CARBON DIOXIDE EMISSIONS FROM SELECTED SOILS IN ZAMBIA: EFFECTS OF NITROGENOUS FERTILIZER AND AGRICULTURAL LIME.

By
ASTRIDAH NGOMA

A Dissertation Submitted in Partial fulfillment of the requirements for the Degree of Master of Science in Integrated Soil Fertility Management

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Department of Soil Science
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DECLARATION

I, Astridah Ngoma, hereby declare that all work presented in this dissertation is my own and has never been submitted for a degree at this or any other university.

Signature…………………………….. Date…………………………………..

APPROVAL PAGE

This dissertation of Ms. Astridah Ngoma is approved as fulfilling part of the requirements for the award of the degree of Master of Science in Integrated Soil Fertility Management by the University of Zambia.

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DEDICATION

This dissertation is dedicated to my family and friends who encouraged and supported me throughout this period.

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I would like to thank God for having granted me this opportunity and for giving me strength to go through difficult times during the course of my studies. I would also like to thank my supervisor Mr. V. Shitumbanuma for his inspiring contribution, encouragement and fatherly guidance, for which I will forever be grateful.

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ABSTRACT

Soils can serve as sources or sinks of atmospheric carbon dioxide (CO_2) depending on how they are managed. As atmospheric CO_2 concentrations continue to rise there is need to find ways of reducing CO_2 emissions from soils. This study was conducted to assess the effects of applying agricultural lime and an NPK fertilizer on CO_2 emissions from soils and to identify soil properties that have a significant influence on soil organic carbon (SOC) contents and on soil organic carbon mineralization. Soil samples collected from surface horizons of cultivated fields from four Zambia Agricultural Research Stations were used. They were characterized for their particle size distribution, pH, total nitrogen, SOC, plant available P, effective cation exchange capacity (ECEC), and lime requirements. A 14-week laboratory incubation study was conducted to measure effects of treatments on CO_2 emissions from the soils. The treatments were: (i) soil alone, (ii) soil with fertilizer (iii) soil with agricultural lime and (iv) soil with fertilizer and agricultural lime. The samples were incubated in 1 dm^3 plastic jars at room temperature and CO_2 emissions were measured and recorded weekly. Seasonal CO_2-carbon emissions across the soils ranged from 378 to 543 mg C/kg soil with a mean of 473 mg C/kg soil. The mean seasonal carbon mineralization rate across soils was 0.043 or 4.3 %. Non statistically significant differences were observed between mean seasonal CO_2-C emissions of soils with amendments and those of the control. However, soils with combined inorganic fertilizer and agricultural lime had significantly lower CO_2 emissions than soils with inorganic fertilizer alone with seasonal C emission rates of 3.6 % and 4.9 % respectively, and mean residence times (MRTs) of 28 and 20 seasons respectively. The results suggest that on acid soils, applying inorganic fertilizer with agricultural lime may be a better soil management practice for reducing CO_2 emissions from soils than applying inorganic fertilizer alone. The SOC content was found to be significantly ($p < 0.001$) and strongly positively correlated ($r = 0.93$) with the clay content, and moderately positively correlated ($r = 0.60$) with soil pH. Carbon mineralization rates were highly significantly ($p < 0.001$) positively correlated ($r = 0.88$) with the soil C:N ratio. The mean residence time (MRT) of SOC was significantly ($p < 0.001$) negatively correlated ($r =-0.88$) with the soil C:N ratio, indicating that soils with high C:N ratios emit more CO_2 compared to soils with low C:N ratios. Therefore, applying inorganic N fertilizer to high C:N ratio residues is likely to result in lowering CO_2 emission and promote C sequestration in the soil.

Key words: *Soil organic carbon,* CO_2 *emission, carbon mineralization rate, Mean residence time, inorganic fertilizer, agricultural lime*

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CHAPTER ONE

1.0 INTRODUCTION

Soil is the largest pool of terrestrial organic carbon in the biosphere, and it contains more carbon (C) than plants and the atmosphere combined (Schlesinger, 1997). Soil organic carbon (SOC) is dynamic as the anthropogenic impacts on soil can turn it into either a net sink or a net source of Green House Gases (GHGs). In other words, the SOC reservoir is not static, but is constantly cycling between the different global carbon pools in various molecular forms (Kane, 2015). Soil organic carbon therefore, is an important component of the global carbon cycle, as it is one of the largest C reservoirs that exchanges actively with atmospheric carbon dioxide (CO_2) (Baldock, 2007). A small change in forest soil C inventories can thus result in a large change in atmospheric CO_2 concentration (Raich and Schlesinger, 1992).

Soil is a major source of atmospheric CO_2. Carbon dioxide is an important greenhouse gas which accounts for about 60 % of the total greenhouse effect (Rastogi *et al.*, 2002). It is released from the soil through soil respiration, which includes microbial respiration, root respiration and faunal respiration primarily in the soil surface where the bulk of plant residues are concentrated. It also includes the chemical oxidation which is more pronounced at higher temperatures (De Jong *et al.*, 1974).

According to Wiese *et al.*, (2017), in this era of climate change, land degradation and biodiversity loss, soils have become one of the most vulnerable resources in the world. After carbon enters the soil as organic matter from soil fauna and flora, it can persist for decades, centuries or even millennia. The SOC can be eventually lost as CO_2 or methane (CH_4) emitted back into the atmosphere, or as eroded soil material or dissolved organic carbon washed into rivers and oceans. It is, therefore, important to quantify the changes that occur in SOC on global scale if we are to maximize the benefits of SOC to human well-being, food production, and climate regulation. This soil C loss mechanism can be determined and quantified by either measuring CO_2 emission or through other indicators such as change in soil microbial biomass C or change in soil C fractions (Al- Kaisi *et al.*, 2008).

Agricultural activities, such as some soil management practices, have been identified as potential sources of CO_2 emissions. In theory, application of nitrogenous fertilizer affects CO_2 emissions directly by providing nitrogen to crops and microbes, and indirectly by influencing soil pH, which in turn affects microbial activity (Jensen *et al.*, 1994). According to Kuzyakov *et al.*, (2000), mineralization of organic C and N occurs when inherent and added organic materials in the soil are altered by heterotrophic microbes. Manzoni *et al.*, (2008) report that the decomposition of different manures and crop residues applied to soil depends on their C:N ratios. This is usually narrowed by the application of inorganic N.

Apparently, research results show varying effects of N fertilizer application on soil microbial biomass and CO_2 emissions. A number of analyses of N fertilization effects on SOC decomposition showed that N can have positive, neutral, or negative effects on decomposition, depending on substrate chemistry, ambient N decomposition rates, and the amount of N fertilizer added. For instance, a report by Knorr *et al.*, (2005) showed that N generally reduced decomposition of substrates with high lignin concentrations but stimulated decomposition of substrates with low lignin concentrations.

Soil acidification is a natural process in regions with medium to high rainfall, and agricultural production can accelerate soil acidification processes through leaching of basic ions (such as Ca^{2+} and Mg^{2+}) which are replaced by hydrogen ions, through removal of agricultural produce from the land, and through addition of fertilizers and soil amendments that can acidify the soil (Kennedy, 1986). Application of lime therefore helps to improve soil health status by increasing soil pH, improving base saturation, Ca^{2+} and Mg^{2+}, and reducing Al and Mn toxicity (Black, 1993).

The Intergovernmental Panel on Climate Change IPCC, (2007) assumes that the entire C contained in lime materials is eventually released to the atmosphere as CO_2. On contrary, the review of terrestrial and ocean C dynamics conducted by Hamilton *et al.*, (2007) indicates that it is unlikely that all C from agricultural lime is released to the atmosphere following application to soils. The biogeochemical theory suggests that the dissolution of carbonate minerals can act as either a net source or sink for CO_2 and the dissolution of lime may sequester CO_2 equal to roughly 25 to 50 % of its C content (Hamilton *et al*., 2007).

Other studies have also shown that liming is one of the factors of CO_2 emissions responsible for global warming (Bernoux *et al.*, 2003) as a result of $CaCO_3$ hydrolysis reactions in the soil (Chan and Heenan, 1998). Additionally, microbial activity is intensified by the improved soil chemical conditions after liming (Adachi *et al.*, 2009). According to the IPCC (2007), soil respiration associated with liming practices is estimated based on the limestone composition and the annually applied lime rate.

Soil moisture is another factor that affects soil respiration and hence CO_2 evolution (Johnson *et al.*, 1994). In general, increasing soil moisture would increase CO_2 evolution up to an optimum level, above which it would reduce CO_2 evolution. Periodic drying and wetting of soil has a pronounced influence on CO_2 evolution. CO_2 production declines as water content falls below field capacity. When the soil is rewetted the activity of the microbes, which were in a latent state in the dry soil increases accompanied by release of air trapped in the soil pores, contributing to an increase in CO_2 evolution. Drying can therefore inhibit CO_2 production in soils (Doran *et al.*, 1990).

Increased levels of atmospheric CO_2 have prompted research to assess the contributions of industrial, agricultural, and environmental practices to current and potentially continued emissions of CO_2. Enormous scientific progress has been achieved in understanding and explaining SOC dynamics. Yet, protection and monitoring of SOC stocks at national and global levels still face complicated challenges due to impeding effective on-the-ground policy design and regionally adapted implementations (Rosenstock *et al.*, 2016).

1.2 Statement of the Problem

Global warming is now established as a fact and increasing levels of CO_2 in the atmosphere are partly responsible for the warming. Emissions of CO_2 from the soil to the atmosphere are a known fact. In other countries, there are conflicting reports on effects of nitrogenous (N) inorganic fertilizer applications to soils on CO_2 emission to the atmosphere. The effects of applying N inorganic fertilizers and agricultural lime to soils on CO_2 emissions have not been investigated in Zambia. Therefore, there is need to locally establish the effects of these two soil amendments on CO_2 emissions from soils to the atmosphere if the country is to adopt mitigation measures in agriculture to deal with global warming.

1.3 Justification of the Study

Soils in Zambia generally have low organic matter contents especially those under cultivation. Nitrogenous chemical fertilizers and lime are major farming inputs that are used in Zambia. In the western and northern regions of Zambia many small-holder farmers are very hesitant to use chemical fertilizers because they believe chemical fertilizers degrade the productivity of the land. There have been very few studies done locally to assess the effects of nitrogenous chemical fertilizers and agricultural lime on soil carbon emissions. Therefore, there is need to generate local knowledge on how these inputs affect the productivity of the soil in the long run. The aim of this study was to quantify the levels of CO_2 emitted from selected soils in Zambia under cultivated conditions due to application of nitrogenous inorganic fertilizer and agricultural lime.

1.4 Objectives

1.4.1 Main Objective

The main objective of the study was to assess the effects of applying nitrogen-containing chemical fertilizer and agricultural lime on carbon dioxide emission from selected soils in Zambia under laboratory conditions and to determine soil properties that significantly influence SOC contents and soil carbon mineralization rates.

