EFFECT OF NITROGEN SOURCES ON NITROUS OXIDE EMISSION, MAIZE (Zea mays L) YIELD AND NITROGEN USE EFFICIENCY IN WESTERN KENYA

BY

MASIKA DAVID MUSUYA

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DECLARATION

I certify that this thesis is my original work and has not been presented for a degree in Maseno University or in any other University. The work reported herein was carried out by myself and all the sources of information have been specifically acknowledged by means of references.

Signature..............................   Date...

Masika David Musuya   PG/AF/0001/2012

This thesis has been submitted for examination with our approval as the University supervisors

Prof. Harun Okello Ogindo

Signature..   **Date......................................**

School of Agriculture and Food Security

Department of Applied Plant Science

Maseno University

Prof. Peter Asbon Opala

Signature...   **Date....................................**

School of Agriculture and Food Security

Department of Soil Science

Maseno University

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DEDICATION

This work is dedicated to my father Ezekiel Musuya who gave his best to see me through school and my dear wife Ruth and daughter Angeline for their continuous encouragement, and above all the God Almighty who gives me strength every day.

ABSTRACT

Nitrogen deficiency is a major limiting factor for maize production in western Kenya, therefore, nitrogen fertilizer inputs are required to increase yields in the region. However, most resource poor farmers use low rates of inorganic fertilizers leading to low maize yields. While high rates of inorganic fertilizer application may increase yields, they are however associated with low nitrogen use efficiency (NUE) and emission of greenhouse gases (GHGs) to the environment. Cattle manure may be used as a mitigation option but it is not available in sufficient quantities to meet N needs of the crop. Combining cattle manure and inorganic N fertilizers can result into increased NUE, higher yield and reduced GHGs emission compared to either of them applied alone, due to synergistic effects and improved synchronization of nutrient release and uptake by crops. Hence, the need to come up with a better approach in managing N fertilizers more efficiently to increase yield while keeping emission of GHGs at lower levels. The main objective of this study was to evaluate the effect of applying inorganic and organic sources of nitrogen fertilizer or their combination on N_2O gas emission, maize yield and NUE. The study was conducted in 2014 during the long rainy season at two sites with contrasting soil characteristics; a highland (Kericho West District) and lowland (Nyando District).The experiment consisted of six treatments i.e. a control with no N input, urea applied alone at 30 kg N ha^{-1} and at 100 kg N ha^{-1}, manure applied alone at 30 kg N ha^{-1}, a combined application of manure and urea each providing 50 kg N ha^{-1}, and NPK fertilizer applied at 100 kg N ha^{-1}. A completely randomized design with three replicates was used in the highland where the soil was homogenous, but in the lowland where the soil was heterogeneous, a randomized complete block design was used. Soil gases were sampled using the general static chamber methodology and the N_2O emissions quantified by use of a SRI 8610C gas chromatograph. Maize yield was determined at harvest and the NUE calculated after plant samples analysis. There were significant differences in N_2O emissions among treatments with a cumulative seasonal emission range of 0.11 kg N_2O-N ha^{-1} (control) to 0.31 kg N_2O-N ha^{-1} (urea100 kg N ha^{-1}). Sole manure and urea at 30 kg N ha^{-1} did not significantly increase N_2O emission above the control. However, sole urea and NPK at 100 kg N ha^{-1} produced a significantly higher emission compared to all other treatments. Occurrence of floods and droughts during the season in the lowland resulted into low yields that did not show any treatment effects. However, yields differed significantly in the highland ($p < 0.05$). The highest grain yield of 3.98 ton ha^{-1} was realized from combined manure and urea at 100 kg N ha^{-1} while the control treatment gave the least yield of 1.36 ton ha^{-1}. Sole urea fertilizer at both 30 kg N ha^{-1} and 100 kg N ha^{-1} did not show significant difference in maize yield from the control treatment. However, sole manure at 30 kg N ha^{-1}, integration of manure and urea, and NPK at 100 kg N ha^{-1} increased yield significantly. N-uptake followed a similar trend as grain yield at both sites. Application of urea alone resulted in relatively higher N_2O emissions per unit of yield compared to other treatments. Increasing the N rate led to further increase in emission per unit kilogram of yield. Combining urea and manure produced the lowest N_2O emissions per unit of yield. The findings of this study show that the efficiency of use of nitrogenous fertilizers and maize yield can be increased, while keeping the emission of GHGs from agricultural productions systems to the environment at lower levels by combining both organic and inorganic N sources.

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LIST OF SYMBOLS AND ABBREVIATIONS

GHGs-Greenhouse gases

SSA-Sub-Saharan Africa

N-Nitrogen

NUE-Nitrogen Use Efficiency

N_2O-Nitrous Oxide

FAO-Food and Agriculture Organization

C-Control (no fertilizer applied)

M-Manure applied at 30 Kg N ha^{-1}

N1-Urea applied at 30 Kg N ha^{-1}

N2-Urea applied at 100 Kg N ha^{-1}

NM-Combined urea and manure applied at 50 Kg N ha^{-1} each

NPK-Nitrogen, Phosphorus and Potassium

ANUE-Agronomic Nitrogen Use Efficiency

ANR-Apparent Nitrogen Recovery

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CHAPTER ONE

INTRODUCTION

1.1. Background

Nitrogen is an essential nutrient for crop production, but its availability remains globally the most limiting plant growth factor for non-leguminous crops (Adediran and Banjoko, 1995; Shanti *et al.,* 1997; Vanlauwe *et al.,* 2011; O'Neil *et al.,* 2004). In Kenya, soils have been reported to decline in fertility as a result of continuous cultivation without fertilizer inputs. For example, Smaling *et al.* (1993; 1997) reported an annual net nutrient depletion exceeding 30 kg N ha^{-1} in central Kenya and 112 Kg N ha^{-1} in Kisii, respectively. Similar depletion rates exist in most parts of western Kenya. This loss in soil fertility has resulted into a decline in maize yields in many farmers' fields where yields less than 2.0 ton ha^{-1} have been reported compared to the potential maize yield of greater than 6.0 ton ha^{-1} (Gitari *et al.,* 1996; Hassan *et al.,* 1998). This has greatly contributed to food insecurity issues among the ever increasing population in Kenya and in Africa at large, which becomes a major obstacle in achieving the sustainable development goals of ending hunger and poverty by 2030 (FAO, 2015). There is therefore an urgent need for use of N inputs in order to realize higher yields and increase food security.

Replenishment of soil N requires application of inorganic or organic N fertilizers either alone or in combination (Palm *et al.,* 1997; Vanlauwe *et al.,* 2002a; Shiluli *et al.,* 2003). Inorganic fertilizer N is soluble and therefore readily available for crop uptake and often results into high yields when timely applied and at the correct rates. However, they are too expensive (Bationo *et al.,* 2006; Morris *et al.,* 2007) and resource poor farmers in the region cannot afford them hence only use very low rates. For example, Adiel (2004) reported that smallholder farmers

in Kenya use less than 20 kg N ha^{-1} as compared to the recommended 60 kg N ha^{-1} for maize production.

Nitrogen use efficiency (NUE) provides information about the relative utilization of additional N applied to an agricultural production system of a country or region. It is influenced by various factors such as source of fertilizer N, fertilizer rate, timing of application, method of application, soil type, crop health (plant stresses) and the magnitude of nitrogen loss (Roberts, 2008). Weather conditions such as rainfall, sunshine, temperature and wind-speed influence the rate of volatilization of surface-applied urea-based products (Roberts, 2008). The timing and amount of rainfall influences the rates of leaching and denitrification losses of available nitrate-N (Craswell and Vlek, 1979).While increasing the rates of inorganic N is necessary in increasing maize yields, this often results into reduced NUE. The low NUE from higher inorganic N rates is attributed mainly to leaching, erosion, bypass flow and runoff losses of the readily soluble N fertilizers (Craswell & Vlek, 1979; Sigunga, 1997; Roberts 2008). In addition, increased gaseous losses through volatilization and denitrification processes have resulted in increased emission of greenhouse gases (GHGs) to the environment (Mosier, 1994; Tokuda and Hayatsu, 2001; Khan *et al.,* 2007). For example, N_2O is one of the major GHGs emitted from N fertilizers and contributes to stratospheric ozone depletion (Ravishankara *et al.,* 2009) resulting in global warming. Therefore, understanding the NUE under farming systems has become an urgent task that underlies success in agricultural development globally (Thompson, 2012; Snapp *et al.,* 2014).

Locally available organic N sources such as cattle manure can be used for correcting N deficiency and therefore increase crop yields. They have also been reported to produce lower emissions of GHGs such as N_2O and CH_4 compared to inorganic-N fertilizers (Mapanda *et al.,*

2011) and hence they are likely to have a higher NUE (Kimetu *et al.,* 2004). However, these depend on type and quality of manure, soil type and other soil conditions (Pelster *et al.*, 2012). Cattle manure usually has very low levels of nitrogen (Palm *et al.,* 1997; Rufino *et al.,* 2010). The highest content has been found to be about 2.3% N and the situation is further aggravated by the fact that their storage is poor and therefore most manure on smallholder farms hardly have more than 0.7% N (Palm *et al.,* 1997). Consequently, application of manure often results into lower yields as a result of N-immobilization in soil (Ma *et al.,* 1999; Nhamo, 2002). Another constraint to the use of manure is the low quantities available (Palm *et al.,* 1997), given that a majority of farmer households own none or only small herds of cattle.

Due to the drawbacks that come with either sole application of organic or inorganic sources of N, technologies that combine both N sources have been suggested as better options in increasing NUE and providing a more balanced supply of nutrients (Donovan and Casey 1998). Greater yield benefits can be achieved through combined application of organic and inorganic fertilizers compared to either of them applied alone (Mucheru-Muna *et al.,* 2007; Nziguheba *et al.,* 2002), due to synergistic effects and improved synchronization of nutrient release and uptake by crops (Palm *et al.* 1997). Combining inorganic and organic N sources has also been found to result into lower GHGs emission per unit yield (Mapanda *et al.,* 2011), although there is limited information to support this because many studies (e.g. Nziguheba *et al.,* 2002; Vanlauwe *et al.,* 2002a and 2002b; Shiluli *et al.,* 2003; Mucheru-Muna *et al.,* 2007 etc) in Sub-Saharan Africa (SSA) concentrated mainly on their effect on crop yields.

1.2 Problem statement

Nitrogen deficiency is the main limiting factor on maize production in western Kenya (Sanchez, 2002; Shiluli *et al.,* 2003) and hence, there is need to apply nitrogen inputs in the soil to increase yields in the region. However, most resource poor farmers use low rates of inorganic fertilizers leading to low maize yields. While high rates of inorganic nitrogenous fertilizer applications may increase yields, they are also associated with low NUE and emission of GHGs to the environment (Khan *et al.,* 2007). Emission of N to the atmosphere contributes to the problem of climate change (global warming) which in turn affects food production. Although cattle manure may be used as a mitigation option in reducing GHGs emission (Mapanda *et al.,* 2011), the available manures on most smallholder farms are usually of poor quality with high C:N ratios. They therefore immobilize N and hence release lower quantities of N for plant growth. Combined application of inorganic and organic fertilizers such as cattle manure has therefore been recommended to overcome the problems of sole application of either of the N sources. Combined application of cattle manure and inorganic N fertilizers can result into increased NUE, higher yield and reduced GHGs emission compared to either of them applied alone, due to synergistic effects and improved synchronization of nutrient release and uptake by crops. However, there is limited information to support this because many studies in Sub-Saharan Africa (SSA) concentrated mainly on their effect on crop yields. Hence, this study was set out to evaluate the effect of applying inorganic and organic sources of nitrogen on N_2O emission, maize yield and NUE in two agro-ecological zones in western Kenya.

1.3. The objectives of the study

1.3.1 General objective

The general objective of this study was to evaluate the effect of cattle manure and inorganic sources of nitrogen applied either alone or in combination on N_2O emission, maize yield and NUE in two agro-ecological zones in western Kenya.

1.3.2 Specific objectives

1. To determine the effect of inorganic N fertilizer and cattle manure when applied alone or in combination on N_2O emission at two agro-ecological sites in western Kenya.

2. To determine the effect of inorganic N fertilizer and cattle manure when applied alone or in combination on maize yield at two agro-ecological zones in western Kenya.

3. To evaluate the effect of inorganic N fertilizers and cattle manure when applied alone or in combination on maize NUE at two agro-ecological zones in western Kenya.

1.4 Hypotheses

1. N_2O emission is not significantly influenced by application of different N sources.

2. Maize yield is not significantly influenced by the types of N sources applied.

3. Nitrogen use efficiency by maize is not significantly influenced by different N sources.

1.5 Justification

Maize production in western Kenya depends mostly on external nutrient inputs and climatic conditions. Nitrogen has a very important role in the growth and development of maize; it is the most limiting nutrient to maize production across Southern and Eastern Africa (Sanchez 2002; Shiluli *et al.,* 2003; Snapp *et al.,* 2014) and strongly linked to N_2O emissions. N applied is usually not efficiently taken up and utilized by maize, and this often results into increased GHG emissions that are harmful to the environment. This calls for the development of appropriate

approaches to fertilizer best management practices such as, application of the right nutrient source at the right rate. The findings of this study can be used by smallholder resource poor farmers in improving the efficiency of use of nitrogenous fertilizers and raise yield of maize while keeping the contribution of emission of greenhouse gases from agricultural productions systems to the environment as low as possible.

