QUALITY OF ORGANIC RESOURCE INFLUENCE ON SOIL NITROUS OXIDE (N_2O) EMISSION UNDER MAIZE (*Zea mays L.*) BASED CROPPING SYSTEM

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE IN SOIL SCIENCE

UNIVERSITY OF NAIROBI

DECLARATION

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

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DEDICATION

To the courageous climate change advocates to which this work is an inspiration and to my mother and Father Margaret Ayiecha and Thomas Rogito for the humble beginnings and to the University of Nairobi, Department of Land Resource Management and Agricultural technology for the tutelage and mentorship. To my son Azariah Nyamosi to whom I find strength.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
FYM	Farmyard Manure
GDP	Gross Domestic Product
GHG	Greenhouse gas
CL	*Calliandra calothrysus*
ISFM	Integrated Soil Fertility Management
LR	Long Rains
MS	Maize stover
MT	Soil Moisture
N	Total Nitrogen
N_2O	Nitrous Oxide gas
NUE	Nitrogen Use Efficiency
OR	Organic Resource
ORD	Organic Resource Database
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPSS	Statistical Packages for Social Sciences
SR	Short Rains
SSA	Sub Saharan Africa

ABSTRACT

Integrated Soil Fertility Management (ISFM) has been recommended to address challenges of low soil fertility, by incorporating locally available organic resources (ORs) together with inorganic nitrogen (N) fertilizers. Despite ISFM success in field trials, there is limited information on ORs contribution to atmospheric greenhouse gas concentrations through nitrous oxide (N_2O) emission. A short-term field study was conducted at two sites with different soil types; silt loam (Aludeka) and silty-clay soil (Sidada), to determine the effects of selected ORs (*Calliandra carothyrsus (CL)*, farmyard manure (FYM) and maize stover (MS)) and their combination with inorganic N fertilizer on soil N_2O emissions, available soil nitrogen and maize yields. The study also evaluated the relationship between N_2O emissions and soil organic carbon (SOC), total nitrogen (TN), soil temperature, moisture content, soil nitrate (NO_3^-) and ammonium (NH_4^+). Static manual chambers were set up in the field to collect gas samples to quantify soil N_2O emission. Relative to the control (0.19±0.1 Kg N_2O-N ha^{-1}), cumulative N_2O emissions were significantly (P= 0.01) higher by 6, 9 and 13 fold under MS +N (1.05±0.8 Kg N_2O-N ha^{-1}), FYM +N (1.74±0.8 Kg N_2O-N ha^{-1}) and CL +N (2.54±1.2 Kg N_2O-N ha^{-1}), respectively at the Aludeka. At Sidada, cumulative N_2O emissions were similar across all the treatments (P = 0.149). Approximately 240% and 411% of increase in cumulative N_2O emissions across treatments at Sidada and Aludeka, respectively, was related to inorganic N fertilizer application. At Aludeka, cumulative N_2O emissions exhibited significant positive relationship with SOC (r = 760, P = 0.029), TN (r = 0.820, P = 0.013), NO_3^-(r = 0.905, P = 0.002) and NH_4^+ (r = 0.738, P = 0.036), and negatively correlated with soil C:N ratio (r = -0.710, P = 0.049), soil pH (r = -0.739, P=0.036). At Sidada only NO_3- (r = 0.711, P =0.048) exhibited a significant positive correlation with cumulative N_2O emissions. In terms of grain yield at Aludeka, there was a significant (P < 0.001) effect of treatments on maize grain yield, with no observed

significant effect at Sidada ($P>0.05$). FYM +N treatment recorded the highest mean maize grain yield at both Aludeka (10.63 t ha^{-1}) and Sidada (9.23 t ha^{-1}). In Aludeka site, treatments with ORs in combination with inorganic N fertilizers increased maize grain yield in comparison with those without. The study suggests that influence of OR on N_2O emissions in maize based-cropping system vary depending on the type of soil and increases when OR are applied in combination with inorganic N fertilizers. A more understanding of the prevailing environmental soil conditions especially on soil texture is necessary for finding the best treatment combination in terms of yield and N_2O emission reduction under the ISFM approach.

CHAPTER ONE

1. INTRODUCTION

1.1 Background Information

The African continent relies on agriculture as the major source of livelihood and main contributor of GDPs (Shiferaw *et al*., 2011). Maize is the main staple crop to most of the Sub Saharan Africa (SSA) population and is grown on about 27 million hectares, representing approximately 30% of the cultivated land under cereals (Cairns *et al*., 2013). Although such a large area is occupied by maize crop in the region, average yields of 1.9 metric tons per hectare (mt/ha) have been obtained, which is below the world average crop potential of 5.01 mt/ha (Shiferaw et al., 2011). This shows that there is a significant yield gap between the actual and potential maize yield production (Vanlauwe et al., 2011), which shows that there is an unexploited potential for increasing maize production in SSA. Low soil fertility has been cited as the major biophysical cause of declined per-capita food availability in SSA smallholder farmers, with a reduction from 150 to 130 kg per person for the past 35 years of the production (Bationo, 2003). The declined food availability has been attributed to insufficient nutrient supply, poor soil management (Waithaka & Shepherd, 2006), leaching, soil erosion, and gaseous losses (Jaetzold and Schmidt, 2005). Maize research on smallholder farming system in SSA has emphasized the attainment of high yields per hectare to use of increased fertilizer inputs (Kimani *et al.*, 2004). In most of SSA, the use of fertilizer in sufficient amounts is not possible due to the high costs of the fertilizers (Chianu *et al*., 2012). This has led to farmers relying on locally available organic residues (OR) to address low soil fertility constraints (Vanlauwe *et al*., 2010).

New technologies such as the Integrated Soil Fertility Management (ISFM), conservation agriculture and agroforestry (Mtangadura *et al*., 2017), are yet to be fully adopted by the smallholder farmers, who are the significant maize producers (Blackie and Jones, 2015). Recently, SSA agriculture intensification has gained support, partly because there is a growing acceptance that improved farm productivity is an important step in breaking the vicious cycle characterizing rural poverty (Vanlauwe *et al*., 2010). The use of ISFM in particular, has been of main focus in agronomic research on soil fertility improvement in maize cropping systems in SSA (Vanlauwe *et al*., 2010). The ISFM mainly involves a combination of inorganic fertilizer and OR to achieve sustainable agricultural intensification and to increase crop productivity and profitability among smallholder farming systems (Muyayabantu *et al*., 2012; Roobroeck *et al*., 2016).

However, the role of ISFM in climate change mitigation on N use efficiency has limited investigations through the application of OR amendments on the soil. The ORs have several functions in intermediate microbial reactions resulting in N_2O production. N_2O is produced due to mineralization of organic N found in OR which releases ammonium resulting in nitrification to nitrate and denitrification of nitrate to molecular dinitrogen (Charles *et al*., 2017). As a result, environmental benefits with OR amendments of soils can be offset depending on the degree of N_2O emissions (Senbayram *et al*., 2012). An understanding of N fertilizer contribution to N_2O emissions in maize cropping systems may assist in minimizing GHG emissions at the same time maintaining an improved crop productivity (Mapanda *et al*., 2012). An understanding of N release will also help smallholder farmers in managing the diverse OR in a way to maximize the uptake of nutrients and reduce gaseous losses (Kimetu *et al*., 2006). The study focused on measuring N_2O fluxes in the field from maize plots under three OR amendments namely, maize (*Zea mays)* stover, *Calliandra calothyrsus* and farmyard manure with and without inorganic N fertilizer. The study aimed at collecting experimental data that is going to contribute to the development of solutions to improve on soil fertility in maize cropping systems and management practices.

1.2 Problem statement

Maize is one of the major staple crops in SSA serving as a source of food and as nutritional security for millions of households (Cairns *et al*., 2013). In the western region of Kenya, cultivation of this important crop is mainly done by smallholder farmers (Olwande, 2012) who obtain low yields. The low yields are due to limited access to inorganic fertilizer coupled with low soil fertility, soil moisture stress and soil degradation in smallholder farming systems. These challenges will be worsened further due to rising abiotic and biotic stresses as a result of climate change (Butterbach-bahl et al., 2013). This calls for an adoption of soil nutrient management strategies that will result to increased yields at the same time improved soil fertility, mitigation and adaptation of climate change.

However, increase in food production is one of the sources of atmospheric N_2O emissions (Mosier, 2001), though the N fertilizer fraction that transitions to N_2O (which is a potent greenhouse gas) in maize based cropping systems is not known, because it is dependent on the cropping system in terms of soil properties, climate and management activities. With the uncertainty in N_2O emission rates from different ORs, a study for maize systems in SSA is needed to investigate on the relationship between environmental and management factors that control these emissions (Chadwick *et al*., 2011). ISFM has shown a potential to utilize ORs to improve on crop yield and at the same time reduce GHG emissions in different environments on different types of soil and climatic conditions (Senbayram *et al*., 2012). However, the role of ISFM in climate change mitigation on N use has limited investigations through application of different OR amendments on soil.

A combination of inorganic N fertilizer with ORs will raise the amount of N available to the crop which may result to soil N loss through N_2O emissions (Bru et al., 2008). This shows that an understanding of N_2O emissions in the fields is complex because of diverse nature of the factors that regulate N_2O production, which include soil type and uncertain physical and chemical characteristics of the ORs (Li et al., 2013). Consequently, the extent and direction to which N_2O emissions takes place is dependent on the quality of OR and ratio of organic to inorganic N inputs applied to soil (Baggs *et al*., 2003; Frimpong & Baggs, 2010). Therefore, the interaction between inorganic N fertilizer and ORs on N emissions in the soils must also be understood. A study is therefore needed to address the problem of agricultural N_2O emissions under ISFM approaches with different types of OR amendments.

1.3 Justification

Estimation of N_2O emissions under a maize cropping system would generate data required for identification of a good nitrogen nutrient management involving the application of ORs of different qualities in maize cropping systems in SSA. Determination OR with inorganic nitrogen fertilizer that minimizes nitrogen losses due to N_2O emissions would increase nitrogen use efficiency and reduce on the costs of fertilizers. Understanding the key drivers responsible for N_2O emissions from different soil and climatic conditions is essential for the development of a good soil structure due to good soil organic matter management. Knowing the best sustainable approach to maize intensification that rely on suitable organic resources for nutrient sources will be particularly important in overcoming hunger and improve on food security of smallholder farmers.

1.4 Objectives

1.4.1 Main Objectives

To determine the relationship between nitrogen losses through nitrous oxide emission and soil nitrogen changes, under different integrated soil fertility management practices in a maize-based cropping system.

1.4.2 Specific objectives

i. To quantify and compare N_2O emissions from soils treated with selected ORs and or in combination with inorganic N fertilizer in two different sites.
ii. To determine available soil N in soils amended with selected ORs and inorganic N fertilizer.
iii. To assess the influence of applied OR and inorganic N fertilizer on maize yield and yield scale N_2O emissions.

1.5 Hypotheses

i. Application of organic amendments and inorganic N fertilizer has no effect on N_2O emissions under maize cropping systems.
ii. Addition of organic amendments and inorganic N fertilizer has no influence on available soil nitrogen.
iii. Maize yield and yield scale N_2O emissions are not affected by the organic and inorganic N fertilizer.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Integrated soil fertility Management

One of the suitable approaches to address the problem of declined agricultural productivity in Sub Saharan Africa (SSA) is the use of innovative technologies such as ISFM (Herman and Lal, 2008). However, the adoption rate of ISFM in Kenya is low due to an array of factors, which range from economic to environmental factors hindering the adoption (Okalebo *et al*., 2006; Waithaka *et al*., 2007). Economically, ORs application have negative financial returns compared to inorganic N fertilizer use due to the high costs of labor in the use of ORs inputs (Opala and Nyongesa, 2004). However, ISFM increases economic growth and helps in reducing poverty levels by increasing agricultural productivity and output (Okalebo *et al*., 2006). This is especially important in the SSA region, since agriculture is the major backbone of most households. On the environmental front, ISFM if not well managed can result to inefficient use of agricultural inputs, which can lead to reduced productivity, soil degradation and likely destruction of the environment (Gentile *et al*., 2011). However, increased agricultural intensification through ISFM helps in promoting biodiversity through the provision of ecosystem services such as food and nutrient cycling by plants and microorganisms and helps in improved soil health (Sanginga and Woomer, 2009).

ORs are an important component of ISFM, since their application improves chemical, physical and biological properties of soil, in turn enhancing the availability and uptake of nutrients by crops (Mucheru-Muna *et al*., 2014). The N and P released from ORs are in less soluble forms than nutrients released from inorganic N fertilizers. The response of the crops to the OR application will therefore depend on the nutrient deficiencies present in the soil and nutrients release from the OR. The ORs have different qualities based on their biochemical composition and as a result, when they decompose, different quantities of nutrients are released in soils (Palm et al., 2001). This reflects the dissimilarities in nutrient availability and the overall crop yield in response to the different ORs application. However, combination of OR and inorganic N fertilizer inputs has been shown to be a better management option for rural smallholder cropping system in tropics as none of these inputs is sufficiently available in large quantities (Alley and Vanlauwe, 2009). The OR available locally to smallholder farmers, apart from being affordable, could be utilized to improve the reducing soil fertility in the long-term (Mucheru-Muna *et al.*, 2014). Therefore, the nature of benefits realized from the combination of inorganic and organic nutrients sources needs further study on their interaction to the environment (Mtambanengwe *et al.*, 2006).

