main objective of the study was to assess soil organic matter (SOM) dynamics in a maize cropping system receiving a biomass transfer application of Senna *spectabilis* (senna), *Tithonia diversifolia* (tithonia), *Leucaena leucocephala* (leucaena) and *Calliandra calothyrsus* (calliandra) as organic resources and fertilizer for nutrient supply.

To do this the following specific objectives were pursued:

1. To determine the relative contribution of different organic inputs on SOM fractions and the relative effects of these fractions on nutrient supply
2. To assess the change in SOM-related soil properties as affected by organic input management

1.5 Hypotheses

The working hypothesis for this study was 'the quality and/or quantity of SOM pool can be managed by altering the type of organic inputs added to the soil and this change in SOM status is expressed in chemical, physical and biological properties'.

The following specific hypotheses were pursued:

1. Organic resource quality/quantity has no impact on the size and quality of the SOM pool

2. Soil organic matter-related soil properties are not influenced by organic input management regimes

1.6 Justification and significance of the study

Smallholder farms in most parts of the country are experiencing declining food production as a result of continuous cropping, crop harvests and losses of nutrients due to soil erosion and leaching. The role of SOM in improving farm nutrient capital has been recognized as an option to sustainable agriculture. Addition of organic resources to improve soil fertility has emerged as an alternative to improving the soil nutrient capital. The emerging dilemma with this practice however is the choice and availability of appropriate organic resources that will ensure optimal nutrient recovery at the same time maintain other soil physical, chemical and biological properties. This study, by evaluating the effects of the various qualities of organic resources on SOM status will help farmers in the choice of appropriate organic nutrient inputs to use as well as the appropriate land management practices to be adopted for optimal nutrient recovery in smallholder agriculture.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Soil organic matter (SOM) reflects the balance among vegetation, soil biota, climate, parent material, time to steady state, and natural and human disturbances in the soil. SOM thus acts as a signature as well as a controller of ecosystem functioning (Paul, 1984). It is one of the primary factors that affects soil quality, water infiltration, erosion resistance, tilth, and adsorption and degradation of pollutants (Doran *et al.*, 1994). Recent interest in SOM as a source-sink in global C budgets result from the assessment that 25% of the radiative climate resulting in global change is attributed to agriculture (Schiniel, 1995). Further, SOM is a major component of the terrestrial sink necessary to balance present global CO_2 budgets (Lugo, 1992; Lal *et al.*, 1995). This therefore, means that SOM dynamics need to be well known for its proper management.

2.2 Importance of soil organic matter

Soil organic matter is key to regulating crop production and influencing essential soil-based environmental services (Vanlauwe, 2004). Key to these benefits from SOM include crop production services such as nutrient supply, water availability, soil structure maintenance, nutrient buffering and other essential miscellaneous benefits such as toxicity regulation and sorption and crops and environmental services such as water use efficiency, carbon sequestration and clean water supply due to reduced ammonia losses.

Ninety to ninety-five percent (90-95%) of the total soil nitrogen (N) is associated or combined with the soil organic fraction (Smith, 1994). SOM also contains approximately 40% of soil phosphorus (P) and 90% of soil sulphur (S). Biologically mediated nutrient availability is largely dependent on SOM decomposition and mineralization processes (Barrios *et al.*, 1996).

SOM contributes to soil aggregation. The activities of microorganisms and soil fauna on SOM promote soil aggregation, which in turn controls air and water relationships for plant growth (Smith, 1994). Soil aggregation leads to greater moisture infiltration (Lavelle, 1988) and provides resistance to water and wind erosion.

The concentration of SOM dictates the level of microbial population. It is the interactive relationship between SOM and the microbial population that controls nutrient cycling in most ecosystems (Smith, 1994).

Both the labile and passive organic carbon compounds are important in detoxification of phytotoxic chemicals. Labile or soluble carbon compounds complex and chelate toxic iron, aluminium and manganese species in the soil solution (Hue *et al.*, 1996), decompose urea and uric acids resulting in improved N availability and reduced toxicity, and decompose and transform applied pesticides (Woomer *et al.*, 1994).

Other important benefits accruing from the maintenance of SOM are nutrient retention and storage, increased buffering capacity of low activity clay soils (Swift and Sanchez, 1984) and increased water-holding capacity (Nelson and Sommers, 1982). SOM also influences soil colour, which in turn influences soil temperature (Nelson and Sommers, 1982).

2.3 Factors influencing soil organic matter dynamics

SOM is in constant fluctuations in the soil. Basic to this is the balance between primary productivity and the rate of decomposition. Moreover soil forming factors namely, climate, topography, living organisms, parent material and time affect this balance. Anthropogenic attributes such as bush clearing and burning (Martins *et al.*, 1991), cultivation (Sanchez *et al.*, 1989), application of organics (Christensen, 1986) and inorganic fertilizers and other land use practices affect the amounts of organic matter in soil either positively or negatively.

The processes in which SOM losses and gains occur are described as turnover, and for carbon, this may be defined as the flux of carbon through the organic carbon in the soil (Jenkinson, 1990). Turnover time in this case is the amount of carbon in the soil divided by the annual input or carbon in the soil (Smith, 1994). Various models have been developed to calculate the turnover time of SOM (Young, 1989). CENTURY model for example separates SOM into decomposable (labile) and resistant fractions that are allocated between an active pool (turnover time <1 year) and a more recalcitrant pool characterized by slow turnover rates due to chemical or physical protection (Parton *et al.*, 1987; Woomer *et al.*, 1994). Pools with a rapid turnover rate are assumed to have an important role in N availability because SOM dynamics and N cycling are closely linked through the processes of N mineralization and immobilization (Duxbury *et al.*, 1989). On the other hand, slowly turning pools play an important role in cation exchange capacity (CEC) reactions in sandy soils and are important in soil aggregation (Woomer *et al.*, 1994; Buyanovzky *et al.*, 1994; Parton *et al.*, 1989).

In soil systems, microbially mediated decomposition and transformation of SOM is the primary driving force in nutrient cycling, which plays a significant role in ecosystem development and functioning. Soil microbial biomass (SMB) plays a major role as a catalyst in the decomposition of SOM and release of inorganic nutrients to the bulk soil where they become available for plant uptake (Smith, 1994). Whereas some researchers argue that measurement of the size of the SMB is key to understanding the turnover rate of the SOM (Ocio *et al.*, 1991), others consider SMB a poor indicator of these changes because factors such as particular species comprising the SMB and the soil moisture can remarkably affect the size of the SMB (Mazzarino *et al.*, 1987).

2.4 Relationship between organic resource quality and SOM formation

Organic constituents are important because the energy available to decomposer organisms depends on the proportion of soluble C, cellulose and hemicellulose and lignin (Nair *et al.*, 1999). Soluble C includes metabolic and storage C, and is primarily responsible for promoting microbial growth and activity (Smith, 1994). Green foliage usually contains 20 to 30% soluble C (Nair *et al.*, 1999). Cellulose and hemicellulose, which constitute 30 to 70% of plant C, are structural polysaccharides of 'intermediate' quality; decomposer microbes attack them after soluble carbohydrates have been depleted. Lignin, which intertwines the cell wall constituents from degradation, is the 'lowest' quality C constituent, providing little or no energy to the decomposers until the last stages of decomposition. Thus the lignin content of the organic material is considered to be the most important factor determining the rate of decomposition (Jama and Nair, 1996; Mafongoya *et al.*, 1997a; Mugendi and Nair, 1997) as well as being a major contributor to humus.

Recent studies on most agroforestry tree species have shown that polyphenols, which comprise a relatively small percentage of the organic material, have a disproportionately large negative influence on decomposition and N release (Palm and Sanchez, 1990; Palm *et al.*, 2001; Mafongoya *et al.*, 1998; Mafongoya *et al.*, 1997a; b). In addition to the C quality, nutrient, especially N-content of plant materials is a major determinant of litter quality. Generally, materials with N content higher than 20 mg g^{-1} are considered to be of high quality, although this can be modified by lignin and polyphenol content (Mafongoya *et al.*, 1997a; b).

2.5 Nutrient recovery from soil organic matter

An important aspect of SOM studies is that of nutrient recovery, which indicates the extent to which the nutrients that are released from biomass decomposition are taken up by the current and subsequent seasons' crops (Nair *et al.*, 1999). Many leguminous tree species used in agroforestry are capable of supplying crops with adequate amounts of N and K but with the exception of P (Palm, 1995). In sub-humid Kenya, for example, Mugendi *et al.* (2000) used ^{15}N to estimate N recovery from tree biomass applied to the soil in an alley cropping experiment. The first season's maize crop recovered only 9 to 13% of the initial ^{15}N, while 55 to 69% was recovered in the soil organic N pool after the cropping season. Although low recovery by a crop of N released from decomposing organic material does not necessarily imply a corresponding build-up of SOM, these studies suggest that a considerable portion of the N added as tree biomass to crop production fields can be retained in SOM.

2.6 Measurement of soil organic matter

Various methods have been developed to measure and characterize SOM. According to Barrios *et al.* (1996), those that use organic C and humic acids may be of limited use to understanding the link between SOM dynamics and nutrient availability because they do not measure the biologically-active SOM fractions. Furthermore small changes in total SOM or C determined on whole soils (WS) are difficult to detect because of the generally high background levels and natural soil variability (Blair *et al.*, 1995). Size and density fractionation therefore show promise for physically dividing WS into SOM pools differing in composition and biological function (Christensen, 1992) hence offering a better measure of SOM dynamics in agricultural systems.

Changes in the lability of soil carbon have been proposed by Lefroy *et al.* (1995) as a measure of sustainability. This procedure relies on the ease of oxidation of the soil organic C by potassium permanganate. On the basis of changes in total carbon (CT), a Carbon Pool Index (CPI) can be calculated while on the basis of the changes in proportion of labile C in the soil between a reference site and those subjected to agricultural practices or research treatments, a Lability Index (LI) can be determined.

These two indices can then be used to calculate a Carbon Management Index (CMI) (Blair *et al.*, 1995). When monitored over time or when a new practice is introduced, the CMI can be used to monitor differences in soil C dynamics between treatments over time. Although there is no 'ideal' value of CMI, the index provides a sensitive measure of the rate of change in soil C dynamics of systems relative to a more stable reference soil.

2.6.1 Soil organic matter fractionation

SOM fractionation methods involve soil dispersal prior to size separation and further separation of size fractions by density (Meijboom *et al.*, 1995). Size fractionation is based on the observation that SOM in the sand-size fraction (>53 μm), is often more labile than SOM in the clay- and silt-size fractions (Tiessen and Stewart, 1983). SOM in the sand-size fraction has been termed particulate organic matter (POM) by Cambardella and Elliot (1992).

Aggregate hierarchy theory has been used by many authors to explain the correlation between a reduction in aggregation and loss of soil organic matter (SOM) with cultivation (Elliott, 1986; Cambardella and Elliott, 1993; Beare *et al.*, 1994). Soil aggregates physically protect certain SOM fractions, resulting in pools with longer turnover times (Adu and Oades, 1978). Defining SOM pools that relate to soil structure and delineating SOM fractions that are functionally meaningful are important challenges for research and are necessary for a better understanding of SOM dynamics. For example, Christensen (1986) described the importance of differentiating the free and intra-aggregate SOM in conceptual models of physically based SOM pools. Intra-agregate organic matter is incorporated and physically stabilized within macroaggregates (Cambardella and Elliott, 1992) while free organic matter is found between aggregates. This difference in position within the soil matrix and the resultant accessibility of SOM to soil organisms leads to pools that differ in stability and dynamics (Golchin *et al.*, 1994).

The concept of aggregate hierarchy involves the aggregation of primary particles and clay microstructure into microaggregates (53-250 μm), which in turn are organized into macroaggregates (>250 μm) (Guggenberger *et al.*, 1999). Soil microorganisms especially fungi, play an important role in the formation and stabilization of macroaggregates (Gupta and Germida, 1988). As a result of the binding effects from the fungal mycelia, Elliott (1986) proposed that macroaggregates have elevated C concentrations because of this organic matter that binds microaggregates into macroaggregates and showed that this organic matter fraction is the major pool that is depleted as a result of cultivation. Further, a breakdown in macroaggregates results in a release of labile SOM (Elliott, 1986) and its increased availability for microbial decomposition.

2.6.2 Implication of soil organic matter fractions on soil quality

Fractionation has enabled better understanding of SOM dynamics in the soil. Nutrient turnover and recovery studies have relied on the changes in nutrient composition of these pools. In a study by Solomon *et al.* (2000), the C and N contents in particle size separates under the different land use systems studied peaked in clay followed by silt-sized fractions. According to Christensen (1992), SOM associated with sand size fractions mainly consists of macro-organic matter, which is not involved in organo-mineral complexes but is partially occluded within aggregates. This fraction consists of recognizable plant debris with high C:N ratio and low specific weight, and is easily decomposable. This implies that this macro-organic matter is much more susceptible to mineralization, hence contributes significantly to the soil available nutrient pool (Tiessen and Stewart, 1983). The C:N ratio generally decreases with the decreasing particle size fractions indicating an increasing degree of humification (Tiessen and Stewart, 1983; Guggenberger *et al.*, 1994).

The fine clay fraction contains organic materials of narrow C:N ratio, that may be of recent microbial origin, are more labile, and may together with the light organic matter fraction, play an important role in soil fertility (Anderson *et al.*, 1981). The labile fractions, that is, the SOM associated with coarse and fine sand fractions is greatly influenced by land use for example cultivation. Tiessen and Stewart (1983) and Christensen (1992), pointed out that since the turnover rate of SOM associated with sand size fractions is fast, the SOM attached to the labile fractions is rapidly lost. Compared to the labile fractions, the decrease of the stable fractions as a result of cultivation was relatively smaller (Solomon *et al.*, 2000). These results indicate that organo-mineral associations play a very important role in SOM stabilization of the soils.

In general, the redistribution of SOM between particle-size fractions is characterized by a depletion of labile fractions and a shift toward fine silt and coarse clay associated minerals, which have low nutrient availability (Tiessen and Stewart, 1983). Cultivation not only depletes organic matter but may also lower the availability of organically held nutrients, such as N and organic P.

2.7 Carbon isotope technique

The carbon-13 (^{13}C) natural labeling technique has proved to be a powerful approach for tracing the fate of organic matter in soil. This technique is based on the realization that most trees and shrubs used in agroforestry as green manure are of C3 photosynthetic pathway as opposed to the crop, in this case maize, which is a C4 species. C4 and C3 species differ in their delta carbon-13 ($\delta\ ^{13}C$) signature present in their biomass (Balesdent *et al.*, 1987; 1988; Diels *et al.*, 2001). The photosynthetic pathways of C3 and C4 plants discriminate differently for the naturally occurring ^{13}C isotope so that the $^{13}C/^{12}C$ isotope ratio that results can be used to partition SOM as to its origin (Follet *et al.*, 1997). Plant C contains distinctly less ^{13}C than atmospheric CO_2. While atmospheric CO_2 has a $\delta\ ^{13}C$ of –7.5‰, values of plant C range from –22 to -34‰ (averaging -26‰) in C3 plants, to around -11‰ in C4 plants (Veldkamp and Weitz, 1994). Applying C3 organic resources on a soil, which has previously been under C4 vegetation such as grasses, can thus be considered as an *in situ* labeling of SOM (Balesdent *et al.*, 1987;1988). The use of these two isotopically different SOM sources of C led Wedin *et al.* (1995) to suggest that isotopic shifts during the decomposition of litter from four perennial grasses (both C3 and C4 species) are caused by the incorporation of new C from SOM into the litter of microbial decomposers. Also, Gregorich *et al.* (1995) was able to determine that, following 25 years of continuous corn (*Zea mays* L.) grown on a forest soil in eastern Ontario, about 30% of the soil organic carbon (SOC) in the till layer was derived from corn. If changes in time or contrasts between treatments in terms of the ^{13}C signature of plant entering the soil are quantified, SOC models can together with this information be used to predict changes or contrasts in the ^{13}C signature of the SOC.

The efficacy of the carbon isotope technique in assessing SOM dynamics in agricultural lands has been widely demonstrated in the Prairies of the United States (Balesdent *et al.*, 1987; 1988; Wedin *et al.*, 1995) and on a limited scale in West Africa (Diels *et al.*, 2001). Few studies of such a kind have been carried out in the East and Central African region. Considering the success of this technique where it has been tested, there is need to test it in the soils of East Africa.

2.8 Gaps in the literature

The introduction of Intergrated Soil Fertility Management (ISFM) practices has seen the need to evaluate the effects of organic resources of different qualities on the composition and nutrient release of SOM. The extent of contribution of these organic residues to the soil carbon signatures has not been widely understood especially for soils in East Africa. Further, the effect of these organic nutrient sources on selected soil properties under different soil types and under different application duration also require attention in assessing the most appropriate organic resources to use and nutrient management practices that will ensure the sustainability of agricultural systems.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Site description

Three experiments (Nitrogen Management - N1 experiment at National Agriculture Research Laboratories - NARL, Kabete, Phosphorus Management - PM1 experiment at Msinde Farm, Maseno and the Embu Hedgerow Intercropping - HI Embu experiment at the Kenya Agricultural Research Institute Regional Research Centre, Embu) involving the application of different organic resources were evaluated.