1.6 Significance of the study.

The study provided useful information on the effect of N-sources on N_2O gas emission, maize yield and NUE that can be used in making recommendations that optimize N fertilizer use efficiency and yield, while minimizing GHGs emissions to the environment.

<center>**CHAPTER TWO**</center>

<center>**LITERATURE REVIEW**</center>

2.1. Maize *(Zea mays* **L.***)*

Maize (Zea *mays* L.) is produced on nearly 100 million hectares in developing countries, with almost 70 % of the total maize production in the developing world coming from low and lower middle income countries (FAO, 2010). By 2050, demand for maize will double in the developing world (FAO, 2010). Maize is predicted to become the crop with the greatest production globally, and in the developing world by 2025 (Rosegrant *et al.,* 2008). In Kenya, it is the most important grain crop and is produced throughout the country under diverse environments. It is a staple food to a large proportion of people and provides a large fraction of calorie needs to a majority of consumers in urban and rural areas (Nyoro 1992). Nearly all agricultural households plant maize out of which small-scale production accounts for 75% of the total production (Nyoro 2002, Olwende 2012). Successful maize production depends on the correct application of production inputs that will sustain the environment as well as agricultural production. These inputs are adapted cultivars, plant population, soil tillage, fertilization, weed, insect and disease control, harvesting, marketing and financial resources (Jean *et al.,*2003, Olwende 2012).

The Kenyan national average maize yield per hectare is estimated at 1.8 tons (20 bags of 90 kilogram bags). Maize yields however differ by agro-ecological zones as some farmers particularly those in the high potential maize zones have been able to achieve between 4 and 6 tons per hectare (Jean *et al.,* 2003) hence indicating the potential that exists to increase maize productivity. Maize needs 450 to 600 mm of water per season, which is mainly acquired from the soil moisture reserves. It is a warm weather crop and is not grown in areas where the mean daily

<center>7</center>

temperature is less than 19 ^{o} C. The critical temperature detrimentally affecting yield is approximately 32 ^{o} C (Jean *et al.,* 2003). Germination is faster and less variable at soil temperatures of 16 to 18 ^{o} C (Jean *et al.,* 2003). The assimilation of nutrients reaches a peak during flowering. At maturity the total nutrient uptake of a single maize plant is 8.7 g of nitrogen, 5.1 g of phosphorus, and 4 g of potassium (Jean *et al.,* 2003). Each ton of grain produced removes 15 to 18 kg of nitrogen, 2.5 to 3 kg of phosphorus and 3 to 4 kg of potassium from the soil. No other cereal crop utilizes resources more efficient than maize, and its yield per ha is the highest of all grain crops. However, in Africa, maize has been grown continuously without adequate fertilization leading to soil fertility depletion and subsequent low crop yields (Gichuru *et al.,* 2003; Cobo et al., 2010; Sanchez 2002; Smaling *et al.,* 1997), which results to food insecurity. N is reported to be depleted more rapidly than any other nutrients for all major farming systems (Walaga *et al.,* 2000).

2.2.0 Fertilizer materials

2.2 .1 Organic sources of nutrients

Organic materials, such as animal manures, household composts, crop residues, leguminous cover crops, and biomass from leguminous and non-leguminous trees and shrubs, are often used as major nutrient sources to crops. However, their use in most African cropping systems is usually limited by low availability (Palm *et al.,* 1997; Rufino *et al.,* 2010). Although their application usually leads to increased crop yields (Kimetu *et al.,* 2004), lower yields have also been reported as a result of N-immobilization in soil (Ma *et al.,* 1999; Nhamo, 2002). In a study conducted in Zimbabwe, they were found to produce lower emissions of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) compared with the use of mineral-N fertilizers (Mapanda *et al.,* 2011).

The estimation of N_2O from arable soils is highly uncertain, because the emission rates vary depending on agricultural practices, crop type, soil texture, N fertilizer source, and climatic conditions. Identification of mitigation options to climate change requires thorough and many data acquisition of greenhouse gas emissions (Flynn and Smith, 2010). Unfortunately, there is limited or lack of work addressing GHG emissions on the basis of agricultural activities in Africa. The use of manure-N to increase food security and as a climate change mitigation strategy in Africa has been widely debated (Mulvaney *et al.,* 2009). It is generally argued that under the current regional farming systems' setup, the use of cattle manure alone may not sustain the food requirements in Africa (Palm *et al.,* 1997; Rufino *et al.,* 2010). The reason is partly due to the fact that an overwhelming majority of farmer households own none or only small herds of cattle. Western Kenya comprises of smallholder farmers who practice maize farming every year and use manure as source of nutrients, though information on the effect of this organic source of N to yield and GHG gas emission is scanty.

2.2.2 Inorganic sources of nutrients

Inorganic fertilizers are used to overcome nutrient deficiencies, but their use in Africa is limited mainly because of lack of purchasing capacity by the smallholder farmers (Bationo *et al.,* 2006; Morris *et al.,* 2007). The smallholder farmers using inorganic fertilizers in Kenya hardly use the recommended rates (60 kg N ha^{-1}) for maize production, with most of them applying less than 20 kg N ha^{-1} (Adiel 2004). The use of inorganic N-fertilizers has been implicated in loss of soil organic C through increased respiration and GHG emissions (Khan *et al.,* 2007). In addition, this C loss would also decrease soil productivity and agronomic efficiency of applied-N, and would therefore shift the N and C balance in favour of GHG emissions (Mulvaney *et al.,* 2009).

The lower N use efficiency however would likely lead to greater N_2O emissions when more N fertilizer is added.

2.2.3 Combining organic and inorganic sources of nutrients

The combined application of organic and inorganic fertilizers is increasingly gaining recognition as one of the appropriate ways of addressing soil fertility depletion, especially in low-external input systems in Africa and forms an integral part of integrated soil fertility management. Greater yield benefits can be achieved following the combined application of organic and inorganic fertilizers compared to either resource applied alone (Nziguheba *et al.,* 2002; Mucheru-Muna *et al.,* 2007). This could be due to additional benefits that organic inputs confer to the soil chemical and physical properties such as, improvement of soil structure, soil moisture holding capacity, cation exchange capacity and addition of other macro-nutrients such as calcium and magnesium and micronutrients (Palm *et al.,* 1997; Mutuo *et al.,* 2000). In addition, inorganic fertilizers are more soluble and therefore readily available for crop uptake and often results into high yields. Nutrient cycling and the associated yield benefits derived from combining organic and inorganic fertilizers are dependent on a number of factors including climate, bio-physico-chemical soil environment and quality of the fertilizer materials (Chivenge *et al.,* 2009). For example, Tian *et al.* (2007) observed increase in the rate of decomposition and nutrient release from organic materials in wetter climates, but in drier climates decomposition and nutrient release was low.

2.3. Agriculture and Nitrous Oxide Emissions

Agricultural practices such as use of fertilizers are associated with increased production of primary GHGs resulting in global warming. For instance, agriculture contributes approximately 42% of the total GHGs globally (IPCC, 2007). This is derived from manufacture

and use of fertilizers, agrichemicals, operation of on-farm machinery, cropping production systems and changes in land-use. The primary GHGs in agriculture are N_2O, CH_4 and CO_2. The N_2O is produced during both nitrification and denitrification processes which are major contributors of annual N_2O production globally (Mosier *et al.,* 1998), CH_4 is majorly from enteric digestion of ruminants and anaerobic decomposition of organic matter especially from irrigated rice paddies (Yue *et al.,* 2005) and CO_2 is mainly from aerobic decomposition of organic matter. Nitrification and denitrification are both microbial processes in the soil (Bouwman, 1990). A variety of factors control rates of these two microbial processes that produce N_2O. Important variables are soil water content, temperature, nitrate or ammonium concentrations, available organic carbon for denitrifying bacteria, and pH (Signor *et al.*, 2013)

Agricultural N_2O emissions are thought to arise from fertilization of soils with mineral N and animal manures (Millar *et al.,* 2014). However, nitrous oxide is also directly evolved in soil during biomass burning, and enhanced emissions arise during conversion of tropical forest to agriculture (Batjes; Bridges, 1992). N_2O has a Global Warming Potential (GWP) that is approximately 310 times larger than that of CO_2, and an atmospheric lifetime of about 120 years (IPCC. 2007). It also contributes to the depletion of stratospheric ozone (Bouwman, 1990; Ravishankara *et al.,* 2009). Atmospheric concentrations of N_2O increased from approximately 270 ppb during the pre-industrial era to 319 ppb in 2005 (IPCC, 2007). Studies also show that the atmospheric concentration of N_2O is rising linearly at a rate of 0.3% per year (IPCC, 2007). It is estimated that the global annual emission from fertilized cropland is 3.3 ton N_2O-N year^{-1} with an additional 0.8 ton N_2O-N year^{-1} from fertilized grassland (Stehfest; Bouwman. 2006). Synthetic fertilizer-N, applied directly to the soil is the main source of the increase in N_2O attributed to agriculture. As worldwide fertilizer-N demand is expected to rise from 100 million

tonnes in 2006 to >135 million metric tons in 2030, N_2O emissions are expected to rise further in future (FAO, 2010). A study by Crutzen *et al*. (2008) estimated that every kilogram of fertilizer-N applied to soil will eventually lead to 30–50 g N_2O-N emission.

Despite detrimental effects on N_2O emissions and other losses of reactive N to the environment, N fertilizer remains essential to global crop production. After water availability, N availability remains globally the most limiting plant growth factor for non-leguminous crops (Adediran and Banjoko, 1995; Shanti *et al.,* 1997; Vanlauwe *et al.,* 2011; O'Neil *et al*., 2004). The relationship between crop productivity and fertilizer N input is not linear but follows the well-known diminishing return function. Obtaining higher yields and effective N-fertilizer use efficiency is inherently difficult to achieve (Cassman *et al.,* 2002). This is because highly productive agricultural systems are often associated with large N losses to the environment, including N_2O emissions.

Addition of fertilizer to arable land affects N_2O emissions. Malhi *et al.* (2006) reported that the amount of N lost as N_2O was higher from N-fertilized than from zero-N plots cultivated with barley (*Hordeum vulgare* L.), pea (*Pisum sativum* L.), wheat (*Triticum aestivum* L.) and canola (*Brassica naptis* L.). Yue *et al.* (2005) found that N_2O emissions significantly increased from rice fertilized with urea. However, Adviento- Borbe *et al* (2007) showed that in four high-yielding maize systems, N_2O emission peaks were mainly associated with high temperature and high soil water content resulting from rainfall or irrigation events, but less clearly related to soil NO_3-N levels. Because interactions among the physical, chemical, and biological variables are complex, N_2O fluxes from agricultural systems are highly variable in both time and space (Duxbury and McConnaughey, 1986; Smith,1990; Clayton *et al.,* 1994). Consequently, prediction of N_2O emissions associated with the source of N applied to a specific field or fixed

by legumes (Mosier, 1993) is not yet reliable. Such predictive capabilities are needed because N_2O emission derived from agriculture alone is 42% of the total annual emissions (IPCC, 2007).

2.4 Nutrient use efficiency

Nutrient use efficiency is defined as the ability of a genotype/cultivar to acquire nutrients from growth medium and/or to incorporate or utilize them in the production of shoot and root biomass or utilizable plant materials (Blair,1993). Higher nutrient use efficiency by plants could reduce fertilizer input costs, decrease the amount of nutrient losses, and enhance crop yields. Sustainable nutrient management therefore, must be both efficient and effective to deliver anticipated economic, social, and environmental benefits. Recovery of applied inorganic fertilizers by plants is low in many soils. Estimates of overall efficiency of these applied fertilizers have been about 50% or lower for N (Baligar and Bennett, 1986a, 1986b). These lower efficiencies are due to significant losses of nutrients by leaching, run-off, gaseous emission and fixation by soil. These nutrient losses can potentially contribute to degradation of soil and eventually lead to overall environmental degradation.

2.4.1 Measures of nutrient use efficiency and their application

There are a number of common measures of nutrient use efficiency, as defined by Dobermann (2007), along with their applications and limitations.

Agronomic efficiency (AE) is calculated in units of yield increase per unit of nutrient applied. It closely reflects the direct production impact of an applied fertilizer and relates directly to economic return. The calculation of AE requires knowledge of yield without nutrient input, so is only known when research plots with zero nutrient input have been implemented on the farm. If it is calculated using data from annual trials rather than long-term trials, nutrient use efficiency of the applied fertilizer is often underestimated because of residual effects of the application on

future crops. Therefore, estimating long-term contribution of fertilizer to crop yield requires long-term trials.