2.2 The use of Organic Resources to Improve Soil Fertility

ORs generally represent a major source of nutrients compared to the inorganic fertilizers in soil fertility maintenance and improvements, particularly in East Africa. Most of the ORs used by farmers are crop residues and animal manures (Opala and Nyongesa, 2004). The main limitation farmers face on the use of ORs is that the application rates depends on the availability of sufficient quality and quantities of ORs for specific crops (Mtambanengwe *et al.*, 2007; Palm *et al.*, 2001). Another challenge facing farmers is the varied nature of ORs nutrient content depending on the climate, soil properties, and production systems where they have been grown (Palm *et al.*, 2001). Most of the ORs used by the farmers have low nutrients supply, especially in terms of N and P (Okalebo *et al.*, 2006). This means that large quantities of ORs must be provided to meet the nutrient requirements of the crops. In addition, many of the ORs compete with other uses within smallholder farms, as a source of livestock feeds and fuel, making it difficult to improve soil fertility in the region. In the recent past, research on ORs has been increased and its focus has been shifted on the use of ORs with inorganic N fertilizer as an intervention aiming to increase nutrient release from the ORs to meet the nutrient requirements of the crops (Vanlauwe *et al*., 2015).

The FYM is the most common OR used by the smallholder farmers in the East African region (Snijders *et al*., 2008). The use of FYM in maize production is typical for the SSA smallholder farmer, in terms of wealth in agriculture (Hickman *et al*., 2014). This is because cattle are important animals in the farming systems in the region, supplying the bulk of the amounts and abundance of nutrients that are released and transferred to the soils (Rufino *et al*., 2006). Due to the diversity of livestock production systems, it is difficult to determine the quality and quantity of nutrients from the FYM (Lekasi *et al*., 2003). Many studies have indicated that quantities of FYM that are available from smallholder farms are not enough to meet the nutrient demands of the crops (Opala and Nyongesa, 2004). However, some studies have also found that the production of FYM in some areas can be 495 mg N/kg under good management (Lekasi *et al*., 2003). Nevertheless, there is scarcity of the FYM to meet demand from crop farmers, which has led to studies on how to increase the quality and quantity of the FYM under the different livestock systems. Importantly, the emphasis has been put on better design storage facilities that minimize losses after excretion, to avoid contamination and assist in minimal N loss (Paul et al., 2009).

2.3 The Soil Nitrogen Cycle

Nitrogen is a dynamic element that is transformed biochemically or chemically through a complex web of reactions known as the global N cycle (Galloway, 2003). The N is the main limiting soil nutrient for primary food production among the microbial heterotrophs. Different N compounds originate from inorganic fertilization, animal waste, atmospheric and symbiotic N fixation, and plant residue incorporation to the soil (Farrell *et al*., 2014). Within the N cycle, >99% of all the N exists as unreactive N_2 gas. The remainder is the reactive N which includes all biologically, photochemically, and radiatively active N compounds in the atmosphere such as inorganic reduced forms (e.g., NH_3 and NH_4), inorganic oxidized forms (e.g., NOx, N_2O, and NO_3), and organic compounds (e.g., urea). The reactive forms which are on the increase in the environment due to anthropogenic activities are important because of their function to life and have also been shown to impact on the environment (Galloway, 2003).

The soil N cycle includes the transformations of organic to inorganic N forms in a process referred to as N mineralization, and in the transformation of inorganic to organic forms in a process referred to as immobilization and these processes are mediated by soil microbes (Gentile et al., 2008). In the soil N cycle the N enters the system through anthropogenic inputs such as inorganic and organic fertilizers (Charles et al., 2017). Inorganic N fertilizer contributes to 30% of the total N used for crop production with the ORs contributing to 35% of the total N (Charles *et al.*, 2017). Potential N loss is directly related to inorganic N, and it is of importance when NO_3^--N, which is loosely held increases in the soil profile (Cassman *et al.*, 2002). On the other hand, N can also be lost from the soils through denitrification of NO_3 to N_2O or N_2, leaching of NO_3, or volatilization of NH_3. The anthropogenic activities have adversely affected both the global and soil N cycle. Anthropogenic activities such as N fertilizer application in agricultural systems is one of the main significant drivers of N_2O emissions (Koehler *et al.*, 2009). As a result of the projected increase in N fertilizer use, reactive N forms are on the increase in the environment which leads to different environment impacts. Emissions from reactive N including N_2O are possibly the most environmental damaging because of their potent nature in the atmosphere (McElroy and Wang, 2005).

2.4 Nitrous Oxide and Greenhouse Gases

Nitrous oxide is one of the three main greenhouse gases which include carbon dioxide (CO_2) and methane (CH_4) (Mosier et al., 2005). These gases are important because they allow the incoming shortwave solar radiation to the atmosphere then absorb outgoing longwave radiation, resulting to the trapping of heat in the atmosphere (Mosier et al., 1996). The GHGs have different characteristics due to their effect on global warming potential emanating from their lifespan, concentration and ability to absorb longwave radiation in the atmosphere. For example, CO_2 with a concentration of 385 ppmv is the most abundant contributing approximately 60% of the anthropogenic GHG effect (Mosier et al., 2005). CH_4 which contributes to about 15% of the anthropogenic GHG effect, have a concentration of 1800 ppbv in the atmosphere, but it is 21 times more effective at trapping heat than CO_2 (Lindau et al., 1993). N_2O contributes approximately 5% of the anthropogenic GHG effect. Although its concentration in the atmosphere is only 317 ppbv, it has a global warming potential that is 300 times that of CO_2 due to its longevity in the atmosphere (approximately 100 yr) and high capacity for absorbing longwave radiation (Ravishankara et al., 2009). N_2O also demonstrates other adverse environmental effects beyond affecting global warming as it is involved in the production and destruction of ozone, and generation of acid rain (Fenn et al., 2003).

2.5 Pathways of Nitrous Oxide Production

Soils are the major sources of N_2O production to the atmosphere (Charles et al., 2017). There are many processes leading to N_2O production, which is summarized by (Butterbach-bahl et al., 2013). N_2O can also be a result of reduction of NO_3^- in processes such as co-denitrification and in dissimilatory NO_3 reduction to NH_4 (Hickman *et al*., 2014). But the main natural processes that produce N_2O in the soil within the N cycle are microbial nitrification and denitrification as discussed below.

2.5.1 Nitrification

Nitrification is the aerobic microbial oxidation of NH_4 to NO_2 and then to NO_3 with N_2O gas as a byproduct (Paulino et al., 2010). This process is dominated by autotrophic organisms requiring oxygen (O_2), CO_2, and NH_4 as substrate for survival, it can also be undertaken by heterotrophic nitrifiers which utilize soil organic carbon (Wrage-Mönnig et al., 2018). N_2O production during nitrification is as a result of two processes: chemodenitrification and nitrifier denitrification. In chemodenitrification, N_2O production is due to abiotic transformations of nitrification intermediates, especially NO_2. During nitrifier denitrification, nitrifiers use NO_2 as an electron acceptor producing N_2O (Wrage-Mönnig et al., 2018).

There are several environmental factors that affects the rates of nitrification which includes; soil moisture, temperature, substrate availability, pH and O_2 availability (Dick et al., 2006). Soil moisture is a major soil factor that affects soil gas emissions, because it controls most of the microbial activity by regulating available O_2 to soil microbes (Butterbach-Bahl *et al*., 2013). The nitrifying bacteria use O_2 that is available in soil pores and thus emissions from nitrification occur predominantly in soils with less water filled pore space (WFPS). According to Mapanda *et al*. (2012) the distribution and amount of rainfall strongly influences the contribution of applied N to N_2O emissions, as compared to maize productivity and N uptake. Overall, WFPS of up to 60% results to an increased nitrification rates (Griffin et al., 2002). WFPS above 60% leads to a decline in availability of O_2 and CO_2 substrate for nitrifiers as a result of severely restricted diffusion rates (Weier et al., 1993).

Another important factor for soil N_2O emissions is soil temperature (Oertel *et al*., 2016). N_2O production rates are low at soil temperatures < 5 °C as the nitrifier activity is inhibited, and increases with an increase in temperature. However, there is an optimum temperature range within which microbial activities takes place. Increased soil temperature results in a high soil respiration and higher emissions rates due to an increased microbial metabolism, a positive feedback response. Substrate availability is highly affected by organic N mineralization rates and N fertilizer application. As substrates increases the production of N_2O also increases (Zebarth et al., 2008). Additionally, pH regulates N_2O production from the nitrification process. Soil pH below 4 inhibits nitrification and the optimum range has been shown to be between pH ranges of 6 to 8 (Azam et al., 2002).

2.5.2 Denitrification

Denitrification is the anaerobic microbial reduction of NO_3 to N_2. The N_2O is an intermediate product (Senbayram et al., 2012). The microbes responsible for denitrification are the facultative anaerobes denitrifiers which make use of NO_3 as terminal electron acceptors in the absence of O_2 (Burton et al., 2008). As a result, denitrification takes place in high soil water and NO_3 contents and in reduced diffusion rates of O_2 into the soil. Additionally, denitrification is dependent on oxidizable C availability in the soil hence heterotrophs are the major organisms responsible for the process to take place (Šimek et al., 2002). Denitrification has been shown to increase in soils rapidly in WFPS exceeding 70% due to low O_2 concentration (Zhang et al., 2012). Optimum N_2O is produced with low O_2 concentrations leading to a reduction in NO_3. A decline in O_2 concentration in soil due to a rise in soil respiration and due to increase in soil temperatures forces N_2O emissions (Butterbach-Bahl *et al*., 2013). A study done by Zhang *et al*. (2012) showed that WFPS and soil temperature were the main contributors of the large yearly variation in N_2O

emissions. It is therefore important to note that soil temperature and moisture constitute the main causes of denitrification (Butterbach-bahl *et al.*, 2013). Therefore, the rainfall distribution needs to be considered in the emissions factors determination when providing annual GHG inventories at national levels (Mapanda *et al.*, 2012).

Denitrifiers are adaptable to a wide range of soil pH but are most active between pH 7.0 and 8.2 whereas rates of N_2O production mostly increase at pH < 5 to 6 (Šimek et al., 2002). As nitrification also produces NO_3 which is a substrate of denitrification, meaning that denitrification is affected by rates of nitrification in conditions that favor both processes (Wrage-Mönnig et al., 2018). Nitrification and denitrification have been shown to occur at the same time within the same soil profile (Renault and Sierra, 1994).

2.6 Nitrous oxide Emissions under cropping systems

It is well understood that N_2O fluxes resulting from agricultural fields are highly affected by the rate of N fertilizer application (Zhang *et al.*, 2012). Li et al. (2013) reported cumulative N_2O emissions to be different with the type of fertilizer used, and application rate had a slight influence on the total cumulative N_2O emissions per treatment alone. Bru *et al.* (2008) working in a sorghum field with N fertilizer application, observed that plots with high fertilizer input had the highest N_2O emissions. They also found a gradual increase in fluxes of N_2O after a fertilizer application. As a result, using inorganic N fertilizer to increase crop production in nearly all cropping systems, will emit N_2O at high rates. Though, the exact amount of N_2O emission emitted will vary subject to cropping system, fertilization intensity and other factors (Kraus *et al.*, 2016). The timing of fertilizer, type, rate, and placement are important management practices affecting N_2O emissions, though the type of fertilizer is unpredictable as a sole factor for reducing emission (Millar *et al.*, 2010). The timing of N fertilizer application in response to plant demand is important in determining N availability and strongly N_2O fluxes from maize planted in rows. Usually, N demand by the crop is low at the beginning of growing season, increasing rapidly at vegetative stage and drops sharply at crop maturity (Millar *et al.*, 2010).

2.6.1 Nitrous oxide emissions under ISFM practices in maize-based cropping systems

Inorganic fertilizers and ORs provide compounds of NH_4^+ and NO_3^- that initiate the process of nitrification and denitrification (Venterea *et al*., 2012). Consequently, N availability in soils has been identified as a primary driver of these process (Kimetu *et al.*, 2006), occurring when ORs and N fertilizers are applied to the soil (Conrad, 1996). When N enters the soil, many processes take place that can lead to soil N_2O emissions. Most of the agricultural activities tend to encourage most if not all of the processes, and within each of the processes there is more than one pathway for N_2O production (Venterea *et al.*, 2012). Microbial activities in the soil are usually affected by the limitation in C. This is supported by the general argument that C: N ratio mainly determines the mineralization rate of ORs added to the soil. Therefore, plant residue incorporation enhances N_2O emissions and the enhancement is quantitatively reliant on C: N ratio of the ORs. High amount of N_2O emissions is generally associated with lower C:N ratio of ORs incorporated (Huang *et al.*, 2017). A study carried out by (Pugesgaard *et al*., 2017) reported that crop residues are important sources of N_2O where N is limited in the systems. The study showed that N_2O mitigation strategies should aim at slower decomposing crop residues, with emphasis on the balance between anaerobic and aerobic decomposition. The results showed a significant relationship between N_2O emissions and crop residue biomass and that the effect of crop residue can be estimated (Pugesgaard et al., 2017). According to Zhang *et al*. (2012) application of inorganic N fertilizer and ORs could largely lead to a reduction in fertilizer induced N_2O-N from maize plots. This is because OR such as maize stover residues will lead to N immobilization due to its high C: N ratio. The maize residues will result in N immobilization when inorganic N is added, although, immobilization is dependent on the amount of C readily available in the maize residues (Gentile et al., 2011). This shows that OR and inorganic N fertilizer interaction can be explored to benefit crops to match the N nutrient availability and timing with their demand and in the long-term reduce adverse environmental effects.