N1 Kabete experiment is in Central Kenya at 36° 46' E and 01° 15' S and an altitude of 1650 m (Kimetu, 2002). The site is located in the semi-humid climatic zone with a total bimodal rainfall of over 970 mm per annum. The soils are derived from quartz trachyte geological material, and are typical Humic Nitisols inherently fertile, with moderate amounts of organic carbon, Ca, Mg, K but low in available P, clay 40%, sand 23% and silt 37%. The site had in the past been under grasses. N1 Kabete experiment was established in 1999 as a randomized complete block design (RCBD) with ten treatments replicated four times. The objective of the original experiment was to determine fertilizer equivalencies of *Tithonia diversifolia* (tithonia), *Calliandra calothyrsus* (calliandra) *and Senna spectabilis* (senna) organic resources when integrated with inorganic fertilizers, mainly, urea (Kimetu, 2002). The current study considered four out of the total ten treatments of the original experiment.

PM1 Maseno experiment, found in the highlands of Western Kenya on Msinde Farm near Maseno, was established during the short rainy season of 1995 as a RCBD with four replicates (Nziguheba *et al.*, 2000). The site is located at an altitude of 1420 m, a latitude of 0° 06' N and a longitude of 34° 34' E. The mean annual rainfall is 1800 mm distributed into two rainy seasons: the long rainy season from March to August and the short rainy season from September to January. The soil is a Nitisol (FAO, 1990) with 42% clay, 25% silt and 33% sand. Msinde farm had been under mixed native vegetation of grasses and shrubs. The main experiment consists of treatments involving the application of six organic materials of different quality that have been compared to a phosphorus (P) response curve from triple superphosphate (TSP) to assess their P supplying capacity. For the purpose of this study, only three organic treatments and the control were considered as indicated in Table 3.1.

HI Embu experiment is located at the Embu Regional Research Centre (RRC), Eastern Province, Kenya (Mugendi *et al.*, 2000). The centre is located in the central highlands of Kenya at 0° 30' S, 37° 30' E and an altitude of 1480 m. The soils are mainly Typic Palehumult (Humic Nitisols according to FAO, 1990) derived from basic volcanic rocks. They are deep, well weathered with friable clay texture with moderate to high inherent fertility. The site has clay content of 38%, 30% silt and 32% sand contents. Total annual average rainfall ranges between 1200 mm and 1500 mm received in two distinct rainy seasons: the long rain (LR) from mid March to June and the short rains (SR) from October to December. The average monthly maximum temperature is 25° C and the minimum 14° C. The experiment was set up in 1992 to evaluate the influence of soil-incorporated leaf biomass of agroforestry trees on soil fertility and maize yield, and to gain more understanding on the processes involved in the fate of nitrogen (N) released from the decomposing biomass. The experiment is a RCBD with ten treatments and four replicates. The current study considered four of the ten treatments in the assessment of the effect of organic resources on the quality of the SOM formed.

3.2 Experimental setup

Since the study aimed at evaluating the effects of the organic resources on the quality of SOM formed, only a selection of the treatments in each of the original experiment receiving the organic resources of interest were considered for this study as indicated in Table 3.1.

Table 3. 1: Selected experimental treatments from N1 Kabete, PM1 Maseno and HI Embu experiments

Experiment	Year of establishment	Treatments	Quantity of organic resources applied	Quantity of inorganic nutrients applied
N1 Kabete	Short rain 1999	Control	-	-
		Fertilizer	-	60 kg N ha^{-1}
		Tithonia diversifolia	1.3 t DM ha^{-1}	-
		Senna spectabilis	1.8 t DM ha^{-1}	-
		Calliandra calothyrsus	1.9 t D ha^{-1}	-
PM1 Maseno	Short rain 1995	Control	-	-
		Tithonia diversifolia	5 t DM ha^{-1}	
		Calliandra calothyrsus	5 t DM ha^{-1}	-
		Senna spectabilis	5 t DM ha^{-1}	-
HI Embu	Short rain 1992	Control	-	-
		Fertilizer	-	50 kg N ha^{-1}
		Calliandra calothyrsus	*2.3 t DM ha^{-1}	-
		Leucaena leucocephala	*2.3 t DM ha^{-1}	-

DM = Dry matter; t = tones; ha = hectares; kg = kilograms

* Organic residues varied based on in situ production on the calliandra and leucaena hedgerows and ranged between 1.8 and 2.3 DM ha^{-1}

Table 3.2 presents some quality parameters of the organic resources applied in N1 Kabete, PM1 Maseno and HI Embu experiments. Calliandra, with the highest polyphenol content, was considered as of lower quality as compared to the other organic resources. Senna was intermediate while tithonia and leucaena were of the highest quality due to their high nitrogen contents but relatively lower lignin and polyphenol contents. Preliminary carbon-13 values on the organic resources showed senna to have a delta ^{13}C of -24.2‰, calliandra -21.6‰ and tithonia -22.4‰.

Table 3. 2: Chemical properties for the organic materials used in N1 Kabete, PM1 Maseno and HI Embu experiment

Site	Organic Resource	% N	% P	% PP	% Lignin
N1 Kabete	Tithonia	4.4	0.5	2.2	7.3
	Senna	3.4	0.2	2.6	10.8
	Calliandra	2.7	0.1	7.7	16.0
PM1 Maseno	Tithonia	3.7	0.3	3.7	12.0
	Senna	3.6	0.2	2.2	13.2
	Calliandra	3.5	0.2	7.9	12.1
HI Embu	Calliandra	4.0	-	11.8	11.6
	Leucaena	4.0	-	3.3	6.9

PP – Polyphenol, P – Phosphorus, N – Nitrogen
(Source: Mugendi *et al.* 1999a; Kimetu, 2002 and Nziguheba, 2001)

3.3 Maize yield trend analysis

Crop yield data for the three experiments have been discussed by Nziguheba *et al.* (2000), Mugendi *et al.* (2001) and Kimetu (2002). For the purpose of this work, however, a brief refence to the above works is made in support of the beneficial effects of organic residue application on crop production.

3.4 Soil sampling and analyses

Soil samples were collected from the selected experiments before the onset of the long rains (LR) of 2002. Soil was collected from the 0-10 cm top layer, as this is where most impact of added organic matter is felt. A narrow range of the bulk density of the soils from the three experiments in this layer also justified the choice and comparison of emerging SOM results. The soil from each treatment was bulked, a subsample taken for mineral N analysis while the bulk of the soil was air dried, the big clumps gently broken down, and passed through a 2-mm sieve in readiness for chemical analysis and fractionation. The soils total N, C, inorganic N and soil respiration were determined for the surface soil following methodologies as described by Anderson and Ingram (1993), Okalebo (1993) and ICRAF (1995). All these parameters were then related to the respective organic resources and the resultant crop yields for the respective treatments.

3.4.1 Determination of total carbon and nitrogen

Analysis of total carbon and total nitrogen for soils was done on an automated nitrogen and carbon (ANCA) mass spectrometer (Diels *et al.*, 2001). Samples were finely ground (pulverized) using a pestle and mortar prior to the above analyses.

3.4.2 Determination of soil inorganic nitrogen (nitrate and ammonium-N)

Soil inorganic nitrogen that is nitrate-N (NO_3^- -N and ammonium-N (NH_4^+-N) analyses were done according to procedures described in the ICRAF Laboratory methods of soil and plant analysis (Anderson and Ingram, 1993; ICRAF, 1995). Soil moisture was determined on a subsample of field moist soil after drying at 105° C for 24 hours. Twenty grams (20 g) of field moist soil was then extracted with 100 ml of 2*N* KCl by shaking for 1 hour at 150 reciprocations per minute and subsequently filtered gravimetrically using prewashed Whatman No. 5 filter papers. Nitrate was determined from the 2*N* KCl extract by cadmium reduction while ammonium ions were determined by the salicylate-hypochlorite colorimetrc method with subsequent determination of nitrite and ammonium ions. Nitrate and ammonium-nitrogen were determined colorimetrically at 525 and 655 nm respectively. The inorganic N was then expressed on a dry soil basis.

3.4.3 Soil respiration

A subsample of air dried soil from each treatment was moistened to approximately 45% of the water holding capacity (WHC) and preincubated for 7 days prior to incubation. This was necessary to check on the CO_2 flush resulting from rapid microbial activity as a result of the wetting of the soil. After 7 days, plastic containers with fifty grams of soil were placed in 250 ml gas jars and sealed with plastic lids along with 10 ml of 1*M* NaOH placed in a small glass vial. The jars were incubated at 25° C for 7, 14, 28 and 56 days. Five 250 ml jars without soil were also incubated similarly as blanks. At every sampling time all the other NaOH traps were changed and replaced with new ones and left to incubate to the next sampling time. This was done to prevent oversaturation of the NaOH solution and also to avoid any CO_2 effects on the decomposition process. From the different jars at any sampling time, 5 ml of the NaOH solution was taken and titrated with 0.1*N* HCl to determine the amount of CO_2-C absorbed.

3.4.4 Potassium permanganate oxidation method

Potassium permanganate oxidizable carbon was determined following the method of Blair *et al.* (1995; 1997) though with minor modifications. A portion of soil containing approximately 15 mg of organic C was shaken in 25 ml of 33.33*mM* (*millimoles*) $KMnO_4$ for 24 hours instead of 1 hour extraction time. This was to increase reaction time for complete carbon oxidation. The soil suspensions were then centrifuged, and the supernatants diluted in the ratio of 1:1000 with deionised water. The $KMnO_4$ consumption was then colorimetrically determined at 600 nm.

3.4.5 Determination of the isotope carbon-13 (^{13}C)

Analysis of delta carbon-13 ($\delta^{13}C$) for pulverised soil samples was done on an automated nitrogen and carbon (ANCA- analyser) mass spectrometer (Diels *et al.*, 2001). Carbon isotope composition was expressed in delta-13 ($\delta^{13}C$) units using the international Pee De Belemnite (PDB) reference standard:

$$\delta^{13}C\text{‰} = \left[\frac{^{13}R_{sample}}{^{13}R_{standard}} - 1\right] \times 1000$$

$$\text{Where: } {}^{13}R = \frac{^{13}C}{^{12}C}$$

3.4.6 Soil fractionation procedures and aggregate separation

SOM fractionation was done following a modification to the soil fractionation method as described by Six *et al.* (1998; 2000). The following scheme (Figure 3.1 & 3.2) for aggregate and size fractionation was adopted. Soil fractionation was done on a sample of 100 g dry weight. Prior to fractionation, the soil was capillary wetted overnight for 18 hours at 4° C using the setup in Figure 3.1.

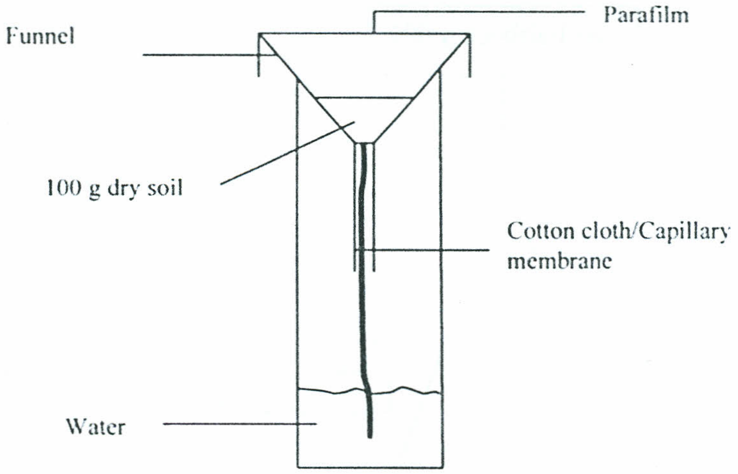

Figure 3. 1: Improvised soil capillary pre-wetting apparatus used before soil organic matter fractionation

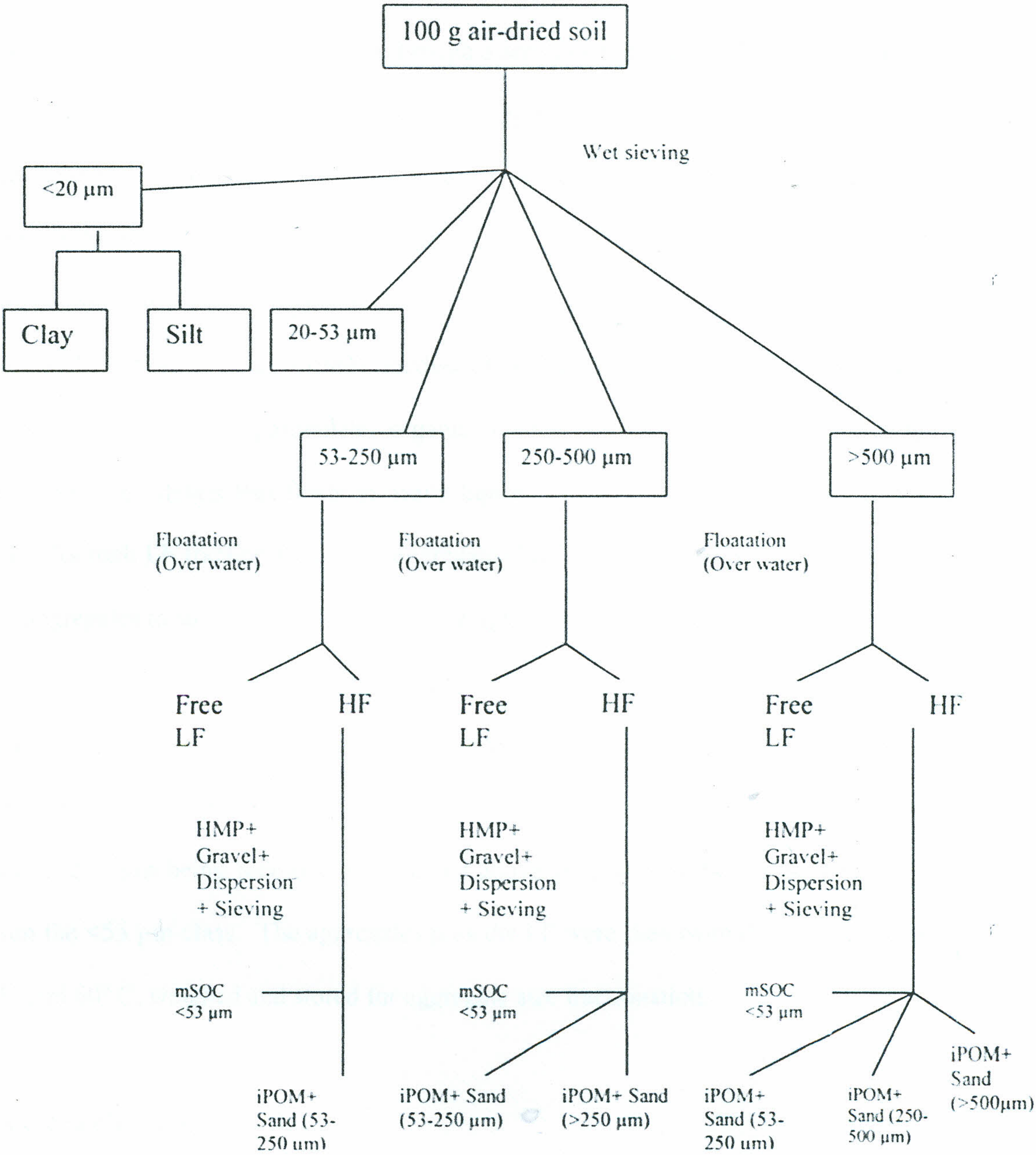

Figure 3. 2: Soil organic matter aggregate class and intra-aggregate fractionation scheme

3.4.6.1 Aggregate separation

The capillary wetted soil was sieved through a series of four sieves (500 µm, 250 µm, 53 µm and 20 µm). To ensure minimal aggregate disruption, the sample was submerged in water on top of the 500 µm sieve and the aggregates separated by moving the sieve in a bucket of water up and down 3 cm for about 2 minutes. After the washing, the stable aggregates were then washed into a moisture beaker. As observed by Sollins *et al.* (1984), studies of SOM require distinguishing mineral-associated from free particulate organic matter. Most free SOM is usually undecomposed debris that floats in heavy liquids and is referred to as light fraction (LF). As such LF fraction from each aggregate class was separated by gentle swirling the aggregates to suspend and decanting any light fraction floating on water.

Water plus soil that passed through the preceding sieve was then poured onto the next sieve and the washing repeated and the floating materials in classes >500, 250-500 and 53-250 µm being retained as discussed above (Figure 3.2). No LF was isolated from the <53 µm class. The aggregates plus the LF were then oven dried at between 55° and 60° C, weighed and stored for aggregate size fractionation.

3.4.6.2 Sedimentation cycle

Sedimentation process for the separation of the clays from silt was carried out at room temperature (25° C). Silt and clay was isolated from the <20 µm aggregate fraction following the aliquot method. In brief, the total soil plus water passing through the 20 µm sieve was weighed, thoroughly mixed and a subsample (1:5) collected for subsequent sedimentation cycle. The subsample collected was placed in a 1 litre-measuring cylinder and made to the mark with water. The aliquot was then mixed by tumble inverting the cylinder 20 times and left to settle for 2 h 10 minutes. The top 20 cm fraction was then siphoned from the top. This represented the clay fraction (0-5 μm). Material that settled after this time is considered to be silt (5-20 μm). The siphoning process was repeated (at least 4 times) until the water in the cylinder became clear, an indication that the entire clay fraction had been removed. The two fractions were then flocculated using hydrochloric acid (HCl) dried and weighed prior to C and N analysis.