1.4.2 Specific Objectives

The specific objectives of the study were:

1. To determine selected physical and chemical properties of the soils that had a significant influence on soil organic carbon contents.
2. To assess the effects of: (i) NPK fertilizer (ii), agricultural lime, and (iii) NPK fertilizer and agricultural lime on CO_2 emissions from selected soils under laboratory conditions.
3. To evaluate the relationship between selected soil properties and mineralization rates of SOC.

1.5 Hypotheses

The Research hypothesis (Ha) in the study was:

1. There are significant differences in CO_2 emissions from soils treated with (i) NPK fertilizer, (ii) agricultural lime, and (iii) NPK fertilizer and agricultural lime.

The Null hypothesis (Ho) in the study was:

1. There are no significant differences in CO_2 emissions from soils treated with (i) NPK fertilizer (ii) agricultural lime and (iii) NPK fertilizer and agricultural lime.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Importance of Soil Organic Carbon

Soil organic matter (SOM) is very important with respect to availability of plant nutrients and improvement of physical, chemical, and biological properties of soils (Kundu *et al.*, 2007). Decomposition of soil organic matter facilitates nutrient availability by releasing the nutrients in plant-available form. Plants are nourished by nitrogen, phosphorus and other nutrients released from SOM. Maintenance of SOC is therefore, essential for sustainable agricultural production, as declining soil C generally results in decreased crop productivity (Lal, *et al*., 2006).

Soil organic matter also improves soil structure. The improved soil structure due to the addition of organic matter enhances the water holding capacity and infiltration of the soils, resulting in better moisture availability in the landscape. Root development and tolerance to rainfall variation is also significantly enhanced in soils with improved aggregation due to soil organic matter (Milne *et al*., 2015). Crop roots benefit from improved soil aeration and the enhanced infiltration of water, which reduce rates of runoff and erosion (Thomas and Jerome, 2015).

The SOC pool in agricultural lands is capable of enhancing agricultural production sustainability and serves as a potential sink of atmospheric CO_2 (Lal, 2004). In addition to the atmospheric benefits of carbon capture in the soils, the ecology and function of agricultural systems are also improved, resulting in physically cohesive soils which resist wind or water erosion. In effect SOM helps to aggregate soil mineral particles and also serves as a nutrient and energy source for organisms whose activities also improve the soil. Therefore, SOM contributes directly to the improvement of soil productivity, which is beneficial both in agriculture and the environment (Bronick and Lal, 2005). High carbon stocks in the soil are thus critical for the effective functioning of the soil as a medium of plant growth and as an environmental resource that plays an important role in the global C cycle (Lee *et al*., 2006).

2.2 Natural factors that influence the soil organic carbon content

According to Alexandra and Jose, (2005) changes in SOC are determined by the balance of carbon inputs over losses. In some studies, it is reported that soil carbon levels are determined by factors such as rainfall, temperature, climate, soil organisms, topography, vegetation and soil texture and many others. In this study, some of these factors were taken into consideration in order to minimize their effects on SOC.

2.2.1 Temperature

Temperature is one of the factors that controls the rate of decomposition of plant residues. Decomposition normally occurs more rapidly in tropics than in temperate areas (Jenkinson and Ayanaba, 1977) because of the higher temperatures in soils of the tropics compared to temperate regions which promote higher microbial activity. Soils in cooler climates commonly have more organic matter because of slower mineralization or decomposition rates than in tropical regions (Ladd and Amato, 1985). Zambia is located in the tropical region, therefore the rate of decomposition of soil organic matter is higher than is expected in temperate regions. This has contributed to having low organic matter content in most soils of Zambia. Hence, large annual rates of organic matter inputs are needed to maintain an adequate soil organic matter content in cultivated soils.

2.2.2 Soil Moisture

Soil moisture or rainfall is another factor that influences the rate of soil organic matter decomposition. Water is essential for maintaining the catalytically active state of soil enzymes (Jiang and Zhang, 2002), therefore, the soil biological activity requires air and moisture. Optimal microbial activity is believed to occur when the moisture content is near field capacity, when the moisture is equivalent to 60 percent total pore space. When soil is saturated, it results in poor aeration, which causes a reduction in oxygen availability and consequently a reduction in the mineralization rate of organic materials because organisms become inactive due to the anaerobic conditions (Linn and Doran, 1984). During drought spells, the microbes in the soil become dormant. In rainy season, when most farming activities take place, there is higher microbial activity than in dry season. Therefore, this is the time when high carbon mineralization rates occur.

2.2.3 Soil Texture

Rice, (2002) also identified texture of the soil as another property that has an influence on the soil organic matter content. Soil organic matter tends to increase with increasing clay content. For instance, (Prasad and Power, 1997) reported that under similar climatic conditions, the organic matter content in clay soils was two to four times more than in sandy soils. This is because soils with higher clay content have a higher potential for aggregate formation which physically protects organic matter particles from decomposition by soil microbes. In this study, the effects of soil texture were investigated in order to determine their effects on SOC contents.

2.2.4 Topography

The topography is also believed to play a part in soil organic matter accumulation. Quideau, (2002) reported higher levels of SOM at the bottom of the slopes than at mid or upper slope positions. This may be due to wetter conditions at the bottom than at mid or upper slopes, and organic matter is usually transported to the lowest point in the landscape through runoff and erosion. In this study, the soils were collected in fairly flat lands were there was minimum transportation of organic materials to the lower parts of the slopes.

2.3 Management practices that influence soil organic carbon levels

In agricultural systems, soil carbon levels tend to be variable and dependent on management practices. Decline in SOC in agro-ecosystems is often attributed to the effects of cultivation. Cultivation changes the quality and quantity of SOC inputs to soil and soil physical properties that affect C decomposition. According to West and Post (2002) it takes several decades to reach a new equilibrium of SOC after cultivation. Below are some management practices that affect the levels of SOC.

2.3.1 Replacement of perennial vegetation

Replacement of perennial vegetation or the conversion of native ecosystem such as forests, grasslands and wetlands to agricultural uses, and the continuous harvesting of plant materials, lead to significant losses of plant biomass and soil C. Mann, (1986) estimated a 20 % loss of SOC following the cultivation of forests or grasslands, equivalent to 1500 g m^{-2} of SOC in the surface 0.3 m of soil, with the greatest rates of change occurring in the first 20 years. Davidson and

Ackerman, (1993) in the USA reported that 20 years of cultivation in the temperate region could result in a 40 % decline in SOC from the A horizon to about 0.3 m depth, with more than 50 % of such losses occurring within the first 5 years.

2.3.2 Tillage

Tillage is also one of the major practices that reduce the organic matter levels in the soil. Chan *et al.*, (2002) in Wagga wagga, Australia reported that tillage removed mainly particulate SOC (> 53 µm) which accounted for 80 % of the total C loss, while, stubble burning mainly resulted in the loss of SOC associated with the mineral fraction of soil (>53 µm). When the soil is ploughed, organic residues in the soil come into contact with air and microorganisms which accelerate the decomposition of the SOM and increases the emission of CO_2 into the atmosphere, resulting in the decline of SOM (Dick *et al.*, 1988).

2.3.3 Application of Nitrogenous fertilizers

Application of nitrogenous fertilizers is also believed to affect the SOM decomposition although its effect on C losses from ecosystems is poorly understood. This is because it is not yet clear if the impact on microbial activity is a direct effect of the increase in N availability or a result of indirect effect of the fertilizer inputs on other soil chemical properties (Khalafalla and Hamed, 2015). Studies on the nitrogenous fertilizer application have shown varying results of the effect of N fertilizer applications on CO_2 emissions. Studies show that adding N to the soil can increase, decrease or have no effect on the SOM decomposition rate. For instance, Kowalenko *et al.*, (1978) found that soils fertilized with N had low soil CO_2 emissions both in field and laboratory studies. Ramirez *et al.*, (2012) also found that applying N fertilizers reduced CO_2 emissions in 28 soils across North America, covering regions with wetlands, forest, grasslands and deserts. Other researchers such as, Cleveland and Townsend, (2006) reported an increase in soil CO_2 fluxes after addition of N and P to plots under field experiments, but observed a decrease in soil respiration after adding C, N and P in the a laboratory incubation study.

According to Craine, *et al.*, (2007), one of the factors that could account for the observed variations in the CO_2 emissions upon applications of N, is the C: N ratio of the soil, which is reported to be influenced by factors such as the climate, soil conditions, vegetation types and agricultural management practices.

2.3.4 Application of agricultural lime

The two major soil fertility constraints in the savannah, sub-humid and semi-arid regions are low inherent nutrient reserves and rapid acidification under continuous cultivation due to the low buffering or cation exchange capacities of soils (Jones and Wild, 1975). Liming agricultural soils is frequently necessary because most crops are intolerant to low pH and because N fertilizers tend to acidify the soils (Barber, 1967). Liming increases the pH, base saturation, exchangeable Ca^{2+}, in the case of dolomitic lime levels of Mg^{2+} and also to increase microbial activity and improve soil organic matter status, resulting in increased availability of several other nutrients (Persson *et al*., 1990).

Applying agricultural lime to the soil can make it become a source or a sink for CO_2 depending on the soil pH or whether the reaction occurs with strong acid or carbonic acid. Hamilton *et al.,* (2007) show that the dissolution of calcium carbonate is a net sink for CO_2 in soils with relatively high pH, in which H_2CO_3 is the primary acid that reacts with carbonate minerals. In soils with very low pH or where nitrification is the major acidifying process, calcium carbonate is a net source of CO_2. According to Hamilton *et al*., (2007) dissolved CO_2 from root and microbial respiration exists in equilibrium with the weak acid H_2CO_3, which reacts with solid carbonates as shown in equations 1, 2 and 3 below.

Equation 1 shows the formation of carbonic acid from the dissolution of CO_2 gas in water

$$CO_{2\,g} + H_2O_l \rightleftarrows H_2CO_{3\,aq} \qquad \text{Eq 1}$$

Equation 2 shows the dissolution of dolomite, a carbonate mineral by carbonic acid to release bicarbonate ions.

$$CaMg(CO_3)_{2\,s} + 2H_2CO_{3\,aq} \rightleftarrows Ca^{2+}{}_{aq} + Mg^{2+}{}_{aq} + 4HCO_3^-{}_{aq} \qquad \text{Eq 2}$$

Equation 3 shows the dissolution of calcite by carbonic acid to release bicarbonate ions.

$$CaCO_{3s} + H_2\,CO_{3aq} \rightleftarrows Ca^{2+}{}_{aq} + 2HCO_3^-{}_{aq} \qquad \text{Eq 3}$$

Equation 3 can be written as equation four, showing the reaction of CO_2 and water with calcite

$$CaCO_{3s} + CO_{2g} + H_2O_l \rightleftarrows Ca^{2+}{}_{aq} + 2HCO_3^-{}_{aq} \qquad \text{Eq 4}$$

In the above reactions the weathering of the carbonate minerals by carbonic acid serves as a sink for CO_2 which is retained in the bicarbonate ions as part of the alkalinity created by the weathering of carbonate mineral.