Among the factors that determines the rate of N transformations and release to the mineral pool are the quality and quantity of ORs, which can also be manipulated to determine the N immobilization and timing of N release available from the different ORs (Sarkodie-Addo *et al*., 2003). Temporal immobilization and slow release of N for crop uptake has been shown to be key in reducing N loss to the environment through GHG emissions and leaching from ORs application (Gütlein et al., 2017). Many of the existing studies have only looked at soil N_2O emissions following sole application of OR and inorganic fertilizer (Baggs *et al*., 2003), and have shown that the degree of N_2O emissions response depends on N fertilizer and OR type. Baggs *et al*. (2003) found that a combination of OR and inorganic N fertilizer, showed no interactive effects on N_2O emissions depending on the OR type and the cultivation technique. Effect of the OR and inorganic N fertilizer application on N availability and N_2O emissions, and their possible interactions have not yet been fully looked at (Baggs *et al*., 2003). Research is therefore required to examine the effects of the two organic and inorganic N fertilizer types on N_2O fluxes and the mechanism involved in their interactions, to help to mitigate soil N_2O emission from agriculture. Charles *et al*. (2017) showed that the rate of decomposition and N release to the soil and GHG emissions from soils fertilized with ORs are influenced by soil texture. This means that to achieve optimum OR quality and quantity that can match the crop demand without N being lost through emissions, soil textural classes must be understood and how they interact with inorganic N fertilizer and ORs on N emissions.

2.7 Available Soil nitrogen changes under different Organic Resources

Most of the nutrients from the ORs are in organic form, thus mineralization is required for the nutrients to be available to crops. The OR quality controls the mineralization and immobilization, through C: N ratio as it regulates patterns and rates of N release to crops through decomposition rates (Huang *et al*., 2017). The mineralization of ORs in the soil results to an increase while immobilization results to a decrease in available soil N. Generally, NH_4 is the immediate product of mineralization (Huang *et al*., 2017). Studies have shown that materials with C: N ration <25 stimulate mineralization while those >25 have been shown to stimulate immobilization. For example, when FYM and CL of low C: N ratio <20 is added to the soil, microbes obtain N as a result of mineralization, thus available soil N increases. It is for this reason FYM and CL are recommended to be used as a fertilizer. In contrast maize stover with a C: N ration >50 when added to the soils takes time to degrade, since maize stover do not have sufficient N for microbes to make their own proteins, resulting to immobilization leading to a decrease in available soil N due to the competition of N by the crops (Gentile et al., 2008). As other microbes are consuming nitrogen rich ORs resulting to mineralization another within the same soils might be consuming ORs rich in C but low in N resulting to immobilization. Therefore, it is recommended for low quality ORs to be applied in combination with inorganic N fertilizer to ensure sufficient N availability to maize plants (Mtambanengwe *et al*., 2006). This calls for an understanding of the OR nutrients supply patterns, to assess the potential capture by the crops (Chikowo *et al*., 2013).

Numerous studies on the decomposition of ORs and N release pattern in the tropical cropping systems have been presented in a review by Vanlauwe *et al*., (2010). However, the drivers responsible for the decomposition and nutrient supply have not been fully understood. The interplay between abiotic and biotic factors such as moisture, temperature, OR quality, texture, biological activities and pH require further investigations (Nieder and Benbi, 2008).

High available soil N have been reported to be high in the beginning of the season as a result of addition of ORs. Then the concentration gradually decreases towards the end of the season in response to the crop N demand and as a result of leaching below the crop root zone depending on the rainfall intensity. Potential N loss is directly related to inorganic N, and it is of importance when NO_3^--N, which is loosely held increases in the soil profile (Cassman *et al*., 2002). On the other hand, soil NH_4^+-N is protected from the cropping systems since its strongly held by the soil colloids (Kimetu *et al*., 2006). However, determination of available soil N has not been fully covered because of the different practices in crop management at different locations resulting from variations in soil types and rainfall regimes. Whereas N balances under different maize cropping systems have been carried out, few studies have incorporated different ORs contributions. This calls for studies to explore and understand N dynamics in low input systems under ISFM practices such as in SSA where mineralization of N is done in situ and look at its influence on crop growth (Masso et al., 2017).

The OR quality has been given more emphasis because it can easily be manipulated. Generally, ORs with high % N >2.5%, low lignin <15% and polyphenol <4% are considered to be of a high quality as they decompose faster to release nutrients than low quality ORs which immobilize to release nutrients slowly during the decomposition (Mtambanengwe *et al*., 2006). This led to the development of the Organic Resource Database (ORD) containing OR quality parameters ranging from C: N, lignin, polyphenol and macronutrients from around 300 species of plants in the tropics (Palm *et al*., 2001). The studies on OR management and classification came up with four classes

(Palm *et al*., 2001). Class I ORs are high quality with N >2.5%, lignin <15% and polyphenols <4%. They decompose rapidly to release nutrients, and thus are highly advised to be applied to soils directly. These ORs increase short term N supply and may result in low NUE if the total N applied is high. Class II are intermediate quality ORs with N >2.5%, lignin >15% and polyphenols >4%. They have high decomposition rate, resulting in a faster release of nutrients, consequently, are highly recommended to be applied to soils. The class III ORs have low N content and are also considered to be of intermediate quality with a slow release of nutrients due to its biochemical recalcitrance as a result of lignin <15% and polyphenols <4% contents (Gentile et al., 2011). The class II ORs decomposition is usually delayed and the potential to improve the maize growth by other than provision of N is higher compared to the ORs of class I and III. Usually class III ORs have delayed decomposition due to a lack of N resulting in temporarily immobilization of N thereby leading to a competition for N by the crops. Although in the long-term the class III ORs result in a substantial improvement in NUE. Therefore, Class II and III have been recommended to be applied and perform better when mixed with either inorganic N or class I ORs. Consequently, higher quality ORs in class II such as CL will mineralize faster in soils compared to low quality ORs in class III such as MS. However, mineralization and nutrient release from the low quality ORs can be altered through incorporation of inorganic N fertilizer with the OR (Vanlauwe *et al*., 2010).

FYM does not follow any of the trends in OR classes and thus is in a separate class of ORs that have decomposed before application on soil. According to Blanchet *et al*. (2016) FYM has been shown to improve soil physicochemical and moisture conditions, and emphasis on a criteria on FYM quality to be linked to nutrient release and crop performance should be recognized based on the chemical qualities of the FYM. There is also a need to identify the appropriate timing of FYM application to the soil, since the quality of FYM and its nutrient release patterns in arable lands has been a major challenge resulting from its handling, storing and its original source (Zingore *et al.*, 2008).

2.8 Effects of Organic Resources and inorganic N fertilizer on Maize yields and yield scale emissions

Maize is grown globally under different types of soils with a relatively higher production potential than other cereal crops (Shiferaw *et al*., 2011). It is one of the major staple crops in SSA serving as a source of food and as nutritional security for millions of smallholder rural farmers (Cairns *et al*., 2013). However, currently, maize yields per hectare in the region have stagnated and are below its agro- ecological production potential (Bationo, 2003). Soil fertility depletion has been identified as the major biophysical cause of food insecurity in SSA. With the increasing population, productivity must be raised to meet the looming challenge of food security. In this regard, appropriate food production innovations should be availed to the farmers, since maize crop uses large quantities of nutrients from the soil, leading to further nutrient depletion (Kimani *et al*., 2004; Tittonell *et al*., 2010).

Some studies have shown that the maize yield in the short term is mainly determined by the quality of ORs, with high quality mineralizing faster than low quality ORs (Alley and Bernard, 2009). A good measure of soil fertility is the SOM content which contributes to positive soil properties such as CEC, nutrient stocks, soil moisture and aeration which are properties that improve crop yield. SOM also releases N which is better synchronized with the plant N demand than that of inorganic N fertilizer resulting to a better N use. Therefore, combination of inorganic N fertilizer sources with ORs high in N may be a better remedy compared to both sole inorganic N fertilizer and ORs application to achieving high yields. The inorganic N fertilizer have been shown to have an additive effect when applied with different OR qualities. Numerous studies have obtained high maize grain yields from a combination of OR and inorganic N fertilizer inputs compared to inorganic N fertilizer (Kimetu *et al*., 2004; Mucheru-Muna *et al*., 2007). However, with continued maize production over the prolonged period, there were no significant differences in maize yields between sole inorganic and organic fertilizers (Kihanda *et al*., 2006; Kimetu *et al*., 2008). The authors assumed that this was associated with the level of soil degradation and the amount of response depending on the type of OR added (Kimetu *et al*., 2008). On the other hand, OR like FYM in farms introduces some heterogeneity in terms of C and N content, which affects our ability to evaluate its effects on maize yields independent to soil type (Lekasi et al., 2003).

A change in crop production usually affects crop yield (Gao and Bian, 2017). As a result of this, it is not yet known which crop management strategy is more effective in balancing between N_2O emission mitigation at the same time increase crop yield (Hickman et al., 2014). A practice to reduce N_2O emissions can either result to an increase or reduction in maize yield. For example, a replacement of inorganic fertilizer with OR can reduce N_2O emissions but could result to a reduction in crop yields compared to sole inorganic fertilizer application (Hui et al., 2017). A combination of OR with inorganic N fertilizer can mitigate N_2O emissions but could either increase or reduce crop yields. Therefore, an understanding of both crop yields and N_2O emissions is important in optimizing cropping systems (Gao and Bian, 2017). Even though many studies have looked at different cropping systems impact on N_2O emissions, few studies have linked the N_2O emissions to yields (Kurgat et al., 2017). Some studies have suggested that assessment of cropping systems per unit yield referred to as yield scale is beneficial in the sustainable intensification of cropping systems and in N_2O emissions mitigations (Scheer et al., 2012).

2.9 Chamber Techniques

Chamber techniques use bases and lids placed atop the soil to estimate soil respiration exchange with the atmosphere (Kiese, 2010). The use of chambers in soil gas respiration ensures change in gas concentration can be detected easily without the disturbance of the soils and the natural processes controlling responsible for emissions (Rochette and Hutchinson, 2005). This technique is relatively inexpensive to build as it entails simple fabrication and can be widely used in a range of field conditions due to their portability and sensitivity to low emissions rates. It is for this reason that the chamber technique has been used for more than eight decades and their wide acceptance in N_2O and trace gas emissions(Rochette and Bertrand, 2006).

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Description of the study sites

The study was conducted on two farms where the International Institute of Tropical Agriculture (IITA) has been conducting long-term maize crop trials on different ORs integrated with and without inorganic N fertilizer since 2005 based in Siaya and Busia Counties, Western Kenya. In Busia, the experiment was set up in Lukolis division, Aludeka location ($0^0$34' 28.8''N; 34^0 11'26.8'E), in the eastern part of Lake Victoria. The area is in lower midland 2 (LM2) agro-ecological zone at 1200-1350 m above sea level. Soils are classified as Orthic Acrisols (Jaetzold *et al.*, 2005), which are well drained and are of low fertility**.** The physicochemical characteristics include silt loam (31% sand and 13.39% clay) with an average pH of 5.4 and soil organic C and total N content of 0.55% and 0.05% in top 15 cm. The rainfall pattern in the area is bimodal, with an annual rainfall of 1450-1650 mm (Jaetzold *et al*., 2005). Long rains (LR) start in March and end in June, while the short rains (SR) last from October to December**.** The average long-term mean monthly maximum and minimum temperature is 22.3^{o}C and 21.4^{o}C. Maize (*Zea mays L.*) is the dominant food crop grown in the area, intercropped with common beans (*Phaseolus vulgaris L*). Other crops grown in the area are cassava (*Manihot esculenta),* sorghum (*Sorghum bicolor*), finger millet (*Eleusine coracana*), pigeon peas (*Cajanus cajan*) and bananas (*Musa spp. L.*). Vegetables and fruits are mostly grown for home consumption. Soil fertility measures undertaken in the area is by use of inorganic and organic fertilizers (Jaetzold *et al.*, 2005).

In Siaya County, the experiment was set up in Maranga location in Sidada village ($0^0$08' 33.9''N; 34^0 25'15.7'E) located in the Lower Midland 1 (LM1) agro-ecological zone, at an altitude of 1300-

1500 m above sea level. Soils are dystric Nitisols, which are well drained, very deep, red to dark red and friable clay soils. Soil physicochemical characteristics are silty clay soil (0.1% sand and 55.69% clay) with an average pH of 4.9 and soil organic C and total N content of 2.08% and 0.18% in top 15 cm. Rainfall in the area is bimodal, with an annual rainfall of 1500-1900 mm (Jaetzold *et al*., 2009). The LR occurs from March to June, while SR occurs from October to December. The average long-term monthly maximum and minimum temperature in the area is 21.8^{0}C and 20.9^{0}C, respectively. Maize (*Zea mays L.*) is the dominant food crop grown in the area, intercropped with common beans (*Phaseolus vulgaris L*). Other crops grown in the area are sweet potatoes (*Ipomea batatas (L.) Lam*) and cowpeas (*Vigna unguiculata*). Poor quality and degrading soils are the most common problem in this area. Soil fertility enhancement is therefore critical in this area because soil nutrients have been severely exhausted through continuous cropping without replenishments (Jaetzold *et al*., 2009). Improving soil nutrients will result in better crop yields, especially for the main staple crop, maize.