3.4.6.3 Isolation of intra-aggregate organic matter

Isolation of intra-aggregate organic matter held within the aggregates was done by shaking a subsample of the macro- and micro-aggregates together with sodium hexametaphosphate (HMP) and a scoop of gravel for 16 hours on a tumbler shaker at 50 turns per minute (Fig 3.2). Wet sieving of the aggregates through 500, 250 and/or 53 μm sieves followed this. Light fraction (LF) in these aggregates was then separated by floatation as described above. The LFs formed the intra-aggregate organic matter. The materials retained on the sieves were then dried (55-60° C) and weighed and analysed for C, N and $\delta^{13}C$.

As observed by Elliott *et al.* (1991), sand content in the aggregate classes may dilute the SOM contents and hence make it difficult to compare organic matter contents of the different aggregate size classes. As such sand contents derived after dispersion of the respective aggregate size classes were subtracted from the weights of the respective aggregate sizes prior to calculation of the fractions aggregate TOC and TON.

3.4.7 Soil core sampling and soil moisture retention determination

Bulk density of the experimental soil was determined by use of undisturbed sample cores. A sharp edged steel ring was driven into the soil to a depth of 5 cm and carefully excavated to minimize soil disturbance. Excess soil on both ends of the ring was then cut free using a sharp straight edged knife. The rings plus the soil were then dried at 105° C to constant weight. The bulk density was calculated as follows:

$$D = (M_1 - M_c)/V$$

Where D = Bulk density (g cm^{-3})

M_1 mass of the core sampler and oven dry soil (g)

M_c = Mass of the core sampler (g)

V = Volume of the core sampler

Soil water retention was determined using a Soil Moisture Extractor Equipment following the methodology as described by ISRIC (1987). Undisturbed soil cores obtained from the three experiments were collected before the onset of the 2001 long rains using bulk density sampling rings. The water content was determined for the soil samples after equilibrating them with water at various suction (tension) values.

For low tensions, undisturbed cores were used while for high suction values the samples were disturbed. Sand tension plates were used to determine the moisture content of soil up to pF = 2. The cores were placed over the sand tension plates and the cores saturated with water for at least 24 hours. This moisture content at saturation was termed the saturation point and is assumed to be at pF = 0. A suction was then applied to the plates for subsequent moisture retention readings at pF = 1.0, 1.5 and 2.0. For pressures between pF = 2.0- 2.5, the cores were placed in sand kaolin boxes and moisture extracted using the pressure plate extractors. The pF ranges 0-2.5 formed the low pressure points and were determined on undisturbed soil cores. High pF value (pF = 3.7 and 4.0) moisture retention were determined on disturbed soil samples after application of pressure at 15 bars.

The above data was used to generate the soil water retention curves, otherwise called the pF curves. pF is defined as the logarithm of the moisture suction or as the negative logarithm of the moisture tension (ISRIC, 1987).

3.5 Statistical analyses

Analysis of variance (ANOVA) was conducted using Genstat for Windows version 6 to determine the effects of the treatments on SOM composition. Data for the SOM fractions was then analyzed together to determine the possible SOM fraction-treatment interactions. Other statistical tools applied included regression analysis. Means found to be significantly different were separated using the least significant difference (LSD) at $P \leq 0.05$.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the study. First, the maize yield trend analyses for PM1 Maseno, HI Embu and N1 Kabete experiments are presented. Secondly, the soil inorganic nitrogen (available N) in the three experiments is discussed. Other data presented and discussed include soil total C, N and carbon-13, soil respiration trends, potassium permanganate oxidizable carbon ($KMnO_4$-C), bulk density, water retention and SOM aggregates.

4.2 Maize yields from PM1 Maseno, N1 Kabete and HI Embu experiments

Maize yield trend analyses for N1 Kabete, PM1 Maseno and HI Embu experiments have been reported by Kimetu (2002), Nziguheba *et al.* (2000) and Mugendi *et al.* (2000) respectively. In all studies, application of both organic and inorganic nutrient sources resulted in greater maize grain yields as compared to the control treatment. In general, grain yield variations in N1 Kabete experiment for the period of study were minimal. This could be attributed to the short life of the experiment (5 seasons of organic residue application) as well as the low amounts of organic residues applied.

Maize yield for PM1 Maseno experiment for the organic residue application phase (SR 1995- LR 1998) are discussed by Nziguheba *et al.* (2000). In their study, maize yields among the different treatments in this experiment were quite different due to considerable fluctuations in rainfall. Further, yields were higher during the long rainy season as compared to the short rainy seasons. When considering the total yield cumulated after six seasons of organic residue application, the yield of the organic treatments and the control were in the order control < calliandra < senna < tithonia. In PM1 Maseno experiment, higher maize grain and stover yields continued to be attained three and a half years (7 seasons) after termination of organic residue application (SR1998 to SR2001). The results indicate that application of large quantities of organic residues can result into a larger residual effect even after application of organic residues is terminated. Similar observations have been made by Niang *et al.* (1996) in their study in western Kenya. Despite the better performance of the maize in treatments receiving organic residues as compared to the control, there was a general decline in the soil fertility as evidenced from the declining crop yields in all the treatments with time over the residual period. This could be attributed to declining soil fertility as a result of low external nutrient input and nutrient removals from harvests. This shows that whereas organic residues can have a long-term effect on the soil quality, there is need to frequently apply external sources of both organic and inorganic nutrient sources if the yields are to be sustained (Smithson and Giller, 2002). These results above agree with the observations made in the long term experiment (established in 1976) at Kabete Kenya, where despite continued application of organic residues there has been a general decline in maize crop yields and soil organic carbon (Swift *et al.*, 1994; Kapkiyai *et al.*, 1998).

Maize crop yields for HI Embu experiment have been discussed by Mugendi *et al.* (1999a; 1999b). In their work, application of ex-situ grown calliandra and leucaena prunings with or without fertilizer resulted in higher maize grain yield than in the non-fertilized and fertilized treatments.

4.3 Soil chemical and physical properties

4.3.1 Soil inorganic nitrogen in N1 Kabete, HI Embu and PM1 Maseno, experiments

Figure 4.1 shows the soil inorganic N for the 0-10 cm soils from N1 Kabete experiment before the short rain season of 2002. Mineral N was higher in all treatments receiving organic resources as compared to the fertilizer and the control treatments. Further, mineral N was significantly different ($P \leq 0.05$) across the treatments with senna treatment recording the highest inorganic N content (26.1 mg N kg^{-1} of soil) followed by tithonia (24.1 mg N kg^{-1}), calliandra (21.0 mg N kg^{-1}) then fertilizer (19.0 mg N kg^{-1}) while the control had the lowest inorganic N content of 16 mg N kg^{-1} of soil.

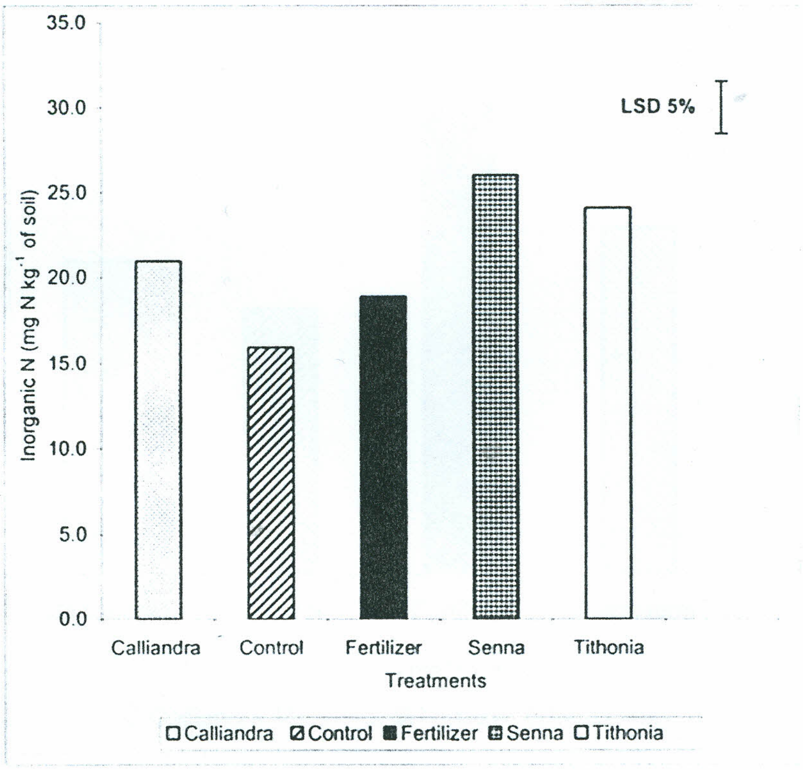

Figure 4. 1: Soil inorganic N before the long rains 2002 season in N1 Kabete experiment in the 0-10 cm layer

Higher mineral N contents in the organic treatments as compared to the fertilizer and control treatments points to the continued mineralization of the N held in the SOM pools even after the end of the previous cropping season. Such nitrogen held within the SOM pools can be utilized during the subsequent cropping seasons.

Soil inorganic N contents in the treatments of Embu experiment before the LR 2002 season were significantly different ($P \leq 0.05$) with the fertilizer treatment recording the highest mineral N content of 72 mg N kg^{-1} of soil (Figure 4.2). Other treatments were in the order leucaena = calliandra > control.

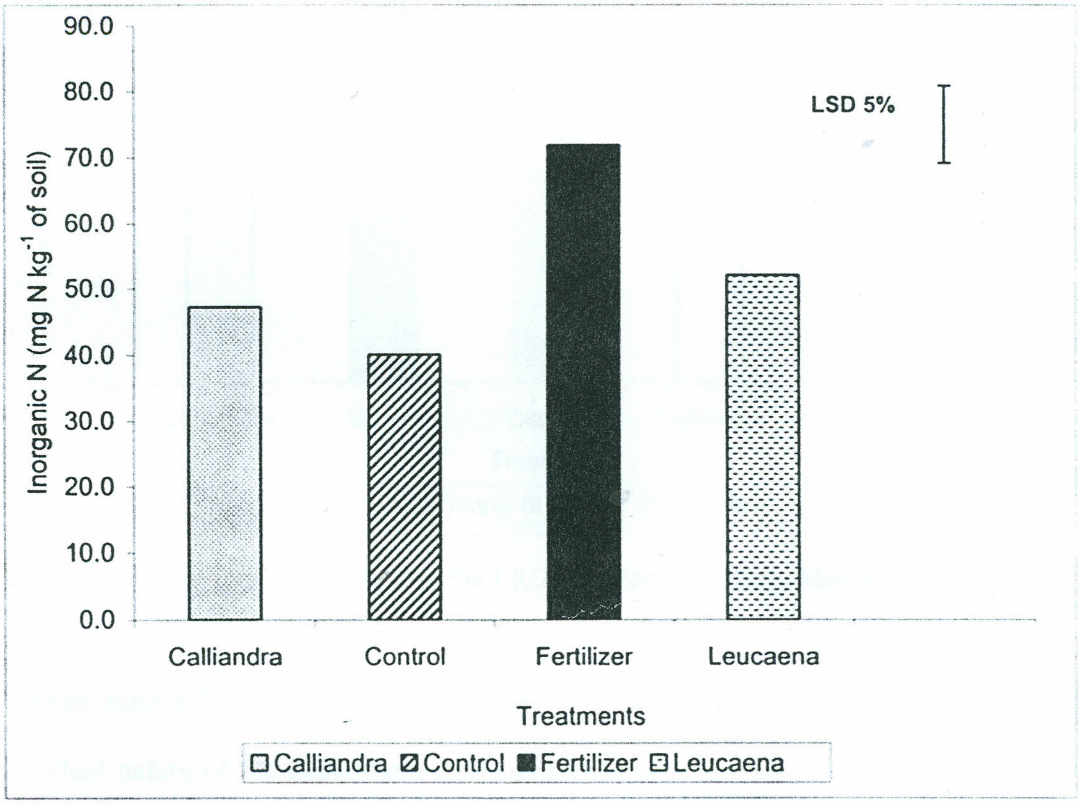

Figure 4. 2: Soil inorganic nitrogen before the LR 2002 season in HI Embu experiment

Highest N contents in fertilizer treatment can be attributed to the readily soluble inorganic fertilizer. On the other hand lower mineral N contents in leucaena and calliandra treatments as noted by Mafongoya *et al.* (1997 a; b) suggest mineral N immobilization and storage in the less labile soil organic matter pools.

Soil inorganic N contents from PM1 Maseno experiment were not significantly different and were lower than those observed in N1 Kabete and HI Embu experiments (Figure 4.3).

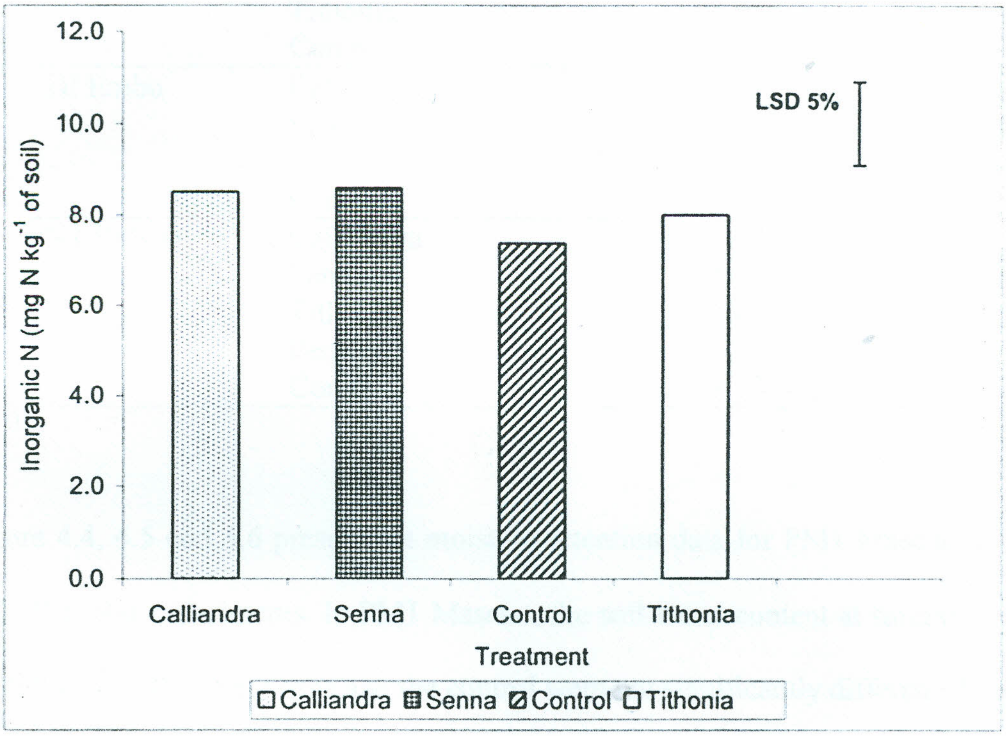

Figure 4. 3: Soil inorganic N before the LR 2002 season in PM1, Maseno experiment

Lower mineral N contents in the PM1 Maseno experiment could be attributed to the residual nature of the experiment and suggest the need for continued application of both organic and/or inorganic nutrient sources if higher nutrient supply and crop yields are to be maintained.

4.3.2 Bulk density and soil moisture retention in PM1 Maseno, N1 Kabete and HI Embu experiments

The bulk density was not significantly affected by organic residue management regimes at any of the sites (Table 4.1). This pointed to the observation that changes in soil physical properties take a long time to be observed.

Table 4. 1: Bulk density for soils from PM1 Maseno , HI Embu and N1 Kabete experiments

Experiment	Treatment	Bulk density (g cm^{-3})
PM1 Maseno	Calliandra	1.07
	Senna	1.09
	Tithonia	1.11
	Control	1.12
HI Embu	Calliandra	1.06
	Leucaena	1.07
	Fertilizer	1.10
	Control	1.07
N1 Kabete	Calliandra	1.18
	Senna	1.16
	Tithonia	1.20
	Fertilizer	1.17
	Control	1.19

Figure 4.4, 4.5 and 4.6 present the moisture retention data for PM1 Maseno, N1 Kabete and HI Embu experiments. In PM1 Maseno, the soil water content at saturation (pF = 0) for tithonia, calliandra, senna and the control were not significantly different (Figure 4.4).