Alternatively, when carbonate minerals react with very strong acids such as HNO_3 produced by the nitrification of NH_4^+ to NO_3^-, or with very strongly acid soils the dissolution of carbonate minerals serves as a source of CO_2 which can be released into the atmosphere as shown in equation 5 below:

$$CaMg(CO_3)_{2s} + 4HNO_{3aq} \rightleftarrows Ca^{2+}aq + Mg^{2+}aq + 4NO_3^{-}aq + 2CO_{2g} + 2H_2O_l. \qquad \text{Eq 5}$$

Schwab *et al.*, (2007) also confirmed it using calcite at low pH as shown in equation 6 below:

$$CaCO_{3s} + H_2O_l + 2H^+ \rightarrow Ca^{2+}\ aq + 2H_2O_l + CO_{2g} \qquad \text{Eq 6}$$

West and McBride, (2005) also reported that CO_2 is the end-product when agricultural lime reacts with strong acids such as those that are liberated from nitrification of ammonium in soils. The use of high amounts of ammonium-fertilizers in soils where nitrification occurs, therefore, has the potential of increasing CO_2 emissions when agricultural lime is applied to soils. Therefore, liming of soils and maintaining alkalinity has the potential of reducing CO_2 emissions into the atmosphere and could be considered as one potential strategy in mitigating global climate change.

2.4 Effects of CO_2 emissions on climate change

According to the World Meteorological Organization (WMO, 2012) the concentration of CO_2 in the atmosphere has increased from 280 ppmv at the beginning of industrial revolution to the present-day value of 391 ppmv. This increase has largely been attributed to anthropogenic activities such as agricultural land use changes, burning of fossil fuels, deforestation, emission from automobiles, forest fires, and others activities. The elevated CO_2 levels are considered to be a contributory factor to the risk of global warming and climate change. Climate change poses a major threat to food security through its strong adverse effects on agriculture.

Of the many greenhouse gases, carbon dioxide is an important compound that affects the processes of global warming and is considered as an initiator of global climate change. According to Lal, (2015), in view of the heavy demand for agricultural production to meet the needs of the growing population, the impact of agricultural practices on the soil, climate, gaseous emission, water resources, biodiversity and others, concern must be considered more now than in the past.

2.5 Mitigation measures for CO_2 emissions

To offset the adverse effects of climate change, emissions of CO_2 and other greenhouse gases must be reduced. It is well known that vegetation and soils are major storage sinks of atmospheric CO_2 (Franzluebbers, 2005). Therefore, reducing CO_2 emission by sequestering C in the soil is of critical importance. It is, therefore, necessary to find ways of reducing CO_2 emissions from the soils and of enhancing carbon storage in soils in order to mitigate the adverse effects of climate change (Wiese *et al*., 2017). Soil management practices such as manuring, reduced tillage, and mulching can help in sequestering organic carbon in the soil. Soil C sequestration in turn can improve soil quality and reduce CO_2 emissions into the atmosphere associated with agricultural activities (Caldeira, 2004).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Location and description of Sites

This study was initiated in December, 2017. The soils used in the study were obtained from four sites. The sites were in Kasama, in Agro-ecological region III, Mongu, in Agro-ecological region IIB and Kabwe and Chilanga districts in Agro-ecological region IIA of Zambia. All the samples were collected from fields at Agricultural Research Stations belonging to the Zambia Agricultural Research Institute (ZARI) of the Ministry of Agriculture. Figure 1 shows the location of the sites where the soil samples were collected:

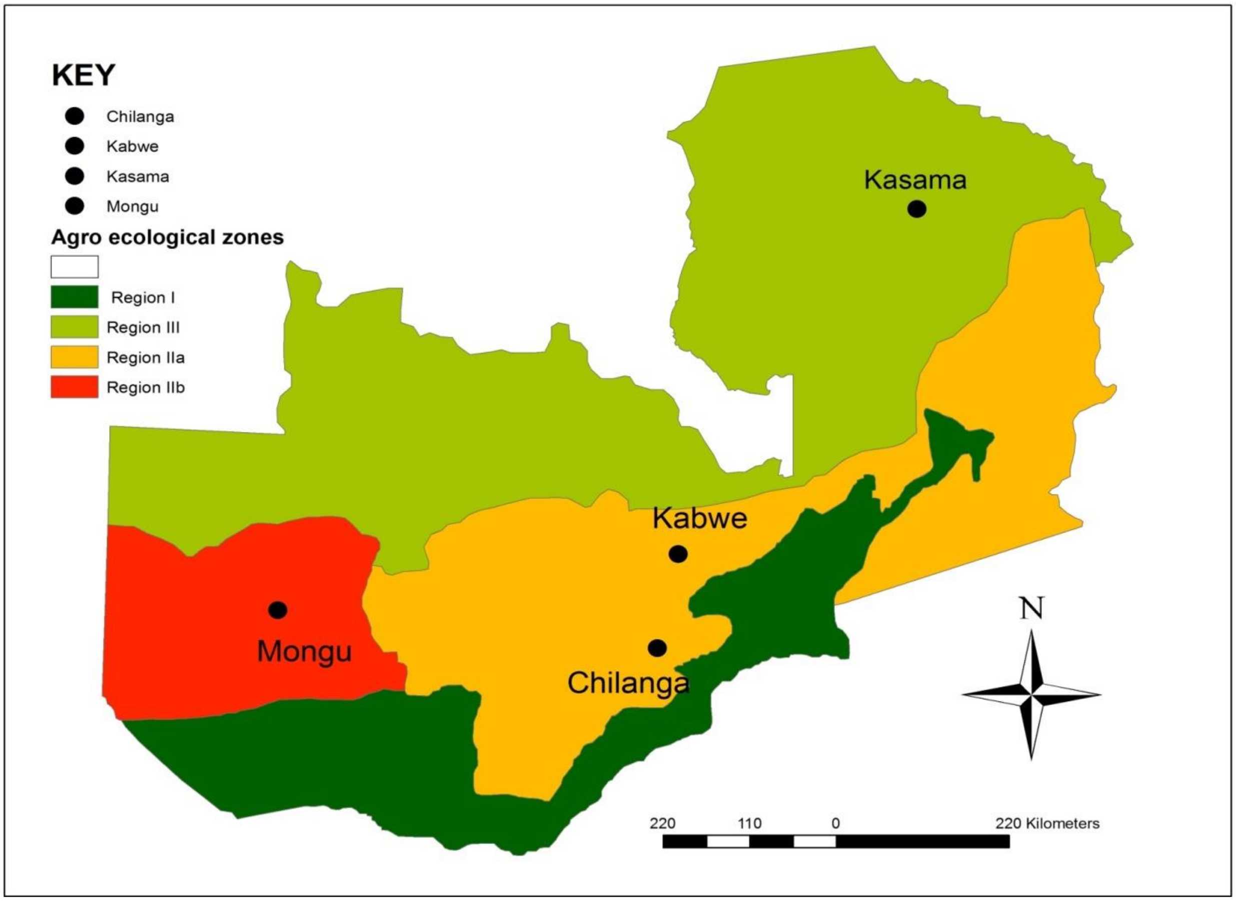

Figure 1. Agro-ecological zone map of Zambia showing sources of soil used in this study

Table 1 shows the locations of the sampling sites and the local and international classifications of the soils sampled.

Table 1. Location of sampling sites and classifications of soils used

Site	Longitude	Latitude	Soil Series	USDA Soil Classification
Kasama	31.22652º E	10.17072º S	Misamfu	Typic Kandiustult
Mongu	23.22652º E	15.07892º S	Kande	Arenic Tropohumod
Kabwe	28.49467º E	14.39481º S	Mushemi	Typic Kandistualf
Chilanga	28.25401º E	15.54725º S	Makeni	Ultic Haplustalf

3.2 Soil Sampling and Preparation

Soil samples were collected from surface horizons (0- 20 cm) of cultivated fields at Agriculture Research Stations. The fields used had previously been used for agronomic activities. Soil sampling was conducted on relatively homogeneous 20 m x 20 m plots. Simple random sampling was employed across the plots. A spade was used to collect soil samples from the surface horizons which were placed in a plastic bucket. Subsamples at each site were composited into one bulk sample and packed in plastic bags with labels indicating the date, GPS coordinates, name of the sampling site, and the sample identity. The sampling bags from each site were placed in a large polythene bag for transportation to the laboratory. About 50 kg of soil were collected from each site.

3.3 Characterization of soils and liming materials

In the laboratory, the soils from the field were air dried, crushed using a mortar, disaggregated and then passed through a 2 mm sieve. The fraction of the soils passing through a 2 mm sieve was retained and used to carry out soil laboratory analysis. The methods used to determine selected physical and chemical properties of the soils are described below.

3.3.1 Soil Reaction (pH)

The soil pH was measured in 0.01M $CaCl_2$ solution using a soil to solution ratio of 1: 2.5, using a digital pH meter (McLean, 1982). Ten grams of air-dried soil was weighed into a 50 mL plastic bottle to which 25 mL of 0.01M $CaCl_2$ solution was added. The suspension was then shaken on a mechanical shaker for 30 minutes. After shaking, the soil suspension was allowed to stand for about 30 minutes to allow most of the suspended clay to settle out from the suspension. The soil pH was then measured by immersing the pH electrode into the supernatant soil solution.

3.3.2 Bray-1 Extractable Phosphorus

Plant available P levels in the acid soils were extracted using the Bray -1 method as described by Bray and Kurtz (1945). The extraction method of Olsen *et al.,* (1954) for plant available P was on the alkaline soils (pH > 7.0). The concentrations of phosphorus in the solution were determined by measuring the absorbance of light at a wavelength of 882 nm using a spectrophotometer.