Apparent recovery efficiency (RE) is one of the more complex forms of nutrient use efficiency expressions and is most commonly defined as the difference in nutrient uptake in above-ground parts of the plant between the fertilized and unfertilized crop relative to the quantity of nutrient applied. It is often the preferred nutrient use efficiency expression by scientists studying the nutrient response of the crop. Like AE, it can only be measured when a plot without nutrient has been implemented on the site, but in addition requires measurement of nutrient concentrations in the crop. And, like AE, when calculated from annual response data, it will often underestimate long-term nutrient use efficiency.

Physiological efficiency (PE) is defined as the yield increase in relation to the increase in crop uptake of the nutrient in above-ground parts of the plant. Like AE and RE, it needs a plot without application of the nutrient of interest to be implemented on the site. It also requires measurement of nutrient concentrations in the crop and is mainly measured and used in research.

Partial factor productivity (PFP) is a simple production efficiency expression, calculated in units of crop yield per unit of nutrient applied. It is easily calculated for any farm that keeps records of inputs and yields. It can also be calculated at the regional and national level, provided reliable statistics on input use and crop yields are available. However, partial factor productivity values vary among crops in different cropping systems, because crops differ in their nutrient needs. Hence, geographic regions with different cropping systems are difficult to compare with this indicator.

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of "removal to use"). Less

frequently it is reported as "output minus input." PNB can be measured or estimated by crop producers as well as at the regional or national level. Often the assumption is made that a PNB close to 1 suggests that soil fertility will be sustained at a steady state. However, since the balance calculation is a partial balance and nutrient removal by processes, such as erosion and leaching are usually not included, using a PNB of 1 as an indicator of soil fertility sustainability can be misleading, particularly in regions with very low indigenous soil fertility and low inputs and production, such as Sub-Saharan Africa. Also, all nutrient inputs are rarely included in the balance calculations, thus the modifier, partial, in the term. Biological N fixation, recoverable manure nutrients, biosolids, irrigation water, and the atmosphere can all be nutrient sources in addition to fertilizer. Values well below 1, where nutrient inputs far exceed nutrient removal, might suggest avoidable nutrient losses and thus the need for improved nutrient use efficiency (Snyder and Bruulsema, 2007); attainable values, however, are cropping system and soil specific. A PNB greater than 1 means more nutrients are removed with the harvested crop than applied by fertilizer and/or manure, a situation equivalent to "soil mining" of nutrients. This situation may be desired if available nutrient contents in the soil are known to be higher than recommended. However, in cases where soil nutrient concentration is at or below recommended levels, a PNB >1 must be regarded as unsustainable (Brentrup and Palliere, 2010).

Internal utilization efficiency (IE) is defined as the yield in relation to total nutrient uptake. It varies with genotype, environment and management. A very high IE suggests deficiency of that nutrient. Low IE suggests poor internal nutrient conversion due to other stresses (deficiencies of other nutrients, drought stress, heat stress, mineral toxicities, pests, etc.).

2.4.2 Nitrogen Use Efficiency

In most cases it is helpful to use more than one nutrient use efficiency term when evaluating any management practice, allowing for a better understanding and quantification of the crop response to the applied nutrient. However, this study focuses on the Agronomic Nitrogen Use Efficiency (ANUE) and Apparent Nitrogen Recovery (ANR) since they closely reflect the direct production impact of an applied fertilizer nutrient and the potential for nutrient loss from the cropping system. Nitrogen has a very important role in the growth and development of maize. It increases the protoplasm content and thus increases cell size, leaf area and photosynthetic activity. However, not all of the applied fertilizer ends up in the crop. Part of the fertilizer nutrients are lost to the wider environment and contribute to environmental problems such as climate change (Conway and Pretty, 1991; Smalling, *et al.,* 2006).

ANUE and ANR provide information about the relative utilization of additional N applied to an agricultural production system of a country or region. They are influenced by various factors such as source of fertilizer N, fertilizer rate, timing of application, method of application, soil type, crop health (plant stresses) and the magnitude of nitrogen loss (Roberts, 2008). Weather conditions such as rainfall, sunshine, temperature and wind-speed influence the rate of volatilization of surface-applied urea-based products (Roberts, 2008). The timing and amount of rainfall influences the rates of leaching and denitrification losses of available nitrate-N (Craswell and Vlek, 1979). Nitrogen Use Efficiency (NUE) is directly linked to both crop yield and N_2O emission and improving NUE have been listed among today's most critical and daunting research issues (Thompson, 2012) and raising the efficiency with which farmers use N fertilizers is crucial for achieving sustainable agricultural productivity growth, food security, poverty reduction and protecting the environment (Cassman *et al.,* 2002)

CHAPTER THREE

MATERIALS AND METHODS

3.1. Location and site characterization

The study was carried out within a 10 km x 10 km block known as the Lower Nyando Block located in Kericho and Kisumu counties in western Kenya (Between 0º13'30''S - 0º24'0''S, 34º54'0''E – 35º4'30''E) identified by the Climate Change, Agriculture and Food Security (CCAFS) project, as one of the "hot spots" (regions and system of high mitigation potential and high vulnerability for food insecurity). The lowland field was located in North Nyakach sub-location in Kisumu county at an altitude of 1226 m above sea level, latitude of 0.3085◦S and longitude of 34.9882◦E, while the highland field was located in Soin sub-location in Kericho county at an altitude of 1676 m above sea level, latitude of 0.3516◦S and longitude of 35.0561◦E. The population of the area within the block was about 750,000 people (Mango *et al.,* 2011), mainly Luo and Kalenjin, with a high human population density, with farm holding often less than 1 ha per household. More than 80% of this population formally or informally depends on agriculture for their livelihood. The agricultural structure in the region is mainly subsistence, consisting of mixed cropping systems with maize, sorghum, and sugarcane being the main crops grown.

The lowland has a sub-humid tropical climate while the highland shows a humid tropical climate. The region experiences two types of rain seasons in a year. The long rain season experienced throughout the whole region from April to July (Verchot *et al.,* 2007) and the short rain season which differs slightly depending on the location, but usually occurs in September/October (Onyango e*t al.,* 2005). The lowland receives an annual rainfall of about 1,100 mm, while the highland receives about 1,700 mm (ICRAF, 2003).

Temperatures remain relatively stable throughout the year, although average annual temperatures change spatially depending on the altitude. In the lowlands, average annual temperature is 22.2 ℃ while in the highlands it is 16.9 ℃ (Verchot *et al.,* 2007). The annual monthly maximum temperatures in the lowlands range from 29 to 31 ℃, while the annual monthly minimum temperatures range from 12 to 16 ℃ (Onyango *et al.,* 2005). In the highlands, the annual monthly maximum temperatures range from 19 to 27 ℃, while the annual monthly minimum temperatures range from 5 to 12 ℃ (Onyango *et al.*, 2005).

Soil at the lowland is Vertisol (locally known as Black Cotton soils), derived from Holocene alluvial deposits, frequently occurring in saline or sodic phases with deep profiles and moderate to low fertility. The predominat soil at highland site is Nitisols which is deep well drained and structurally stable (Waruru *et al.*, 2003). Figure 1 shows the location of the study site (10 km x 10 km block known as the Lower Nyando Block located in Kericho and Kisumu counties in western Kenya).
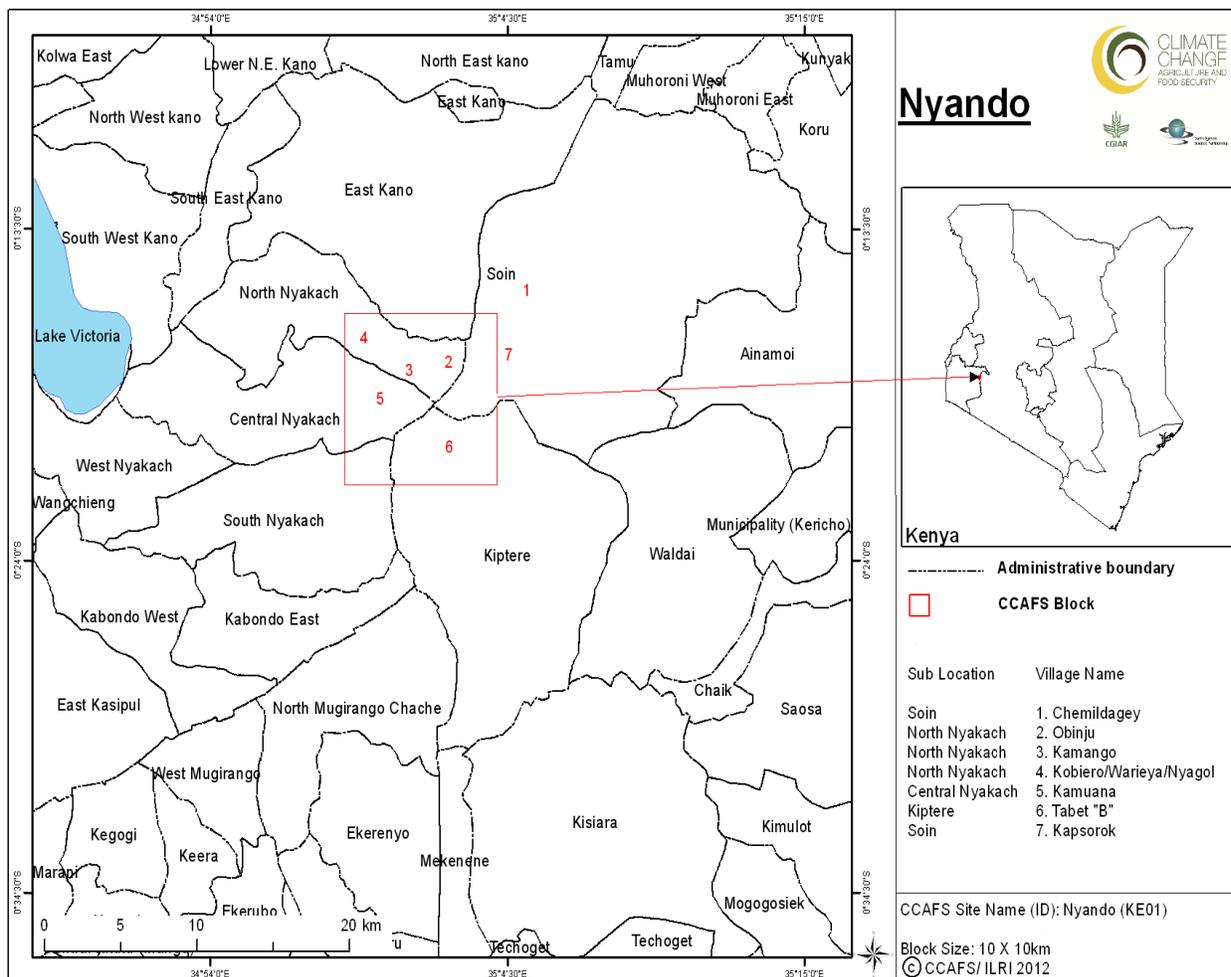
Figure 1: Location of the study site in Nyando, Kenya

3.2.0 Experimental design and trial implementation

3.2.1 Treatments and experimental design

Six treatments replicated 3 times were applied (Table 1). They included a control (no fertilizer), manure alone of N equivalent at 30 kg N ha^{-1}, urea 30 kg N ha^{-1}, urea 100 kg N ha^{-1}, urea 50 kg N ha^{-1} combined with manure 50 kg N ha^{-1} and NPK (17:17:17) at 100 kg N ha^{-1}. The application rates for the treatments were same at both experimental sites. Well composted cattle manure of 0.7 % N obtained from ILRI Nairobi provided organic N, while urea and NPK were used as inorganic N. The quantities of manure which were equivalent to 30 kg N (4.3 ton ha^{-1}) and 50 kg N (7.2 ton ha^{-1}) each were obtained to be used in treatments 2 and 5 respectively.

The experiment was randomized complete block design (RCBD) in the lowland (Figure 2) and completely randomized design (CRD) in the highland (Figure 3). The designs were adopted depending on the slope, soil heterogeneity, size and shape of the experimental farms. The highland farm was homogeneous and suitable for CRD while the lowland one was heterogeneous, hence the need to adopt an RCBD to account for soil variability.