3.2 Experimental design and field management

This study was conducted to examine the effect of OR application with or without inorganic N fertilizer on N_2O, from maize plots. The OR type was represented in the main plot (6×12 m), whereas the addition of inorganic N fertilizer was the sub-plot (6×6 m) (Figure 1). Replication was established through experimental blocking. Blocks were separated with a buffer strip of 1m. Within each main plot, inorganic N fertilizer was added with the OR in one subplot, while OR was applied without inorganic N in the other sub-plot. Three OR amendments were used in this study namely; *Zea mays* stover, *Calliandra calothyrsus* and farmyard manure (FYM) giving a total of eight treatment combinations as follows;

1. Control without inorganic N (CON –N)

2. Control with inorganic N (CON +N)
3. *Calliandra carothyrsus* without inorganic N (CL -N)
4. *Calliandra carothyrsus* with inorganic N (CL +N)
5. Farmyard manure without inorganic N (FYM -N)
6. Farmyard manure with inorganic N (FYM +N)
7. Maize stover without inorganic N (MS -N)
8. Maize stover with inorganic N (MS +N)

All ORs were incorporated through shallow tillage during planting at a rate of 1.2t C/ha/yr with C equivalent content on a dry matter basis. All plots were applied with muriate of potash (MOP) and triple superphosphate (TSP) as basal fertilizers at planting at the rates of 60kg K/ha and 60kg P/ha, respectively. Split application of urea was done in all +N plots at a rate of 120kg N/ha. Two thirds of urea were applied at planting and a third during top dressing 35 days after planting. Maize variety DH 35 was sown manually on 13th and 17th March 2018 in Sidada and Aludeka, respectively at a spacing of 25 cm within rows and 75 cm between rows. Land preparation by hand ploughing was done on 6th -9th February and 6th March 2018 at Aludeka and Sidada, respectively. Two maize seeds were placed in per hole and thinned to one plant per hole two weeks after emergence when first weeding was done on 10th and 18th April 2018 at Sidada and Aludeka, respectively. The second weeding was done six weeks after planting on 5th and 6th May 2018 at Aludeka and Sidada, respectively. There was another third weeding done at Aludeka on 29th May 2018. Maize harvesting was done in 1st and 5th July 2018 at Aludeka and Sidada, respectively. All field managements were done according to the farmers' practices, so the trial reflects conventional management practices.

3.3 Generation of organic resources

Farmyard manure was acquired locally from farmers' farms at Luanda which is close to the experimental site. Cattles reared by the farmers are mostly of the local breed which falls under same livestock management component representatives of the western region. The animals are dominantly fed on grass. The FYM was heap stored as is the local practice in the region before transferred to the fields, therefore it represents farmers' quality manure. No bedding material was added to the pens. The FYM produced was therefore a mixture of dung and urine.

Calliandra was grown on fields adjacent to the experimental field plots established by the IITA at Sidada site. The leaf and shoot biomass were harvested at the beginning of the planting season and incorporated into the fields during planting and inorganic fertilizer application.

Maize stover cuttings were collected from previous maize harvest and were kept air dry and stored until incorporation at the beginning of the growing season. ORs were analyzed for P, C, and N contents at ETH in Zurich right before their application (Table1).

3.4 Gas sampling and auxiliary measurements

Static chambers made of plastic were used for gas sample collection. At each site, there were 48 permanent frames (27 × 37.5 ×10 cm, length ×width × height) - two per sub-plot - inserted to about 7 cm depth into the soil prior to sampling. The two frames were arranged to represent the entire plot adequately. One frame was placed between two maize plants within the row, and another frame was placed between two maize rows. The frames remained in place throughout the growing season. During gas sampling, plastic chamber lids (27 × 37.5 × 11 cm) fitted with rubber seals were placed on top of the frames and closed air-tight using metallic clips to make the chamber gas tight.

Gas sampling started on 6th March and ended on 5th May 2018. Gas samples for determining of soil GHG fluxes began a day before OR incorporation, eight times after OR planting from 13th and 17th March at Sidada and Aludeka respectively. Samples were collected thrice in the period from 28th March to 15th April when inorganic N fertilizer was applied. Gas samples were collected from 8.00 am to 1 pm, for a total of 20 sampling events at each site.

On each sampling occasion, four gas samples were collected from septum-equipped ports at one side of the tightly closed chamber lid at an interval of 0, 15, 30 and 45 min immediately after the lids were mounted on top of the fixed frames. One of the chambers was fitted with a digital probe thermometer (TFA- Wertheim) for measuring air temperature inside the closed chamber. A battery-driven fan inside each chamber for mixing of air to obtain a homogenous gas sample of the headspace air and a vent with about 1m long tube was connected to avoid air-pressure build-up and at the same time preventing air-influx (Rochette and Bertrand, 2007)**.** The gas samples were collected using a 60ml Polypropylene syringe (Omnifix® BRAUN) through a septum sealed sampling port using the pooling method as described in (Arias-Navarro *et al.*, 2017). Gas samples from two chambers within one subplot were mixed in the syringe to obtain a homogenous sample, 15ml injected immediately to an evacuated 10 ml vial with a septum and aluminum crimp seal and 45ml flushed out using a needle (Beckon Dickinson, 23G 1''-Nr. 16, 0.6 * 25mm).

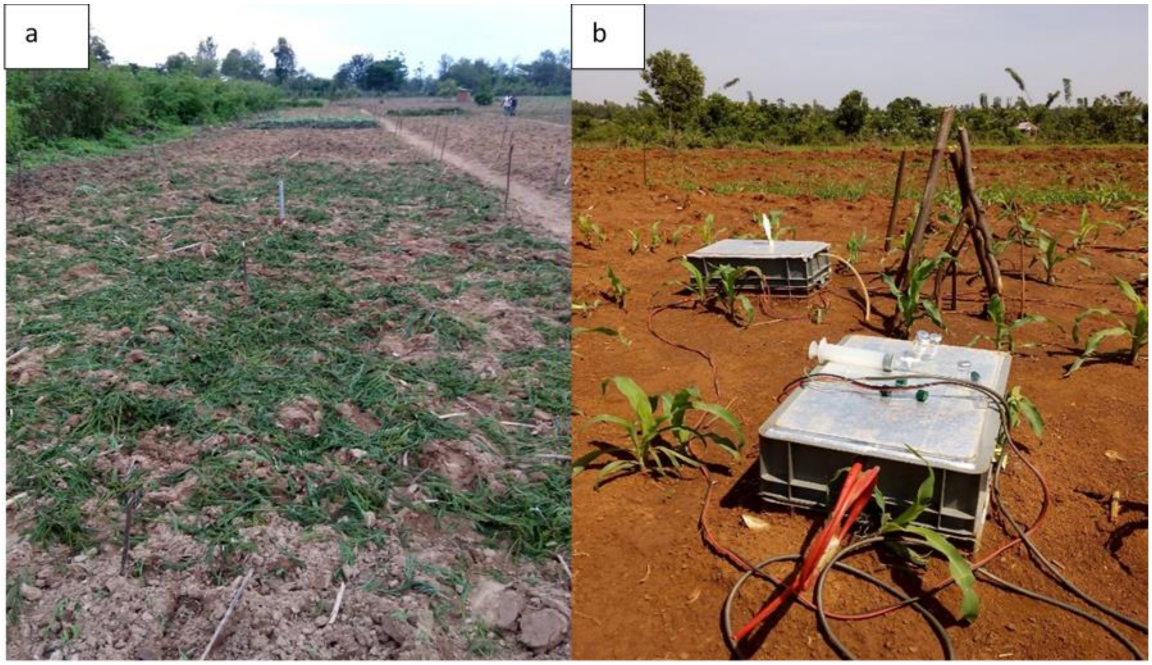

Figure 1. a) Organic resource incorporation at Aludeka b) manual chambers for gas sampling at Sidada

Soil temperature was recorded at a vertical depth of 5cm per plot in each sampling plot using a digital Pro-Check sensor (Decagon Devices). Atmospheric pressure was taken once during the study period and recorded using a Digital Atmospheric pressure gauge (BY-2003P-Shanghai Yiou Instrument Equipment). Daily soil water content in each sampling plot at a depth of 5 cm in each sampling plot was measured using (10HS automatic moisture sensors Decagon devices, Pullman WA USA) connected to a data logger (Em50-Decagon).

The gas samples were analyzed for N_2O concentration using a GC (SRI Institute, model 8610C) at Mazingira Centre, International Livestock Research Organization (ILRI) in Nairobi. The GC analytical method is described in detail by (Rosenstock et al., 2016)**.**

Daily fluxes were calculated by regressing observed headspace changes in N_2O concentration in gas against the chamber closure time for each sampling date independently after accounting for air temperature and pressure. The calibration was done by comparing the peak areas of gas samples to the peak area of standard gas with known N_2O concentration**.** The GC minimum detection limit was 1.42 $\mu gN_2O\text{-}N\ m^{-2}\ h^{-1}$ and fluxes below this detection limit were set to zero according to (Parkin et al., 2012). The cumulative N_2O fluxes were obtained by calculating the area under the flux-time curve and summing the results while assuming linear changes in measurements between time intervals (Wanyama et al., 2018).

3.5 Soil sampling and Organic Resource analyses

3.5.1 Mineral N

Soil samples for mineral N determination were taken from each plot on three occasions during the study period: (a) before land preparation and first inorganic N fertilizer application, (b) a week after second inorganic N fertilizer application, and (c) after harvest. Samples were collected using a soil auger at a depth of 0-15 cm. Ten hand push-probe samples were collected across both diagonals of the plot, composited and put into one composite sample zip-lock bag per plot to represent a replicate treatment plot. The samples were stored in a cooler box and transported to Mazingira Centre at ILRI within 24hrs of sampling for analysis.

Twenty grams of soil were extracted with 100 ml 2M KCL at room temperature. After extraction, samples were centrifuged at 3000 rpm for 10 minutes and analyzed spectrophotometrically to determine NO_3^--N and NH_4^+-N (Hood-Nowotny *et al*., 2010; Aranguren *et al*., 2018).

3.5.2 Total P

To determine total P in soil at Sidada, 200 mg of dry soil were subsampled and filled into glass tubes and weights recorded. At Aludeka a 250 mg soil subsample was taken to enable a better detection. For the OR samples, 140 mg (CL and MS) and 180 mg (FYM) of residues was weighed in glass tubes. For analysis 4.4 ml of digestion mix containing 30% H_2O_2, Se-powder, Li_2O_4S and

36N-concentrated H_2SO_4 was added to the soil and ORs as described in (Anderson & Ingram, 1993) and the mix processed in digestion block as follows:

i. Digestion at 360°C for 2.5 h
ii. Cooling down to room temperature

The digested mix was then filled up to 10 ml with millipore H_2O, shaken and subsampled.

The measurement was conducted by applying the malachite green method using Malachite reagent 1(R1) and reagent 2 (R2) according to (Ohno & Zibilske, 1991).

After shaking, 0.4 ml or 0.7 ml or 0.3 ml sample was mixed with 2ml of millipore H_2O and each 0.4 ml of R1 and R2. Test measurements showed lower P concentration and difficulties in sensitivity for soils with higher sand content in Aludeka. Thus, 0.7 ml of samples were taken for these soils and 0.4 ml for the Sidada. 0.3 ml were taken from the OR samples.

Calibration curves were made with blanks accordingly (0.4 ml blank or 0.7 ml or 0.3 ml, respectively). The reagent-sample mix was let to rest for one hour before measuring. The colorimetric measurement was then done with a spectrometer (VWR Visible spectrometer, V-1200) at a wavelength of 610 nm. Total P concentrations in samples from Aludeka 2005 were measured with another measurement device (Shimatzu UV-1800) due to very low P concentration and therefore insufficient sensitivity of the spectrometer as described above. Calibration curves were made using millipore H_2O. 1ml sample was mixed with 1ml millipore H_2O and both 0.4 ml M1 and M2. The mix was let rest for one hour and measured at wavelength of 610 nm.

3.5.3 Total C and N analysis

The total C and N analysis of both soil and OR samples was conducted using a *CHN628 Series Elemental Determinators* equipment (LECO-Corporation, 2012). Soils were subsampled to 200 and 250 mg for Sidada and Aludeka, respectively. For ORs, between 100 to 150 mg were weighed, and for FYM 200 mg were weighed and enclosed in a capsule. The N and C contained in the capsules was combusted by oxygen through oxidation to NOx- and CO_2, respectively. NOx was then reduced to N_2 and detected as N content and CO_2 as C content (LECO-Corporation, 2012).

3.5.4 pH analysis

The pH analysis of soil samples was determined using 10 g of dry soil mixed with 25 ml of millipore H_2O. The mixture was shaken for 24h at speed of 144 rpm. After settling for about three hours, pH value was measured using a pH-electrode.