To prepare the standard curve for the light absorbance at 882 nm due to the presence of P in solution, solutions containing 0 ppm and 1 ppm P were prepared. The absorbance of light at 882 nm in solutions containing 0 and 1 ppm P was then measured on a spectrophotometer. The data obtained was used to prepare the calibration curve relating the concentration of P in the sample to the absorbance of light at 882 nm wavelength. The concentration of P in the solution was obtained using the equation 7 below:

$$Pconc\left(\frac{mg}{L}\right) = \left(\frac{(Conc\ Std - Conc\ blk)(mg.L^{-1}}{(Abs\ Std - Abs\ blk)(Absunits)}\right) * (Abs\ Sample)(Absunits) \qquad \text{Eq 7}$$

where:

Conc Std: concentration of P in standard; Conc blk: concentration of P in blank; Abs std: Absorbance of standard solution; Abs blk= Absorbance reading for blank; Abs Sample: Absorbance reading for sample

Bray1 extractable P in the soils was calculated from concentrations of P in the soil extracts as shown in equation 8:

$$Bray\ 1\ P\left(\frac{mg}{kg\ soil}\right) = Pconc\left(\frac{mg}{L}\right) * DF * Vol\ Extract(L) * \frac{1}{g\ soil} * \left(\frac{1000g}{kg}\right) \qquad \text{Eq 8}$$

3.3.3 Particle Size Analysis

Particle size analysis was determined using the Bouyoucos hydrometer method described by Day (1956). The percentages of sand, silt and clay obtained from the particle size analysis were plotted on a USDA textural triangle to obtain the textural classes of the soils.

3.3.4 Determination of Soil Organic Carbon

The soil organic carbon content in soils was determined using Walkley and Black method (Nelson and Sommers, 1982). One gram of air-dry soil was weighed into a 250 mL conical flask to which 10 mL of 1 N $K_2Cr_2O_7$ was added followed by 20 mL of concentrated H_2SO_4, using a pipette. The suspension was swirled for one minute and placed in a fume hood for 30 minutes. Then 150 mL of distilled water and 10 mL concentrated H_3PO_4 were added. Ten drops of the diphenylamine indicator was added to the suspension, which was then titrated using 1 N of $FeSO_4$ until the solution turned green. The volume of $FeSO_4$ used was recorded. A similar titration was conducted on solution without soil sample that served as a blank. The volume of $FeSO_4$ used for the titration with the blank was also recorded. The percentage of Organic carbon in the sample was calculated using equation 9:

$$\%\,Org\ C = \left(\frac{0.4 * NFeSO_4 * Vol(FeSO_4\ Blk - FeSO_4\ Sample)L}{g\ soil}\right) \qquad \text{Eq 9}$$

The percentage of soil organic matter (SOM) in the sample was calculated from the amount of organic carbon found in the soil sample and multiplying the value with the Van Bemmelen factor of 1.72 as shown in equation 10:

$$\%\,SOM = 1.72 * \%\,Org\ C \qquad \text{Eq 10}$$

3.3.5 Determination of Total Nitrogen

Total nitrogen in the soils was determined using the Kjeldahl method described by Bremner and Mulvaney, (1982). In this method, the N in the soil sample was converted to ammonium (NH_4^+) by digestion with concentrated H_2SO_4 which promotes oxidation of organic matter and conversion of organic-N to ammonium, the Na_2SO_4 was a salt used to increase the temperature during digestion. The 3 g catalyst made by mixing 10 g K_2SO_4, 10 g $CuSO_4$ and 1 g Se powder, was used to increase the rate of oxidation of organic matter by H_2SO_4. The ammonia in the digest was liberated by distillation of the digest with 10 mL of 10M NaOH and then collected the distillate in 20 mL boric acid indicator (H_3BO_3). The distillate was titrated with 0.01M HCl until the colour changed from green to pink. The same procedure was followed using the reagents used in analyzing the samples, without the sample. To calculate the concentration of N in the soil sample equation 11 was used.

$$\% \text{ N} = \frac{\text{Conc HCl}\left(\frac{mol}{L}\right)*\text{Vol HCl (Blk}-\text{Sample)L}*\left(\frac{14g\ N}{mol}\right)}{mass\ of\ soil\ (g)} \text{ x } 100 \qquad \text{Eq 11}$$

where: Blk: the blank

3.3.6 Exchangeable Acidity

The exchangeable acidity was determined by soil extraction with 1N KCl and titrating the extract with 0.01 N NaOH as described by (McLean, 1982). Ten grams of air-dried soil was weighed into a 250 mL plastic bottle to which 100 mL of 1N KCl was added. The suspension was shaken on the mechanical shaker for 1 hour. After shaking, the suspension was filtered and 25 mL of the filtrate was pipetted into a 250 mL conical flask to which 100 mL of distilled water was added and mixed thoroughly. Then 5 drops of phenolphthalein indicator were added to the solution and it was titrated with 0.01N NaOH to a permanent pink end-point. The amount of exchangeable acidity was calculated using equation 12 shown below:

$$Exch\ Acidity\left(\frac{meq}{100g}\right) = \left(\frac{eq}{L}\right) NaOH * VolNaOH(\ Sample - Blk)mL * \left(\frac{Vol\ Extract\ mL}{Vol\ Aliquot\ mL}\right) * \left(\frac{100}{g\ soil}\right) \qquad \text{Eq 12}$$

3.3.7 Exchangeable Bases in soils

The exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) were determined after extraction with 1M ammonium acetate (NH_4OAc) buffered at pH 7 as described by Doll and Lucas, (1975). Ten grams of soil was weighed into a 250 mL Erlenmeyer flask to which 50 mL of 1M NH_4OAc buffered at pH 7.0 was added. The suspension was shaken on the mechanical shaker for 30 minutes and then filtered. The concentrations of K^{+} and Na^{+} were measured directly from the filtrate by flame emission method. To measure the concentrations of Mg^{2+} and Ca^{2+}, 10 mL of the filtrate was pipetted into 100 mL volumetric flask to which 20 mL of 5000 $mg.dm^{-3}$ strontium chloride ($SrCl_2$) solution was added. This was made up to the mark with NH_4OAc extracting solution in the 100 mL volumetric flask. Thus, the original sample was diluted by a factor of 10. The concentrations of Mg^{2+} and Ca^{2+} in the extracts were measured on the Atomic Absorption Spectrophotometer (AAS). The concentrations of cations in the soil were calculated using equation 13 below:

$$Conc\ Cation\ in\ soil\ \left(\frac{cmol+c}{kg\ soil}\right) = \frac{\left(\frac{mg}{L}\right)*Vol\ extract(L)*D.F*\frac{1000g}{kg}}{g\ of\ soil*\frac{molar\ massCat(mg)}{cmol+c}} \qquad \text{Eq 13}$$

where: DF is the dilution factor

3.3.8 Lime Requirement

Lime requirement is the amount of lime required to bring the soil condition to a desired state in relation to its original level of acidity. There are several approaches used to determine the lime requirements of soil depending on the desired objective for applying agricultural lime to the soil. In this study, the lime requirement was determined by calculating the amount of lime required to neutralize the exchangeable acidity of the soils. This was then multiplied by a factor of two to take into account the buffering effect of the soil. Lime requirements were determined using equation 14:

$$\frac{LR(gCaCO3)}{kg\ soil} = 2 * exch\ Acidity\left(\frac{cmol}{kg\ soil}\right) * \frac{0.5gCaCO3}{cmol\ acidity} * \frac{100}{ENV} \qquad \text{Eq 14}$$

where: ENV is the effective neutralizing value of liming material. The 2 is the assumed buffering factor of the soil for acidity.

3.3.9 Lime Quality

Agricultural lime varies in its purity and is rarely 100 % pure because it various factors (Lungu, 2015). Therefore, before using an agricultural liming material, it is important to assess its physical and chemical properties which can then be used to determine its quality for use. The most critical factors are its acid neutralizing capacity (ANC) or its acid neutralizing value (NV) and the fineness of the lime particles. The methods used to determine these two parameters are described below.

3.3.10 Neutralizing Value

The acid neutralizing value (NV) is defined as the ratio of the amount of acid neutralized by 100g of a liming material to that the amount of acid neutralized by 100g of pure $CaCO_3$ (Shitumbanuma, 2015). The NV is expressed as a percentage. The method described by Jackson (1958) was used to determine the NV of a liming material.

3.3.11 Fineness Factor (FF)

Lime is very poorly soluble in water and dissolves slowly in soil solution. The particle size of the lime is an important property that affects the reactivity or rate at which agricultural lime reacts with acid in soils. It is generally desirable to have very fine lime particles as these tend to be more effective in reacting with acid than coarse textured materials. The fineness of agricultural lime was determined by sieving 100 g of lime through a 2 mm and 0.250 mm sieves. The lime particles retained on the 2 mm, on the 0.250 mm sieve and those that passed through the 0.250 mm sieve were weighed. Their masses where then expressed as a percentage of the original mass of lime. Particles coarser than 2 mm were assigned fineness factor of 0, those retained on the 0.250 mm sieve were assigned 0.5 while those finer than 0.250 mm were assigned a fineness factor of 1. The fineness factor was calculated using equation 15 below:

$$FF = \frac{\lfloor(\%\ lime\ retained\ on\ 0.250\ mm\ sieve * 0.5) + (\ \%\ lime < \ 0.250\ mm * 1.0\ )\rfloor}{100} \quad \text{.....eq 15}$$

3.3.12 Effective Neutralizing Value

Effective neutralizing value (ENV) was calculated by multiplying fineness factor and neutralizing value of the lime used in the study.

3.4 Experimental Design

The laboratory incubation study used to measure CO_2 emissions was laid out as a Randomized Complete Block Design (RCBD) with four treatments and four replications on four soils, where the soils served as the blocks. Table 2 gives a description of the treatments used in the study.

Table 2. Description of treatments used

Treat ID	Treatment	Treatment Description	Replication

1	Empty jars	Blank	4
2	Soil (Control)	1 kg Soil alone	4
3	Soil + Fertilizer	1 kg Soil + 1.5 g Comp D	4
4	Soil + Lime	1 kg Soil + LR(g) for soil	4
5	Soil + Fertilizer + Lime	1 kg Soil + 1.5 g Comp D + LR(g) for soil	4

3.5 Determination of carbon dioxide evolution from soils

The laboratory incubation experiment was conducted to measure the amount of CO_2 emitted from the soil samples as a result of aerobic soil respiration over a period of 14 weeks. For the incubation study air dry soil samples that had passed through a 2 mm sieve were used. Fifty grams of air-dried soil was weighed into 1 dm^3 plastic jars. About 6.3 mL, 6.5 mL, 2.25 mL, and 13.4 mL of water were added to the 50 g samples of soil from Kabwe, Kasama, Mongu, and Chilanga respectively, corresponding to the amount of the moisture required to occupy 60 % of total pore spaces in each soil. Then 100 mL plastic bottles containing 5 mL of 0.2 M NaOH were placed inside the plastic jars containing the soil. The jars were then tightly sealed with lids to prevent gaseous entry and escape. Blank treatments consisting of 1 dm^3 empty plastic jar containing 20 mL beakers with 5 mL of 0.2 M NaOH were also included to capture atmospheric CO_2 in the jars. The jars were then placed in an incubator at room temperature with an average of 21.5 ^{O}C for the 14 week incubation period.