Table 1: Treatments, N-sources, rates and the quantity of the fertilizer material applied per experimental plot

Treatments	N-source Organic	Inorganic	Total N kg ha^{-1}	Quantity/plot (56.25m^2) g
1. Control (0 kg N ha^{-1})	0	0	0	0
2. Manure 30 kg N ha^{-1}	30	0	30	24000
3. Urea 30 kg N ha^{-1}	0	30	30	367
4. Urea 100 kg N ha^{-1}	0	100	100	1200
5.Urea 50 kg N ha^{-1} + Manure 50 kg N ha^{-1}	50	50	100	611 urea + 40000 manure
6. NPK 100 kg N ha^{-1}	0	100	100	3300

N2	NM	NPK	C	M	N1
C	NPK	N2	N1	NM	M
M	C	N2	NPK	NM	N1

C= Control (no fertilizer); M=Manure 30 kg N ha^{-1}; N1=Urea 30 kg N ha^{-1}; N2=Urea 100 kg N ha^{-1}; NM=Urea+ Manure (50 kg N ha^{-1} each) and NPK= NPK (17:17:17) 100 kg N ha^{-1}

Figure 2: Randomization of experimental units at the lowland site (Randomized complete block design)

N1	NPK	NM	M	C
NM	N1	N2	C	M
NPK	N2	NPK	N1	NM
		N2	C	M

C= Control (no fertilizer); M=Manure 30 kg N ha^{-1}; N1=Urea 30 kg N ha^{-1}; N2=Urea 100 kg N ha^{-1}; NM = Urea + Manure (50 kg N ha^{-1} each) and NPK= NPK (17:17:17) 100 kg N ha^{-1}

Figure 3: Randomization of experimental units at the highland site (Completely randomized design)

3.2.2 Field layout

The plots were set to accommodate the six treatments replicated three times, leading to a total of eighteen plots measuring 7.5 x 7.5 m each in each experimental sites. The arrangement for field layout was adopted depending on the size and shape of the experimental farms.

3.3 Trial establishment and management

The study was conducted during the long rain season (April to August) in 2014. Land preparation started by ploughing early in February and March to have the field ready for planting at the onset of rains in April. This was done twice by use of an ox-drawn plough which is used by most farmers in the sites. The ploughing depth was maintained at approximately 20 cm throughout to ensure uniformity across the sites. This study focused on maize as the test crop because it is the main cereal crop grown in the study sites. The same crop was used at both sites to make possible direct cross-comparison between the two agro-ecological zones. An improved variety of maize hybrid 614D that is commonly used by local farmers was chosen for planting.

Planting was done at the onset of the rainy season at each site. Maize was planted at spacing of 30 cm (intra-row) and 75 cm (inter-row). Planting ropes marked at 30 cm intervals using ink were used to achieve the required intra-row spacing by making planting holes adjacent to the marks. For efficiency and to avoid bent rows, the holes were made on the same side of the

rope with use of hand held hoes. Two seeds were planted per hole at a depth of about 5-7 cm and later thinned to one for each station. Fertilizer materials were applied in the planting holes at planting time and covered with some soil before placing seeds to avoid direct contact between them. The fertilizers were pre-weighed, using a sensitive balance (1g accuracy). Weeding was done twice to keep the plots free from weeds as they compete with crops for nutrients, water and light. This was done by use of hand held hoes and by shaking soil off from their roots to prevent them from further growth.

Harvesting was done when the crop was at physiological maturity. Grain, stover and core yields in each plot were determined from a net-plot of 3 rows x 2.5 m. The cobs were harvested in such a way that the husks remained on the plant, counted and their total weight determined. All the plants in the net-plot were cut at the soil surface and total stover fresh weights determined in the field. Five representative stovers were selected randomly, cut into 5 cm strips, mixed well, and a subsample of about 500 g taken. The weight of these fresh sub-samples were recorded and then taken to the laboratory for drying. Five cobs were also randomly selected and fresh weight determined (done by ordering the cobs from small to large and then selecting 5 cobs such that a representative sample of the whole range of sizes was selected) and taken to the laboratory for processing and analysis.

3.4. Plant samples analysis

The plant samples (grains, stovers and cores) obtained at harvest were taken to the laboratory at World Agroforestry Centre in Kisumu where grains were removed from cores and their fresh weights determined. Grains were oven dried at 60ºC for 2 days to standardize their moisture content to 15 % while the cores and stovers were air dried for 7 days and their dry weights measured. The moisture content of grain was determined by an SR7801G grain moisture

meter. The grains, cores and stover samples were then ground into fine powders (0.25 mm), by using a RETSCH cutting mill SM 200 and 20 g of each sample packed into zip locked sampling bags. The samples were taken to the International Livestock Research Institute (ILRI) laboratory in Nairobi, where they were further pound into micro-milled powders (5 μm) by use of a RETSCH ball mixer mill MM 400 and analyzed for N using a CN analyzer elemental combustion system (Costech International S.p.A., Milano, Italy) fitted with a zero-blank auto-sampler.

3.5. Calculation of nitrogen use efficiency

The results of plant samples analysis and the maize yield were used to calculate the total N uptake, Agronomic Nitrogen Use Efficiency and the Apparent Nitrogen Recovery (ANR) according to (Cassman *et al.* 1998) using the following equations:

Total N uptake $= (C_g*Y_g + C_s*Y_s + C_c*Y_c)$

$$\text{Agronomic N use efficiency} = \frac{100*(\text{Trt Y} - \text{Con Y})\text{kg ha}^{-1}}{\text{Total N applied kg ha}^{-1}}$$

$$\text{Apparent N recovery efficiency} = \frac{100*(\text{Trt N uptake} - \text{Con N uptake})\text{kgha}^{-1}}{\text{Total N applied kg N ha}^{-1}}$$

- C_g, C_s and C_c = grain, stover and cores N concentrations respectively
- Y_g, Y_s and Y_c = grain, stover and cores yield respectively
- Trt Y= Treatment maize yield
- Con Y= Maize yield of the control treatment.
- Trt N uptake= Treatment nitrogen uptake
- Con N uptake= Nitrogen uptake by control treatment.

3.6. Soil sampling and analysis

Soil samples were taken prior to treatments application at both sites. From each plot, two composite samples from two depths; topsoil (0 -10 cm) and subsoil (10-20 cm) were taken using a soil corer (five soil samples from each depth were taken along the two diagonals of the plot by taking a sample at the center and other four at either side from the center on the diagonals, they were thoroughly mixed and sub-samples of 500 g each put in polythene bags). The samples were then taken to the World Agroforestry Centre laboratory in Kisumu where they were air-dried by spreading them in thin layers on paper sheets. The samples were re- packed and taken to the World Agroforestry Centre laboratory in Nairobi where they were oven dried at $40^{\circ}c$ for a week and then grounded into fine powders that were analyzed for total N, C, pH and bulk density. Soil pH was measured in 2: 1 water: soil solution. Soil bulk density was determined gravimetrically as described by (van Reeuwijk, 2002). Soil carbon and nitrogen concentrations were determined by extraction (1 : 5 soil : solution) with 2M KCl, reduction with vanadium and green indophenol method on an Epoch microplate spectrophotometer (BioTek, Winooski, VT) as described by (Bolleter *et al.,* 1961).

3.7. Gas sampling

Soil gas emissions were sampled using the gas pooling technique (Arias-Navarro *et al.,* 2013), which is suitable for keeping small-scale emission variability as low as possible. Sampling was done once in a week, any time of the day, taking into account the atmospheric pressure and temperature for the purposes of gas flux calculation. This started from the time of planting up to the time of harvesting the crop. Gaseous emissions from soil were trapped using chambers located randomly within the sampling plots. The chambers were installed during treatment application (planting) time. Each plot had three chambers fixed across the intra-row

spacing with its width covering more than half of this spacing so as to get as close as possible to where the treatments were applied (without disturbing crop roots). Excessive heating of chambers from direct sunlight was prevented by covering the sampling chambers with aluminum foil.

The emitted gas in each chamber was collected into 10 ml glass vials using a 60 ml-graduated syringe. This was done by first taking the heights of the base (fixed) chambers above the ground approximately at the center of the four sides for the purpose of calculating the chamber volume. This was recorded on the data sheet containing the name of the sampling person, plot ID, date, air pressure, environmental condition, vegetation and soil status. The chamber lids, lined with the sealing materials to ensure there was no leakage during gas sampling time, were used to close the bases. They also had a septum through which the gas was sampled, a fan and temperature sensors.

Cables from the battery were connected to all the lids to power the fans (Figure 4) and then the temperature sensors switched on. Time, T1 (0 min) and initial temperatures of the chambers were recorded and immediately closed tightly by using clips (Figure 5) and the gas sampled by using a 60 ml-graduated syringe; 20 ml of gas from each chamber was collected from all the three chambers of every plot (Figure 6), ending up with 60 ml of gas in the syringe (by closing the stop-cock of the syringe before pulling out the needle from septum of each chamber). By using an exhaust needle and the sample syringe needle, a properly labeled vial was flushed up to 20 ml mark with sample gas and swiftly the exhaust needle was removed and the vial filled with the remaining gas such as to create an overpressure. The stop-cock was closed and the syringe pulled out while holding the needle so as not to lose any sample. The vial number/label was then recorded on the data sheet. The process was repeated for time T2 (15

min), T3 (30 min) and T4 (45 min). During sampling for time T4, the final temperature of the chambers was recorded on the data sheet. Temperature sensors were inserted into the soil just outside the chambers for soil temperature recording. The ambient temperature was measured by a thermometer and then recorded on the data sheet. Soil moisture and electrical conductivity were also measured weekly during gas sampling time by using a soil probe at 15 cm depth just outside all chambers. The vials were then transported to the laboratory for analysis within four days of sampling.
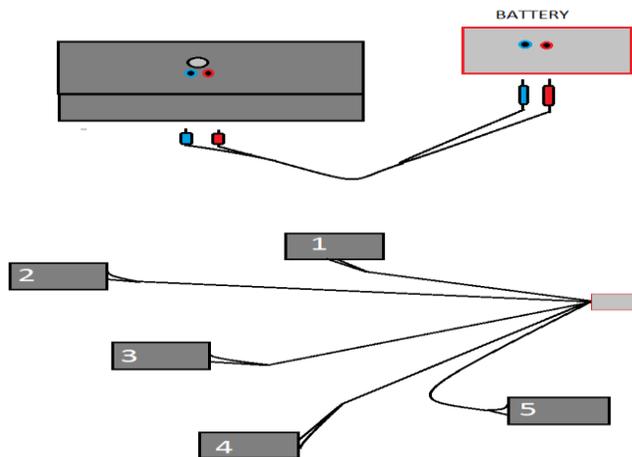
Figure 4: Connecting the cables to the battery and chambers
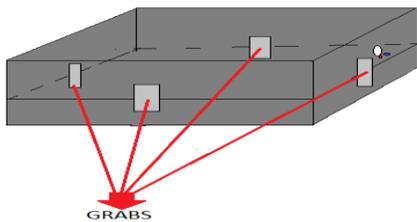
Figure 5: Clipping the chamber lid to the anchor base (Closing chambers)
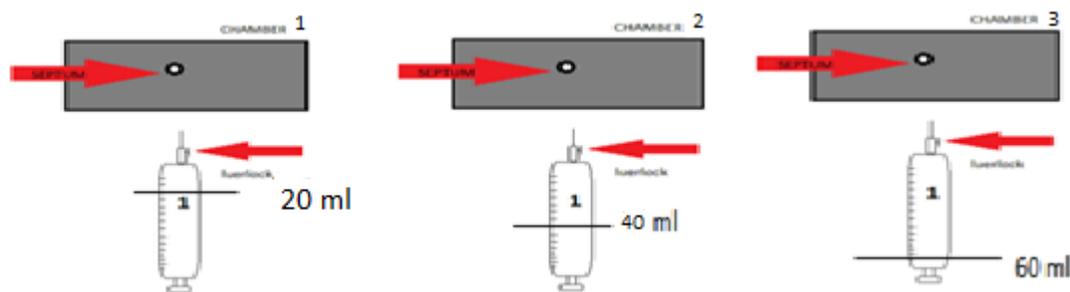
Figure 6: Pooling method of gas sampling to give a composite gas mixture from the three chambers

3.8. Analysis of gas samples

The air samples were taken to the laboratory at Maseno University within four days of sampling, where they were analyzed for CO_2, CH_4 and N_2O by gas chromatography on an SRI 8610C gas chromatograph 25 (9' Hayesep D column) fitted with a 63Ni-electron capture detector for N_2O and a flame ionization detector for CH_4 and a thermal conductivity detector for CO_2. Pure N_2 was the carrier gas at a flow rate of 20 ml min^{-1}. A calibration gas (standard gas with known CO_2, CH_4 and N_2O concentrations in synthetic air) was run after every fourth sample analyzed on gas chromatograph and the relation between the peak area from the calibration gas and its concentration was used to determine the CO_2, CH_4 and N_2O concentrations of the headspace samples.

3.9. Calculation of N_2O fluxes

N_2O fluxes were calculated from the observed rate of change in headspace/chamber concentrations over time (between 0 and sampling after 15, 30 and 45 minutes) using linear regression, taking into account the atmospheric pressure and temperature during the time of sampling (corrected for chamber temperature and air pressure). A four point sampling in time approach was chosen in order to reduce uncertainties in the estimated emissions.