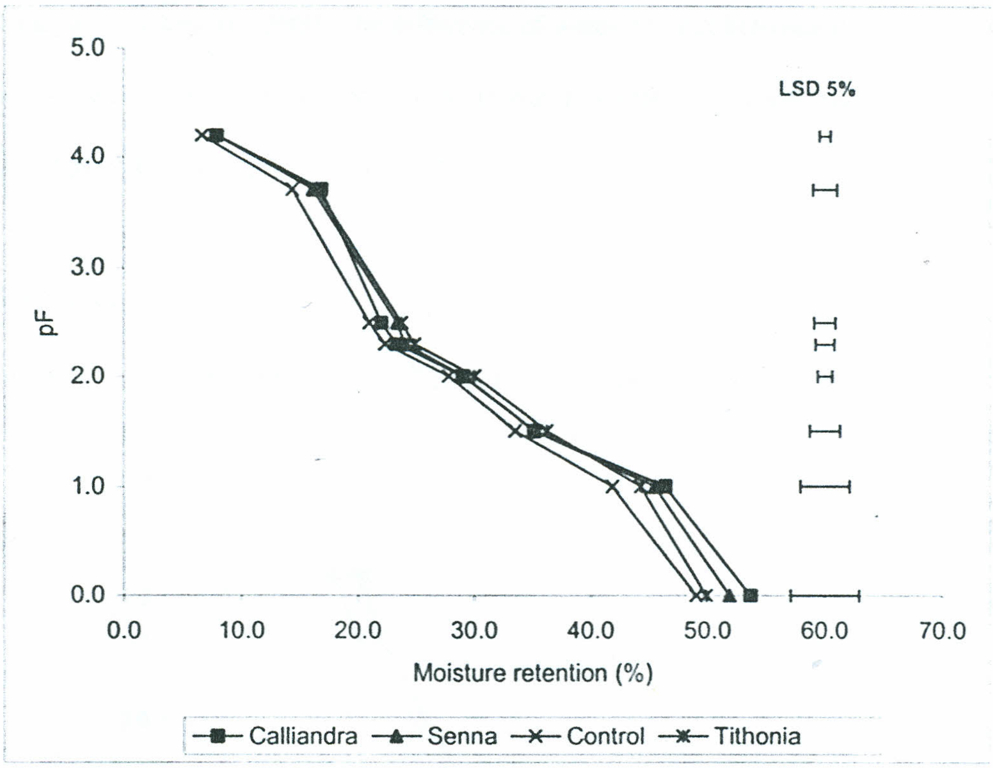

Figure 4. 4: Soil water retention curves for the soils from PM1 Maseno experiment

The soil moisture contents at this level were 53.7% for calliandra, 51.9% for senna, 49.9% for tithonia and 49.0% for the control treatment. Similarly the moisture retention was not significantly different for the same treatments at pF 1, 1.5 and 3.7. However, water retention was significantly different (*$P \leq 0.05$*) for the treatments considered at field capacity (pF = 2) with tithonia treatment recording soil water content of 30.0%, while senna, calliandra and the control recorded soil moisture contents of 29.05%, 28.96% and 27.78% respectively. Similarly, water retention at the wilting point (pF = 4.2) was significantly different (*$P \leq 0.05$*) and was of the order calliandra = senna = tithonia > control. The amounts of water held between the water holding capacity (pF = 2) and the wilting point (pF = 4.2) indicated more water contents in organic treatments as compared to the control treatment. As observed by

Binayak and Mousli (2000), the difference of water content between the wilting point and the water holding capacity represents water available to plants and is relevant to soil-vegetation-atmospheric interactions.

In N1 Kabete experiment, the soil moisture retention at the different pressure points was narrow and only significant at higher pF values pF = 3.7 and 4.2 (Figure 4.5).

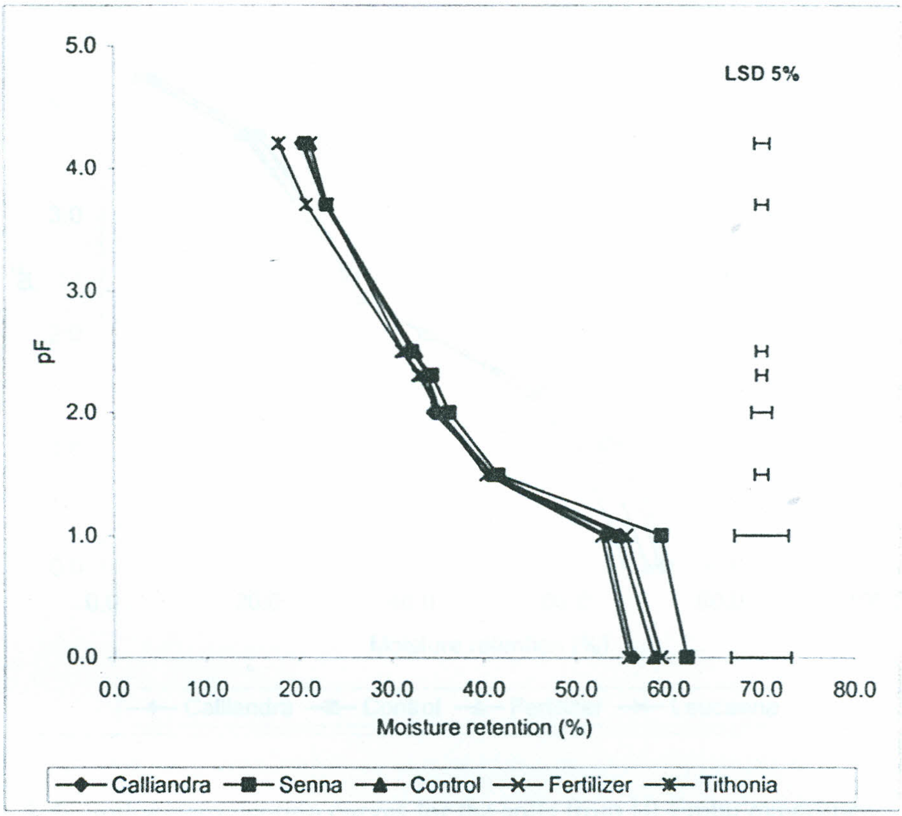

Figure 4. 5: Soil water retention curves for the soils from N1 Kabete experiment

At saturation point (pF = 0), senna treatment recorded soil moisture retention of 62.0% while tithonia treatment recorded water content of 55.5%. The general similarity in the soil moisture contents in this experiment could be as a result of the short duration of organic residue application which may have resulted in minimal effects on the soil organic matter and hence on the water retention capacity of the soil.

Soil moisture retention in HI Embu experiment was not significantly different for pFs 0, 1.5, 2.0, 2.3 and 2.5. However, it was significantly different for pF 1.0, 3.7 and at the wilting point. For pF 4.2 (wilting point) the soil moisture retention across the treatments was in the order fertilizer = calliandra > leucaena = control (Figure 4.6).

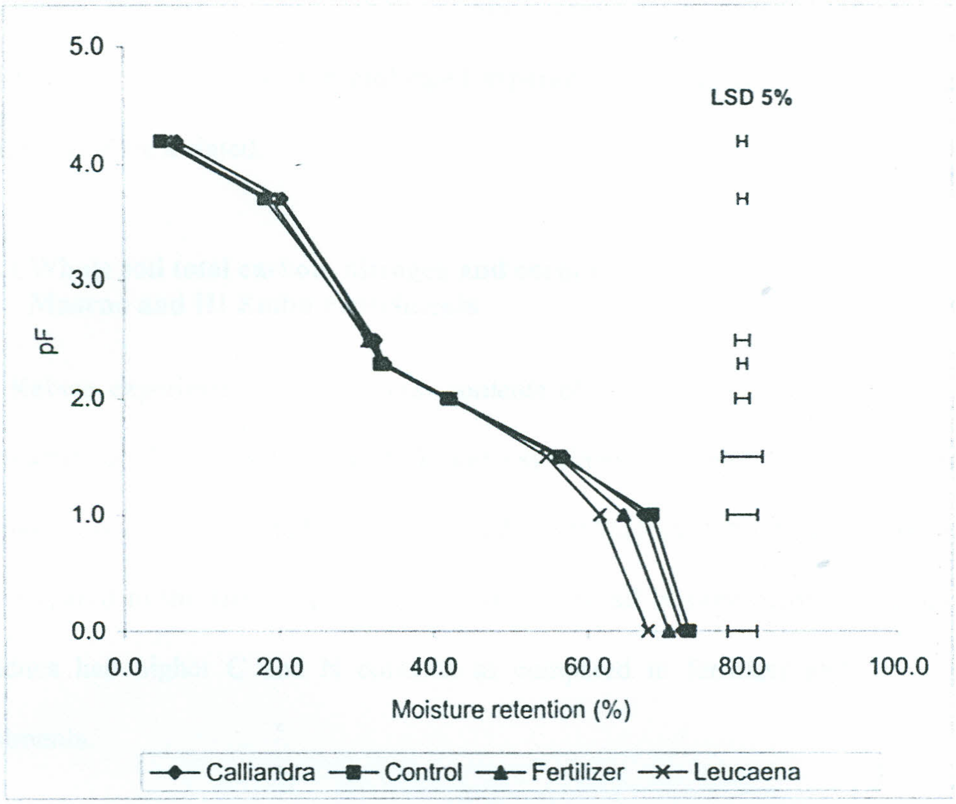

Figure 4. 6: Soil water retention curves for the soils from HI Embu experiment

All treatments in HI Embu experiment had high soil carbon contents greater than the 2% recommended for soils in Kenya (FURP, 1987) and this may have contributed to generally similar water retention across most of the pF points. However, significant differences observed for pF = 3.7 and 4.2, indicate that application of organics or fertilizer tended to improve soil organic matter hence the soils ability to hold more water at points near the wilting point.

In general, soil moisture retention trends in PM1 Maseno experiment were more defined as compared to those observed in N1 Kabete and HI Embu experiments. This is as a result of defined effects of the applied organic resources on the SOM pools, unlike in N1 Kabete and HI Embu where as a result of the young age of the two experiments and the continued residue application, the soils had mixed SOM properties. The results thus indicate that studies on soil physical properties such as soil moisture retention require prolonged experimentation for the effects among the treatments to be isolated.

4.3.4 Whole soil total carbon, nitrogen and carbon-13 in N1 Kabete, PM1 Maseno and HI Embu experiments

N1 Kabete experiment had narrowest contents of C, N and carbon-13 contents as compared to PM1 Maseno and HI Embu experiments (Table 4.2). This could be attributed to the short period of organic residue application in N1 Kabete experiment as compared to the latter experiments. Despite this, all treatments receiving organic residues had higher C and N contents as compared to fertilizer and the control treatments.

Table 4. 2: Whole soil total carbon, nitrogen and carbon-13 signatures of N1 Kabete soils as at March 2002

Treatment	Percent C (%)	Percent N (%)	Carbon-13 (δ PDB)
Calliandra	1.81	0.14	-12.15
Senna	1.86	0.14	-11.95
Tithonia	1.84	0.14	-12.18
Fertilizer	1.78	0.14	-11.96
Control	1.79	0.14	-11.92
SED	**0.04**	**0.01**	**0.28**

PDB = Pee Dee Belemnite reference standard
SED = Standard error of differences of means

Soil carbon-13 signature for the whole soil (WS) from N1 Kabete was not significantly different and indicated a delta ^{13}C signature closer to that of C4 vegetation. Values ranged from -11.92‰ to -12.18‰ (Table 4.2). These signatures tended to be closer to the C4 ^{13}C signature of maize residues of about -12.00‰ (Schwartz *et al.*, 1986). This indicates that despite the application of the C3 organic resources (calliandra, senna and tithonia) in this experiment, a minimal shift in the WS carbon-13 had occurred. Reasons for the narrow ranges of C, N and ^{13}C in N1 Kabete may be the rapid mineralization of the organic residues due to increased aeration as a result of tillage, higher soil temperatures leading to higher decomposition rates, lower litter inputs and the shorter duration of organic residue application in this experiment (Nandwa, 2001). As observed by Paustian *et al.* (2000), gains in soil C can be enhanced if proper management is maintained and that increases in soil C stocks require increasing C inputs and/or reducing soil heterotrophic respiration.

Total C values for HI Embu treatments were higher than the recommended critical value for soil carbon of 2.0% (Table 4.3) for Kenya as reported by FURP (1987).

Table 4. 3: Whole soil total carbon, nitrogen and carbon-13 signatures of HI Embu soils as at March 2002

Treatment	Percent C (%)	Percent N (%)	Carbon-13 (δ PDB)
Calliandra	2.48	0.21	-16.69
Leucaena	2.52	0.21	-16.32
Fertilizer	2.47	0.20	-16.07
Control	2.35	0.19	-15.65
SED	**0.13**	**0.01**	**0.25**

PDB = Pee Dee Belemnite reference standard
SED = Standard error of differences of means

Such a favourable SOC content in HI Embu experiment could be attributed to the continued application of the organic resources to the soil. Leucaena treatment had soil C content of 2.52% while calliandra, fertilizer and the control had C content of 2.48%, 2.47% and 2.35% respectively. Higher soil carbon content in the calliandra treatment could be due to the low decomposition as explained by its higher polyphenol and lignin contents (Palm and Sanchez, 1990; Mafongoya *et al.*, 1998). Such slow decomposing organic residues can have a greater contribution to the stored soil C pool.

Soil total N in HI Embu treatments was significantly different and was of the order leucaena = calliandra = fertilizer > control. As with the soil carbon, continued mineralization of leucaena and calliandra organic residues may have resulted in the build up of soil organic matter N pool.

Whole soil carbon-13 values were significantly different for the treatments in HI Embu experiment. This was as a result of the less negative $\delta^{13}C$ signature observed in the control (-15.65‰) treatment as compared to the highest $\delta^{13}C$ of –16.07‰ observed in the calliandra treatment. The great shift observed in the $\delta^{13}C$ signature between the treatments receiving organic residues and the control indicate a greater contribution to the soil C from the continued application of the leucaena and calliandra organic residues. As observed by Ong *et al.* (1996), C4-weeds tend to lose their competitive advantage in terms of higher light–use efficiency at light saturation as shading by a growing maize crop increases. As a result Diels *et al.* (2001) observed that weeds can significantly result in an input of carbon-13 into the cropping system. This study did not consider the contribution from weeds to the soil/fraction $\delta^{13}C$ signatures from weeds and this may explain the more negative delta ^{13}C observed in the control treatments in the three experiments.

Whole soil total C, N and ^{13}C values of soil from PM1 Maseno experiment. Is given in Table 4.4.

Table 4. 4: Whole soil total carbon, nitrogen and carbon-13 signatures of PM1 Maseno soils as at March 2002

Treatment	Percent C (%)	Percent N (%)	Carbon-13 (δ PDB)
Calliandra	1.83	0.16	-18.09
Senna	1.86	0.16	-18.10
Tithonia	1.80	0.15	-17.82
Control	1.59	0.14	-17.46
SED	**0.047**	**0.004**	**0.173**

PDB = Pee Dee Belemnite reference standard
SED = Standard error of differences of means

Whole soil (WS) total carbon for PM1 Maseno experiment was significantly different ($P \leq 0.05$) (Table 4.4) and was of the order senna = calliandra = tithonia > control. Senna treatment recorded WS C content of 1.86%, calliandra (1.83%), tithonia (1.80%), while the control recorded WS C content of 1.59%. The high C contents in senna and calliandra treatments as compared to the tithonia treatment could be attributed to the lower quality of these two organic resources, which results in lower rates of mineralization leading to C build-up.

As with C, total N across the treatments was significantly different ($P \leq 0.05$) and was highest in all treatments receiving organic resources as compared to the control treatment (Table 4.4). This indicates that application of organic resources can help increase the soil N contents. Further, as observed by Gachengo *et al.* (1999), lower quality organic resources such as calliandra and senna will result in larger build up of soil N pools as compared to high quality resources such as tithonia.

Carbon-13 signature for PM1 Maseno was more negative as compared to HI Embu and N1 Kabete experiments indicating a greater shift in the type of soil C towards a C3 signature contributed by the application of C3 organic materials (senna, tithonia and calliandra). In relation to the control, senna treatment had the largest shift in delta ^{13}C signature followed by calliandra and tithonia. The greater C3 labelling observed could be due to the larger quantities of the organic residues applied (5 t dry matter per season) as well as the longer duration of organic residue application as compared to the N1 Kabete experiment.

The delta carbon-13 ($\delta^{13}C$) of SOM is comparable to that of the source plant material (Schwartz *et al.*, 1986) and thus every change in vegetation between C3 and C4 plants or the application of organic residues to the soil as organic manure as in the above experiments result in a corresponding change in the $\delta^{13}C$ value of the SOM (Lefroy *et al.*, 1995).

4.3.5 Carbon dioxide evolution from PM1 Maseno, N1 Kabete and HI Embu experiments

In PM1 Maseno experiment, calliandra treatment recorded CO_2 evolution of 69.0 mg CO_2-C kg^{-1} of soil at day 7 while tithonia, senna and control recorded a CO_2 evolution of 68.7 0, 65.6 and 49.3 mg CO_2-C kg^{-1} of soil respectively (Figure 4.7). The CO_2 evolution doubled after 14 days of incubation and was significantly different between the organic treatments and the control. At day 28 with senna treatment recording a cumulative CO_2 evolution of 194.4 mg CO_2-C kg^{-1} of soil, calliandra released 190.5 mg CO_2-C kg^{-1} kg of soil, tithonia 167 mg CO_2-C kg^{-1} of soil while the control had the least cumulative CO_2 production of 129.5 mg CO_2-C kg^{-1} of soil. At day 56, CO_2

evolution among the treatments was significantly different and was in the order calliandra = senna = tithonia > control. By day 56, the proportion of whole soil carbon respired was significantly different (*$P \leq 0.05$*) across treatments and accounted for between 1.21% and 1.74% of the whole soil total carbon (Table 4.5).