At 7 day intervals, the bottles containing NaOH solutions were removed from the jars. The NaOH solutions were titrated with 0.1 N HCl. Carbon dioxide emissions were measured from the CO_2 captured in 0.2 M NaOH solution, using the method for Soil Respiration described by Jenkinson and Powlson, (1976). In order to maintain the amount of moisture required to occupy 60 % of total pore spaces, the soils that lost moisture were reweighed and the difference between the mass of soil with 60 % moisture and the actual mass of the soil was used to determine the amount of water to add.

3.5.1 Determination of carbon mineralization rate (k) and Mean Residence times (MRT)

The decomposition of organic matter is often reported to follow the first order rate law. It was assumed that carbon mineralization from the soils followed the first order rate law. Equation 16 describes the mineralization of carbon following the first order rate law.

$$\text{Cum Ct} = \text{Co}\ (1\text{-exp}^{-kt}) \qquad \text{Eq} \quad 16$$

where: Ct: is the CO_2-C mineralized or evolved at time t,

Co: is the potential mineralizable C pool,

k: is the carbon mineralization rate constant.

To determine the value of the carbon mineralization rate constant (k) also known as the rate constant, a plot of the natural logarithm (ln) of the amount of C remaining in the soil at time t against time (t) was made. The slope of the equation was used to obtain the value of k as indicated in equation 17.

$$\ln(\text{Co-Ct}) = \ln(\text{Co}) - kt \ \ldots\ldots\ldots \ \text{Eq } 17$$

From equation 17 the value of k was obtained using equation 18.

$$k = \frac{1}{t} * [In(Co - Ct) - In(Co)] \qquad \text{Eq } 18$$

The Mean Residence Time (MRT) of the organic carbon in the soil, which is a measure of the average duration of carbon in the soil when the steady state rate of decomposition has been attained was calculated using equation 19:

$$\text{MRT} = \frac{1}{k} \qquad \text{Eq } 19$$

where: k is the carbon mineralization rate constant.

3.6 Statistical Analysis

Figures of weekly CO_2 emissions were recorded from which the cumulative CO_2 emissions were calculated. To determine if there were significant differences due to treatment effects, the General Linear Model (GLM) was used instead of the Analysis of Variance (ANOVA), because one of the soils used only had two treatments. Because the ANOVA model only works when the design is balanced, it could not be used in this study. But the GLM is able to handle unbalanced designs. Duncan’s Multiple Range Test (DMRT) was used to compare separated treatment means, when results of the GLM indicated significant differences among treatment means. A linear correlation analysis was carried out to establish whether there were significant linear relationships between selected soil properties and soil organic carbon contents. It was also used to establish whether there were significant relationships between selected soil properties and carbon mineralization rate constants k and the mean residence times (MRT) of SOC. To establish the best predictors of SOC, k and MRTs in natural or non- amended soils, stepwise regression analysis was used. The significance level used to establish statistically significant differences was 0.05. All statistical analysis were carried out using SAS Software Version 9.0 windows.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Properties of Soils used in the study

A summary of the results of selected properties of the soils used in the study are presented in Table 3. The soils from Kasama were sandy clay loam, sand for soils from Mongu, soils from Kabwe were loamy sand and clay for soils from Chilanga.

Table 3. Selected properties of the soils used in the study

Soil Properties	Sites			
	Kasama	Kabwe	Mongu	Chilanga
pH (0.01M $CaCl_2$)	4.49	5.24	5.19	7.25
SOC (%)	1.10	1.09	0.96	1.26
Total N (%)	0.02	0.03	0.01	0.02
Avail P (mg.kg soil^{-1})	20.08	20.51	10.46	10.97*
C: N Ratio	55.0	36.0	96.0	63.0
Exch acidity (cmolc.kg soil^{-1})	0.94	0.49	0.55	NA
ECEC (cmolc.kg soil^{-1})	2.09	2.06	1.57	7.09
LR (mg$CaCO_3$.kg soil^{-1})	940	490	550	NA
Sand (%)	67.1	87.6	95.60	14.0
Silt (%)	7.1	5.2	1.12	11.2
Clay (%)	26.8	7.2	3.28	74.8
Textural Class	Sandy Clay Loam	Loamy Sand	Sand	Clay

*Plant available P in the alkaline soil was determined by the Olsen procedure

According to agronomic classification for soil pH measured in 0.0l M $CaCl_2$ (Mc Philips, 1987) the soils from Kasama were very strongly acid, while soils from Kabwe and Mongu were moderately acid, and soils from Chilanga were alkaline. Among these four soils, the ones that required liming were the three acid soils from Kasama, Kabwe and Mongu. In terms of the lime requirements, the soil from Kasama had the highest followed by the soil from Mongu and then the soil from Kabwe.

The classification of SOC in Zambian soils according to Zambia Agriculture Research Institute (ZARI) is as follows: (i) levels of SOC less than 1 % are low, (ii) levels of SOC between 1 and 2 %, are moderate and (iii) levels of SOC greater than 2 % are high (Mukanda, 1982). Based on these criteria, soils from Mongu had low levels of SOC, while soils from Kasama, Kabwe and Chilanga had moderate levels of SOC. Soils from Chilanga had the highest levels of SOC among the soils used in the study. According to Musinguzi, *et al*., (2013) the threshold level of SOC for sustaining soil quality is about 2 % with a critical lower limit of 0.5 %. Using this classification, all the four soils had moderate levels of soil organic carbon.

Metson, (1961) classified levels of total nitrogen in soils as follows: (i) soils containing less than 0.1 % N have very low levels of N; (ii) soils containing between 0.1 and 0.2 % N, have low levels of N; (iii) soils containing between 0.2 and 0.5 % N, have medium levels of N; (iv) soils containing between 0.5 and 1.0 % N have high levels of N, (v) while soils with more than 1.0 % N have very high levels of N. Therefore, based on this classification, all the four soils in the study had very low levels of nitrogen, indicating that nitrogen was likely to be a limiting nutrient to crop production in these soils.

According to Havlin *et al.,* (2005), the interpretation of levels of Bray 1 extractable P for maize production are as follows: (i) soils with less than 12 mg P/kg soil, have low levels of P, (ii) soils with between 12 and 25 mg P/kg soil, have moderate levels of P; while (iii) soils containing more than 25 mg P/kg soil, have high levels of P. Based on this classification, soils from Kasama and Kabwe had moderate levels of plant available P while soils from Mongu and Chilanga, had low levels of plant available P.

The C:N ratio plays a key role in determining soil organic carbon and nitrogen mineralization. Deng, *et al*., (2013) pointed out that the greatest SOM decomposition would occur at the substrate C:N ratio of 25:1. When organic materials with a C:N ratio greater than 24:1 are added to the soil, this results in a temporary nitrogen deficit due to immobilization. However, if the C:N ratio is less than 24:1, it results in a temporary nitrogen surplus resulting from mineralization of SOC. The general order of the C:N ratio of the soils in the study were: Mongu > Chilanga > Kasama > Kabwe and their C:N ratios were all above 25:1.

4.2 Properties of agricultural lime used

Table 4 presents the properties of the agricultural lime used in the study. It had a NV of 95.5 % and a fineness factor of 0.994, indicating that nearly all the lime particles were fine enough to effectively react with soil acids in one crop growing season. Because of the high degree of fineness of the lime the ENV of the agricultural lime used was about 95 %, indicating that the liming materials used was expected to be highly reactive within one crop growing season as long as the soils were moist.

Table 4. Selected properties of the agricultural lime used in the study

Neutralizing Value (NV) %	Fineness Factor (FF)	Effective Neutralizing Value (ENV) %
95. 5	0.994	94.9

4.3 Effects of soil properties on soil organic carbon content

Carbon dioxide emissions from soils mainly originate from aerobic microbial respiration during the decomposition of soil organic matter and from the respiration of plant. According to Gagnon, (2016) the CO_2 emitted during the laboratory incubation originates from heterotrophic respiration and corresponds to C oxidative losses from soil organic matter. Since SOC is the source of CO_2 emitted from the soil into the atmosphere, it is important to establish some of the factors that have an influence on SOC contents. A linear correlation analysis was, therefore, conducted to establish the relationship between SOC contents and selected soil properties. The results of the analysis are presented in Table 5.

Table 5. Pearson correlation matrix of selected soil properties. Coefficients (r) and Prob >|r| (p), where H0: Rho = 0.

Variable	SOC (%)	pH	% Clay	C:N ratio

SOC (%)	1.0000	0.60	0.93	0.36
		< .0001	< .0001	0.0069
pH	0.60	1.0000	0.72	0.57
	<.0001		< .0001	< .0001
% Clay	0.93	0.72	1.0000	0.68
	< .0001	<.0001		<.0001
C:N ratio	0.36	0.57	0.68	1.0000
	0.0069	<.0001	<.0001	

The results show that the SOC content of the soils was strongly positively correlated (r = 0.93) with the clay content, moderately positively correlated (r = 0.60) with soil pH and only weakly positively correlated (r = 0.36) with the C: N ratio. Results of a Stepwise multiple regression analysis of the SOC with pH, clay content, and C: N ratio showed that the clay content was the strongest predictor of SOC with a partial $R^2 = 0.86$, followed by the soil pH with a partial $R^2 = 0.36$, while the C:N ratio had only a weak influence on SOC. Figure 2 shows the relationship between the clay content and the SOC. It shows that the SOC content of the soils generally increased with increasing soil clay content.

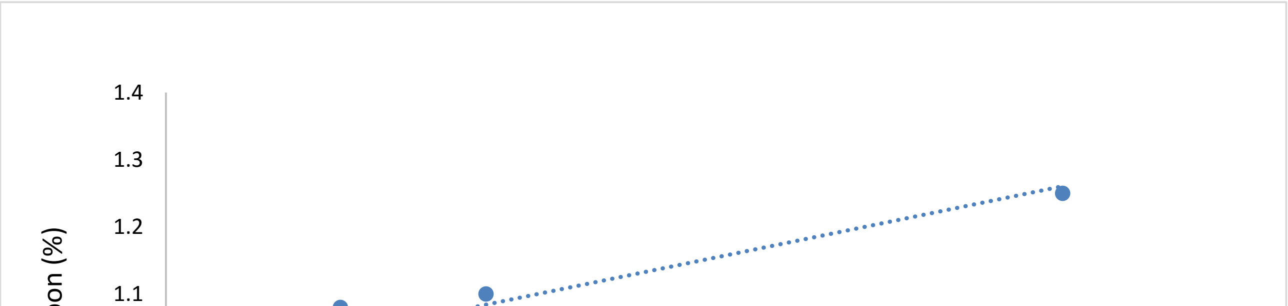

Figure 2. Relationship between soil organic carbon and soil clay content

Soil from Chilanga, with the highest clay content, had the highest content of soil organic carbon, while the sandy soils from Mongu, which had the lowest clay content, had the lowest soil organic carbon content. Ladd *et al*., (1985) also found a significant positive linear relationship between residual labelled C in topsoil and the clay contents of the soils. According to Sopher and Baird, (1998), soil texture affects litter decomposition by altering soil water availability, pore size distribution, nutrient availability and surface area. Sandy soils are reported to have a limited capacity to stabilize organic compounds on mineral surfaces compared to the clay, which in turn affects their capacity to store SOC (Scott, 1996).