The following formula was used in calculation of N_2O fluxes.

$$F = \frac{C*MW*VCh*60*10^6}{ACh*VM*10^9}$$

Where:

- F is the N_2O flux rate ($\mu g\ m^{-2}\ h^{-1}$)

- C is the slope of N_2O concentration with time (ppb/min)

- Mw is the molecular weight of component (g/mol)

- Vch is the headspace/chamber volume (m^3)

- Ach is the basal chamber area (m^2)

- Vm is the corrected standard gaseous molar volume ($m^3 mol^{-1}$)

NOTE: Vm= $(22.4*10^{-3} m^3 mol^{-1}*(273.15+temp)/273.15)*(air\ pressure/1013)$

The formula is multiplied by 60 to express the fluxes per hour, and divided by 10^9 to convert ppb to g and multiplied by 10^6 to convert g to μg. N_2O fluxes are given in $\mu g\ N\ m^{-2}\ h^{-1}$. Cumulative seasonal emissions were estimated for the treatments using trapezoidal integration between sampling dates.

3.10. Statistical data analysis

One-way analysis of variance was carried out to establish any significant treatment effects on N_2O emission, maize yield and NUE ($p < 0.05$). The least significant difference of means (LSD) was used to separate treatment means to determine significance difference. The GenStat statistical package version 37.2 was used in the statistical analysis of data.

CHAPTER FOUR

RESULTS

4.1. Soil characteristics at the study sites

Soil properties at two depths, just before treatments application are shown in Table 2. The soils at the highland site were more acidic than at the lowland. The highland site also had higher carbon and nitrogen contents, which were almost twice the levels at the lowland. However, lower bulk density and C: N ratio was obtained at the highland than at the lowland.

Table 2: Soil properties at the highland and lowland sites at the beginning of the experiment

Parameter	Highland		Lowland	
	0-10 cm	10−20 cm	0-10 cm	10−20 cm
%C	2.29	2.27	1.23	1.23
%N	0.24	0.24	0.12	0.11
C:N Ratio	9.54	9.46	10.25	11.18
pH	5.6	5.6	6.6	6.6
Bulk density gcm-3	0.96	1.00	1.23	1.27

4.2. Rainfall, soil moisture, soil temperature and air temperature

The highland site received a higher amount of seasonal rainfall of 790.40 mm than the lowland site which received a total of 551.80 mm during the four month's duration of the experiment (Figure 7). The soil moisture ranged from 13.4 % to 43 % at the highland farm and 9.6 % to 64.8 % at the lowland farm (Figure 7). The greatest soil moisture content was obtained during weeks 5 and 6 from both sites, at the same time when rainfall amount was highest. The lowest soil moisture content was recorded in weeks 7 and 8 when rainfall was minimum at the highland and there was no rainfall at all at the lowland site. The variations in soil moisture during the season were more closely correlated (r^2=0.776 & 0.867) to seasonal rainfall patterns for highland and lowland sites respectively. The soil temperature at a depth of 15 cm ranged from

17.6 to 25.8°C with a mean of 22.0°C at the highland and 23.0 to 28.9°C with a mean of 25.3°C at the lowland site. The atmospheric temperatures in the lowland site were considerably higher (average daily minimum 16.0°C and maximum 30.9°C) than in the highland (average daily minimum 13.0°C and maximum 27.2°C).
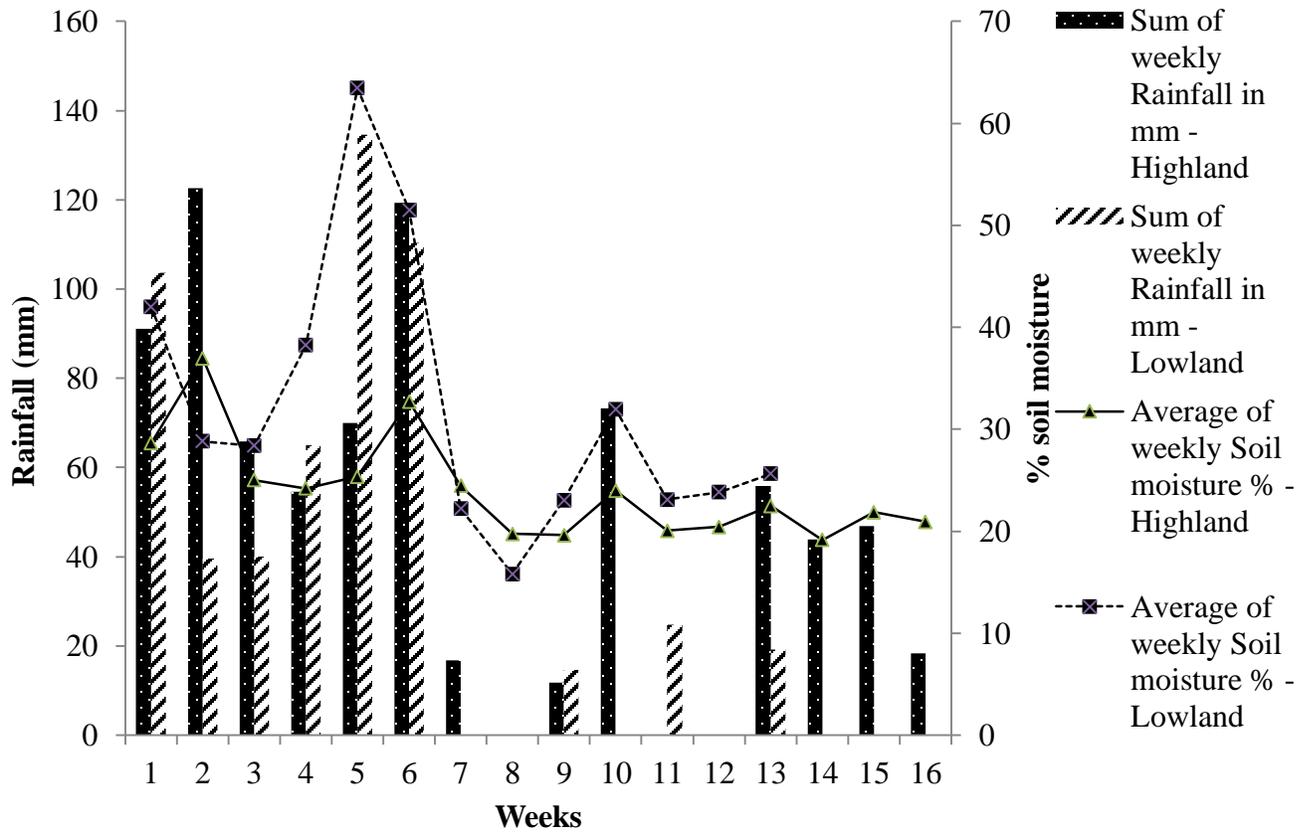
Figure 7: Amount of rainfall and changes in soil moisture content in the highland and lowland sites from 23rd April to 28th August 2014.

4.3. Soil N_2O emission trends over the season

Higher amounts of N_2O were emitted from plots with urea and NPK than those with manure at both sites during the first week of application. A further increase in N_2O emission from all treatments was observed in the highland site during the second week but there was a sharp decrease in the lowland (Figures 8 and 9). Lower emission was recorded in weeks 3 and 4 but then increased instantly in weeks 5 and 6 (when soil moisture content was high) with greater effect observed in the lowland (Figures 9). A substantial drop in emission was seen again in all the treatments at both sites starting from week 7, when the moisture contents were low (Figure 8 and 9). Towards the end of the experiment, N_2O emission from manure treatments at both sites tended to increase again with a significant effect observed at the highland (Figure 9).
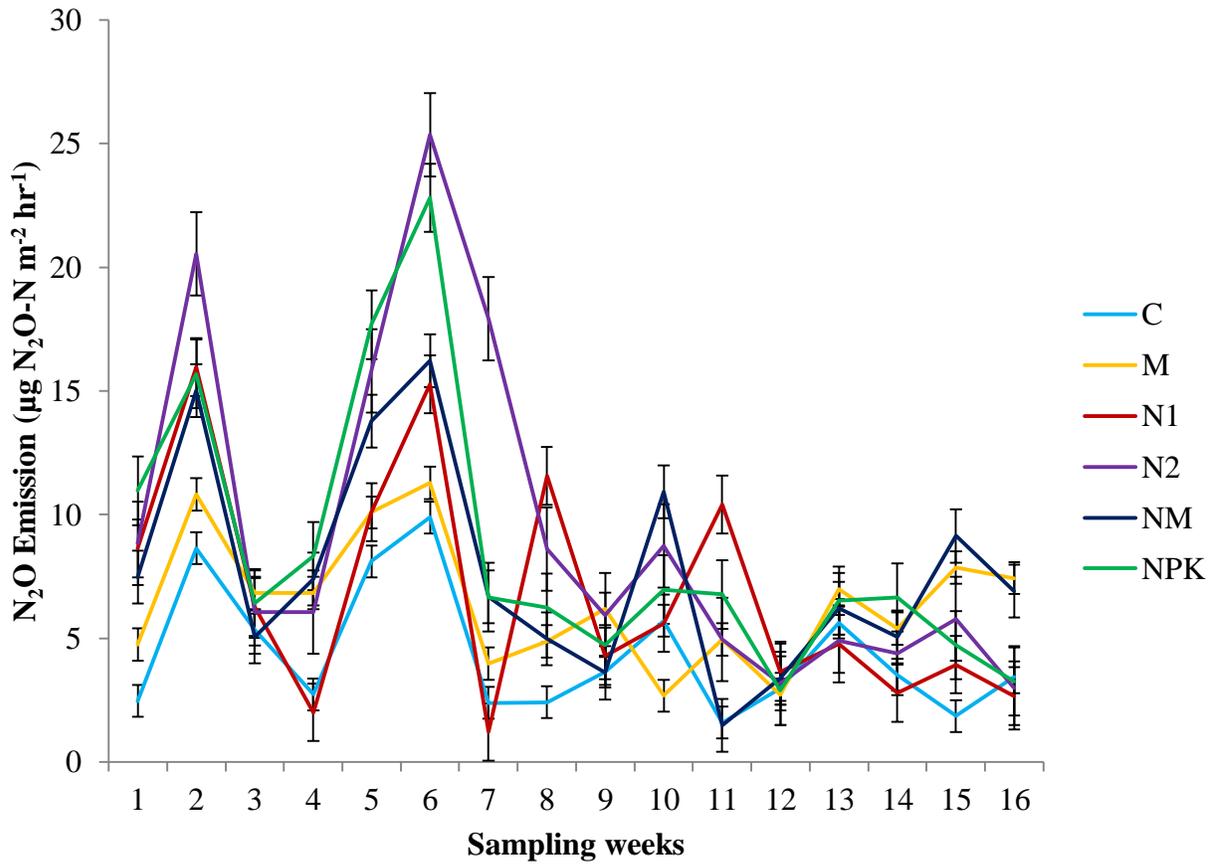
C= Control (no fertilizer); M=Manure 30 kg N ha-1; N1=Urea 30 kg N ha-1; N2=Urea 100 kg N ha-1; NM=Urea+ Manure (50 kg N ha-1 each) and NPK= NPK (17:17:17) 100 kg N ha-1

Figure 8: N_2O emission trends in the highland during 2014 long rain season from 3rd May to 28th August.
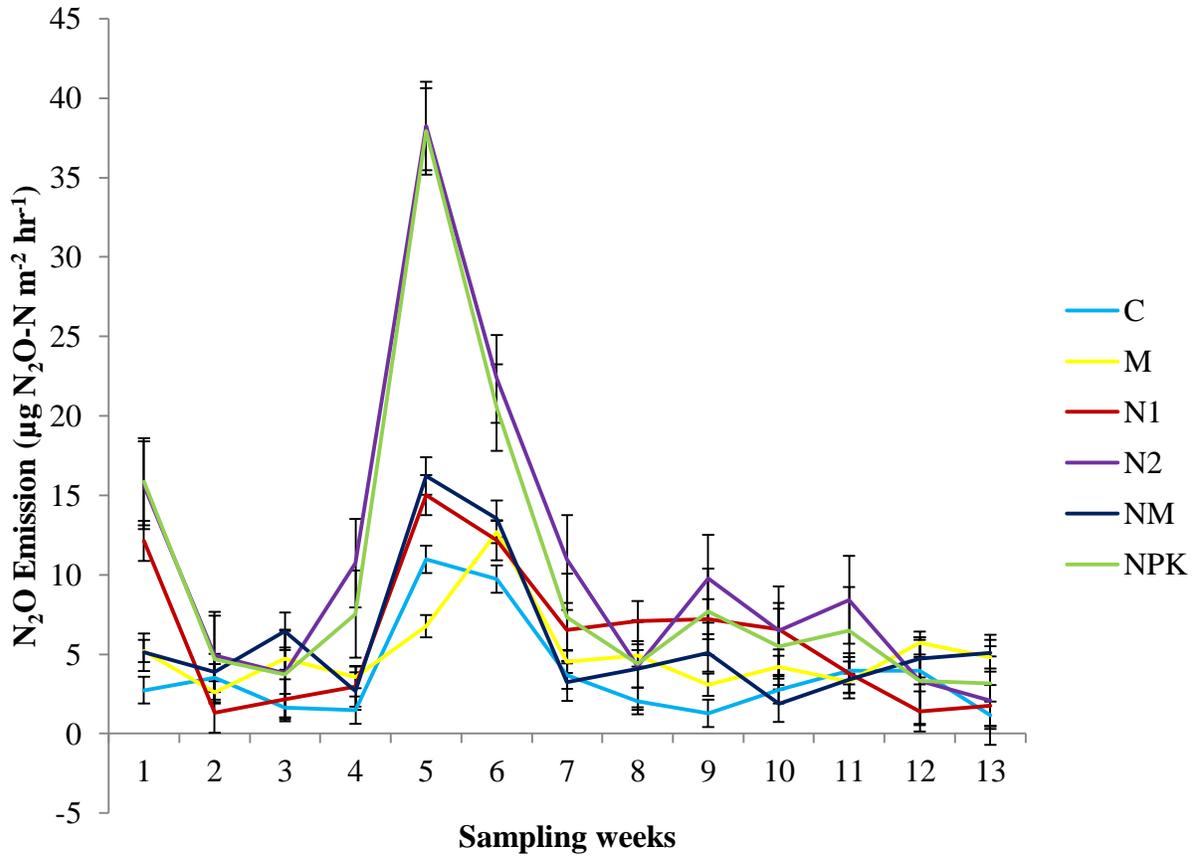
C= Control (no fertilizer); M=Manure 30 kg N ha^{-1}; N1=Urea 30 kg N ha^{-1}; N2=Urea 100 kg N ha^{-1}; NM=Urea+ Manure (50 kg N ha^{-1} each) and NPK= NPK (17:17:17) 100 kg N ha^{-1}

Figure 9: N$_2$O emission trends in the lowland during 2014 long rain season from 23rd April to 23rd July.