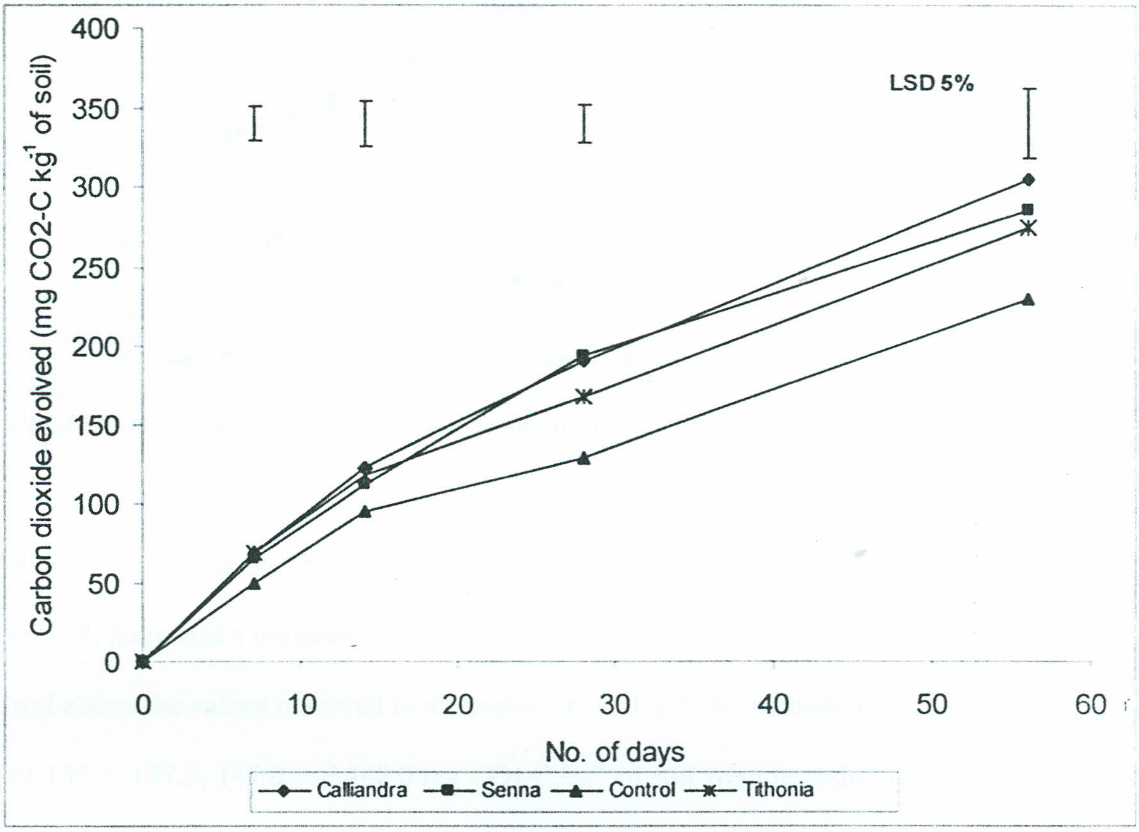

Figure 4. 7 : Soil respiration trends from PM1 Maseno experiment

In N1 Kabete experiment, CO_2 evolution was significantly different (*$P \leq 0.05$*) across the treatments at day 7 of incubation with calliandra treatment recording the highest CO_2 evolution of 68.7 mg CO_2-C kg^{-1} of soil while the control had the least CO_2 evolution of 50.1 mg CO_2-C kg^{-1} of soil (Figure 4.8).

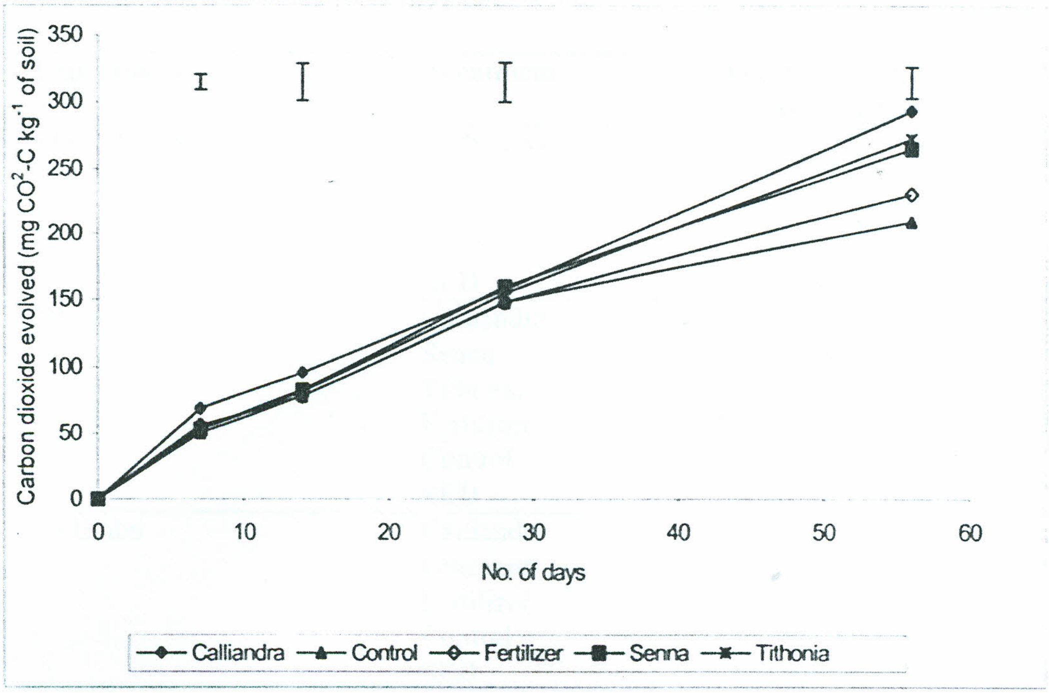

Figure 4. 8: Trends in carbon dioxide production from N1 Kabete experiment

Rapid CO_2 production observed at this stage indicates rapid soil mineralization. At day 14, there was a minimal increase in CO_2 production of about 27 mg CO_2-C kg^{-1} of soil above the values observed in all treatments at day 7. A cumulative CO_2 evolution of 159.2, 157.3, 147.6 and 148.0 mg CO_2-C kg^{-1} of soil were recorded for the senna, calliandra, fertilizer and control treatments respectively at day 28. By day 56 of soil incubation, a total proportion of 1.74, 1.40, 1.28 and 1.20% of the total soil carbon had been respired from the calliandra, senna, fertilizer and control treatments respectively (Table 4.5). Higher proportion of CO_2 respired in calliandra treatment as compared to senna and tithonia point to the persistence in the soil of this low quality organic resource and hence showing the potential of prolonged supply of food (carbon) to the microbes with continued mineralization.

Table 4. 5: Proportion of carbon respired from PM1 Maseno, N1 Kabete and HI Embu experiments

Experiment	Treatment	Percent of TOC respired
PM1 Maseno	Calliandra	1.74
	Senna	1.58
	Tithonia	1.43
	Control	1.21
	SED	**0.13**
N1 Kabete	Calliandra	1.74
	Senna	1.40
	Tithonia	1.42
	Fertilizer	1.28
	Control	1.20
	SED	**0.07**
HI Embu	Calliandra	1.29
	Leucaena	1.03
	Fertilizer	1.01
	Control	1.02
	SED	**0.08**

Whole soil cumulative CO_2 production in HI Embu experiment was not significantly different at days 7, 14 and 28. However, 51.6, 46.5, 48.0 and 30.0 mg CO_2-C kg^{-1} of soil were respired for leucaena, calliandra, control and fertilizer treatments respectively at day 7 and increased to 100.2, 89.9, 74.0 and 65.7 mg CO_2-C kg^{-1} of soil for calliandra, leucaena, control and fertilizer treatments respectively at day 14 (Figure 4.9). At day 56, cumulative CO_2 produced was significantly different with calliandra recording CO_2 production of 317.8 mg CO_2-C kg^{-1} of soil. Leucaena, fertilizer and control treatments recorded a cumulative CO_2 production of 257.8, 247.3 and 238.7 mg CO_2-C kg^{-1} of soil respectively. The above quantities of carbon respired accounted for 1.29, 1.03, 1.01 and 1.02% of the whole soil TOC for calliandra, leucaena, fertilizer and the control treatments respectively (Table 4.5).

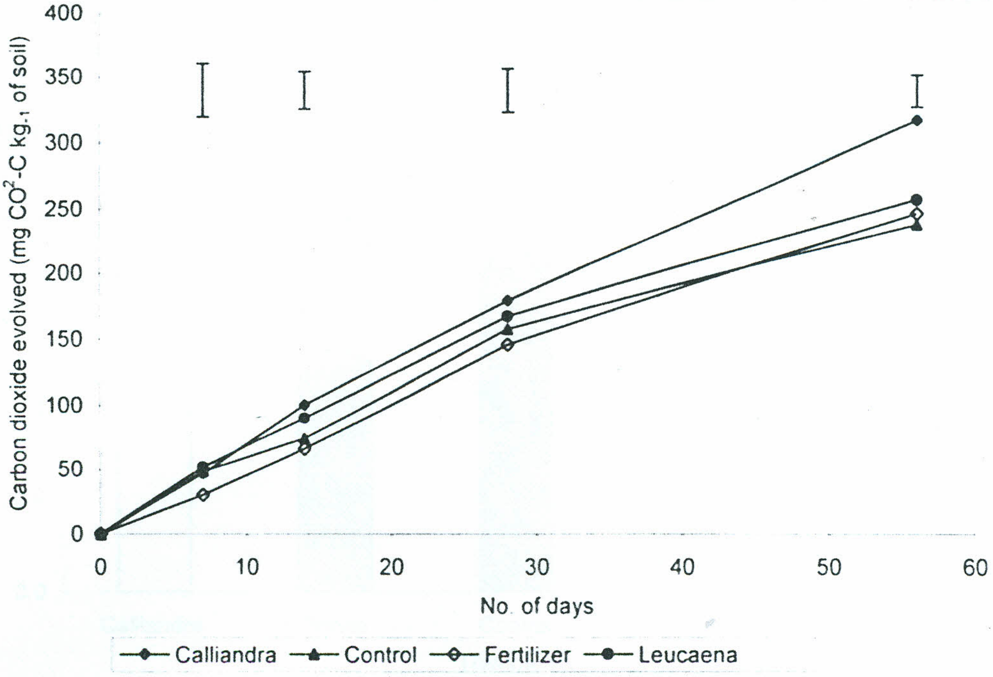

Figure 4. 9: Trends in carbon dioxide production from HI Embu experiment

4.3.6 Potassium permanganate oxidizable carbon ($KMnO_4$-C) in PM1 Maseno, HI Embu and N1 Kabete experiments

The labile carbon, as represented by the potassium permanganate oxidizable carbon ($KMnO_4$-C), were significantly different ($P \leq 0.05$) for PM1 Maseno. Potassium permanganate carbon was in the order calliandra = senna = tithonia > control (Figure 4.10).

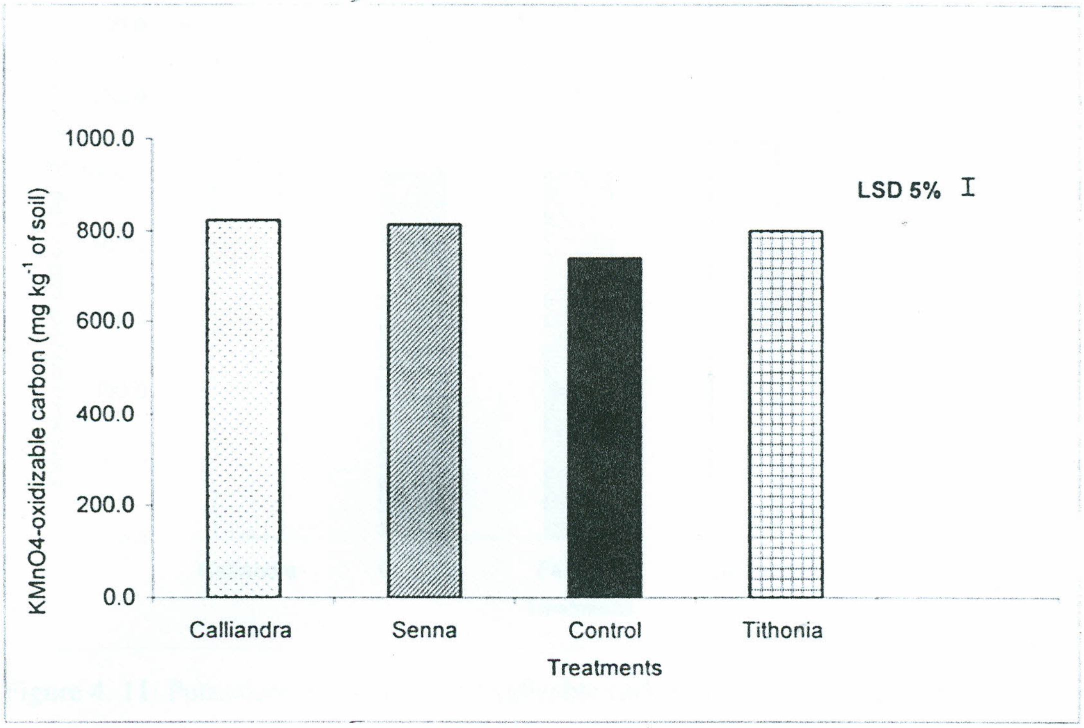

Figure 4. 10 : Potassium permanganate oxidizable carbon in PM1 Maseno experiment

Calliandra recorded a KMnO4 content of 824.8 mg C kg^{-1} of soil while senna, tithonia and the control recorded $KMnO_4$-C contents of 815.5, 800.5 and 739.4 mg C kg^{-1} of soil respectively. In N1 Kabete experiment, like in PM1 Maseno, $KMnO_4$-C was significantly different at 5% with tithonia recording $KMnO_4$-C content of 753.5 mg C kg^{-1} of soil while the control had the least content of 709.0 mg C kg^{-1} of soil (Figure 4.11).

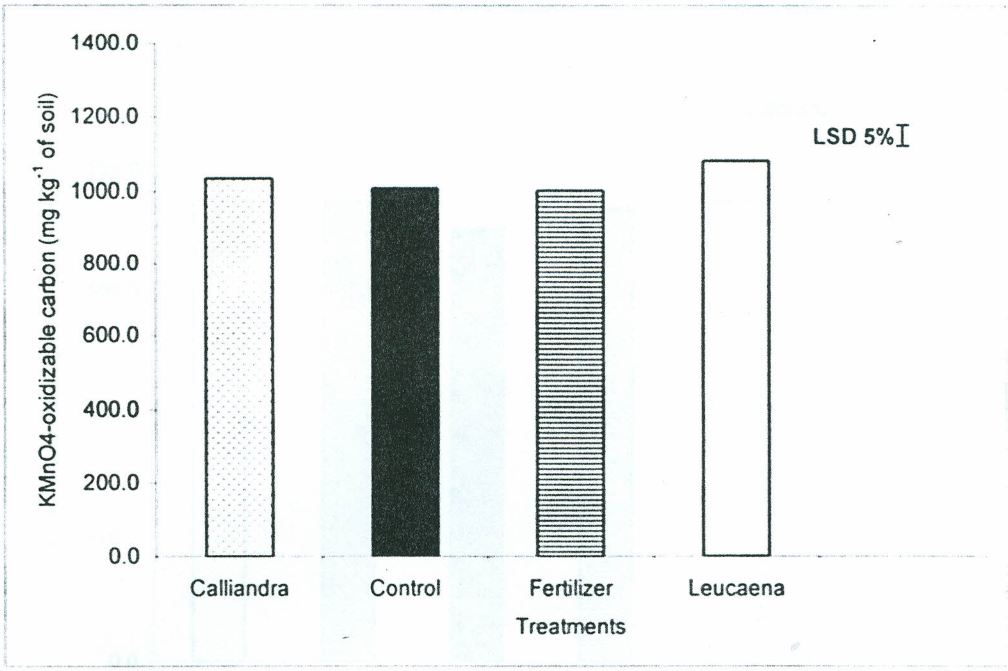

Figure 4. 11: Potassium permanganate oxidizable carbon in HI Embu experiment

Of the three experiments, HI Embu had the highest $KMnO_4$-C contents. In this experiment, leucaena recorded a $KMnO_4$-C content of 1081.0 mg C kg^{-1} of soil, calliandra 1034.9 mg C kg^{-1} of soil, control 1009.0 mg C kg^{-1} of soil while the fertilizer treatment recorded $KMnO_4$-C content of 1003.4 mg C kg^{-1} of soil (Figure 4.12).

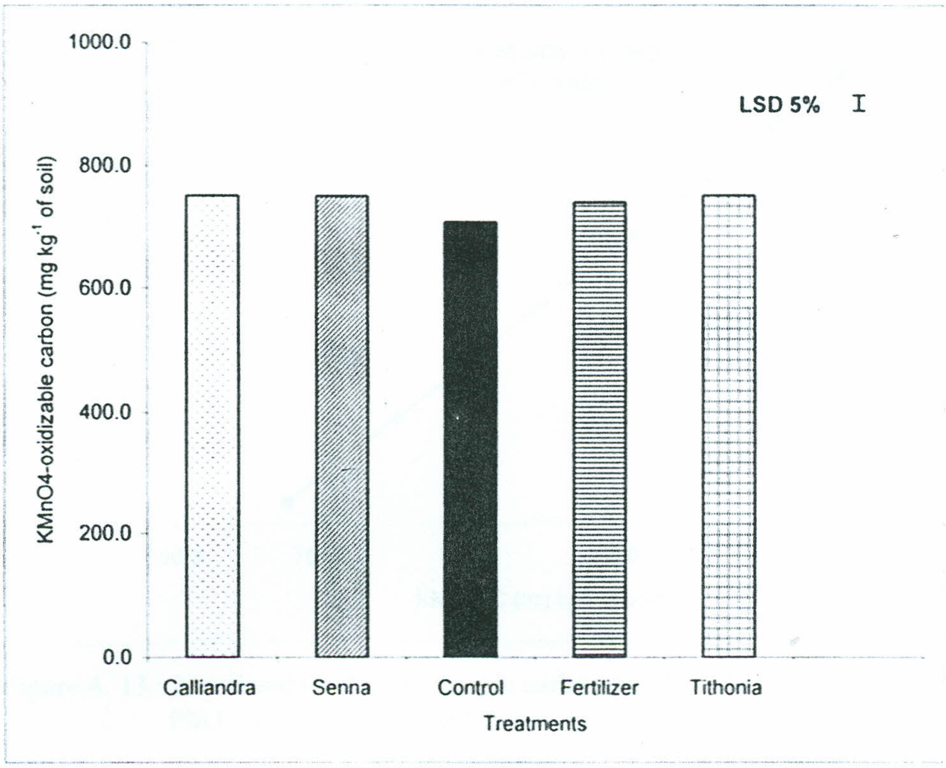

Figure 4. 12 : Potassium permanganate oxidizable carbon in N1 Kabete experiment

The variations observed in the three experiments concur with the observation made by Blair *et al.* (1997) that the labile carbon as estimated by the $KMnO_4$ oxidation technique is extremely sensitive to soil management. There was a high correlation (r = 0.99) between the soil total carbon and the potassium permanganate oxidizable carbon in the three sites. This indicated that application of organic resources improved soil organic carbon with a subsequent improvement in the labile carbon fraction. (Figure 4.13, 4.14 & 4.15). The above results are within the ranges observed by Wang *et al.* (2003) in a study on Australian soils who observed $KMnO_4$-C contents of between 852-8104 mg C kg^{-1} of soil and with a close correlation between $KMnO_4$-oxidizable carbon and TOC (r = 0.98).