4.4 Effects of fertilizer and lime applied to soil on CO_2-C emissions

Table 6 shows means of the cumulative CO_2-C emissions from the four soils over a 14-week incubation period. Detailed GLM Tables for the results presented in Table 6 are in Appendices 1 to 8. The general order of CO_2-C emissions from soils was: Chilanga > Mongu > Kasama > Kabwe.

On alkaline Clay soils from Chilanga, no statistically significant differences in CO_2 emissions were observed between the control and the treatment with chemical fertilizer alone. Therefore, applying NPK fertilizer did not increase the CO_2 emissions in these alkaline soils.

Table 6. Cumulative CO_2-C loss from four different soils after 14 weeks of incubation

Treatment	Chilanga	Kabwe	Mongu	Kasama
	mg CO_2-C kg soil^{-1}			
Untreated Soil	817.8^{a}	286.2^{b}	411.6^{ab}	376.8^{a}
Fertilizer alone	812.4^{a}	432.9^{a}	536.4^{a}	391.2^{a}
Lime alone	NA	414.6^{a}	537.0^{a}	396.6^{a}
Fertilizer and Lime	NA	333.6^{ab}	334.2^{b}	467.4^{a}
Mean	815.1	366.8	454.8	408.0
CV	10.6	20.5	20.1	20.0

Mean values within a column with the same superscript are not significantly different at $P \leq 0.05$ level.

On moderately acid Loamy Sand soils from Kabwe, treatments with fertilizer alone and with agricultural lime alone had significantly higher CO_2 emissions than the control. This could be due to enhanced microbial activity. The CO_2 emissions from the treatment with a combination of fertilizer and agricultural lime were not statistically significantly different from those of the control. These results imply that applying NPK fertilizer alone or lime alone increased CO_2 emissions while applying both NPK fertilizer and agricultural lime did not increase CO_2 emissions.

On moderately acid Sand soils from Mongu, the CO_2 emissions from treatments with the NPK fertilizer alone, lime alone and, combined fertilizer and lime were not significantly different from those of the untreated soil, implying that applying the NPK fertilizer alone or lime alone or the combination of the fertilizer and lime does not contribute to an increase in the CO_2 emissions. However, the treatments with combined fertilizer and lime had significantly lower CO_2 emissions than the treatments with fertilizer alone and agricultural lime alone. This trend was also observed in the soils from Kabwe. Therefore, it is more advantageous to apply a combination the fertilizer and lime as this does not only improve soil quality but also helps reduce the CO_2 emissions unlike applying them separately.

On strongly acid Sandy Clay Loam soils from Kasama, no statistically significant differences in CO_2 emissions were observed among the four treatments. In this soil type, applying the fertilizer alone or lime alone or the combination of the fertilizer and lime did not result in an increase in the CO_2 emissions. These results imply that heterotrophic soil respiration is not affected by either fertilizer or lime addition. The results, are therefore, consistent with the findings reported by Wilson *et al.*, (2000) in Michigan, USA that showed that inorganic fertilizer application had no influence on soil microbial biomass. The report by Lee *et al.,* (2007) also showed that application of inorganic fertilizers had no significant effect on soil microbial biomass and CO_2 emissions.

4.5 Effects of fertilizer and lime on CO_2 emissions, C mineralization rate (k) and MRT across soils

Table 7 shows mean values of the seasonal cumulative CO_2-C emissions, carbon mineralization rate constants (k) and mean residence time (MRT) of organic carbon for different treatments across soils. Detailed GLM Tables for the results presented in Table 7 are in Appendices 9 to 16. The results show that there was no significant difference between the mean k values of the treatments with fertilizer alone, lime alone and the combination of the fertilizer and lime to that of the control. This implies that the rate at which organic carbon was being mineralized per week was similar for all the three treatments as that of the control. However, the treatments with fertilizer alone and lime alone had significantly higher mean k values than the treatment with combined fertilizer and lime. This result suggests that applying a combination of fertilizer and agricultural lime on acid soils resulted in a significantly lower rate of carbon mineralization than using the fertilizer or lime alone. This result is consistent with the lower cumulative CO_2 emissions from soils treated with a combination of fertilizer and lime compared to soils that received fertilizer alone.

Table 7. Mean seasonal C emission, mineralization rates (k and K) and MRT of organic C for different treatments across soils

Treatment `	N	Cum-C (mgC.kg soil^{-1})	k (week^{-1})	K (season^{-1})	MRT (seasons)
Control	16	473.10^{ab}	0.0031^{ab}	0.0422^{ab}	27.07^{a}
Fertilizer alone	16	543.22^{a}	0.0036^{a}	0.0490^{a}	21.50^{b}
Lime alone	12	449.20^{bc}	0.0032^{a}	0.0434^{a}	24.06^{ab}
Fertilizer and lime	12	378.40^{c}	0.0026^{b}	0.0360^{b}	28.38^{a}
Mean		467.72	0.0032	0.0431	25.11
CV (%)		19.76	21.04	20.57	22.65

Mean values within a column with the same superscript are not significantly different at $P \leq 0.05$ level. One season* = 14 weeks

The MRT of organic carbon in a soil is inversely related to k of organic carbon in the soil. The MRT indicates the time it would take for SOC to completely be mineralized from the soil into CO_2 at an average mineralization rate of k if there are no further additions of C materials to the soil. The treatment with fertilizer and lime had the highest MRT of organic carbon among the treatments used. Furthermore, the MRT was significantly greater than that of the treatment with fertilizer alone. This suggests that in general, on acid soils applying fertilizer and agricultural lime was more likely to result in longer retention of organic carbon in the soil than applying fertilizer alone. For the purpose of carbon sequestration on acid soils, it may therefore be more beneficial to apply fertilizer and lime than fertilizer alone. Applying fertilizer and agricultural lime on acid soils is known to replenish nutrients taken up by plants and to ameliorate soil acidity. The application of fertilizer and agricultural lime on acid soils therefore seems to be a better soil management practice than applying fertilizer alone.

4.6 Factors affecting carbon mineralization rate in soils

To establish the factors that had a significant effect on the carbon mineralization rate constant k, the cumulative carbon mineralization, (Cum-C) and the mean residence time (MRT) of soil organic carbon a correlation analysis was carried out on the variables k, Cum-C, MRT, soil pH, SOC and the C:N ratio of the soils. The mean values of the above listed soil properties on the soils used in the study prior to the addition of amendments are presented in Appendix V. Table 8 shows results of the correlations analysis among the above-mentioned soil properties.

Table 8. Pearson's correlation matrix for selected soil properties. Coefficients, and Prob > |r| under H0: Rho=0.

	k	CumC	MRT	C:N	Org C	pH	Clay
k	1.00000	0.97748 .0001	-0.94382 <.0001	0.88209 <.0001	0.55263 0.0264	0.74917 0.0008	0.74569 0.0009
CumC	0.97748 <.0001	1.00000	-0.88099 <.0001	0.88673 <.0001	0.71274 0.0019	0.82641 <.0001	0.86565 <.0001
MRT	-0.94382 <.0001	-0.88099 <.0001	1.00000	-0.82224 <.0001	-0.36110 0.1694	-0.57566 0.0196	-0.57865 0.0189

Since Cum-C, k and MRT were the three parameters of interest related to carbon emissions from soils, they were taken as the dependent variables of interest in this study. The soil properties assessed as potential predictors of carbon emissions were: (i) the C:N ratio, (ii) the SOC content (iii) soil pH and (iv) the clay content. The C:N ratio had the strongest positive ($r = 0.882$) and significant ($p < 0.001$) correlation with k, followed by the soil pH. Correspondingly, the C:N ratio also had the strongest negative ($r = -0.822$) and significant ($p < 0.001$) correlation with the MRT of soil organic carbon. This implies that the C:N ratio had a higher significance on carbon mineralization and this was reflected in its influence on both k and MRT.

Figures 4 and 5 show the relationship between C:N ratio and the C- mineralization rate constant (k) and C:N ratio and the MRT of SOC. Figure 4 shows that the soils with high C:N ratios emitted more CO_2 into the atmosphere than soils with lower C:N ratios. Figure 5 shows that the MRT of SOC in soils with high C:N ratios, was shorter than that of soils with low C:N ratios. High C:N ratios are associated with high levels of organic carbon, while low C:N ratios are associated with low levels of organic carbon. High carbon mineralization rates are more likely to occur in systems with high C:N ratios than in systems with low C:N ratios. Therefore, it seems that the use of organic materials with low C:N ratios would help reduce emissions of CO_2 into the atmosphere and promote sequestration of carbon in the soils for a longer period of time.

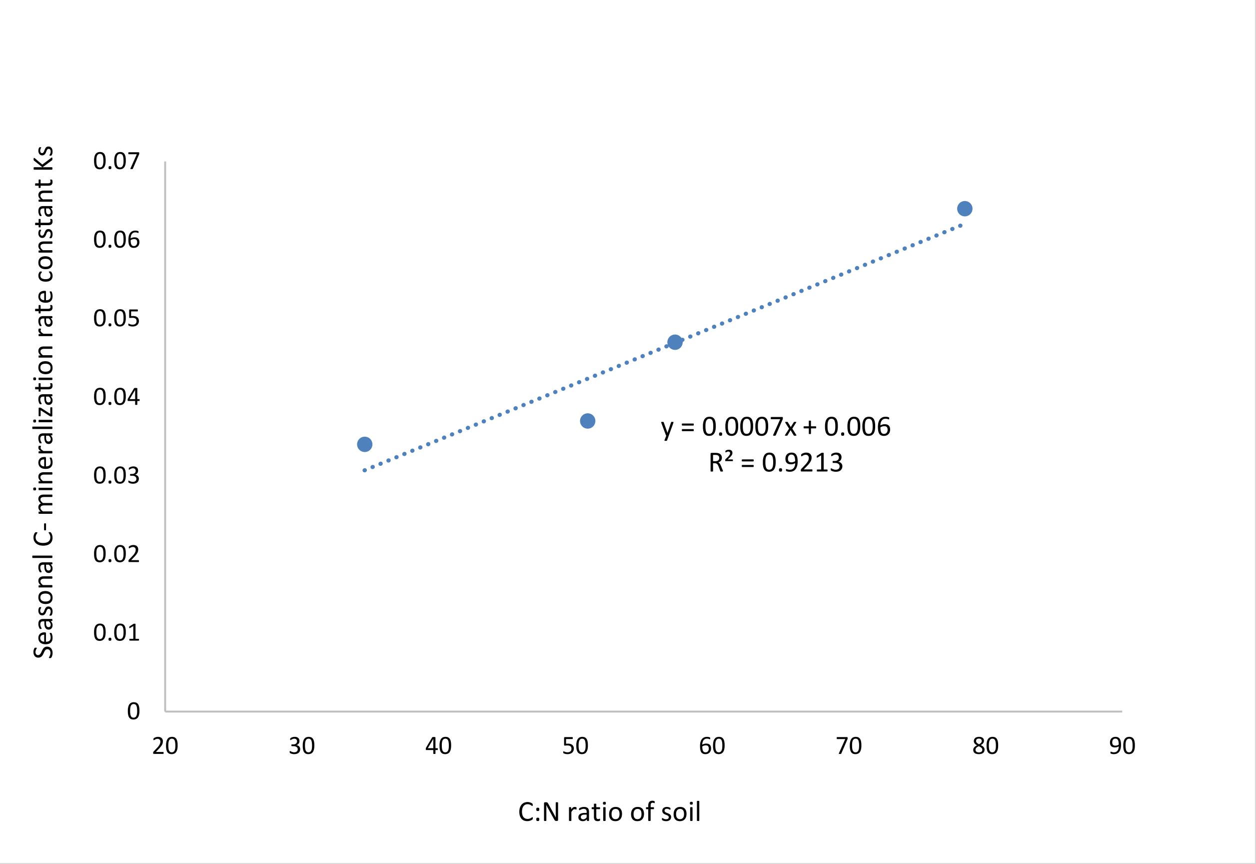

Figure 3. Relationship between the C:N ratio and seasonal CO_2-C emission rates from soils