4.4. Soil N$_2$O emission

Table 3 shows the average N$_2$O fluxes during the season at both sites of the experiment. The highest N$_2$O emissions were obtained from treatments that received urea and NPK at a rate of 100 kg N ha^{-1} which had means of 11.45 µg N$_2$O-N m^{-2} hour^{-1} and 10.98 µg N$_2$O-N m^{-2} hour^{-1} at the highland, and 10.76 µg N$_2$O-N m^{-2} hour^{-1} and 9.97 µg N$_2$O-N m^{-2} hour^{-1} at the lowland respectively, while the control treatment produced the lowest fluxes. There was no significant difference in N$_2$O emissions from treatments with urea and NPK at 100 kg N ha^{-1} at both sites (Table 3). The N$_2$O emissions from urea and manure applied alone at the same rate (30 Kg N ha^{-1}) and combined urea and manure at 100 Kg N ha^{-1} did not significantly differ from those emitted by the control treatment at both sites. A significant decrease in N$_2$O emission was noted when urea was combined with manure at 50 kg N ha^{-1} each in the highland and lowland compared to when urea fertilizer was applied alone at the same rate. The total cumulative emissions of N$_2$O from the six treatments, estimated over a period of 112 and 91 days for highland and lowland respectively are shown in Figures 10 & 11. There was a positive relationship between N-rate and N$_2$O emissions (r^2=0.68 & 0.69) in the highland and lowland respectively, and the effect of N-source was also apparent, with the treatment that received urea at 100 kg N ha^{-1} producing the highest seasonal emissions of 0.31 kg N$_2$O-N ha^{-1} and 0.3 kg N$_2$O-N ha^{-1} in the highland and lowland respectively (Figures 10 and 11). Control treatment (no fertilizer) gave the lowest total seasonal emissions of 0.13 kg N$_2$O-N ha^{-1} and 0.11 kg N$_2$O-N ha^{-1} for highland and lowland respectively.

Table 3: Average N$_2$O fluxes in a season at the highland and lowland sites

Treatments	Highland Emission (μg N$_2$O-N m^{-2} hr^{-1})	Lowland Emission (μg N$_2$O-N m^{-2} hr^{-1})
Control (No fertilizer)	4.49	3.78
Manure 30 kg N ha^{-1}	6.06	5.36
Urea 30 kg N ha^{-1}	6.63	5.83
Urea 100 kg N ha^{-1}	11.45	10.76
Urea+ Manure (50 kg N ha^{-1} each)	6.81	6.15
NPK 100 kg N ha^{-1}	10.98	9.97
LSD	**4.16**	**3.71**
CV %	19.30	24.60

Table 4: Statistical comparison of N$_2$O fluxes in a season at the highland and lowland sites

	Site	Average Emission (μg N$_2$O-N m^{-2} hr^{-1})	P
Pair 1	Highland	7.64	.58
	Lowland	6.85	
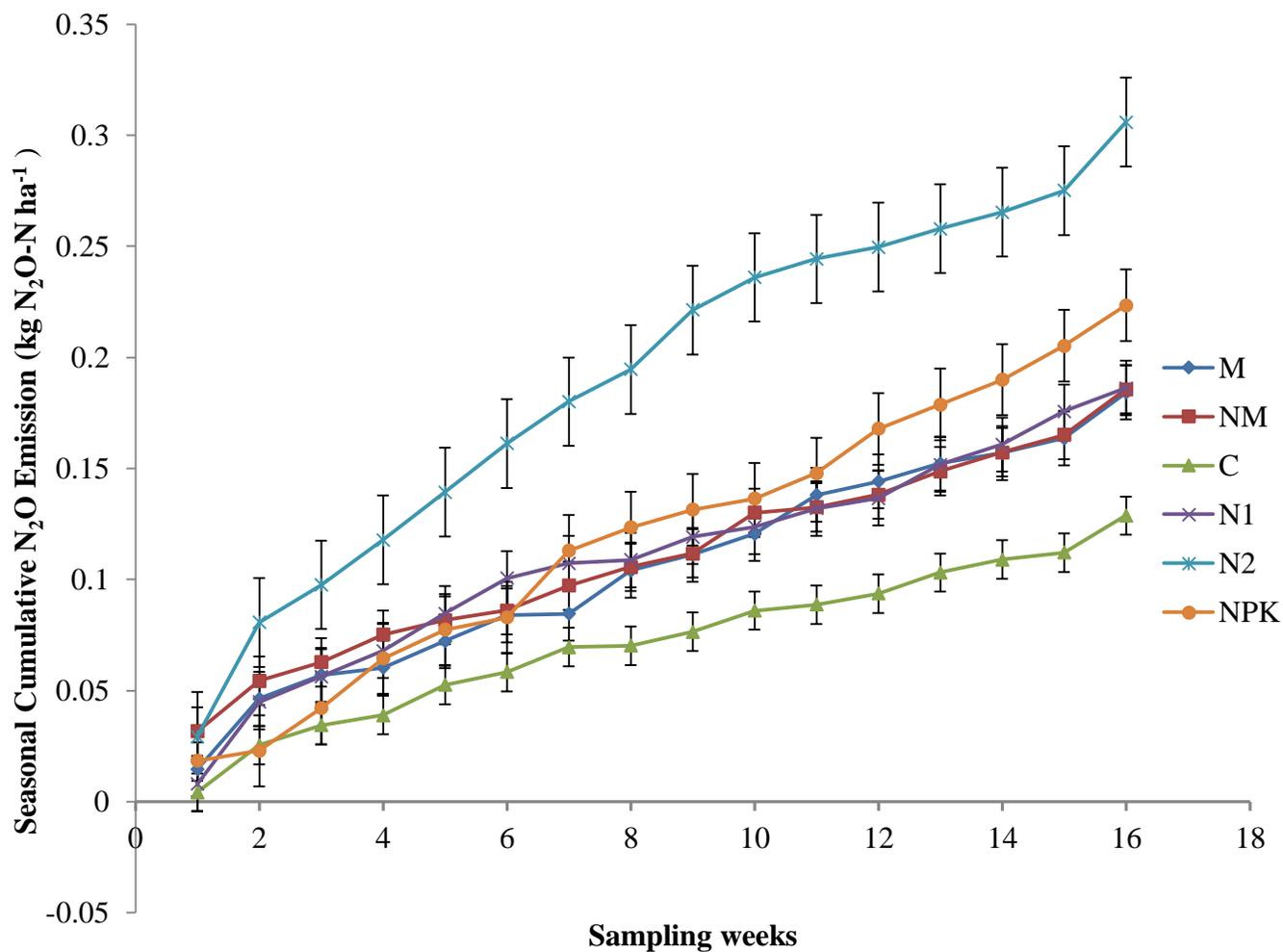
C= Control (no fertilizer); M=Manure 30 kg N ha^{-1}; N1=Urea 30 kg N ha^{-1}; N2=Urea 100 kg N ha^{-1}; NM=Urea+ Manure (50 kg N ha^{-1} each) and NPK= NPK (17:17:17) 100 kg N ha^{-1}

Figure 10: Seasonal cumulative N_2O emissions sampled over a period of 16 weeks at the highland site from 3rd May to 28th August 2014.
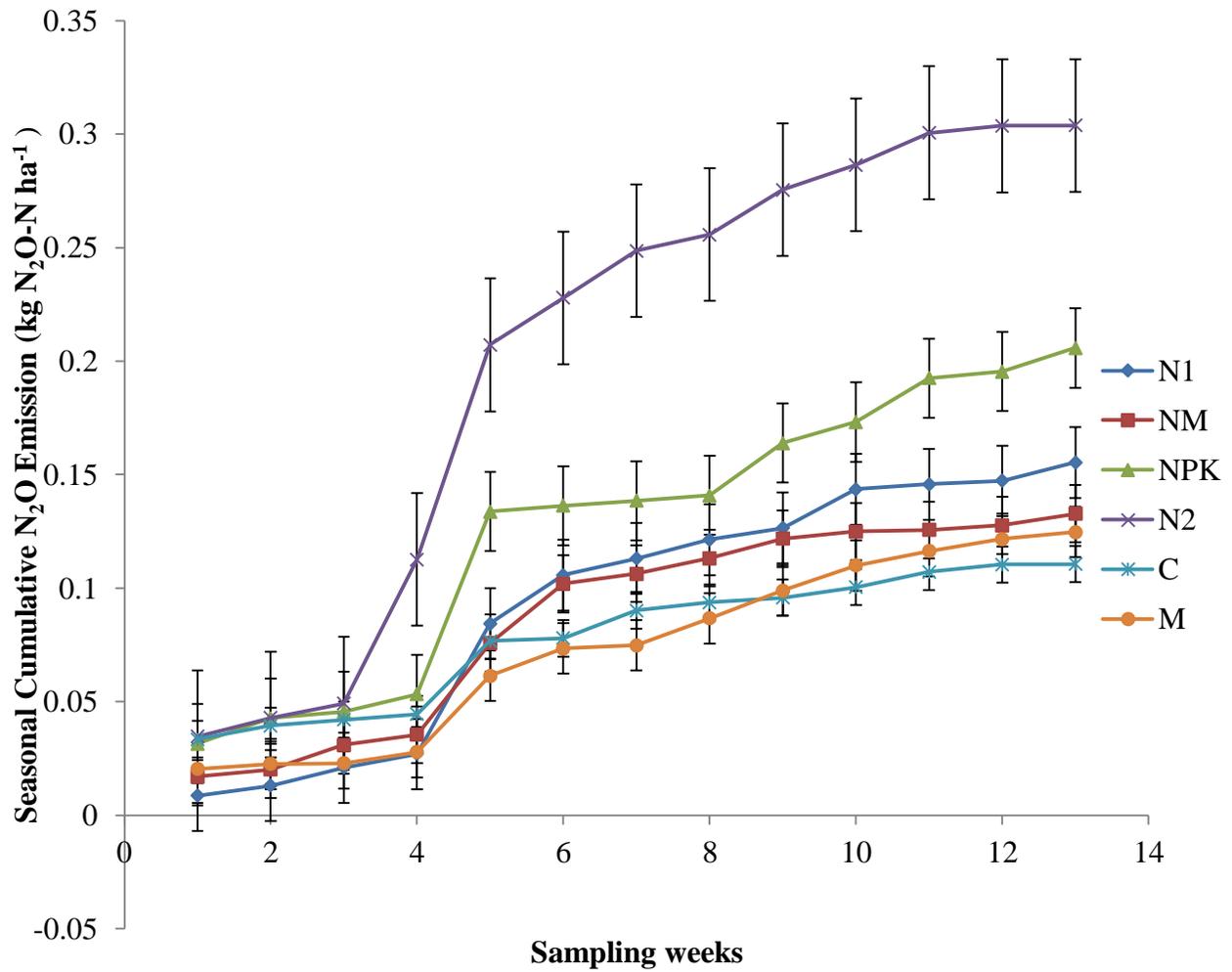
C= Control (no fertilizer); M=Manure 30 kg N ha^{-1}; N1=Urea 30 kg N ha^{-1}; N2=Urea 100 kg N ha^{-1}; NM=Urea+ Manure (50 kg N ha^{-1} each) and NPK= NPK (17:17:17) 100 kg N ha^{-1}

Figure 11: Seasonal cumulative N$_2$O emissions sampled over a period of 13 weeks in the lowland site from 23rd April to 23rd July.