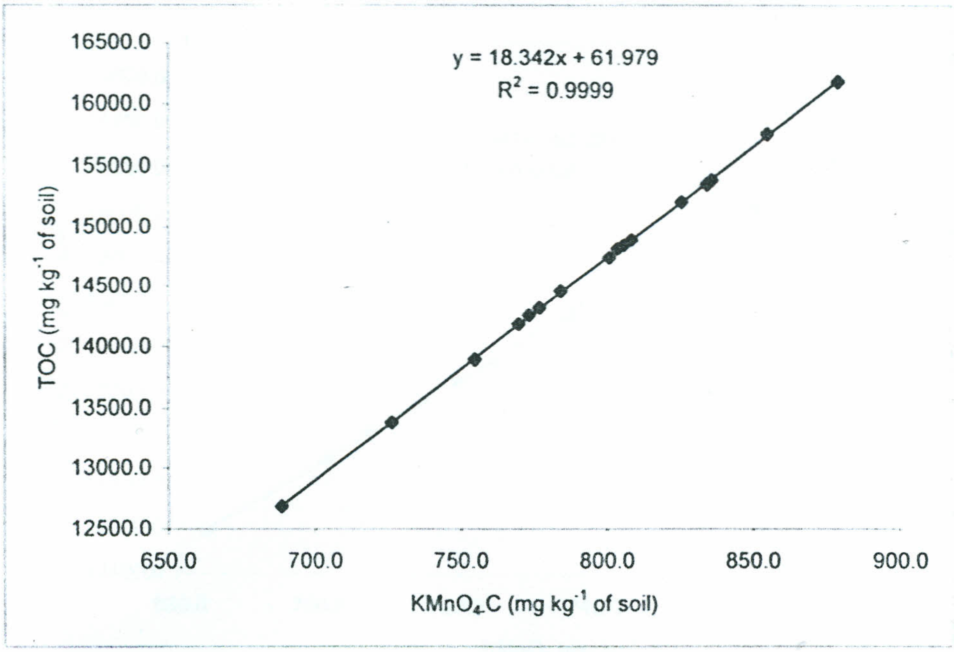

Figure 4. 13 : Relationship of total organic carbon and $KMnO_4$-oxidizable carbon in PM1 Maseno experiment

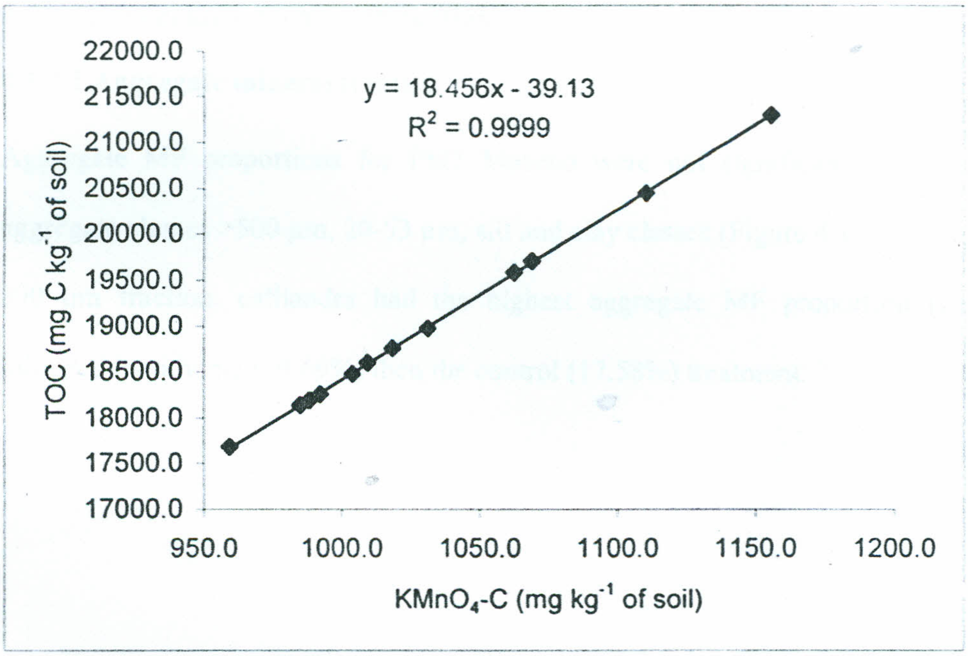

Figure 4. 14: Relationship of total organic carbon and $KMnO_4$-oxidizable carbon in HI Embu experiment

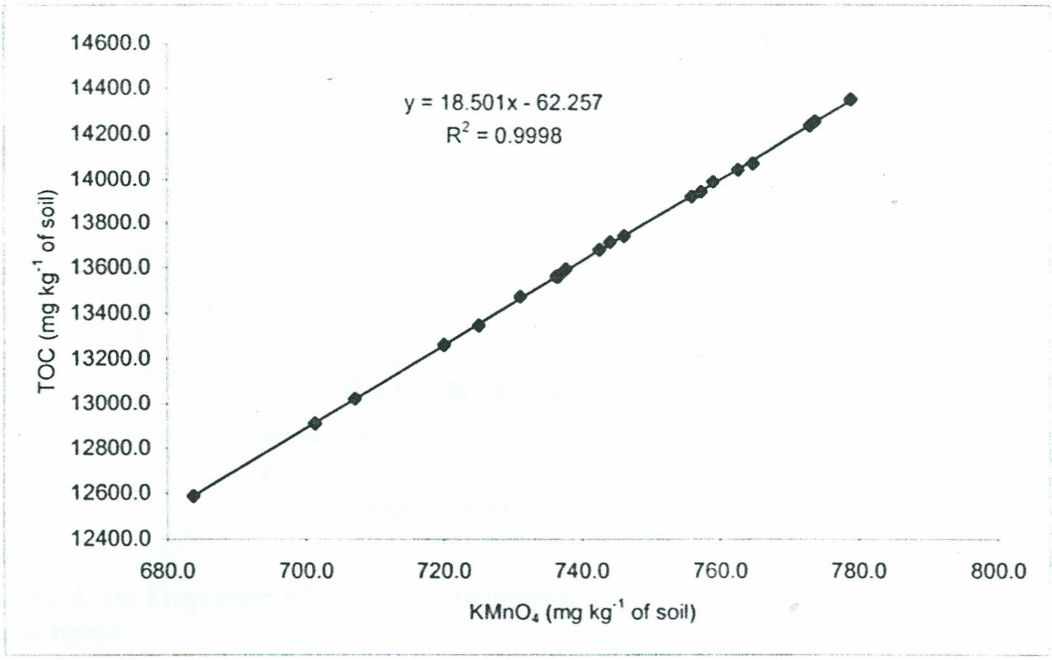

Figure 4. 15 : Relationship of total organic carbon and $KMnO_4$-oxidizable carbon in N1 Kabete Experiment

4.3.7 Soil organic matter fractionation

4.3.7.1 Aggregate mineral fraction

Aggregate MF proportions for PM1 Maseno were not significantly different for aggregate classes >500 µm, 20-53 µm, silt and clay classes (Figure 4.16). For the 250-500 µm fraction, calliandra had the highest aggregate MF proportion (21.10%) followed by tithonia (19.69%) then the control (17.58%) treatment.

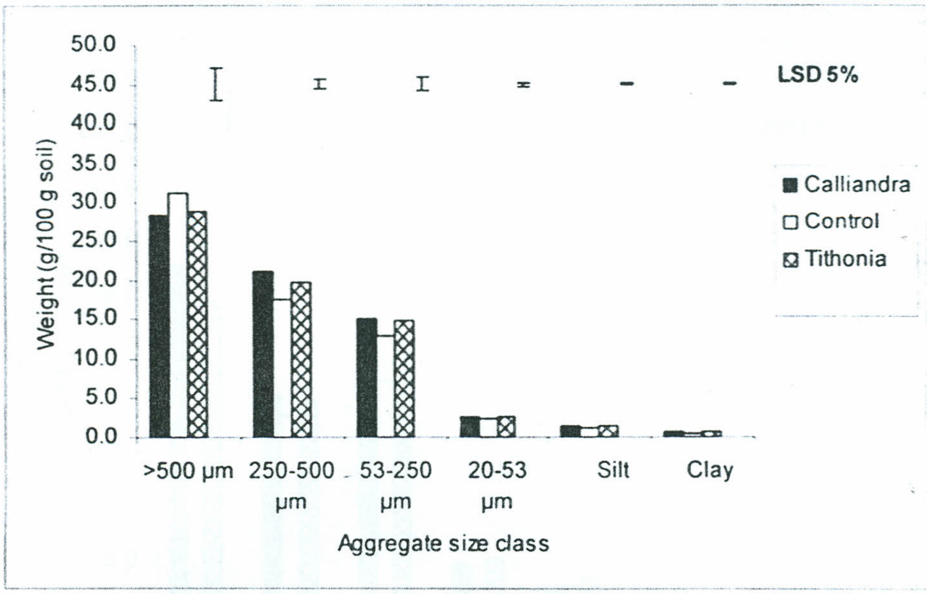

Figure 4. 16: Proportion of the aggregate mineral fraction for PM1 Maseno experiment

In N1 Kabete experiment, only a slight difference in aggregate MF was observed in the silt fraction, where aggregate MF proportions were in the order tithonia > calliandra = control (Figure 4.17).

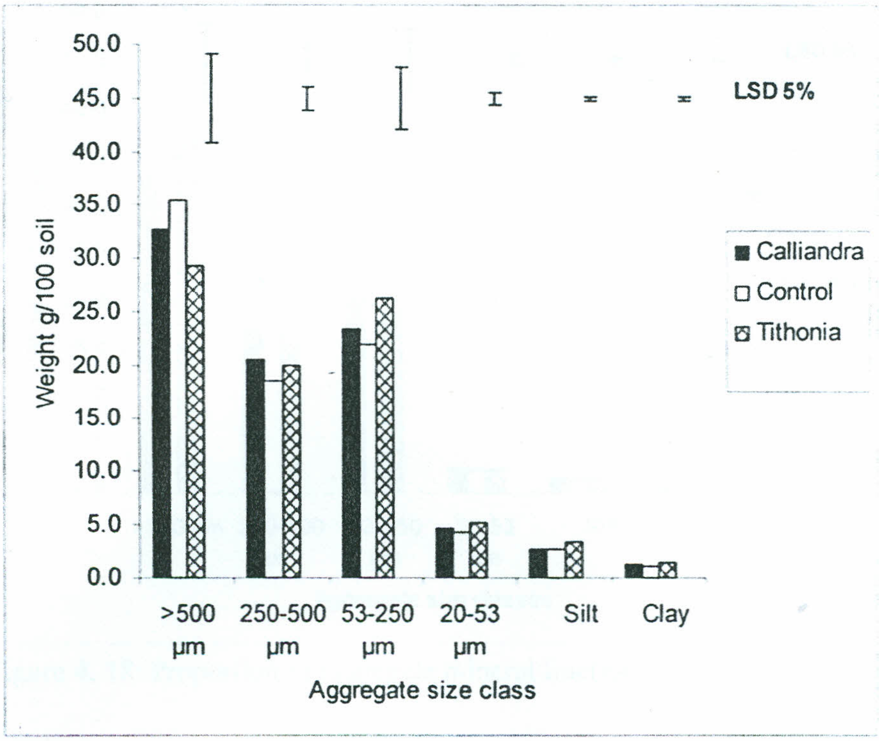

Figure 4. 17: Proportion of aggregate mineral fraction for N1 Kabete experiment

There was no significant difference among the treatments in HI Embu experiment across all aggregate size classes (Figure 4.18). This may be explained by the relatively high and uniform soil carbon contents in both the organic and the control treatments.

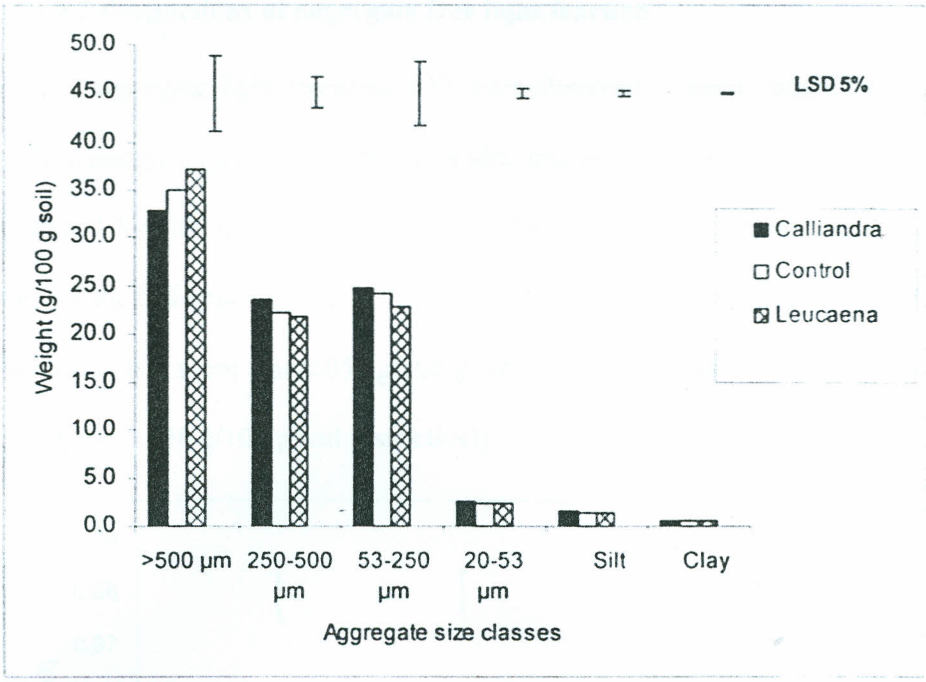

Figure 4. 18: Proportion of aggregate mineral fraction for HI Embu experiment

Despite the above observations, there were higher proportions of macro-aggregates across the three sites. Large proportions of macro-aggregates imply an elevated soil C concentrations resulting from the binding effects from fungal mycelia (Elliott 1986). Further, a breakdown in macro-aggregates would result in the release of labile SOM (Elliott, 1986) and its increased availability for microbial decomposition. The well defined aggregate proportion in PM1 Maseno experiment could be attributed to improved SOM resulting from the large application of organic residues (OR). N1 Kabete soils indicated a substantial decrease in small macro-aggregates (250-500 µm) concomitant with an increase in micro-aggregate mineral fraction (MF). As observed by Six *et al.* (2000) and Paustian *et al* (1997), increasing cultivation intensity could lead to a loss in macro-aggregates and an increase in micro-aggregates, silt and clay contents.

4.3.7.2 Proportions of aggregate free light fraction

Higher aggregate light fractions (LF) were observed in macro-aggregate fractions of PM1 Maseno experiment with calliandra treatment having the highest proportions followed by tithonia and the control in decreasing order (Figure 4.19). There was significant difference in the >500 µm fraction where the proportion of the LF in the calliandra treatment was 0.059 g/100 g soil while that of tithonia and the control were 0.050 and 0.036 g/100 g soil respectively.