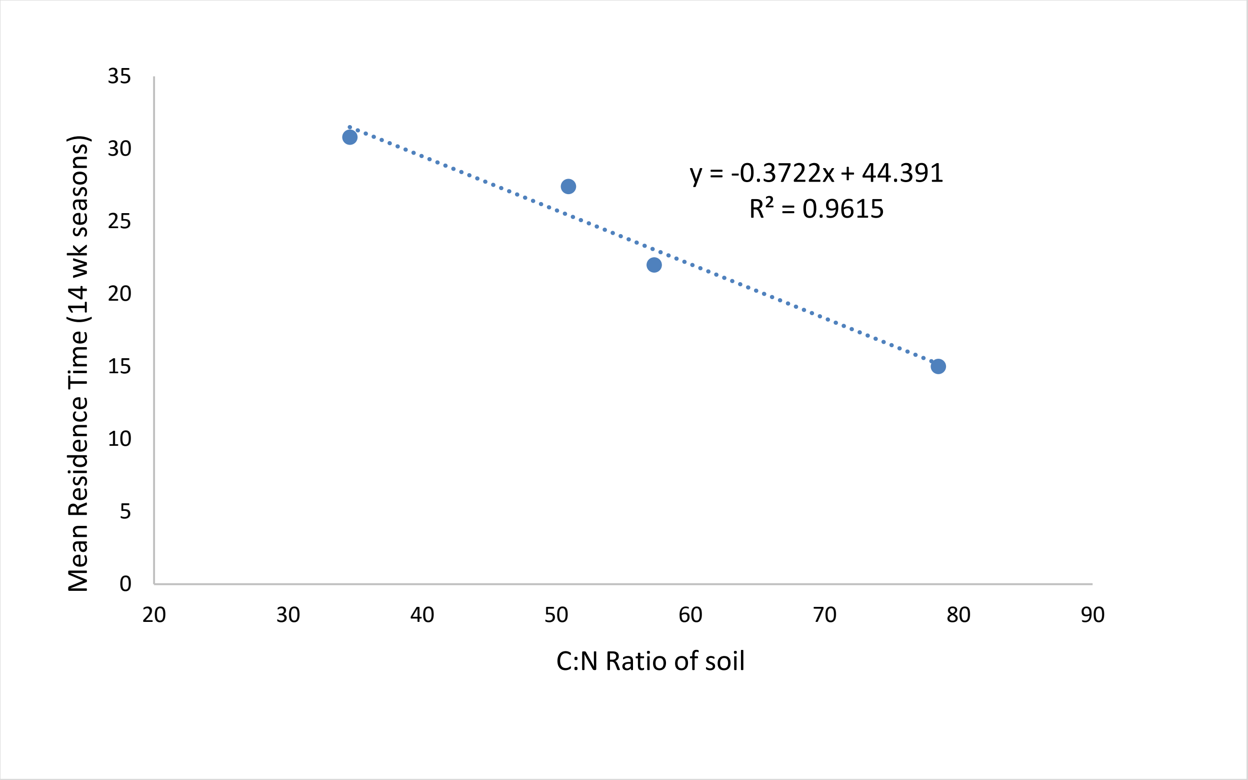

Figure 4. Relationship between C:N ratio and mean residence time of soil organic carbon

The results of this study indicate that the higher the C:N ratio of the soil, the higher the amount of CO_2 emitted from the soil and shorter residence time. A high C:N ratio indicates an abundance of C in the soil, relative to the nitrogen content of the soil. When organic matter materials with high levels of C are decomposed, CO_2 is released into the atmosphere. The organic carbon continues to be mineralized until the C:N ratio of the organic matter is similar to that of soil microbes. Organic carbon mineralization is thus expected to be higher soils with high C:N ratio than in soils with low C:N ratio, the excess C being released as CO_2. High rates of carbon mineralization reduce the residence time of organic carbon in soils. Therefore, the MRT of organic carbon is expected to be longer in soils with low C:N ratios compared to soils with high C:N ratios. Sylvia *et al.,* (2005) reported that higher labile C- containing organic materials increased CO_2 emissions, and reduced the rate of C accumulation in soils. Therefore, applying inorganic N fertilizer to high C:N ratio residues is likely to result in lowering CO_2 emission and promote C sequestration in the soil.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSION

The clay content and soil pH were found to have a significant influence on soil organic carbon contents. Soil organic carbon contents increased with increasing clay content and with increasing soil pH.

The CO_2 emissions from soils treated with fertilizer alone, agricultural lime alone and a combination of fertilizer and agricultural lime were not statistically different from those of soils without these amendments. However, applying a combination of fertilizer and agricultural lime to the soil significantly reduced CO_2 emissions compared to applying fertilizer alone. On acid soils, applying a combination of fertilizer and lime was more effective in reducing carbon emissions than applying fertilizer alone.

The C:N ratio of the soil was found to have a significant influence on carbon mineralization. Soil organic carbon mineralization rates increased with increasing C:N ratio, indicating that greater CO_2 emissions are likely to occur in soils with high C:N ratios compared to in soils with low C:N ratios. In practice, applying inorganic N fertilizer to high C:N ratio residues is likely to reduce CO_2 emissions and result in C sequestration.

5.2 RECOMMENDATIONS

Based on the findings of this study, the following preliminary recommendations can be made:

i. On cultivated acid soils application of fertilizer and agricultural lime should be encouraged as a means of reducing CO_2 emissions from such soils.

ii. The use of already decomposed organic materials with low C: N ratios such as compost rather than fresh organic materials with high C:N ratios on soils should be encouraged to reduce CO_2 emissions from soils.

iii. The effect of applying increasing rates of agricultural lime to acid soils on CO_2 emissions should be investigated to establish optimal lime application rates for minimizing CO_2 emissions from soils.

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APPENDICES

Appendix 1. GLM Table for seasonal carbon emissions from Chilanga soil

```
                              The GLM Procedure

                           Class Level Information

                              Class      Levels   Values

                        Treat         2      fert soil

                          Number of observations   8

Dependent Variable: Cum-C

                                     Sum of

   Source              DF        Squares     Mean Square    F Value    Pr > F

   Model                1        58.32000       58.32000       0.01      0.9327

   Error                6     45122.40000    7520.40000

   Corrected Total      7     45180.72000

          R-Square     Coeff Var      Root MSE     cumC Mean

          0.001291      10.63921      86.72024     815.1000

   Source              DF       Type I SS     Mean Square    F Value    Pr > F

   treat              1     58.32000000    58.32000000      0.01    0.9327
```

Appendix 2. Duncan’s Multiple Range Test for Seasonal carbon emissions from Chilanga soil

```
                    Duncan's Multiple Range Test for Cum-C

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

                     Alpha                       0.05

                     Error Degrees of Freedom       6

                     Error Mean Square              7520.4

                        Number of Means          2

                        Critical Range           150.0

              Means with the same letter are not significantly different.

              Duncan Grouping          Mean      N    treat

                        A               817.80      4    soil

                        A               812.40      4    fert
```

Appendix 3. GLM Table for seasonal carbon emissions from Kabwe soil

```
                          The GLM Procedure

                       Class Level Information

               Class       Levels    Values

               treat            4    fert fertlime lime soil

                      Number of observations    16

Dependent Variable: Cum-C

                                    Sum of

   Source                 DF       Squares     Mean Square    F Value    Pr > F

   Model                   3    56782.3500      18927.4500       3.35    0.0554

   Error                  12    67746.6000       5645.5500

   Corrected Total        15   124528.9500

              R-Square     Coeff Var      Root MSE     Cum-C Mean

              0.455977      20.49141      75.13688       366.6750

   Source                 DF     Type I SS     Mean Square    F Value    Pr > F

   treat                   3   56782.35000     18927.45000       3.35    0.0554
```

Appendix 4. Duncan's Multiple Range Test for seasonal carbon emissions from Kabwe soil

```
NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

                    Alpha                   0.05

                    Error Degrees of Freedom      12

                    Error Mean Square        5645.55

               Number of Means          2        3        4

               Critical Range         115.8    121.2    124.4

          Means with the same letter are not significantly different.

          Duncan Grouping        Mean      N    treat

                    A         432.90      4    fert

                    A         414.00      4    lime

                 B  A         333.60      4    fertlime

                    B         286.20      4    soil
```

Appendix 5. GLM Table for seasonal carbon emissions from Kasama soil

```
                          The GLM Procedure

                        Class Level Information

                Class       Levels    Values

                treat          4      fert fertlime lime soil

                       Number of observations    16

                          The GLM Procedure

Dependent Variable: Cum-C

                                    Sum of

  Source              DF       Squares     Mean Square    F Value    Pr > F

  Model                3    19656.00000     6552.00000       0.99    0.4324

  Error               12    79819.20000     6651.60000

  Corrected Total     15    99475.20000

              R-Square     Coeff Var     Root MSE     Cum-C Mean

              0.197597      19.98954     81.55734      408.0000

  Source              DF      Type I SS     Mean Square    F Value    Pr > F

  treat                3    19656.00000     6552.00000       0.99    0.4324
```