3.6 Yield scale Emissions

With the assumption that the 2-month sampling period covered major peaks in N_2O emissions induced by management and environmental condition during the LR season, the yield scale N_2O emissions were estimated using the cumulative N_2O emissions over this period and the yield data:

Yield scale emissions (g N kg^{-1}) = $\frac{N_2O\ emissons\ \ (kg\ ha^{-1})}{Grain\,Yield\ (Mg\ ha^{-1})}$

3.7 Statistical analyses

Data on mean N_2O fluxes, CUM N_2O fluxes and soil properties between treatments were analyzed using analysis of variance (ANOVA) in a general treatment structure (in Randomized Blocks) using Genstat Statistical Software Version 15 (VSN International, 2012). Statistical differences were tested at $\alpha \leq 0.05$. Means were separated using the Fishers protected least significant difference (LSD). Pearson's correlation analyses were conducted using SPSS (version 23) to determine the relationships between different soil properties and N_2O fluxes.

CHAPTER FOUR

4. RESULTS

4.1 Chemical characteristics of organic resources

Total P concentration was higher under FYM than in CL and MS treatments at both sites. Higher N and C contents were recorded in CL than FYM and MS, while MS recorded higher C: N ratio at both sites (Table 1).

Table 1. Chemical characteristics of the ORs used in the study

Site	Treatment	P (mg P/kg)	N (%)	C (%)	C:N ratio
Aludeka	Farmyard Manure	1718.29	1.08	12.14	11.24
	Maize Stover	395.69	0.55	41.66	75.75
	Calliandra	708.55	2.96	44.89	15.17
Sidada	Farmyard Manure	1512.19	1.07	11.66	10.90
	Maize Stover	275.48	0.55	42.41	77.11
	Calliandra	627.63	2.84	44.88	15.80

4.2 Chemical characteristics of soil

The mean soil TN concentration across the treatments was 0.05 and 0.18% and mean SOC concentration was 0.56 and 2.09 % at Aludeka and Sidada, respectively. Higher TN and SOC were recorded in CL and FYM treatments at both sites. Treatments with inorganic N fertilizer recorded lower pH values than OR treatments alone across the sites (Table 2). Soil C:N ratio ranged from 8.8 to 13.5 and 11.63 to 12.15 at Aludeka and Sidada sites, respectively (Table 2). The mean total P concentrations were lowest at Aludeka and highest at Sidada sites (Table 2).

Table 2. Soil pH, total phosphorus (P), total carbon (C), total nitrogen (N) and C: N ratio of soils taken at the top 15cm from the two different sites, Aludeka and Sidada before planting.

Site	Treatments	pH	C (%)	N (%)	P (mg/kg)	C:N ratio
Aludeka	CON +N	5.06±0.17	0.54±0.05	0.04±0.01	152.1±32.09	13.50
	CON -N	5.57±0.25	0.45±0.01	0.04±0.00	176.7±22.29	11.25
	CL +N	4.99±0.09	0.70±0.12	0.08±0.02	151.5±4.80	8.75
	CL -N	5.57±0.28	0.60±0.01	0.06±0.01	166.4±22.97	10.00
	FYM +N	5.20±0.17	0.64±0.03	0.06±0.00	162.8±10.63	10.67
	FYM -N	5.78±0.07	0.59±0.03	0.05±0.00	167.7±6.50	11.80
	MS +N	5.23±0.61	0.48±0.02	0.04±0.01	159.8±25.32	12.00
	MS -N	5.44±0.17	0.46±0.02	0.04±0.00	178.2±23.00	11.50
Sidada	CON +N	4.58±0.11	1.86±0.02	0.16±0.00	539.1±65.07	11.63
	CON -N	5.15±0.02	1.91±0.07	0.16±0.01	502.4±37.82	11.94
	CL +N	4.51±0.10	2.05±0.14	0.17±0.01	534.7±79.06	12.00
	CL -N	5.03±0.20	2.09±0.10	0.18±0.01	561.0±67.20	11.61
	FYM +N	4.97±0.15	2.38±0.12	0.20±0.01	556.4±48.81	11.90
	FYM -N	5.54±0.22	2.43±0.10	0.20±0.02	664.4±93.82	12.15
	MS +N	4.68±0.11	1.99±0.14	0.17±0.00	490.3±52.43	11.71
	MS -N	5.04±0.09	2.00±0.04	0.17±0.01	580.2±3.21	11.76

Note: Values are mean ± standard deviation.

4.3 Soil mineral N concentrations during the study period

The NH_4^+-N and NO_3^--N concentrations in OR and control treatments were similar at the beginning of the season ($P>0.05$). NO_3^--N concentration was the dominant form of soil mineral N at both sites, with an average of 8.24 and 20.26 mg kg^{-1} at Aludeka and Sidada, respectively. The highest concentration was observed for FYM +N and lowest for CON -N treatments ($P<0.05$) (Figure 2). Mean NH_4^+-N was 2.34 and 7.31 mg kg^{-1} for Aludeka and Sidada, respectively, with no significant difference observed between the treatments ($P>0.05$).

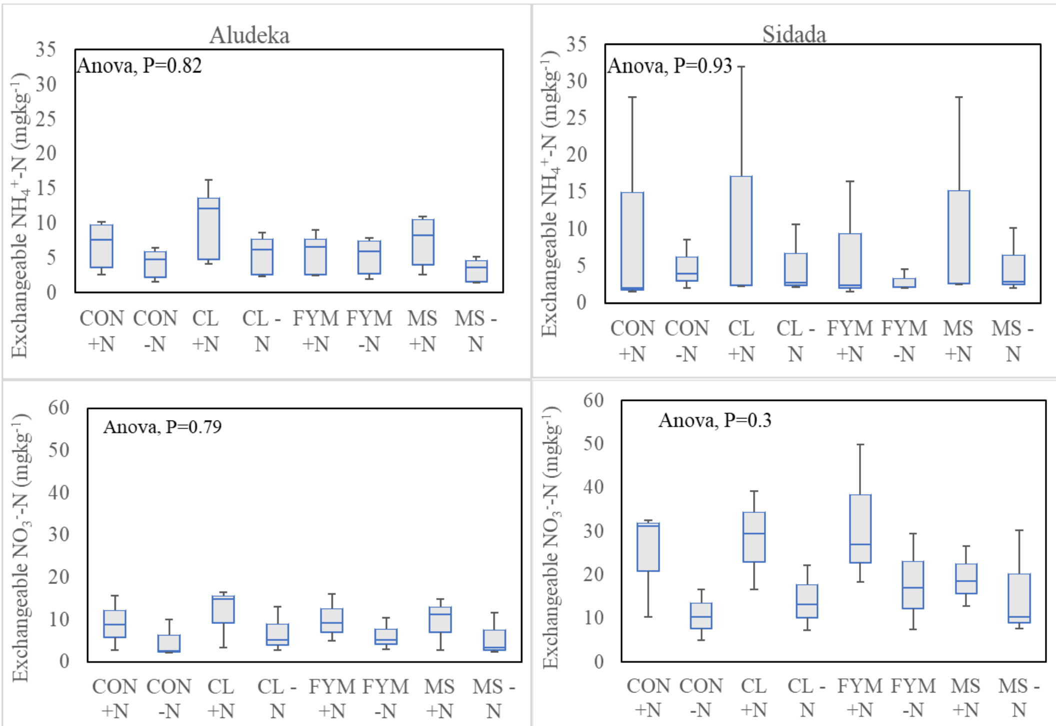

Figure 2. Box plots showing NH_4^+-N (mg/kg) (a, b) and NO_3^--N (mg/kg) (c, d) for Aludeka and Sidada, respectively, under different organic resource application with and without mineral N fertilizer application. Whiskers represent standard deviation error bars. NB: CON: control, CL: Calliandra calothyrsus, FYM: Farmyard manure and MS: Maize stovers, +N: With inorganic N fertilizer, -N: Without inorganic N fertilizer.

4.4 Soil moisture and temperature during the study period

Mean soil MC increased greatly after planting at both sites. At Aludeka site soil MC reached a maximum on 19th March and then declined to the lowest on 3rd April before sharply increasing to the highest on 9th April and maintained high levels to 23rd April (Figure 3). At Sidada site soil MC maintained higher levels from 17th March to 16th April. The mean soil MC varied from 0.18 to 0.33 m^3/m^3, and 0.19 to 0.35 m^3/m^3 at Aludeka and Sidada sites, respectively. The mean soil MC was significant between the treatments at both sites with Aludeka site (0.27 m^3/m^3) recording lower value than Sidada site (0.32 m^3/m^3) ($P<0.001$).

The mean soil temperature of the eight treatments increased gradually after 15th and 19th March, reached a maximum on 24th march and 10th April at Sidada and Aludeka, respectively. Mean soil temperature ranged from 26.5°C to 39.5°C at Aludeka, and from 24.13°C to 37.04°C at Sidada, with a seasonal mean of 33.10°C and 30.68°C for Aludeka and Sidada, respectively.

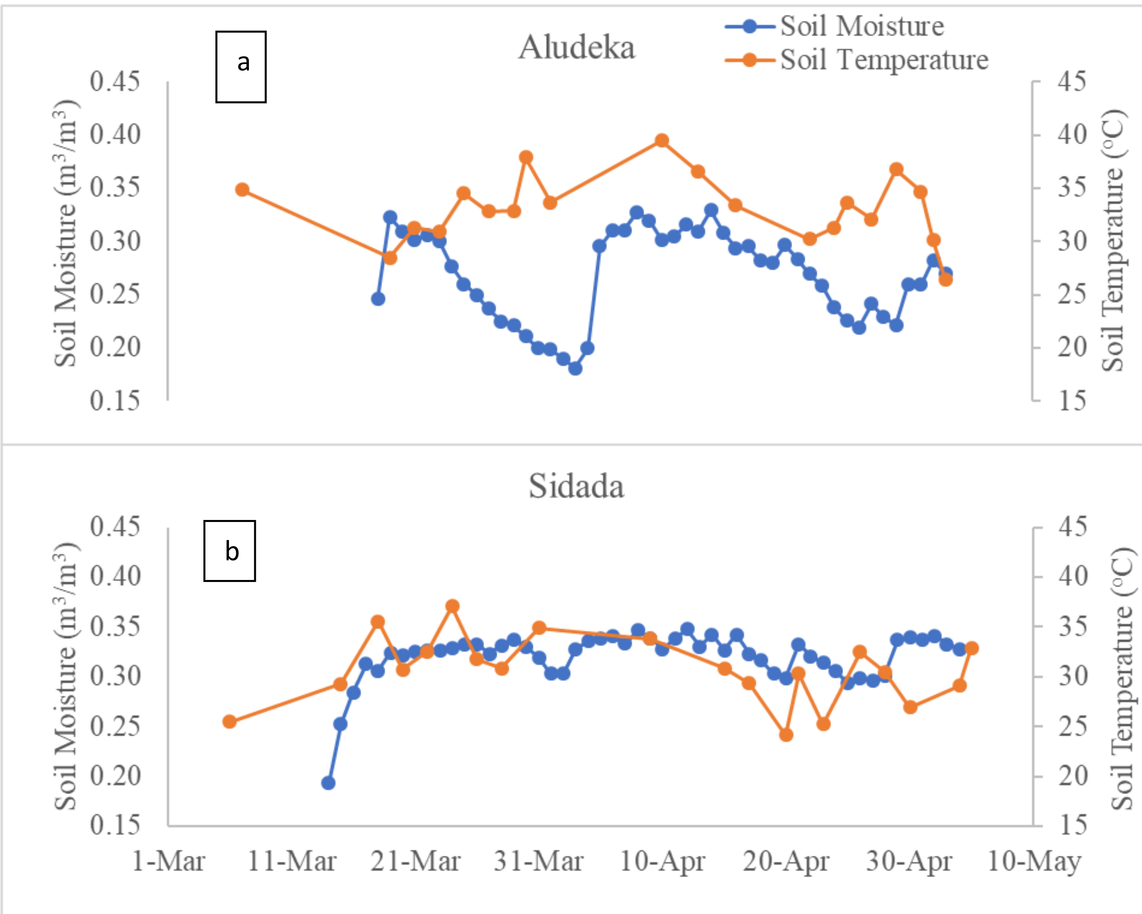

Figure 3. Average daily soil moisture and temperature (5 cm depth) at a) Aludeka and b) Sidada sites during the study period.

4.5 Soil N_2O fluxes under different treatments during the study period

OR with N fertilizer application significantly increased N_2O emissions and produced higher fluxes compared to OR treatments alone at both sites (P>0.001) (Table 3). There was a small N_2O fluxes before planting and then increased for a period of about 15 days at the beginning of the sampling season, before gradually decreasing to background emissions towards the end of the sampling season under all the treatments. The N_2O emissions after top dressing with inorganic N fertilizers remained low regardless of the high soil MC during this period. This was contrary to a high pulse emission of N_2O emissions after first inorganic N application, which coincided with high soil MC (Figure 4 and 5).