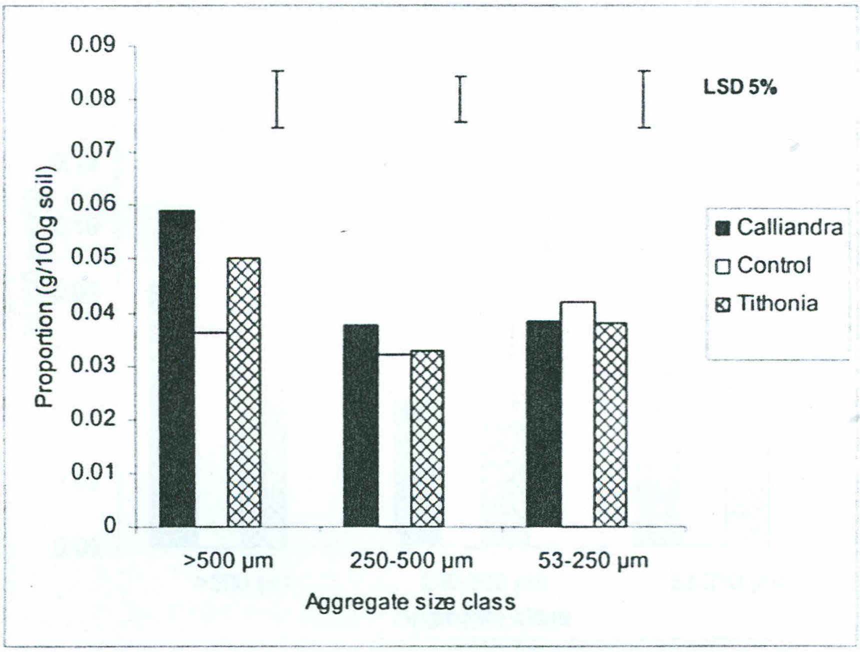

Figure 4. 19: Proportion of aggregate light fraction for PM1 Maseno experiment

Higher LF in calliandra treatment could be attributed to slow decomposition of calliandra which results in the persistence of calliandra residues in the soil. There was a generally higher micro-aggregate LF as compared to the small macro-aggregate (250-500 µm) fractions. This is an indication of increased mineralization of organics from the large macro-aggregate LF to the micro-aggregate fraction. Further, a nonsignificant high proportion of micro-aggregate LF was found in control compared to calliandra and tithonia treatments.

In N1 Kabete, there was no significant difference in the three aggregate LFs although there was a build up in the micro-aggregate (53-250 µm) LF as compared to the small macro-aggregate (250-500 µm). LF were highest in calliandra followed by control and lastly tithonia (Figure 4.20).

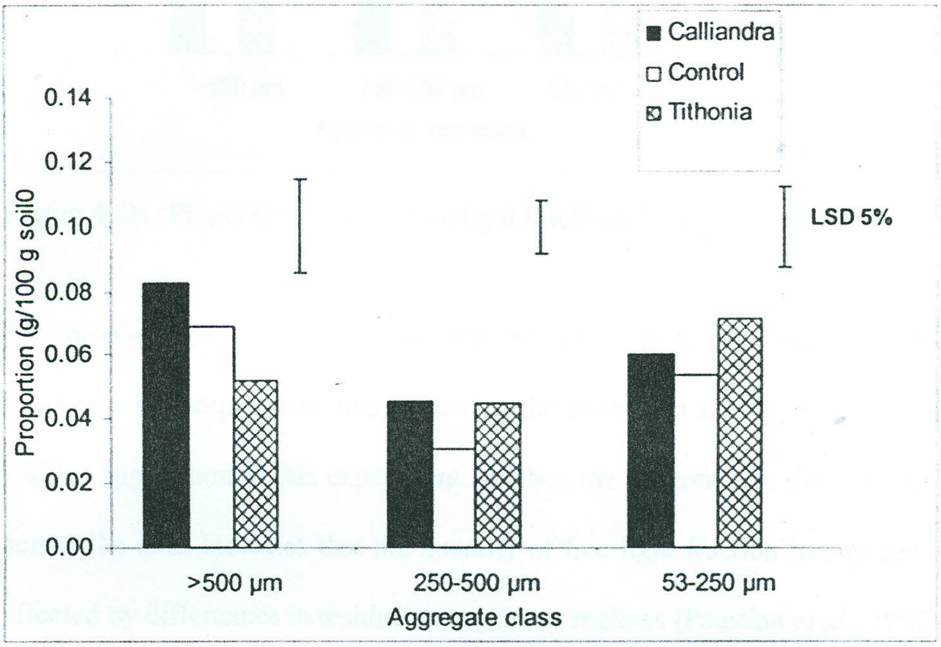

Figure 4. 20: Proportion of aggregate light fraction for N1 Kabete experiment

In HI Embu experiment, calliandra had the highest LF proportions in the 250-500 µm class where calliandra recorded a LF proportion of 0.085 g/100 g soil as compared to tithonia with 0.057 and the control with 0.052 g/100 g soil (Figure 4.21).

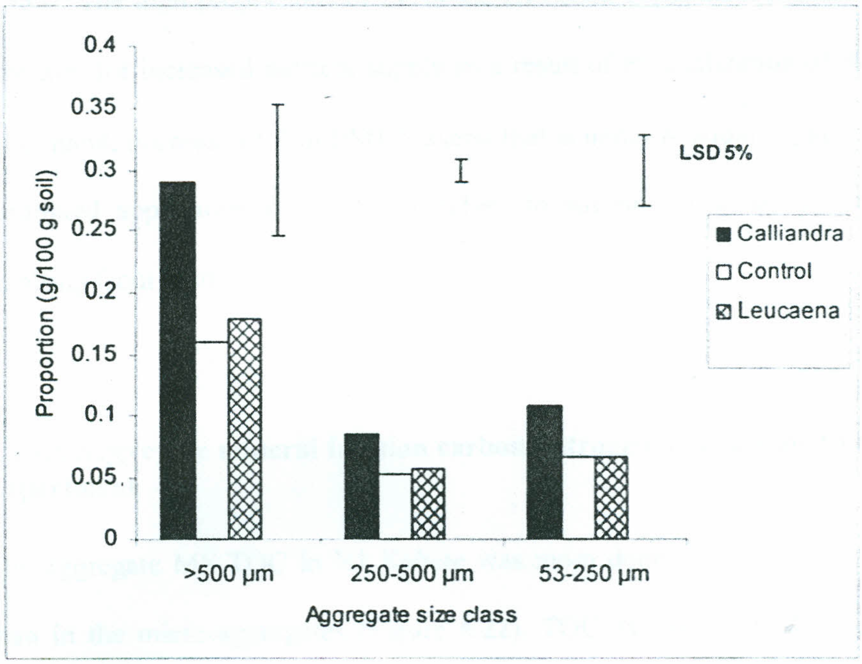

Figure 4. 21: Proportion of aggregate light fractions for HI Embu experiment

As compared to N1 Kabete and PM1 Maseno, HI Embu experiment had higher aggregate LF proportions thus indicating the beneficial effects of continued organic residue application in this experiment. Further, the difference in the free light fraction across the sites indicates that the quantity of free light fraction in any soil is mostly affected by differences in residue management regimes (Paustian *et al.*, 1997).

As observed by Six *et al.* (1999) coarse free LF is probably less chemically recalcitrant than the fine free LF (53-250 µm) due to the less advanced stage of decomposition of the coarse free LF. The LF consists of recognizable plant debris with high C:N ratio and low specific weight, and is easily decomposable (Christensen, 1992). Further, the C:N ratio in the LF generally decreases with the decreasing particle size separates indicating an increasing degree of humification and implying that this macro-organic matter is much more susceptible to mineralization, and thus contributes significantly to the soil available nutrient pool (Tiessen and Stewart, 1983). The high proportions of LF in the HI Embu experiment means that there is a potential for increased nutrient supply as a result of mineralization of the LF. On the other hand, decreased LF in PM1 Maseno that is under residual suggests the need for continued application of organic residues to sustain the losses in organic matter resulting from increased oxidation as a result of cultivation.

4.3.7.3 Aggregate mineral fraction carbon, nitrogen and carbon-13 in N1 Kabete Experiment

The aggregate MF TOC in N1 Kabete was more dominant in the macro-aggregates than in the micro-aggregates (Figure 4.22). TOC averaged 11.12 g kg^{-1} soil in the macro-aggregates soil as compared to 4.93 g kg^{-1} soil in the micro-aggregate fractions. Significant differences in the aggregate MF C were only observed in the silt fraction where tithonia recorded a C content of 0.79 g C kg^{-1} soil followed by the control (0.61 g C kg^{-1} soil) then calliandra with a C content of 0.57 g C kg^{-1} soil.

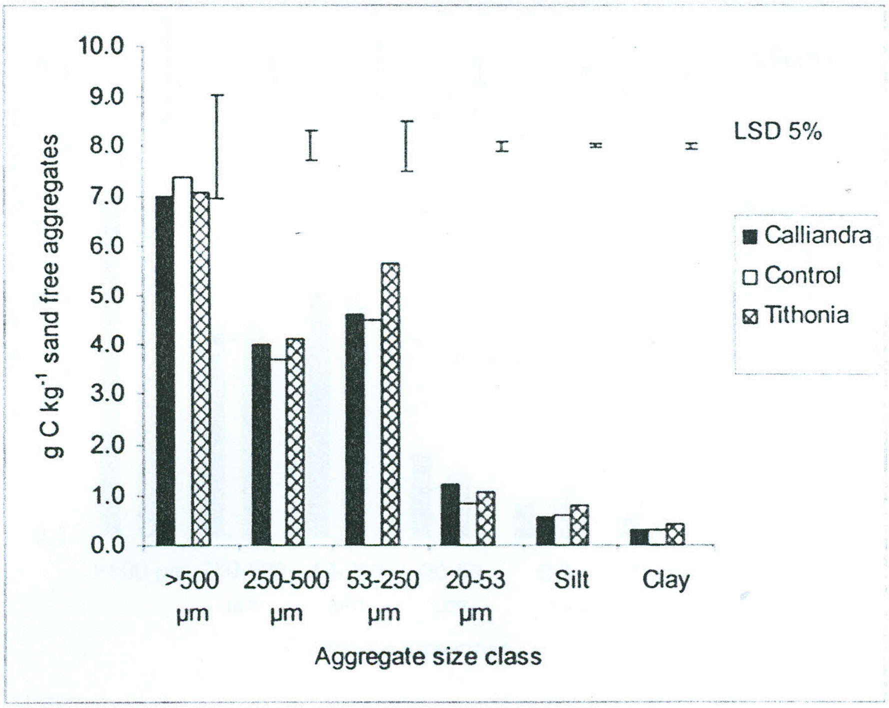

Figure 4. 22: Aggregate mineral fraction carbon for N1 Kabete experiment

As was the case with aggregate C, significant differences in aggregate MF N were only observed in the silt fraction where tithonia recorded aggregate N content of 0.06 g N kg^{-1} soil followed by the control (0.05 g N kg^{-1} soil) and calliandra (0.04 g N kg^{-1} soil) treatment (Figure 4.23). The bulk of the aggregate MF N was observed in the macro-aggregates (>250 µm) in the three treatments. This is an indication that most of the readily available SOM N is stored in the recently incorporated organic residues that have a faster turnover rate. Lower N in the >500 µm fraction for tithonia was compensated by a higher TON in the 53-250 µm fraction indicating that decomposition of tithonia was faster and tended to shift towards the finer aggregate classes.

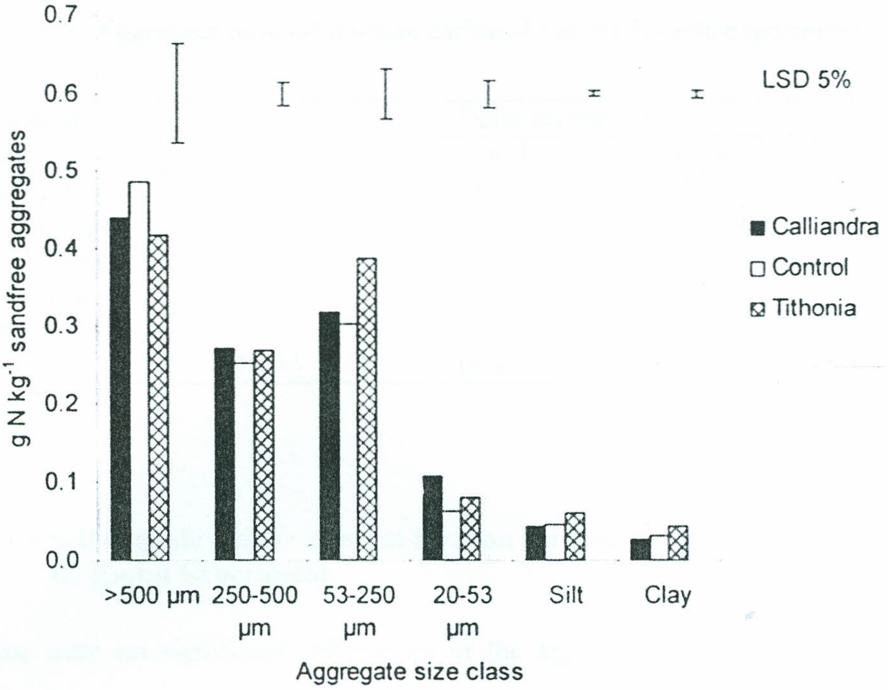

Figure 4. 23: Aggregate mineral fraction nitrogen for N1 Kabete experiment

Despite there being no significant differences in the aggregate MF delta ^{13}C, the carbon-13 values across the aggregate MF classes tended to be more negative as compared to the whole soil ^{13}C values (Table 4.6). This indicated that recently incorporated organic residues tended to accumulate in the various aggregate size classes. This was a good pointer to the fact that using ^{13}C analysis technique, one is able to effectively trace the carbon contribution of the organics in the SOM pools. Relatively less negative ^{13}C values in the control as compared to the organic treatments indicates a lesser labelling effect of the SOM pools in the control treatment. With increased organic mineralization, the organic C tends to be distributed to the finer aggregate classes hence the more negative delta values in the clay and silt fractions.

Table 4. 6: Aggregate mineral fraction carbon-13 in N1 Kabete experiment

Aggregate class	Delta carbon-13 (‰)			
	Calliandra	Control	Tithonia	**SED**
>500 µm	-15.90	-14.98	-16.29	1.25
250-500 µm	-14.85	-15.12	-15.42	1.20
53-250 µm	-15.83	-15.42	-15.83	0.75
20-53 µm	-15.55	-15.05	-15.44	1.05
Silt	-15.72	-15.59	-15.85	1.10
Clay	-15.93	-16.98	-17.31	0.74

4.3.7.4 Soil organic matter mineral fraction carbon, nitrogen and carbon-13 in HI Embu Experiment

There were no significant differences in the aggregate MF C, N and ^{13}C for the treatments in HI Embu experiment (Figures 4.24, 4.25). However as with the N1 Kabete experiment, most of the aggregate MF C and N was dominant in the macro-aggregates as compared to the micro-aggregate fractions.

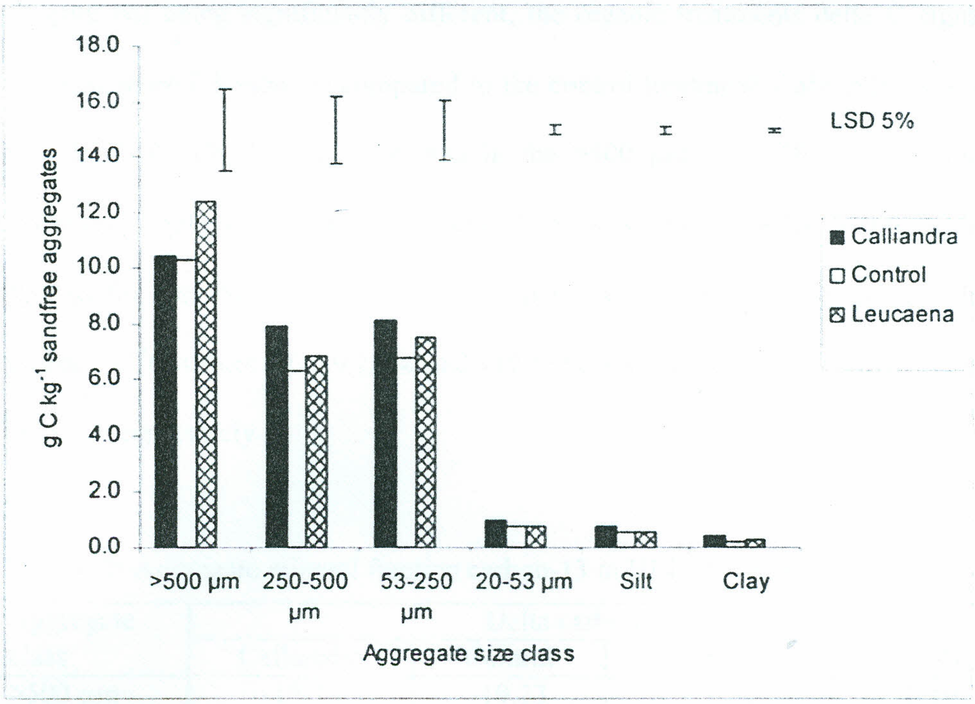

Figure 4. 24: Aggregate mineral fraction carbon for HI Embu experiment

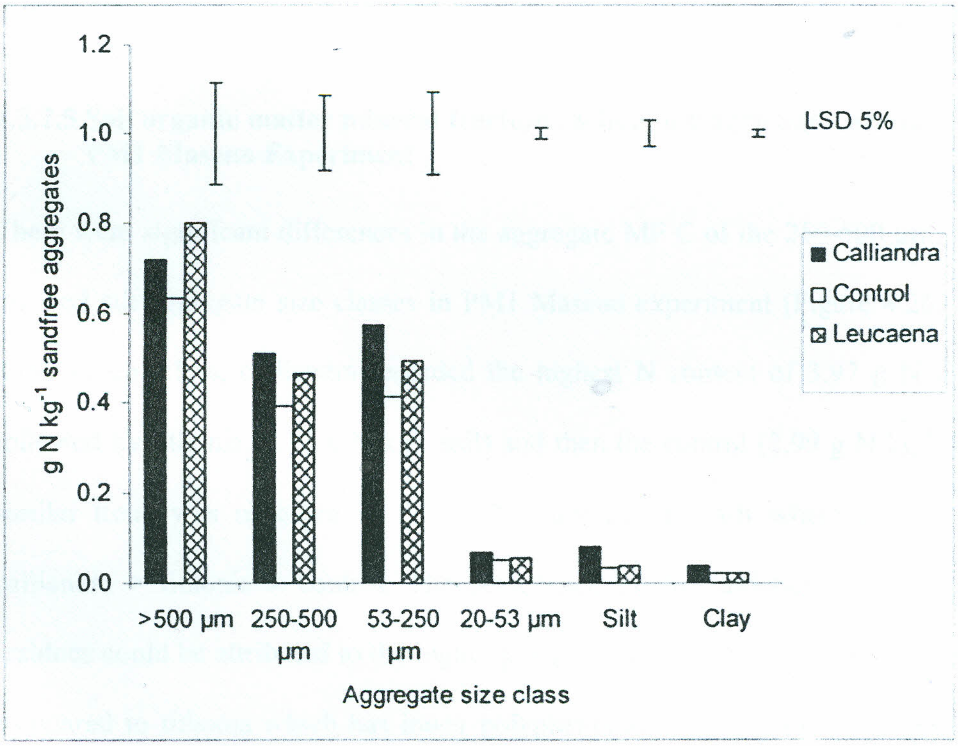

Figure 4. 25: Aggregate mineral fraction nitrogen for HI Embu experiment

Despite not being significantly different, the organic treatments delta C signatures indicated more C3 input as compared to the control treatment. Calliandra recorded a delta $\delta^{13}C$ of -19.34‰ and -19.58‰ in the >500 µm and 250-500 µm fractions (macro-aggregates) respectively (Table 4.7), leucaena recorded -19.67‰ and -19.47‰ for the >500 µm and 250-500 µm fractions respectively while the control recorded $\delta^{13}C$ values of -19.23‰ and -19.13‰ for the macro and micro-aggregate fractions respectively.