4.5. Maize yield

The grain, stover and cores yields at the two sites are shown in Table 5. Generally, the lowland farm had lower yields compared to the highland farm (Table 6). There was no yield at all obtained in block 2 at the lowland experimental farm. This was due to floods and drought spells experienced in the region which badly affected the maize growth. This resulted into high variability of yields among the replicates leading to a very high coefficient of variation (54.9%), hence no significant difference in yield of maize among treatments at the lowland. However, treatment effects on yields ($p < 0.05$) were observed in the highland field (Table 5). Application of sole manure at 30 kg N ha^{-1} significantly increased maize grain yield compared to the control, sole urea applied at the same rate and at 100 kg N ha^{-1}. However, there were no significant differences in yield among the control, urea at 30 kg N ha^{-1} and at 100 kg N ha^{-1}. Urea + manure and NPK application resulted into significantly higher yields than urea applied alone at the same rate (100 kg N ha^{-1}). Urea + manure produced the highest grain yield (3.98 ton ha^{-1}) while the control treatment had the lowest grain yield (1.36 ton ha^{-1}) in the highland site. The same trend was observed in stover and core yields where urea + manure and control produced 9.38 ton ha^{-1} and 5.81 ton ha^{-1} of stovers respectively and 1.42 ton ha^{-1} and 0.72 ton ha^{-1} of cores respectively

Table 5: Maize yield (ton ha^{-1}) from highland and lowland experimental sites

Treatments	Highland			Lowland		
	Grains	Stovers	Cores	Grains	Stovers	Cores
Control	1.36	5.81	0.72	0.64	0.90	0.17
Manure 30 kg N ha^{-1}	3.22	8.38	1.13	1.84	1.95	0.27
Urea 30 kg N ha^{-1}	1.80	5.88	0.72	0.88	1.50	0.19
Urea 100 kg N ha^{-1}	2.13	7.59	0.76	1.41	1.77	0.21
Urea+ Manure (50 kg N ha^{-1} each)	3.98	9.38	1.42	2.00	2.43	0.38
NPK 100 kg N ha^{-1}	3.79	8.89	1.40	1.70	2.74	0.30
LSD	**1.01**	**2.46**	**0.50**	**1.99**	**2.19**	**0.46**
CV%	20.3	17.7	19.1	54.9	37.9	41.3

Table 6: Statistical comparison of maize yield between sites

	Site	Average Yield (ton ha^{-1})	P value
Pair 1	Highland Grain	2.71	.04
	Lowland Grain	1.41	
Pair 2	Highland Stover	7.66	<0.01
	Lowland Stover	1.88	
Pair 3	Highland Core	1.03	<0.01
	Lowland Core	0.25	

4.6. Nitrogen concentration and uptake

Nitrogen concentration was measured in three parts of the maize crop at maturity stage; grains, stovers and cores (Table 7). As earlier mentioned, there were no yields obtained in block 2 of the lowland farm and therefore, the samples were taken from only block 1 and 3 for analysis. Furthermore, the nitrogen concentrations in samples from block 1 were below detection limit, hence N analysis results were only obtained from block 3, and therefore statistical analysis on N concentration and uptake could not be performed at the lowland site. The highest N concentration was found in grains across the treatments (Table 8). The stovers registered the lowest N concentration across the treatments. N concentration in grains, stovers and cores varied and increased significantly with increased rates of fertilizer materials (Table 7).

Similarly, N uptake (concentration × total yield of maize) increased considerably with the rates of fertilizer materials but this varied with fertilizers sources (Table 9). Application of sole urea at 30 kg N ha^{-1} did not show a significant change in total N-uptake (N concentration x total yield of maize) compared to the control treatment. However, a significant increase in total N-uptake was observed when sole urea was applied at 100 kg N ha^{-1}. Application of sole manure at 30 kg N ha^{-1}, significantly increased the total N-uptake compared to sole urea at the same rate. Application of combined urea and manure at 100 kg N ha^{-1} gave a significantly higher N-uptake

than sole urea. However, it did not differ significantly from the application of NPK at the same rates. Generally, the treatments that received either sole manure or in combination with urea produced a greater response of N-uptake over the control than those that received urea fertilizers alone at the same rates. Total nitrogen uptake was positively correlated to total maize yields, (r^2 = 0.916).

Table 7: Concentrations (%) of nitrogen in grains, stovers and cores at maturity stage at the highland site

Treatments	Grains	stovers	cores
Control	0.45	0.03	0.07
Manure 30 kg N ha^{-1}	0.46	0.14	0.11
Urea 30 kg N ha^{-1}	0.36	0.03	0.07
Urea 100 kg N ha^{-1}	0.79	0.08	0.19
Urea+ Manure (50 kg N ha^{-1} each)	0.91	0.24	0.54
NPK 100 kg N ha^{-1}	0.69	0.24	0.25
LSD	**0.24**	**0.04**	**0.26**
CV%	21.3	16.1	69

Table 8: Statistical comparison of concentrations (%) of nitrogen in grains, stovers and cores at maturity stage at the highland site

	Yield components	Average concentrations (%) of nitrogen	P value
Pair 1	Cores % Weight of Nitrogen	0.20	<.01
	Grains % Weight of Nitrogen	0.61	
Pair 2	Cores % Weight of Nitrogen	0.20	<0.01
	Stovers % Weight of Nitrogen	0.13	
Pair 3	Grains % Weight of Nitrogen	0.61	0.01
	Stovers % Weight of Nitrogen	0.13	

Table 9: Total N-uptake at the highland site

Treatments	Total N-uptake in kg N ha^{-1}
Control	11.55
Manure 30 kg N ha^{-1}	28.02
Urea 30 kg N ha^{-1}	15.68
Urea 100 kg N ha^{-1}	27.47
Urea+ Manure (50 kg N ha^{-1} each)	54.45
NPK 100 kg N ha^{-1}	47.51
LSD	**8.39**
CV %	22.40

4.7. Nitrogen use efficiency

NUE was not calculated in the lowland due to higher variations in maize yield among treatments. However, addition of fertilizer materials had significant effect on efficiency of N and its use by the maize crop in the highland site. The control treatment without applied nutrient was used as the reference in calculating the agronomic nitrogen use efficiency and the apparent nitrogen recovery efficiency. The highest agronomic N use efficiency (ANUE) of 43.11 kg grain per kg N was obtained in manure treatment applied alone at 30 kg N ha^{-1}, and this was significantly higher than the one obtained under sole urea at the same rate (Table 10). Sole urea (100 kg N ha^{-1}) treatment gave the lowest ANUE of 7.68 kg grain per kg N, which was significantly lower than that obtained in sole urea at 30 kg N ha^{-1}. Higher ANUE was achieved when manure and urea were combined than when urea was applied solely at 100 kg N ha^{-1}, however, it did not differ from NPK at the same rate. Manure applied alone at 30 kg N ha^{-1} gave the highest apparent nitrogen recovery (ANR) of 54.90 %, while sole urea applied at the same rate gave the lowest ANR of 13.77 % (Table 10). There was no significant difference in ANR obtained under sole urea at 30 kg N ha^{-1} and 100 kg N ha^{-1}. Higher ANR was achieved when manure and urea were combined at 100 kg N ha^{-1} than sole urea at the same rate. However, it did not differ from NPK. The ANUE decreased with the increase in N rates of urea fertilizer applied alone while there was no significant change in ANR with increasing rate of urea fertilizer.

Table 10: The ANUE and the ANR at the highland site

Treatments	A N U E(kg Yield increase kg^{-1} N applied)	ANR %
Control		
Manure 30 kg N ha^{-1}	43.11	54.90
Urea 30 kg N ha^{-1}	14.50	13.77
Urea 100 kg N ha^{-1}	7.68	15.92
Urea+ Manure (50 kg N ha^{-1} each)	26.20	42.90
NPK 100 kg N ha^{-1}	24.27	35.96
LSD	**6.08**	**7.88**
CV %	20.40	25.53

ANUE=Agronomic Nitrogen Use Efficiency, ANR=Apparent Nitrogen Recovery

CHAPTER FIVE

DISCUSSION

5.1. Nitrous oxide emission

During the growing season, low and high rainfall events were recorded which resulted into high and low moisture contents in the soil. Higher N_2O emissions were realized during periods of higher soil moisture contents (Figures 7, 8 and 9) possibly due to increased denitrification process, while lower emissions were obtained during dryer soil conditions/low moisture contents, consequence of the limited denitrification activity. Sigunga (1997) reported that soil moisture content was an important factor influencing denitrification in Phaoezems and Vertisols in Kenya. Moisture content affects denitrification through its influence on level of activities of microganisms such as denitrifying bacteria and also by acting as a diffusion medium through which substrates such as C and NO_3, are translocated to and products such as N_2O and N_2 are removed from the microsites where denitrifiers are metabolically active (Aulakh et al., 1992).

In terms of N source, significant differences in N_2O emissions were observed when urea was applied alone compared to when combined with manure at the same rate (100 Kg N ha^{-1}) at both sites (Table 3). This could be credited to either manure treatments releasing nutrients in better synchrony with plant growth/demand or N being immobilized leading to lower N_2O emissions. There was no significant difference in soil N_2O emission between the control and addition of manure and urea at 30 Kg N ha^{-1} at both sites of the experiment, likely because application rates were low, which was in agreement with a previous study by Pelster *et al.* (2012). The further increase in N_2O emission in the highland during week 2 of sampling (Figure 8) as opposed to a reduction in the lowland (Figure 9) was possibly due to higher C content in

the highland soil than in the lowland which promoted the microbial activities leading to increased emission. Considering the strong correlation between soil C and N and that N is being rapidly mined from soils in the Lake Victoria basin (Zhou *et al.,* 2014), it is likely that soil C is being lost at higher rate in the lowland than in the highland.

Low values of N_2O emission were obtained from both sites during weeks 3 and 4 probably due to reduced soil moisture contents that resulted into greater reduction of denitrification process leading to lower production of N_2O. This could be due to reduced metabolic activities of denitrifiers as a consequence of reduced diffusion of substrates such as C to the microsites (Chapuis-Lardy *et al.,* 2007; Butterbach-Bahl *et al.,* 2013). Nitrification and denitrification are the most important processes that contribute to emissions of N_2O from soil (Ellert and Janzen, 2008; Butterbach-Bahl *et al.,* 2011). They are controlled by environmental factors, cropping systems, soil management practices (Ellert and Janzen, 2008), fertilization and by water regime (Zou *et al.,*2007). Addition of NPK and urea fertilizer materials at a rate of 100 Kg N ha^{-1} significantly increased the N_2O emission compared to other treatments (Table 3) probably due to higher rates of nitrification and denitrification processes which could have been accelerated by more readily available N from inorganic than from organic nitrogen sources (Bouwman *et al.,*1993). Nitrification was also found to be the main process to have significantly contributed to emission of N_2O from soils planted with wheat and fertilized with urea (Aulakh *et al.* 1984). However, N_2O gas can also be produced as a by-product of ammonium oxidation or the end product of incomplete reduction of NO $_3^-$ (Beck-Friis *et al.* 2000).

The seasonal cumulative emissions of 0.13 kg N_2O-N ha^{-1} to 0.31 kg N_2O-N ha^{-1} in the highland and 0.11 kg N_2O-N ha^{-1} to 0.3 kg N_2O-N ha^{-1} in the lowland (Figures 10 and 11) were within the ranges of -0.10 to 1.80 kg N_2O-N ha^{-1} reported by Pelster *et al.* (2015) on smallholder

farms in western Kenya. Mapanda *et al*.(2011) also reported a seasonal N_2O emission range of 0.10 to 0.50 kg N_2O-N ha^{-1} from soil under maize (*Zea mays* L.) grown with organic and inorganic fertilizers at different rates in three seasons on a Chromic luvisols and Haplic lixisols in Zimbabwe.

5.2. Maize yields

The higher maize yields obtained in the highland than in the lowland could be attributed to the relatively more even distribution of rainfall throughout the cropping season and the soil nutrient status which was higher in the highland than in the lowland (Figure 7). This promoted rapid growth of maize since the soil moisture deficits were eliminated. The lowland site experienced instances of high intensity rainfall over shot durations which interchanged with shot spells of drought. This led to cases of flooding and water stress which negatively affected the growth of maize. The increased water stress in the soil could also have meant that most of the organic materials did not fully decompose, thus N was not fully released in time, and if it was, water was not available for the mineralized nutrients to be taken up by the crop. Soil moisture content influences N mineralization and availability and subsequent maize growth and uptake (Vanlauwe *et al.,* 2002). Myers *et al.* (1994) also noted that variability in climatic factors such as rainfall and temperature influence nutrient release from fertilizer materials and uptake by crops. Insufficient moisture has also been reported to limit the response of crops to nutrients (Jama *et al.,* 1997). The timing of the driest spell at weeks 7 and 8 (Figure 7) was at the critical stage (flowering stage) of maize development which meant poor tasseling and silking and hence low yields.