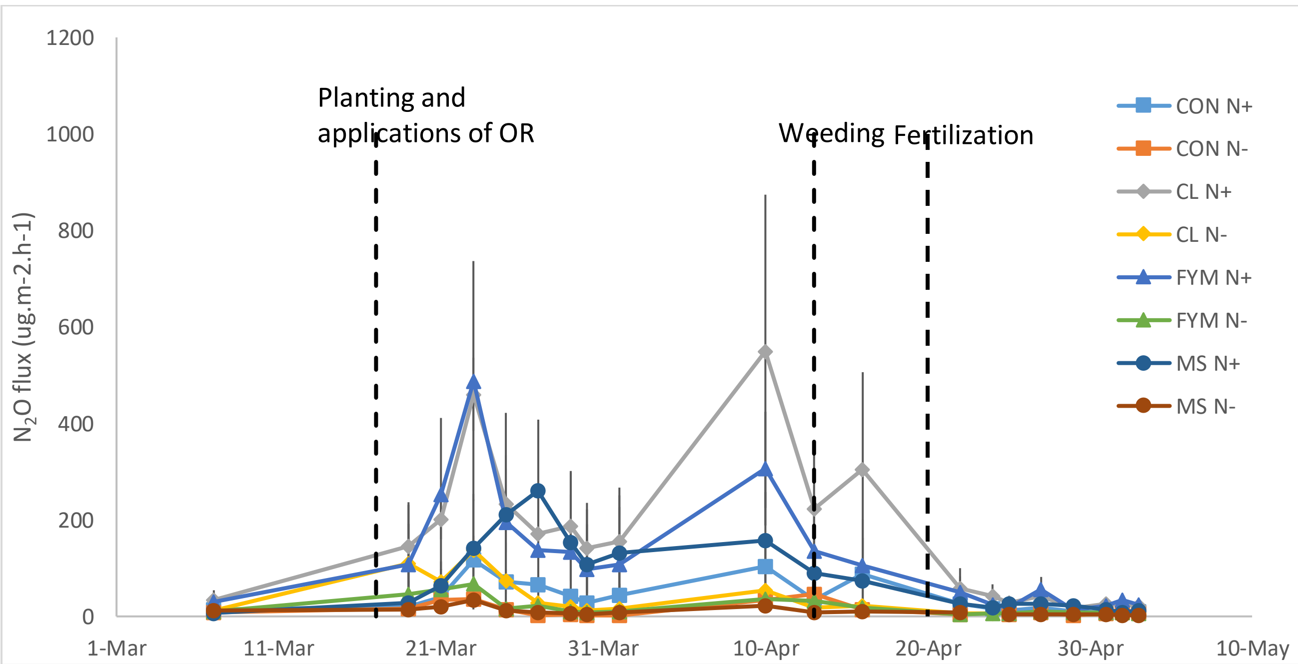

Figure 4. Temporal soil N_2O flux from 7th March to 3rd May 2018 at Aludeka site under different treatments. Whiskers represent standard deviation. Straight vertical dotted lines indicate different farm management activities. NB: CON: control, CL: Calliandra calothyrsus, FYM: Farmyard manure and MS: Maize stovers, +N: With inorganic N fertilizer, -N: Without inorganic N fertilizer.

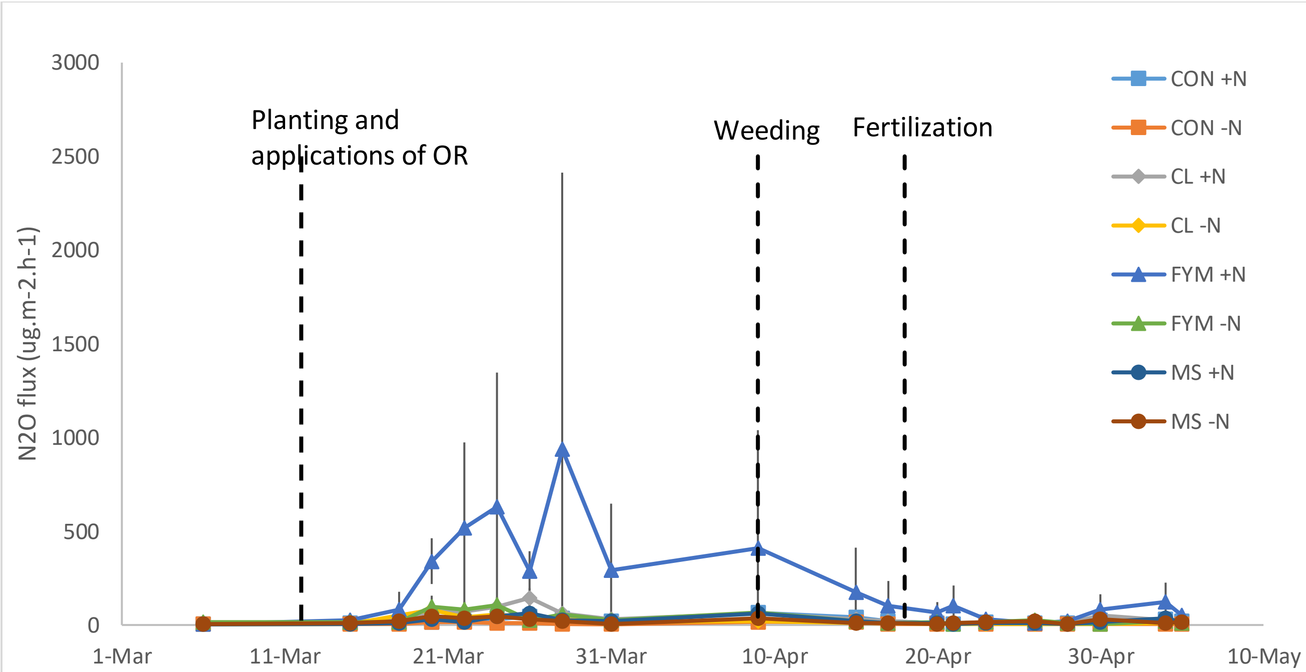

Figure 5. Temporal soil N_2O fluxes from 6th March to 5th May 2018 at Sidada site under different treatments. Whiskers represent standard deviation. Straight vertical dotted lines indicate different farm management activities. NB: CON: control, CL: Calliandra calothyrsus, FYM: Farmyard manure and MS: Maize stovers, +N: With inorganic N fertilizer, -N: Without inorganic N fertilizer.

4.6 Effect of Organic Resources on mean and cumulative N_2O emissions

Mean N_2O fluxes from treatment with inorganic N fertilizer were on average 5 times higher than those without inorganic N fertilizer. Significantly (P<0.001) higher N_2O emissions was observed under CL +N (153.2 ± 170.8 µg m^{-2} h^{-1}) and FYM+N (212.3± 425.1 µg m^{-2} h^{-1}) in Aludeka and Sidada respectively, while lower emissions were observed under MS -N (9.4 ± 9.6 µg m^{-2} h^{-1}) and CON –N (6.8 ± 6.3 µg m^{-2} h^{-1}) in Aludeka and Sidada, respectively (Table 3). A similar trend was observed for cumulative N_2O emissions during the growing season with the treatments exhibiting significant (P=0.03) differences in Aludeka but not at Sidada (P=0.149) (Table 3). There was no significant difference in cumulative emissions between treatments with OR application alone and the control at both sites (P>0.05). There was a significant effect observed on both mean hourly fluxes and cumulative N_2O emissions as a result of total N inputs at Aludeka (P<0.001).

Table 3. Cumulative N_2O fluxes from March to May 2018, maize yield, yield scale fluxes and total N input for studied treatments at the two sites, Aludeka and Sidada. Total N input refers to input through inorganic fertilizer and organic resources

Site	Treatment	Total N input (Kg ha^{-1})	Mean N_2O fluxes (ug.m^{-2}.h^{-1})	Cumulative N_2O fluxes (Kg N_2O-N ha^{-1})	Yield (T ha^{-1})	Yield scale fluxes (g N_2O-N kg^{-1} yield)
Aludeka	CON +N	120	39.65±38.76b	0.61±0.12a	8.28±1.70cd	0.075±0.01
	CON -N	0	11.96±11.53a	0.19±0.10a	4.06±0.23ab	0.046±0.02
	CL +N	215	153.23±170.8e	2.54±1.20c	9.47±1.44d	0.272±0.14
	CL -N	95	30.77±48.27ab	0.52±0.30a	5.19±0.73b	0.103±0.06
	FYM +N	241	117.07±143.5d	1.74±0.79c	10.63±0.23d	0.163±0.07
	FYM -N	121	18.76±20.27ab	0.30±0.10a	5.42±1.17b	0.056±0.02
	MS +N	170	74.48±96.15c	1.05±0.79ab	6.66±2.98bc	0.144±0.05
	MS -N	50	9.43±9.64a	0.16±0.02a	2.36±1.71a	0.136±0.15
	P value		0.001	0.03	0.001	0.107
	LSD		22.56	1.104	2.799	0.1514
Sidada	CON +N	120	22.04±18.71a	0.36±0.12	8.43±0.42	0.043±0.01
	CON -N	0	6.82±6.27a	0.11±0.04	5.1±1.38	0.02±0.0
	CL +N	218	38.61±42.58a	0.54±0.20	7.86±0.98	0.071±0.03
	CL -N	98	22.18±26.99a	0.28±.05	6.24±1.07	0.046±0.01
	FYM +N	237	212.32±425.1b	3.13±3.62	9.23±0.58	0.356±0.43
	FYM -N	117	30.39±39.41a	0.45±0.19	8.81±0.98	0.05±0.02
	MS +N	170	21.08±23.23a	0.33±0.04	7.47±0.95	0.045±0.0
	MS -N	50	16.58±23.44a	0.23±0.26	7.8±3.29	0.026±0.02
	P value		0.001	0.149	0.052	0.194
	LSD		52.84	2.206	2.509	0.2616

Values are mean ± standard deviation. Different lowercase letters indicate significant differences between treatments within columns per site ($P < 0.05$).

4.7 N_2O emissions relationships with soil parameters

For all the sites, soil NO_3^--N was positively correlated with the cumulative N_2O fluxes (P=0.002) and (P=0.048) at Aludeka and Sidada, respectively. On the other hand, soil NH_4^+-N, TN and SOC showed a positive correlation at Aludeka site. The correlation analysis also indicated that there was a negative relationship between soil pH, and C:N ratio with cumulative N_2O emissions at Aludeka (Table 4).

Table 4. Correlation coefficients of linear association between soil properties and cumulative N_2O emissions with n=8

	Aludeka	Sidada
Soil properties	Cumulative N_2O	Cumulative N_2O
Soil pH	-0.739*	0.023
Total C	0.760*	0.605
Total N	0.820*	0.579
Soil P	-0.684	0.072
Soil C: N	-0.710*	0.177
NH_4^+-N	0.738*	0.002
NO_3^--N	0.905**	0.711*
Soil temperature	-0.563	-0.677
Soil moisture	-0.648	0.490

*, ** denote significance at p≤0.05 and p≤0.001, respectively.

4.8 Effect of organic resource on maize yield and yield scale emissions

In Aludeka, there was a significant (P < 0.001) effect of treatments on maize grain yield, with no observed significant effect at Sidada site (P>0.05). FYM +N treatment recorded the highest mean maize grain yield at both Aludeka (10.63 t ha^{-1}) and Sidada (9.23 t ha^{-1}) (Table 3). The MS -N treatment recorded the lowest yields of 2.36 t ha^{-1} at Aludeka, while at Sidada CON -N recorded the lowest yields of 5.1 t ha^{-1}. In Aludeka site, treatments with ORs in combination with inorganic N fertilizers increased maize grain yield in comparison with those without (Table 3). At Sidada site treatments with both sole ORs and those integrated with inorganic N fertilizers increased maize grain yield. In Aludeka site, the treatments with sole organics performed lowly in comparison with the control (Table 3).

Plots amended with ORs had the highest yield scaled emissions with an average of 0.16 and 0.13 g N kg^{-1} yield compared to those without inorganic N fertilizer with an average of 0.09 and 0.04 g N kg^{-1} yield at Audeka and Sidada sites, respectively. CL +N and FYM +N treatments recorded higher yield scale estimate at Aludeka and Sidada sites, respectively (Table 3). In comparison to the two sites, Sidada recorded the lowest yield scale emissions compared to Aludeka (Table 3).

CHAPTER FIVE

5. DISCUSSION

5.1 Effect of organic resources and added inorganic N fertilizers on N_2O emissions

Application of OR and inorganic N fertilizer increases available N in the soil which leads to increased N_2O emissions. Most research have provided N_2O emissions for ORs without looking at the different OR qualities that have been used (Velthof et al., 2003). Our reported values suggest that emissions differ depending on the OR quality used. The effects can be attributed to whether the OR are added with or without inorganic N fertilizer. For treatments with inorganic N fertilizer additions, average cumulative emissions were 1.49 and 1.09 kg N_2O-N ha^{-1} at Aludeka and Sidada, respectively. The reported values are within the reported range of 1 to 2 kg N_2O-N ha^{-1} from Western Kenya region from increased inorganic fertilization (Hickman et al., 2014) and globally from different soil types under ISFM approach (Van Groenigen et al., 2010, Li et al., 2013). For treatments without inorganic N fertilization, the average N_2O fluxes were 0.29 and 0.27 kg N_2O-N ha^{-1}, at Aludeka and Sidada, respectively. These fluxes are below the reported average value of 0.45 kg N_2O-N ha^{-1} for unfertilized agricultural soils in SSA (Dick et al., 2008, Wanyama et al., 2018). The lower values could be attributed to the low OR rates used in this study. Overall, our reported cumulative emissions in the study during the maize growing season are within the values that have been reported in different studies involving incorporation of inorganic fertilizer and organic residues (Sarkodie-Addo et al., 2003, Baggs et al., 2003, Millar et al., 2004).