Appendix 6. Duncan’s Multiple Range Test for seasonal carbon emissions from Kasama soil

```
                    Duncan's Multiple Range Test for Cum-C

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

                     Alpha                   0.05

                     Error Degrees of Freedom      12

                     Error Mean Square         6651.6

                Number of Means         2         3         4

                Critical Range            125.7    131.5    135.1

             Means with the same letter are not significantly different.

           Duncan Grouping         Mean      N    treat

                     A                   467.40      4    fertlime

                     A                   396.60      4    lime

                     A                   391.20      4    fert

                     A                   376.80      4    soil
```

Appendix 7. GLM Table for seasonal carbon emissions from Mongu soil

```
                         The GLM Procedure

                      Class Level Information

              Class       Levels    Values

              treat          4      fert fertlime lime soil

                     Number of observations    16

    Dependent Variable: Cum-C

                                 Sum of
Source              DF          Squares     Mean Square    F Value    Pr > F

Model                3      119304.0000      39768.0000       4.76    0.0207

Error               12      100244.1600       8353.6800

Corrected Total     15      219548.1600

         R-Square     Coeff Var      Root MSE     cumC Mean

         0.543407      20.09641      91.39847      454.8000

Source              DF        Type I SS     Mean Square    F Value    Pr > F

treat                3      119304.0000      39768.0000       4.76    0.0207
```

Appendix 8. Duncan’s Multiple Range Test for seasonal carbon emissions from Mongu soil

Duncan's Multiple Range Test for Cum-C

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	8353.68

Number of Means	2	3	4
Critical Range	140.8	147.4	151.4

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	treat
	A	537.00	4	lime
	A	536.40	4	fert
B	A	411.60	4	soil
B		334.20	4	fertlime

Appendix 9. GLM Table for seasonal carbon mineralization across soils

```
                           The GLM Procedure
                         Class Level Information

              Class       Levels    Values
              soil           4    chilanga kabwe kasama mongu
              treat          4    fert fertlime lime soil
                Number of observations    56
                           The GLM Procedure
Dependent Variable: cumC (Cumulative seasonal C mineralization mgC.kg soil-1)

                                      Sum of
   Source                 DF         Squares     Mean Square   F Value    Pr > F
   Model                   6     1258653.259      209775.543     24.56    <.0001
   Error                  49      418558.635        8542.013
  Corrected Total         55     1677211.894

              R-Square     Coeff Var      Root MSE     cumC Mean
              0.750444      19.76027      92.42301      467.7214

   Source             DF       Type I SS     Mean Square   F Value    Pr > F
   treat               3      191531.824       63843.941      7.47    0.0003
   soil                3     1067121.435      355707.145     41.64    <.0001

   Source                DF     Type III SS     Mean Square   F Value    Pr > F
   treat                  3       70174.395       23391.465      2.74    0.0533
   soil                   3     1067121.435      355707.145     41.64    <.0001
```

Appendix 10. Duncan’s Multiple Range Test seasonal carbon emissions across soils

```
                    Duncan's Multiple Range Test for cum C

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
       rate.
                    Alpha                        0.05
                    Error Degrees of Freedom          49
                    Error Mean Square           8542.013
                    Harmonic Mean of Cell Sizes 13.71429

                     NOTE: Cell sizes are not equal.

               Number of Means          2          3          4
               Critical Range       70.93      74.60      77.01

             Means with the same letter are not significantly different.

              Duncan Grouping          Mean      N    treat

                         A           543.23     16    fert

                    B    A           473.10     16    soil

                    B    C           449.20     12    lime

                         C           378.40     12    fertlime
```

Appendix 11. GLM Table for weekly C mineralization rates (k) across soils

```
                         Class Level Information

               Class       Levels    Values
               treat          4    fert fertlime lime soil
               soil           4    chilanga kabwe kasama mongu
                 Number of observations    56

                          The GLM Procedure
```

Dependent Variable: k (weekly mineralization rate mgC.kg soil^{-1})

```
                                  Sum of
   Source                DF       Squares     Mean Square    F Value    Pr > F
   Model                  6     0.00003820     0.00000637      14.47    <.0001
   Error                 49     0.00002156     0.00000044
   Corrected Total       55     0.00005976

               R-Square     Coeff Var      Root MSE        k Mean
               0.639248      21.04601      0.000663      0.003152

   Source                DF      Type I SS    Mean Square    F Value    Pr > F
   treat                3     0.00000660     0.00000220       5.00    0.0042
   soil                 3     0.00003160     0.00001053      23.95    <.0001

   Source                DF    Type III SS    Mean Square    F Value    Pr > F
   treat                 3     0.00000392     0.00000131       2.97    0.0409
   soil                  3     0.00003160     0.00001053      23.95    <.0001
```

Appendix 12. Duncan's Multiple Range Test for weekly C mineralization rates (k) across soils

```
                    Duncan's Multiple Range Test for k

 NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
                              rate.
                    Alpha                       0.05
                     Error Degrees of Freedom          49
                     Error Mean Square           4.399E-7
                     Harmonic Mean of Cell Sizes 13.71429

                     NOTE: Cell sizes are not equal.

               Number of Means           2            3            4
               Critical Range       .0005090     .0005354     .0005527

              Means with the same letter are not significantly different.

               Duncan Grouping          Mean      N    treat

                    A     0.0035963     16    fert

                    A     0.0031737     12    lime

                 B  A      0.0030870     16    soil

                 B         0.0026225     12    fertlime
```

Appendix 13. GLM Table for seasonal C mineralization rates (K) across soils

```
                         The GLM Procedure


                      Class Level Information
               Class       Levels   Values
               soil           4   chilanga kabwe kasama mongu
               treat          4   fert fertlime lime soil



                   Number of observations    56
                         The GLM Procedure

Dependent Variable: R (seasonal mineralization rate mgC.kg soil)
                                    Sum of
   Source              DF       Squares     Mean Square   F Value   Pr > F
   Model                6     0.00678120     0.00113020     14.40   <.0001
   Error               49     0.00384562     0.00007848
   Corrected Total     55     0.01062682

               R-Square    Coeff Var     Root MSE       R Mean
               0.638121     20.57214     0.008859     0.043063

   Source              DF     Type I SS    Mean Square   F Value   Pr > F
   treat                3     0.00117482     0.00039161      4.99   0.0042
   soil                 3     0.00560639     0.00186880     23.81   <.0001

   Source              DF   Type III SS    Mean Square   F Value   Pr > F
   treat               3     0.00070405     0.00023468      2.99   0.0398
   soil                3     0.00560639     0.00186880     23.81   <.0001
```

Appendix 14. Duncan's Multiple Range Test for Seasonal mineralization rates (K) across soils

```
                 The GLM Procedure


                  Duncan's Multiple Range Test for k


NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error
                       rate.
                 Alpha                     0.05
                 Error Degrees of Freedom         49
                 Error Mean Square          0.000078
                 Harmonic Mean of Cell Sizes 13.71429


                  NOTE: Cell sizes are not equal.
          Number of Means           2           3           4
          Critical Range       .006799     .007150     .007382


       Means with the same letter are not significantly different.


        Duncan Grouping          Mean      N    treat


                A       0.049007     16    fert


                A       0.043384     12    lime


             B  A        0.042161     16    soil


             B          0.036020     12    fertlime
```

Appendix 15. GLM Table for the mean residence time (MRT) of SOC across soils

```
                              The GLM Procedure


                             Class Level Information
                   Class      Levels    Values
                   soil          4    chilanga kabwe kasama mongu
                   treat         4    fert fertlime lime soil
                         Number of observations    56
                              The GLM Procedure
Dependent Variable: MRT (Mean Residence time -14-week seasons)
                                     Sum of
    Source                DF        Squares     Mean Square    F Value    Pr > F


    Model                  6    1947.362674     324.560446      10.03    <.0001


    Error                 49    1585.901160      32.365330


    Corrected Total      55    3533.263833


              R-Square     Coeff Var      Root MSE      MRT Mean
              0.551151      22.65281      5.689054      25.11412
    Source                DF       Type I SS     Mean Square    F Value    Pr > F
    treat                  3     410.894787     136.964929       4.23    0.0097
    soil                   3    1536.467887     512.155962      15.82    <.0001

    Source                DF     Type III SS     Mean Square    F Value    Pr > F
    treat                  3     375.339221     125.113074       3.87    0.0147
    soil                   3    1536.467887     512.155962      15.82    <.0001
```

Appendix 16. Duncan's Multiple Range Test for the MRT of SOC across soils

```
                         The GLM Procedure

              Duncan's Multiple Range Test for MRT

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error

                  rate.

              Alpha                      0.05

              Error Degrees of Freedom         49

              Error Mean Square          32.36533

              Harmonic Mean of Cell Sizes 13.71429

               NOTE: Cell sizes are not equal.

         Number of Means          2          3          4

         Critical Range       4.366      4.592      4.740

       Means with the same letter are not significantly different.

        Duncan Grouping          Mean      N    treat

                A              28.380     12    fertlime

                A              27.066     16    soil

            B   A              24.061     12    lime

                B              21.503     16    fert
```

Appendix 17. Stepwise multiple regression analysis for predictors of SOC in soils

```
                          The STEPWISE Procedure

                      Model: MODEL1

                   Dependent Variable: OrgC


 Stepwise Selection: Step 1

           Variable clay Entered: R-Square = 0.7870 and C(p) = .

                       Analysis of Variance

                           Sum of          Mean

     Source           DF       Squares         Square       F Value    Pr > F

     Model             1       0.03610       0.03610        36.94    0.0001

     Error            10        0.00977      0.00097706

     Corrected Total   11       0.04587

                   Parameter     Standard

        Variable      Estimate        Error        Type II SS   F Value     Pr > F

        Intercept     0.94716      0.01869       2.50849    2567.37   <.0001

        clay             0.01287      0.00212       0.03610    36.94       0.0001

                  Bounds on condition number: 1, 1

----------------------------------------------------------------------------------------------
```

```
Stepwise Selection: Step 2

                 Variable CN Entered: R-Square = 1.0000 and C(p) = .

                              Analysis of Variance

                                      Sum of        Mean

        Source              DF       Squares       Square   F Value   Pr > F

        Model                2      0.04587      0.02293     Infty     <.0001

        Error                9          0            0

        Corrected Total     11      0.04587


Parameter    Standard

             Variable     Estimate      Error      Type II SS    F Value   Pr > F

             Intercept     1.10172        0         0.43312      Infty     <.0001

             clay          0.01159        0         0.02827      Infty     <.0001

             CN           -0.00304        0         0.00977      Infty     <.0001

            Variable selection terminated as the selected model is a perfect fit.

                              Summary of Stepwise Selection

           Variable    Variable     Number    Partial     Model

Step    Entered      Removed      Vars In   R-Square   R-Square     C(p)     F Value    Pr > F

 1        clay                          1        0.7870     0.7870        .         36.94    0.0001

 2        CN                            2        0.2130     1.0000        .          Infty   <.0001
```