The better performance of sole manure at 30 Kg N ha^{-1} over urea fertilizers at 30 Kg N ha^{-1}) and 100 Kg N ha^{-1} (Table 5) was likely due to high release of N through mineralization and

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improved synchronization and plant uptake (Chesson, 1997). All fertilizers in this experiment were applied at the time of planting, and the long duration of growth ensured adequate time for manure mineralization and utilization by the crop at the highland site. On the other hand, this exposed mineral fertilizers to high risks of leaching and gaseous losses as supported by higher N_2O emissions obtained from sole urea treatments (Table 3).

The relatively better performance from sole manure and integration of manure with urea fertilizer in comparison to sole urea could also be due to additional benefits that manure inputs confer to the soil chemical and physical properties. These include, improvement of soil structure, soil moisture holding capacity, cation exchange capacity and addition of other macro-nutrients such as calcium and magnesium and micronutrients (Palm *et al.,* 1997; Mutuo *et al.,* 2000). Higher maize yields with organic and a combination of organics with mineral fertilizer has also been reported in other studies in Kenya (e.g. Mucheru-Muna *et al.,*2007, Mugendi *et al.,* 2007 and Vanlauwe *et al.,* 2002b). It has been postulated that a combination of organic and mineral nutrient sources results into synergy and improved synchronization of nutrient release and uptake by plants leading to higher yields (Vanlauwe *et al.,* 2002b). Cattle manure has also been found to reduce the total concentration of Al in the soils leading to reduction of Al phototoxicity and increased crop growth (Hue, 1992).

The relatively better yield obtained in NPK than urea at the same rate of 100 kg N ha^{-1} (Table 5) was probably due to additional phosphorus and potassium which are key elements in crop establishment, especially during earlier stages of germination and leave formation and therefore may have influenced yield responses to the added N (Sanchez and Jama, 2002). A part from N, P is also reported to be crop yield limiting factor in most soils of western Kenya (Opala *et al.,* 2010) and is likely the main cause why urea application alone did not perform well.

5.3. Nitrogen use efficiency

Treatments that received manure showed higher nitrogen uptake by maize than the urea fertilizer treatment at the same rate (Table 9). This is because well composted organic matter improves soil physical, chemical and biological properties and might release nutrients in better synchrony with plant growth demand thereby improving the efficiency of nutrient uptake (Wang *et al.,* 1984; Maynard, 1994). In addition, this could also be attributed to the slower release of nitrogen from manure treatments due to mineralization and the lower gaseous N losses in form of N_2O emission as found in this study (Table 3). The higher nitrogen uptake observed in NPK treatment than urea treatment at 100 Kg N ha^{-1} could be attributed to the synergistic effect of phosphorus and nitrogen leading to the enhancement of greater soil nutrient uptake and use efficiency (Son *et al.,* 2000). On the other hand, N supplied by inorganic fertilizers is more susceptible to losses through leaching, erosion, denitrification, bypass flow, volatilization or emission to the atmosphere in form of N_2O, all of which impact nitrogen use efficiency (Roberts, 2008). Lower N-uptake obtained under urea fertilizers may be related to N losses from soil via leaching and denitrification (Sigunga, 1997; Craswell and Vlek, 1979). Higher emission of N_2O reported in this study could also have led to this.

Increasing the N rates of sole urea resulted into lower ANUE (Table 10). Lower ANUE observed with the application of sole urea fertilizers at 100 kg N ha^{-1} than at 30 kg N ha^{-1} was likely because of greater quantities of N that was generally added, which resulted into greater losses as observed by relatively lower amount of N uptake (Table 9) and higher cumulative N_2O emission (Figures 10 and 11) from urea at 100 kg N ha^{-1}. Higher ANUE and the ANR were obtained when the combined urea and manure treatment was compared to sole urea. Reduced N losses and improved N synchrony have been proposed to lead to increased N use efficiencies

following the combined application of organic and mineral fertilizers (Vanlauwe *et al.* 2002b), which could be probable reasons for the higher ANUE and ANR under combined urea and manure. However, other factors that determine the size of the crop N sink such as genotype, climate, plant density and abiotic/biotic stresses may also contribute to this (Dobermann and Cassman, 2005). The overall values of average ANUE of 23.15 kg grain per kg N applied and ANR of 32.69 % obtained in this study are within the typical ranges of 10-30 kg grain per kg N and 30-50 % respectively for cereals in sub Saharan Africa as reported by Doberman and Cassman (2005), even though, higher values (>30 kg yield increase per kg N applied and >50 % recovery efficiency) can be found in very well managed systems with low soil N supply. The highest ANR value of 54.90 % in this study also compares well to other published global estimates of 50% by Smil (1999) and 57% by Sheldrick *et al.* (2002) and to estimates for the US and Canada of 56% (Howarth *et al.*, 2002) and 52% (Janzen *et al.*, 2003).

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary

Application of urea and NPK at 100 kg N ha^{-1} produced a significant increase in the emission of N_2O gas compared to combined urea and manure at the same rate from both experimental sites (Table 3). This was probably due to higher rates of nitrification and denitrification processes which could have been accelerated by more readily available N from sole urea and NPK than from combined urea and manure. On the other hand, manure in a combined treatment could have released nutrients in better synchrony with plant growth/demand or N being immobilized leading to lower N_2O emissions. Sole urea and manure at 30 kg N ha^{-1} did not show any significant difference in N_2O emission from the control treatment from both experimental sites likely because application rates were low. Sole urea at 100 kg N ha^{-1} produced significantly higher emission than urea at 30 kg N ha^{-1} because of the higher amount of N that was made available for nitrification and denitrification processes.

The application of sole urea fertilizer at both 30 kg N ha^{-1} and 100 kg N ha^{-1} did not show significant difference in maize yield from the control treatment. However manure applied at 30 kg N ha^{-1} and integration of manure and urea at 100 kg N ha^{-1}resulted into significantly higher yields (Table 5). This was likely due to high release of N from manure treatments through mineralization and improved synchronization of nutrients and plant uptake. All fertilizers in this experiment were applied at the time of planting, and the duration of growth may have ensured adequate time for manure mineralization and utilization by the crop. On the other hand, this exposed mineral fertilizers to high risks of leaching and gaseous losses as supported by higher N_2O emissions obtained from sole urea treatments (Table 3). In addition, it could also be due to

extra benefits that manure inputs confer to the soil chemical and physical properties which include, improvement of soil structure, soil moisture holding capacity, cation exchange capacity and addition of other nutrients such as phosphorus, potassium, calcium, magnesium and micronutrients. NPK gave significantly higher yield than urea applied alone at the same rate, an indication that P and K could be limiting factors to maize yield in these particular soils. Linking maize yield to N_2O emissions revealed that the application of urea alone largely resulted in relatively higher N_2O emissions per unit of produce compared to the manure when applied alone or in combination with urea. Increasing the N rate led to further increase in emission per unit kilogram of yield in a season.

Treatments that received manure showed higher nitrogen uptake by maize than the urea fertilizer treatment at the same rate (Table 9). This is because manure improves soil physical, chemical and biological properties and may have released nutrients in better synchrony with plant growth demand thereby improving the efficiency of nutrient uptake. On the other hand, N supplied by inorganic fertilizers is more susceptible to losses through leaching, erosion, denitrification, bypass flow, volatilization or emission to the atmosphere in form of N_2O as found in this study (Table 3). The higher nitrogen uptake observed in NPK treatment than urea treatment at 100 Kg N ha^{-1} could be attributed to the synergistic effect of phosphorus and nitrogen leading to the enhancement of greater soil nutrient uptake and use efficiency by crops. Lower ANUE observed with the application of sole urea fertilizers at 100 kg N ha^{-1} than at 30 kg N ha^{-1} was likely because of greater quantities of N that was generally added, which resulted into greater losses as observed by relatively lower amount of N uptake (Table 9) and higher cumulative N_2O emission (Figures 10 and 11) from urea at 100 kg N ha^{-1}. Higher ANUE and the ANR obtained under combined urea and manure at 100 kg N ha^{-1} and sole manure at 30 kg N ha^{-}

[1] compared to sole urea at 100 kg N ha^{-1} and 30 kg N ha^{-1} was probably due to synergistic effects and improved synchronization of nutrient release and uptake by crops.

6.2 Conclusion

The posed hypothesis that different N sources do not influence N_2O emissions, maize yield and NUE was not supported by results of this study. The study showed that the emission of N_2O gas is influenced by both the source and rate of N applied and can be substantially reduced by combining N fertilizer sources at lower rates. This was demonstrated by the higher N_2O emissions obtained under sole urea than that in sole manure at the same rate, and lower emissions produced under combined urea and manure than in sole urea at the same rate. This study also proved that N source affects maize yield and there is need to continuously add organic N fertilizers in these particular soils. This was demonstrated by higher maize yield produced under sole manure than in sole urea at both same and higher rates. The presence of other nutrient deficiencies other than N were also suggested in these soils particularly P and K as shown by higher yield obtained under application of NPK and combined urea and manure than sole urea at the same rate. Hence, there is need to apply P and K fertilizers. Similarly, the study also demonstrated the importance of either applying cattle manure or in combination with urea to minimize nutrient losses, as this resulted into both increased ANUE and ANR.

6.3 Recommendation

The findings of this study show that basal application of sole urea fertilizers under maize cropping system should be discouraged since it resulted into lower NUE and yield, while producing higher N_2O emissions. Though, NPK improved the NUE and produced higher maize yield, it also emitted higher amount of N_2O. Applications of either sole cattle manure or in

combination with urea are therefore recommended for adoption since they produced significantly higher NUE, maize yield and lower emission of N_2O.

6.4 Recommendation for further studies

All fertilizers in this experiment were applied during planting time which could have increased the possibility of losses through other processes such as leaching. Split application of N fertilizers could however minimize this due to better synchrony of nutrient availability to the crop demand, and therefore this should be considered for future studies.

Further studies should also investigate in more detail the effect of these treatments on different crops under field conditions and in more than one season. The influence of other limiting nutrients such as phosphorus and potassium on GHGs emissions, yield and nutrient use efficiency was not considered in this study and hence this leaves a gap that has to be addressed in future.

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APPENDICES

Appendix 1: Analysis of variance highland grain yield

Source of variation	DF	SS	MSS	F	pr
Treatment	5	18.43	3.69	8.69	0.001
Error	12	5.09	0.42		
Total	17	23.52			

CV= 20.3

Appendix 2: Analysis of variance highland stover yield

Source of variation	DF	SS	MSS	F	pr
Treatment	5	34.59	6.92	3.76	0.028
Error	12	22.07	1.84		
Total	17	56.66			

CV= 17.7

Appendix 3: Analysis of variance lowland grain yield

Source of variation	DF	SS	MSS	F	pr
Treatment	5	1.99	0.40	0.99	0.503
Block	2	29.27	14.64	36.63	<0.001
Error	10	4.00	0.40		
Total	17	35.25			

CV=54.9

Appendix 4: Analysis of variance lowland stover yield

Source of variation	DF	SS	MSS	F	pr
Treatment	5	2.88	0.58	1.14	0.425
Block	2	32.68	16.34	32.28	<0.001
Error	10	5.06	0.51		
Total	17	40.63			

CV= 37.9

Appendix 5: Analysis of variance highland seasonal cumulative N_2O emission

Source of variation	DF	SS	MSS	F	pr
Treatment	5	0.0767	0.0153	7.0890	0.003
Error	12	0.0260	0.0022		
Total	17	0.1026			

CV= 19.9

Appendix 6: Analysis of variance lowland seasonal cumulative N_2O emission

Source of variation	DF	SS	MSS	F	pr
Treatment	5	0.0832	0.0166	7.4255	0.004
Block	2	0.0003	0.0001	0.0644	<0.001
Error	10	0.0224	0.0022		
Total	17	0.1059			

CV= 27.5

Appendix 7: Analysis of variance highland grains N concentration

Source of variation	DF	SS	MSS	F	pr
Treatment	5	0.7275	0.1455	7.3430	0.002
Error	12	0.2378	0.0198		
Total	17	0.9652			

CV= 21.3

Appendix 8: Analysis of variance highland stover N concentration

Source of variation	DF	SS	MSS	F	pr
Treatment	5	0.1426	0.0285	80.3905	<0.001
Error	12	0.0043	0.0004		
Total	17	0.1469			

CV= 16.1

Appendix 9: Analysis of variance highland cores N concentration

Source of variation	DF	SS	MSS	F	pr
Treatment	5	0.4761	0.0952	5.5351	0.017
Error	12	0.2064	0.0172		
Total	17	0.6825			

CV=69.0

Appendix 10: Analysis of variance N_2O emissions per yield

Source of variation	DF	SS	MSS	F	pr
Treatment	5	29221.14	5844.23	8.39	0.001
Error	12	8362.45	696.87		
Total	17	37583.60			

CV= 24.0