The effects of OR type and inorganic N fertilizer on N_2O emission in our study were affected by the difference in soil texture. This is because mineralization rates are affected by the soil environmental conditions (Griffin et al., 2002; Larkin et al., 2006). Similarly, there was increased

N_2O emissions from treatments with inorganic N fertilizer than from treatments without inorganic N fertilizer and control treatment at Aludeka site with silt loam soil. While at Sidada with silt clay soil we did not report any difference between treatments with and those without inorganic N fertilizer. This we can attribute to the differences in SOC and TN in the two sites, with Sidada recording higher compared to Aludeka (Table 2). According to Gaillard et al. (2016) soil texture influences several factors controlling N_2O emissions spanning from soil aeration, SOC and N availability. The interplay of these factors result to varied N_2O emissions from different soil textures (Jarecki et al., 2008). According to Velthof et al. (2003) the effect of OR on N_2O emissions is larger in soil with low SOC than soils with high SOC content. As a result, addition of inorganic N fertilizer together with OR led to increased N_2O emissions compared to soils receiving sole application of OR and inorganic N fertilizer at Aludeka. The increased N_2O fluxes from OR with inorganic N fertilizer treatments can be due to easily degradable substrates from the inorganic N fertilizer. The present findings at Aludeka seems to agree with previous studies who reported increased annual N_2O production from treatment combination of OR and inorganic N fertilizers (Ding et al., 2010, Frimpong and Baggs, 2010, Charles et al., 2017). Ding et al. (2010) attributed this to high concentration of available N from the inorganic N fertilizer and OR decomposition thus increasing N_2O emissions. Therefore, the relatively higher N_2O emissions from OR with inorganic N fertilizer suggest that inorganic N ferilizer was the major source of N_2O emissions. According to Velthof et al. (2003) since inorganic N fertilizer is mineral it can be directly lost via N_2O emissions by the microbes provided that the substrate is available. On the other hand, a large part of the ORs have to be mineralized first before being lost as N_2O emissions which requires time and can only result to emissions after a certain period of time, and this could explain why OR treaments alone had lower N_2O emissions in our study sites (Table 3). Consequently, the study estimates 239% and 411% of the cumulative N_2O emissions to have been influenced by inorganic N fertilization at Sidada and Aludeka, respectively.

However, high emissions from treatments with inorganic N fertilizer took place for about 15 days after fertilization (Figure 4 and 5). This was closely linked with the first onset of rains which took place for about two weeks in our study areas thus increased soil moisture. Soil moisture is able to move the C and N in the soil matrix resulting to higher rates of N_2O emissions due to anaerobic conditions. Maljanen et al, (2003) noted that N_2O emissions from treatments involving inorganic N fertilizer application is short-lived. This would explain why we had reduced N_2O fluxes before fertilizer application and towards the end of the sampling campaign. The sharp increase in emissions during the first days after OR and inorganic N fertilizer application could also have been due to increased denitrification of NO_3 in the soil by the easily degradable substrates from the fertilizers (Signor et al., 2013). In our study there was no removal of N by the maize crop uptake during the first week of sampling before germination, so the available soil N was high during this period. This may have also contributed to higher emissions at the beginning of the sampling period. The findings are in agreement with Hickman et al. (2014) who observed a high flux emissions following rainfall events. Similarly, the distribution and amount of rainfall strongly influences the contribution of applied inorganic N fertilizer to N_2O flux emissions, as compared to maize productivity and N uptake (Mapanda et al., 2012). Soil temperature is another major driver of any biochemical process in soil for N_2O emissions (Zhang et al., 2012, Butterbach-bahl et al., 2013). According to Wei-xin *et al.* (2007) the optimum temperature for N_2O emissions in cropping systems ranges between 25 to 40^0C. Mean soil temperature during the study period was 30.68^0C and 33.10 at Sidada and Aludeka, respectively, which are within the reported optimum range for

N_2O emission fluxes to take place. However, the sensitivity of N_2O emissions due to changes in soil temperature could be partially attributed to soil MC.

The increased N_2O emissions at Aludeka from FYM and CL with inorganic N fertilizer treatments can be attributed to lower C: N ratio of 11 and 15, respectively (Table 1). This agrees with (Frimpong and Baggs, 2010) working on cowpeas who found a positive correlation of N_2O emissions with C: N ratio below 12. The C: N ratio plays a significant role in decomposition of ORs (Khalil et al., 2002; Huang et al., 2004), whereby lower C:N ratio releases more dissolved organic carbon (DOC) which stimulates microbial activity and mineralization resulting to N_2O emissions (Huang et al., 2004). Khalil et al. (2002) observed an increased rate in nitrification with a reduction in C:N ratio of ORs. The OR with C: N ratio higher than 20 may result to immobilization of N (Huang et al., 2017). This agrees to the observed MS treatments with C:N ratio >75 with no significant increase in N_2O emissions in our study. The higher C: N ratio from MS treatment are difficult to breakdown by the microbes responsible for decomposition and might have resulted to immobilization of N thus lowering N_2O emissions from the soils. In a review by (Charles et al., 2017) many studies have reported C:N ratios higher or equal to 45 with no significant increase in soil N_2O emissions after their applications. Vigil and Kissel, (1991) reported a net equilibrium point between mineralization and immobilization of N to be at C: N ratio of 40. According to Huang et al. (2004) ORs with C:N ratios higher than 75 are difficult to break down due to low available N to microbes responsible for decompositions, as well as high amounts of structural woody materials like lignin and tannins. Similarly, increased C:N ratio results to complete denitrification process taking place resulting to N loss as N_2 instead of N_2O emissions (Thangarajan *et al*., 2013).

However, at Sidada site our findings are contrary to the above observations with no observed significant differences between the OR treatments with C: N ratio below 12. We attribute this to differences in soil properties (Table 2) and environmental factors in our studied sites. According to Charles et al. (2017) ORs with lower C:N ratio of 25, only a part of the variations is explained by the C:N ratio, and attributed emissions to influence from management and environmental related factors. Corroborating these findings, Meng et al. (2005) observed no significant effect in inorganic fertilizer and organic manure with C:N ratio of 7.75, and attributed it to low soil moisture inhibiting denitrification.

5.2 Effect of soil properties on N_2O emissions

In the coarser soils of Aludeka with low SOC, we found a strong correlation of soil NO_3 with cumulative N_2O emissions, and at Sidada with high SOC we observed a weakly correlation with soil NO_3 (Table 4). This could be due to low concentration of SOC at Aludeka site, suggesting that N_2O emissions was C limited in our study. SOC has been shown to play a significant role as a driver of biochemical processes in the soils (Maljanen et al., 2003). The results at Sidada are in agreement with Pelster et al. (2012) working on a silty clay soil observed a weak correlation of N_2O emissions with NO_3 and attributed it to enough SOC available for the microbial processes. (Tenuta et al., 2001; Zebarth et al., 2008) noted that N_2O emissions could be linked to NO_3-concentrations if there is enough C available. According to (Petersen et al., 2008; Chantigny et al., 2010) N_2O emissions correlate with SOC in low C soils, whereas in C rich soils N_2O emissions correlate with NO_3 availability. This could also explain why we had a significant positive correlation between SOC and N_2O emissions at Aludeka. Working on two coarse-textured soils with different C content, (Petersen et al., 2008) found that N_2O emissions were as a result of C availability when soil C content was low. Fine textured soils tend to have more C and higher soil mineral N for microbial denitrification process than coarse textured soils (Chantigny et al., 2010; Charles et al., 2017). Therefore, the no significant differences observed in cumulative N_2O emissions in our treatments at Sidada most likely resulted from high soil mineral N and SOC availability at the site. According to (Leip et al., 2011) N_2O emissions from high-C soils do not have differences due to N source types, but it can be due to the soil properties brought about by increased soil C and N availability. Working on a single N rate and increased C rates, Stevens et al. (1998) recorded higher N_2O emissions at mid-rate than at high C rates and attributed it to NO_3^--N inhibition at high C rates. Graham et al. (2013) noted an increased N_2O emissions with increased NO_3^--N with no significant effect between treatments. Bateman & Baggs (2005) observed that N_2O emissions are not closely related to high NO_3^--N concentrations in soils but could be as a result of SOC which provide substrates of inorganic N and labile organic C for denitrification and nitrification processes. On the other hand, decreased N availability as a result of NH_4 adsorption in soil colloids inhibits the activities of microbes (Hommes et al., 1998). Fine textured soils tend to have higher CEC than coarse textured soils which facilitate NH_4 adsorption (Jarecki et al., 2008). This could explain why we only observed a significant correlation of NH_4 with N_2O emissions at Aludeka with silt loam soils and not at Sidada with a silt clay soil.

However, for FYM at Sidada site we observed a 20-fold increase in N_2O emissions compared to control treatment. The study attributes this to a constant supply of both NO_3 and oxidizable C from FYM for microbial activities resulting to increased N_2O emissions. Furthermore, FYM application results in a high amount of available C and when environmental conditions are favorable, denitrification due to anaerobic conditions takes place resulting in N_2O emissions (Meng et al., 2005a, Ni et al., 2012). Similarly, (Pelster et al., 2012) working on a sandy loam soil observed an increased N_2O emissions rates from plots fertilized with FYM and attributed it to increased C availability.

There should be a suitable pH range of between 5 to 8 for nitrification and denitrification processes to take place, below which the N_2O production will be hampered (Gieseke et al., 2006). The slightly acidic soils at Sidada suggests that pH was not favoring N_2O emissions. This agrees with Hickman et al. (2014) who found no relationship between pH and N_2O emissions in slightly acidic soils. Contrary to the findings at Sidada, we found a negative correlation at Aludeka which suggest that pH can play a significant role in microbial activities. Graham et al. (2017), noted that lower pH (<6) values favored N_2O production from fertilized soils. This they attributed to increased soil microbial activities in lower pH conditions.

5.3 Effects of Inorganic and Organic N fertilizers on maize yield

Application of OR with inorganic N gave higher grain yield compared to sole OR which was prominent in the coarser soils at Aludeka. The slow nutrient release and recovery from the OR compared to OR fortified with N from the N fertilizer may be the cause. Further, to our study, (Kimetu *et al*., 2004) reported an increase in maize yield from OR in combination with inorganic N fertilizer which is also in agreement with Herman and Lal, (2008). Contrary to our study, Mucheru-muna *et al*. (2007) recorded grain yield increase of 227% from CL biomass treatments in Kenya, whereas a study in Zimbabwe by (Mtambanengwe *et al*., 2006) reported grain yield increase of 525% following FYM application. This could be due to the initial high soil fertility in the experiment they were working on.

The added inorganic N fertilizer had a more significant effect with lower C: N ratio ORs of CL and FYM compared to low quality MS with high C: N ratio and control treatments at Aludeka.

This could be attributed to high mineralized N from the inorganic N fertilizer. Since inorganic N fertilizer was split applied, the utilization of the applied inorganic N fertilizer by the crop may have taken place correctly, leading to the high yields obtained from OR with inorganic N in the study. The N nutrient is easily available to the maize plant from the inorganic than from the organic sources (Mallory and Griffin, 2007). When inorganic N fertilizer is added to the soil their significant effect is reflected in the short term in terms of maize yields (Palm *et al.*, 2001). Low maize yield obtained at Aludeka with sole OR treatments may have been caused by initial immobilization of N. The slower release of N due to the high C: N ratio of the MS residues could also have contributed to the low yields from MS treatments at Aludeka. Even the addition of inorganic N (120kg N/ha) to MS treatment was not enough to increase yield probably due to immobilization of N by the residues. According to (Abbasi et al., 2015) MS can immobilize N for around 120 days. In our study we used a maize variety which takes about 150 days to reach physiological maturity. This therefore means that during the cropping season maize crop was deprived of N which is essential for its growth under the MS treatments. The low yields from OR alone at Aludeka reflects the typical trends amongst farmers in smallholder farms who do continues maize monocropping across SSA using low quality ORs (Tittonell et al., 2008).

Generally, adequate rainfall during the growing season may also have had significant effects on the high performance of the maize yields obtained from the sole OR application at Sidada site. This could have contributed to the residual nutrient benefits because of low precipitation from previous seasons which might have resulted to low leaching losses and low removal of grain and stover nutrient harvest (Mtangadura et al., 2017). Importantly nutrients supplied from OR are less soluble and less prone to losses making them more suitable for crop growth than those from inorganic N fertilizer when rainfall is heavy (Kihanda *et al*., 2006). The good maize stands would have also contributed to the high yields obtained in this study in both sites.

The highest concentration of P, TN and SOC which are essential nutrient requirements for maize growth were observed at Sidada site than at Aludeka (Table 2). This was ultimately reflected in the maize grain yields obtained at Sidada site as evidenced by the lack of treatment differences. The high yields observed at Sidada could have been contributed to a comparably high soil fertility of the clay soils than silt loam soils at Aludeka at the start of the experiment. This means that N availability at Sidada site was able to sustain maize productivity. (Tittonell, Shepherd, et al., 2008) observed that farmers who plant in soils with high background soil fertility had increased maize yield compared to those with low fertility.

At 15cm soil depth, there were no significant differences in NH_4 and NO_3 concentrations in both with inorganic N fertilizer between the two sites (Figure 2), as also reflected in the yield between the two sites. There were also differences among the soil P levels at the two sites, and P is known to be deficient in the Western region of Kenya (Nziguheba *et al*., 2002) as evidenced in the yield obtained from OR with and without N treatments at Aludeka site. However, P concentration was higher than the threshold value of 2.4g/kg at both sites that are needed for net P mineralization (Chikowo *et al*., 2010). This means that addition of OR biomass in Sidada released P from OR mineralization while in the soil at Aludeka fixing of P from the OR was taking place (Herman and Lal, 2008). Hence incorporation of OR in soil probably increased P availability to the maize crop and decreased soil sorption at Sidada as compared to Aludeka.