Table 4. 7: Aggregate mineral fraction carbon-13 in HI Embu experiment

Aggregate class	Delta carbon-13 (‰)			
	Calliandra	Control	Leucaena	**SED**
>500 µm	-19.34	-19.23	-19.68	**0.19**
250-500 µm	-19.58	-19.13	-19.47	**0.25**
53-250 µm	-19.26	-19.16	-19.77	**0.40**
20-53 µm	-19.14	-19.33	-19.64	**0.26**
Silt	-19.43	-19.43	-19.72	**0.25**
Clay	-20.96	-21.02	-20.93	**0.23**

4.3.7.5 Soil organic matter mineral fraction carbon, nitrogen and carbon-13 in PM1 Maseno Experiment

There were significant differences in the aggregate MF C of the 250-500 µm, 53-250 µm and silt aggregate size classes in PM1 Maseno experiment (Figure 4.26). In the 250-500 µm class, calliandra recorded the highest N content of 3.97 g N kg^{-1} soil followed by tithonia (3.73 g N kg^{-1} soil) and then the control (2.99 g N kg^{-1} soil). A similar trend was observed in the 53-250 µm and the silt where the order was calliandra > tithonia > control. The persistence of the calliandra derived organic residues could be attributed to the higher polyphenol and lignin ratios of calliandra as compared to tithonia which has lower polyphenol and lignin contents. There was a general decrease in the amount of carbon across all the aggregate size classes suggesting a stabilization of the SOM with continued mineralization without addition of external organic residues.

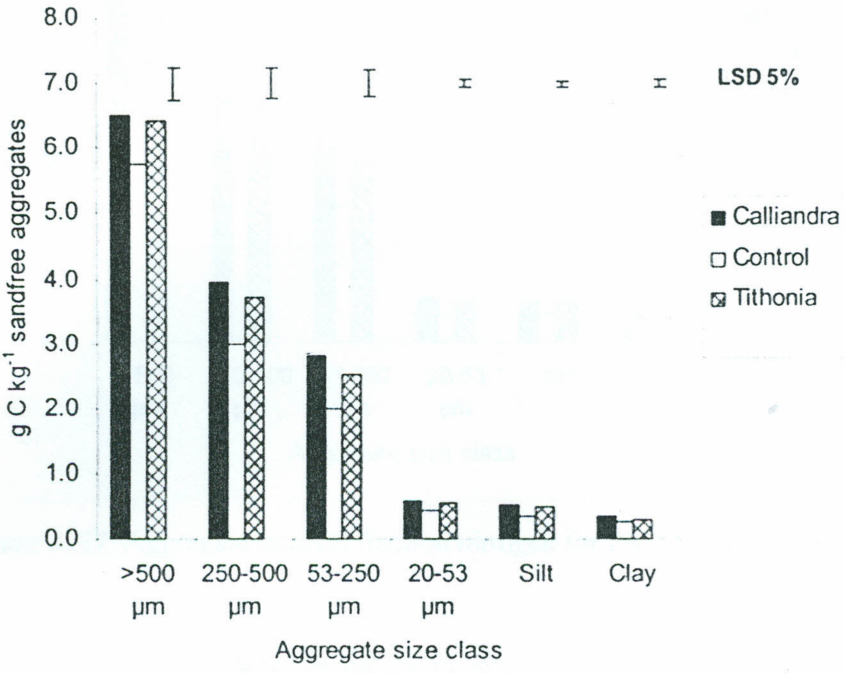

Figure 4. 26: Aggregate mineral fraction carbon for PM1 Maseno experiment

Soil aggregate nitrogen was more defined in this experiment as compared to HI Embu and N1 Kabete experiments (Figure 4.27). Significant differences in the aggregate MF N were observed in the silt fraction where 0.036, 0.033 and 0.024 g N kg^{-1} soil were observed for calliandra, tithonia and the control respectively. On average, calliandra had higher aggregate TON followed by tithonia while the control had the least amount of N. As observed in the other experiments, TON tended to dominate in the macro aggregates as compared to the smaller aggregate size classes confirming the theory of hierarchy distribution of SOM.

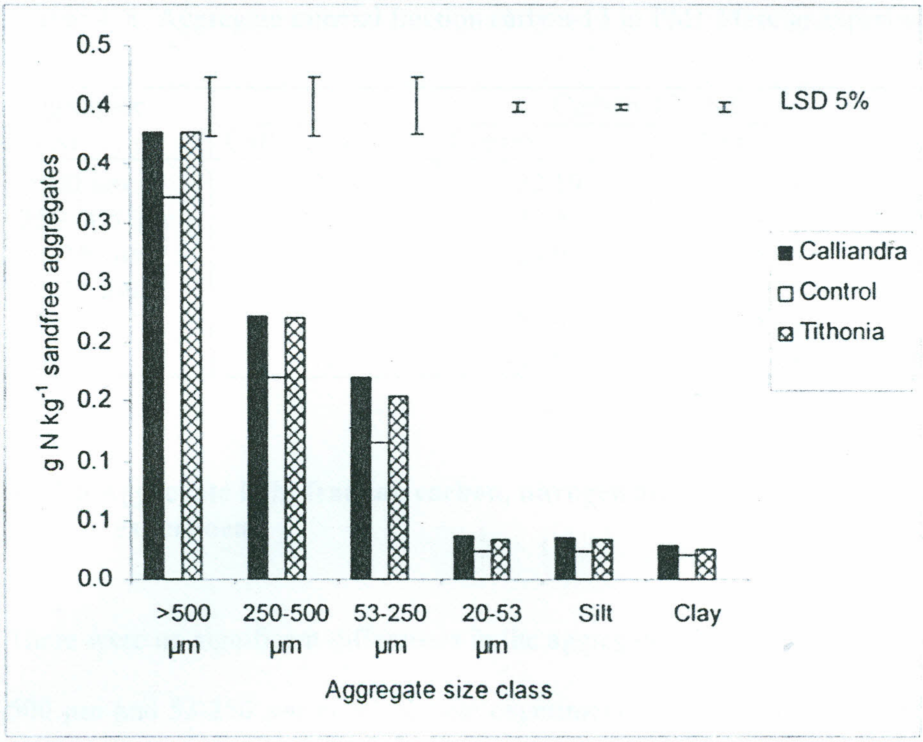

Figure 4. 27: Aggregate mineral fraction nitrogen for PM1 Maseno experiment

Absolute carbon-13 values in the aggregate size classes were more negative in the organic treatments as compared to the control and were also more negative as compared to the whole soil ^{13}C values (Table 4.8). This implies that combining SOM fractionation with δ^{13}C labeling technique was effective in differentiating small changes in the SOM pools occurring due to organic residue application. As noted earlier, such small changes on whole soil C are often obscured by the generally high background C levels and natural soil variability (Blair *et al.*, 1995). The more negative ^{13}C in the clay and silt point to the redistribution of the older organic derived carbon from the recently incorporated SOM to the finer pools where it is fixed.

Table 4. 8: Aggregate mineral fraction carbon-13 in PM1 Maseno experiment

Aggregate class	Carbon-13 (‰)			
	Calliandra	Control	Tithonia	**SED**
>500 µm	-20.59	-20.19	-20.59	0.55
250-500 µm	-20.73	-20.47	-20.65	0.44
53-250 µm	-20.78	-20.93	-20.95	0.56
20-53 µm	-20.98	-20.62	-21.04	0.24
Silt	-21.18	-20.91	-20.94	0.17
Clay	-21.35	-21.98	-21.24	0.32

4.3.7.6 Aggregate light fraction carbon, nitrogen and carbon-13 for N1 Kabete experiment

There were no significant differences in the aggregate LF C in aggregate classes 250-500 µm and 53-250 µm in N1 Kabete experiment (Table 4.9). Aggregate LF N was also not significantly different for the three classes.

Table 4. 9: Aggregate light fraction total carbon, nitrogen and carbon-13 in N1 Kabete experiment

Treatment	Total Carbon (mg kg^{-1} soil)			Total Nitrogen (mg kg^{-1} soil)			Delta ^{13}C (‰)		
	>500 µm	250-500 µm	53-250 µm	>500 µm	250-500 µm	53-250 µm	>500 µm	250-500 µm	53-250 µm
Calliandra	252.0	112.3	117.0	12.59	6.94	12.80	-25.23	-19.66	-18.28
Tithonia	143.0	93.9	144.2	6.98	5.59	10.47	-17.70	-17.36	-18.85
Control	204.0	60.6	96.1	9.71	3.30	6.35	-15.21	-16.33	-17.27
SED	**42.00**	**16.46**	**14.20**	**1.98**	**1.49**	**2.42**	**2.31**	**1.15**	**0.32**

The delta carbon-13 signatures of the LF in this experiment indicated that calliandra had more of its residues persisting in the soil long after the cropping season. This was evident from the more negative $\delta^{13}C$ of the >500 µm (-25.23‰), 250-500 µm (-19.66‰) and 53-250 µm (-18.09‰) (Table 4.9). Tithonia tended to have its LF signatures closer to that of the control; indicating that being of higher quality, most of the it is decomposed during the cropping season and hence little persists in the soil as LF.

4.3.7.7 Aggregate light fraction carbon, nitrogen and carbon-13 for HI Embu experiment

In HI Embu experiment, calliandra had the highest TOC in the all the aggregate size classes and these were significantly different for the >500 μm and 250-500 μm fraction (Table 4.10). This is best explained by the persistence of calliandra due to its lower quality residues (Palm *et al.* 2001). One benefit of such large particulate organic matter (POM) in the soil is the potential for continued mineralization and release of nutrients with continued decomposition throughout the season. On the other hand rapidly decomposing organic residues such as leucaena will persist less in the soil and hence the reason for their lower contribution to the particulate organic matter (POM) pool.

Table 4. 10: Aggregate light fraction total carbon, nitrogen and carbon-13 in HI Embu experiment

	Total Carbon ($mg\ kg^{-1}$ soil)			Total Nitrogen ($mg\ kg^{-1}$ soil)			Delta ^{13}C (‰)		
Treatment	>500 μm	250-500 μm	53-250 μm	>500 μm	250-500 μm	53-250 μm	>500 μm	250-500 μm	53-250 μm
Calliandra	774.0	202.6	230.0	50.1	15.58	18.9	-22.78	-21.46	-20.32
Leucaena	350.0	119.5	117.0	29.7	10.14	10.1	-21.28	-19.85	-19.42
Control	333.0	104.5	115.0	22.1	8.09	10.0	-20.35	-19.29	-19.12
SED	**101.00**	**15.59**	**49.70**	**11.43**	**1.68**	**4.28**	**1.30**	**0.42**	**0.55**

As with the C in the LF, TON was also higher in calliandra treatment as compared to the leucaena and control treatments (Table 4.10). Light fraction N was significantly different ($P < 0.05$) for the 250-500 μm fraction and was of the order calliandra > leucaena > control.

The carbon-13 signature of the LF were significantly different for the 250-500 μm LF with calliandra recording a delta carbon value of –21.46‰ followed by leucaena and then the control with delta ^{13}C of –19.85‰ and –19.29‰ respectively (Table 4.10). The above results point out that calliandra contributed more to the SOM pool as compared to leucaena and the control.

In general, aggregate LF C and N contents were higher in HI Embu experiment as compared to N1 Kabete experiment and this may be attributed to the longer-term application of organic residues which resulted in the accumulation of organic residues in the soil.

In PM1 Maseno, aggregate LF C was no significant difference for the aggregate class 53-250 μm where tithonia recorded LF C content of 144 mg kg^{-1} of soil and was followed by calliandra (117 mg kg^{-1} of soil) and the control (96.1 mg kg^{-1} of soil) (Table 4.11). Aggregate LF N was significantly different for the 250-500 μm class with calliandra recording an N content of 5.52 mg N kg^{-1} soil while tithonia and the control recorded 4.39 and 3.68 mg N kg^{-1} soil respectively. There was also a significant difference in the ^{13}C signatures for the 53-250 μm LF class with tithonia having the highest delta ^{13}C followed by calliandra and then the control.

Table 4. 11: Aggregate light fraction total carbon, nitrogen and carbon-13 in PM1 Maseno experiment

Treatment	Total Carbon (mg kg^{-1} soil)			Total Nitrogen (mg kg^{-1} soil)			Delta ^{13}C (‰)		
	>500 µm	250-500 µm	53-250 µm	>500 µm	250-500 µm	53-250 µm	>500 µm	250-500 µm	53-250 µm
Calliandra	115.8	88.3	117.0	8.08	5.52	12.80	-22.40	-18.46	-18.28
Tithonia	118.0	77.9	144.2	7.91	4.39	10.47	-16.90	-17.20	-18.85
Control	94.3	72.5	96.1	4.72	3.68	6.35	-17.10	-16.71	-17.27
SED	**21.72**	**7.46**	**14.20**	**1.17**	**0.38**	**2.42**	**2.46**	**0.66**	**0.32**

In general HI Embu experiment had more aggregate LF C and N followed by N1 Kabete and PM1 Maseno experiment in that order. This can be explained by the fact that there had been continued application of organic residues in HI Embu unlike in PM1 Maseno where the experiment had been under residual study. The above observation therefore imply that there is need for continued application of organic residues in our farming systems as a basis for maintaining the POM upon which decomposition plays an important role in the immediate nutrient release to the crop.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

Results from the three experiments indicate that application of organic residues can increase food production in low input smallholder farming systems. Secondly, application of large amounts of organics can lead to large residual effects for instance, application of 5 t DM ha^{-1} in PM1 Maseno experiment resulted in higher grain yield three and a half years after organic residue application was terminated. However, considering that availability of such organic residues may be limited, farmers may be encouraged to apply small quantities of the organic residues each season, either alone or supplemented with inorganic fertilizer, to maintain food production. As observed in HI Embu experiment, continued application of approximately 2 t ha^{-1} of organic residues resulted in improved soil N and C as well as increased maize yield over the seasons. Further, the results point to the fact that for a significant change in the SOC and N, large quantities of lower quality organic resources such as calliandra and senna need to be applied to the soil since these are more resistant to breakdown during microbial activity.

Soil respiration results indicated that relatively lower quality organic residues provided more substrate to be consumed by the soil microbes as evidenced from the higher CO_2 evolution from calliandra, leucaena and senna treatments as compared to the tithonia and control treatments. Considering that it is through this feeding process that organic matter is mineralized to supply essential nutrients, farmers should be encouraged to supplement the high quality organic residues that rapidly decompose as well as the inorganic nutrients sources with the lower quality residues so as to ensure synchrony in nutrient supply and eventually increased crop yields.

The results also indicated that the ^{13}C signature can be used to evaluate the extent of the organic residue applied on the whole soil C. N1 Kabete experiment with a shorter lifespan had narrower δ^{13}C values in both organic and control treatments indicating minimal labeling effect from the organic residues applied. On the other hand, greater shifts observed in PM1 Maseno and HI Embu experiments, point to the large quantities and the continued application of the organic residues in the two experiments respectively. By assessing the shifts in the δ^{13}C signature between treatments receiving organic residues and the control, predictions can be made on the contribution of the organics to the SOM pools. The use of this technique should therefore, be expanded to other fields such as assessing the effects of deforestation or land intensification on the soil organic matter quality. Complimenting it with SOM fractionation methods can enhance the use of this technique in SOM studies.

Soil organic matter fractionation revealed large differences in the SOM mineral and light fractions, a testimony that management regimes of different organic residues will contribute differently to the SOM pools. Larger proportions of free light fraction in organic treatments as compared to the control indicated the potential of nutrient release from the mineralization of these SOM pool. This was evident from the higher soil available N and labile N pools in organic treatments as compared to the control.

The above results indicate that as with nutrient depletion and replenishment, three technology categories of replenishing SOC hence SOM need to be pursued; (i) practices that save SOC from loss (ii) practices that add SOC to the system either directly or indirectly and (iii) practices that ensure efficient use of organic materials at different spatial scales.

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