5.4 Yield Scaled N_2O emissions

The influence of added inorganic N fertilizer treatments to maize yield in our study resulted in almost 50% higher yield scale N_2O emissions than from those without inorganic N fertilizer (Table 2), although not significantly different ($P>0.05$). The results therefore suggest that sole application of OR is favorable for controlling the yield scale N_2O emissions. However, the low yields from OR alone as evidenced from Aludeka site suggest that application of OR with inorganic N fertilizer which showed significant difference ($P<0.001$) is necessary for achieving higher crop yields in the region. Importantly, the integrated impact of added inorganic N fertilizer should be determined by the crop yields obtained (Mapanda et al., 2012). Our reported values are within range of yield scale emissions as reported in the Africa maize based cropping systems (Mapanda et al., 2011). Contrary to our findings, Nyamadzawo et al. (2014), found high yield scale emissions from control and low inorganic fertilization treatments. This we can attribute to high OR and N fertilizer application amounts used in this study resulting to high yields compared to the rates of 60 kg N/ha they used.

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Inorganic N fertilizer induced higher N_2O emissions and was more pronounced when applied with ORs. The high emissions were higher in the silt loam soils at Aludeka than the silty clay soils of Sidada suggesting that soil texture plays a role in N_2O emissions. Importantly, SOC level had a greater impact on N_2O emissions, being most significant where SOC was low, implying that less N from mineralized SOC than from inorganic N fertilizer was lost as N_2O emissions. Hence, the reduction of N_2O emissions under high SOC content demonstrates that increasing SOC under an ISFM approach serves as a good mitigation strategy in N_2O emissions from arable soils in SSA. This a reasonable cost-effective management strategy feasible to smallholder farming systems in SSA.

The cumulative emissions at Aludeka under OR treatments were in the order of CL>FYM>MS which suggest that N_2O emissions is dependent on the OR quality, producing higher emissions with lower C: N ratio. Therefore, OR quality and inorganic N fertilizer interactions is therefore important in addressing the problem of N_2O emissions from soils.

Application of OR combined with inorganic N fertilizer improved crop yield. This is further explained by the fact that there was high maize grain yield at both sites from the inorganic N fertilizer alone. However, the grain yield responses to inorganic N fertilizer and OR were shown to be site-specific due to the difference in soil texture across treatments at the two sites. This suggests that added inorganic N fertilizer is more effective in low soil N conditions in terms of yield increase. Though, in the long run when ORs are used results to better soil physico-chemical characteristics and improved soil moisture conditions.

6.2 Recommendations

This study gives an overview of N_2O emissions at two sites with observed soil properties. However, having a closer look at the interpretation of the results, gaps are revealed which cannot be addressed with the present study alone. For example;

i. The differences in N_2O emissions between the two sites which cannot be explained by the data in this study should be researched in detail, especially on the influence of soil texture to soil N_2O emissions.

ii. The effect of FYM to N_2O emissions when supplemented with inorganic N fertilizer was not consistent across the sites, meaning that its interactive effect on N_2O emissions needs to be assessed further.

iii. It is also essential to look at N_2O emissions at different OR rates to conclusively tell the impact of OR quality and quantity to the environment. This will enable the statistical analysis done in this study to be more sensitive to individual OR type and give an overview on ORs at different rates.

iv. The yield response from inorganic N fertilizer rates of 120 kg N used in this study was high. Most farmers don’t use high rates of inorganic N fertilizers, it is therefore important to look at OR combination with lower rates of N to draw a conclusive statement from inorganic contribution to yield and N_2O emissions under ISFM approaches.

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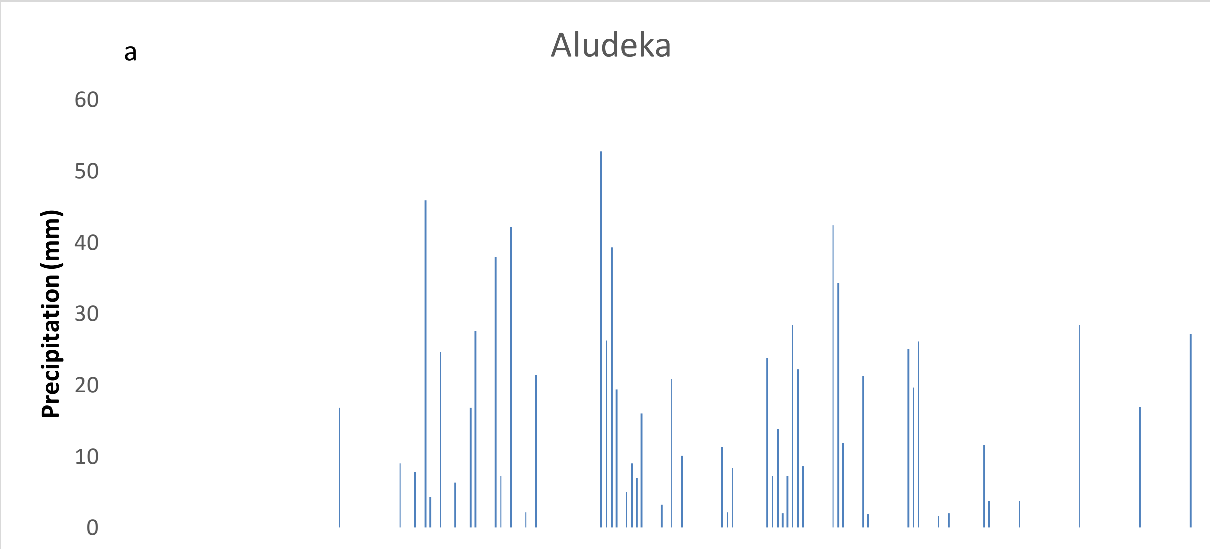
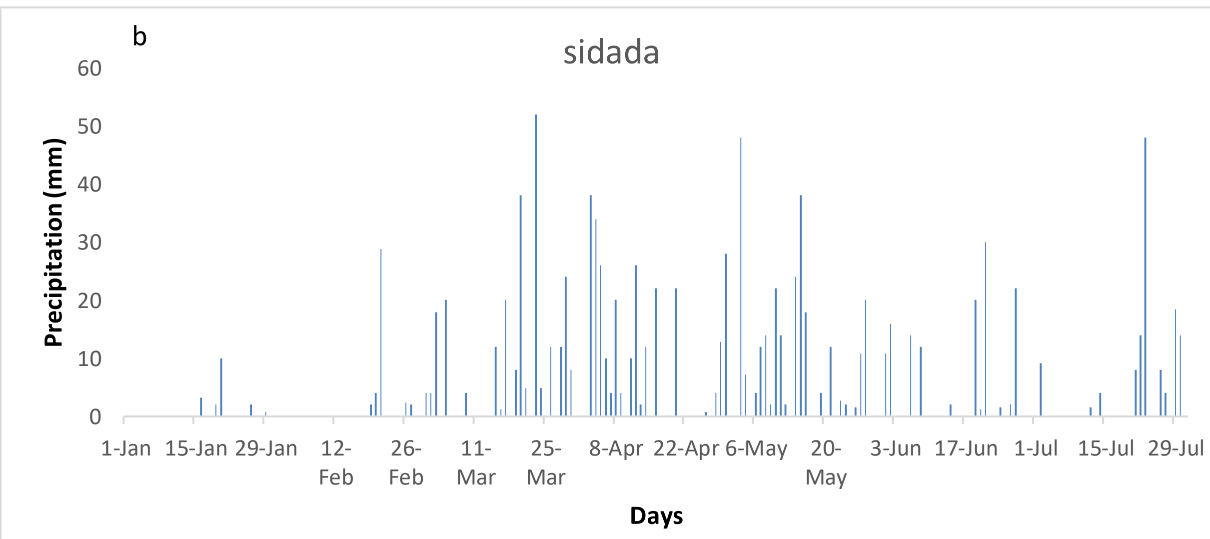
APPENDICES

Appendix 1. Daily precipitation as observed at a) Aludeka and b) Sidada sites





Appendix 2. Field activity Schedule

Site	Activity	Date
	1.Land preparation	3/6/2018
	2.Planting	3/20/2018
	3.Gapping	4/4/2018
	4.Thinning	4/10/2018
	5.First Weeding	4/10/2018
	6.Second Weeding	5/5/2018
	7.Third Weeding	-
Sidada	8.Top-dressing	4/27/2018
	1.Land preparation	7/29-31/2018
	2.Planting	8/11/2018
	3.Gapping	8/20/2018
	4.Thinning	8/24/2018
	5.First Weeding	8/23-24/2018
	6.Second Weeding	9/21-22/2018
	7.Third Weeding	-
Aludeka	8.Top-dressing	9/13/2018

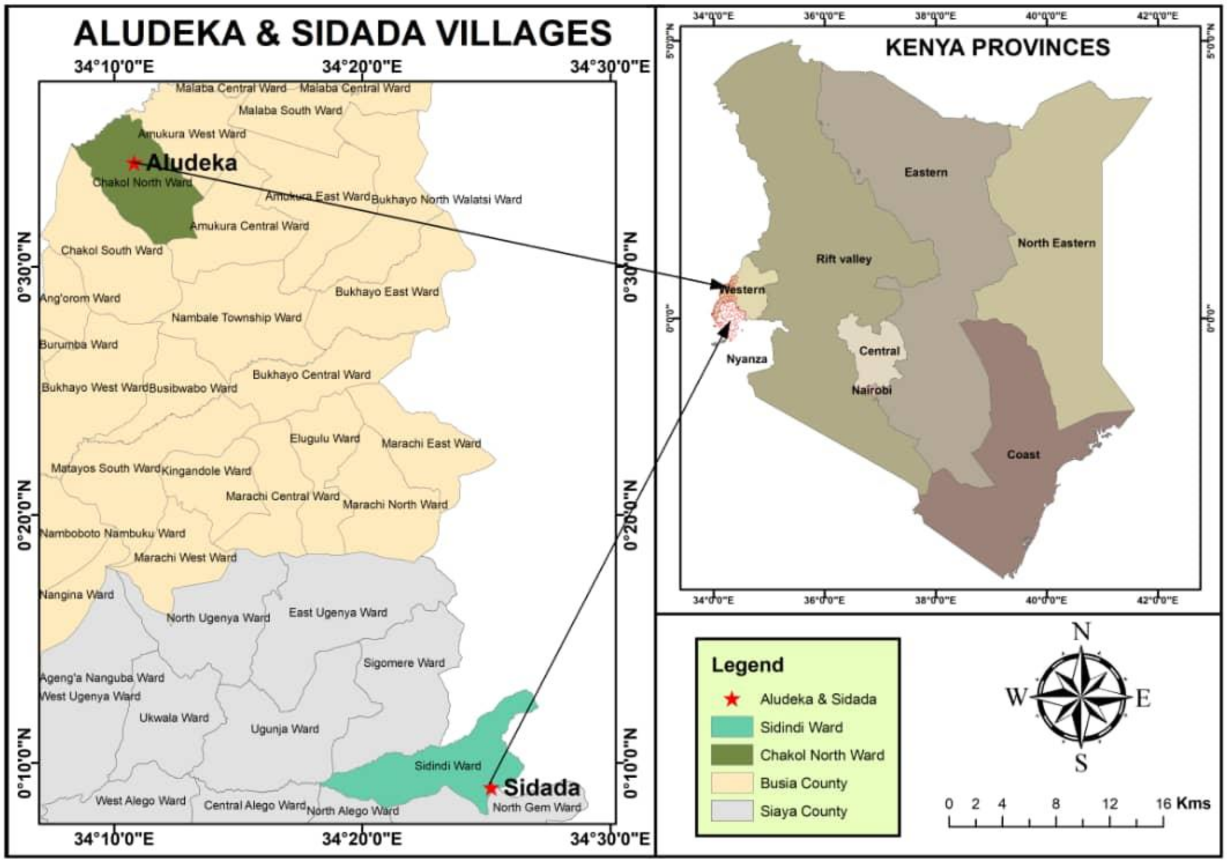
Appendix 3. N_2O Emission factors

	Aludeka		Sidada		Emission Factor Aludeka	Emission Factor Sidada
	Total N applied	CUM N_2O	Total N applied	CUM N_2O		
CON +N	120	0.61	120	0.36	0.35	0.21
CON -N	0	0.19	0	0.11	0.00	0.00
CL +N	215	2.54	218	0.54	0.90	0.08
CL -N	95	0.52	98	0.28	0.35	0.17
FYM +N	241	1.74	237	3.13	0.47	1.17
FYM -N	121	0.3	117	0.45	0.09	0.29
MS +N	170	1.05	170	0.33	0.26	-0.02
MS -N	50	0.16	50	0.23	-0.06	0.24

Appendix 4. Soil Moisture Anova table

Source of Variation	d.f.	s.s.	m.s.	v.r.	F pr.
Site	1	2.38E+02	2.38E+02	96021.54	<.001
Treatment	7	3.93E+01	5.61E+00	2262.08	<.001
Site*Treatment	7	5.78E+01	8.25E+00	3326.29	<.001

Appendix 5. Site map



Appendix 6. Soil sampling