BRACHIARIA BRIZANTHA CV. XARAES YIELDS AND SOIL GREENHOUSE GAS EMISSIONS FROM FERTILIZED HUMIC NITISOLS OF CENTRAL KENYA

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DECLARATION

This thesis is my original work and has not been submitted for award of a degree in any other University.

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DEDICATION

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
BC	Biochar
C	Carbon
CEC	Cation Exchange Capacity
CH_4	Methane
CO_2	Carbon (iv) oxide
CP	Crude Protein
DM	Dry Matter
EC	Electrical Conductivity
ECD	Electron Capture Detector
FID	Flame Ionization Detector
GDP	Gross Domestic Product
GHG	Greenhouse gas
IBI	International Biochar Initiative
ILRI	International Livestock Research Institute
K	Potassium
KCl	Potassium Chloride
kg	Kilogram
N	Nitrogen
N_2	Nitrogen gas
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitric oxide

NO_3^-	Nitrate
NPK	Nitrogen, Phosphorus and Potassium
OA	Organic Amendment
OM	Organic Matter
ORs	Organic Residues
P	Phosphorus
pH	Potential for Hydrogen
ppb	parts per billion
ppm	parts per million
rpm	Rounds per minute
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
WHC	Water holding capacity
WFPS	Water-filled pore space

GENERAL ABSRACT

This study evaluated the effects of organic and inorganic soil fertilization on forage grass *(Brachiaria brizantha cv. xaraes)* yields, soil N availability, and soil greenhouse gas (GHG) emissions in Central Kenya. A field experiment was conducted at the International Livestock Research Institute (ILRI) farm in Nairobi, Central Kenya. A completely randomized block design was set up with three replications in blocks (20 m × 15 m) approximately 50 m apart from each other, each containing six plots (4 m × 2 m) with *Brachiaria brizantha cv. xaraes*. Treatments included one inorganic and four organic soil fertilizers, namely NPK fertilizer, farm-yard cattle manure (FYM), FYM plus biochar (FYM-BC), FYM converted to bioslurry via anaerobic digestion, legume intercropping with Lablab (*Lablab purpureus*), and control (zero fertilizer amendment). Greenhouse gas emissions (N_2O, CO_2 and CH_4) were measured using the static chamber approach for a period of eight months. In addition, soil samples were taken for determination of mineral N concentrations in the forms of nitrate (NO_3^-) and ammonium (NH_4^+). Plant biomass sampling for *Brachiaria brizantha cv. xaraes* grass yields was conducted every ten weeks and above-ground plant dry matter was determined. All fertilizer types were applied at a rate of 45 kg N ha^{-1} one week after each harvest, except for Lablab intercropping, which relied solely on biological nitrogen fixation via the legume (rate not determined in this study). The study was conducted between October 2018 and August 2019 comprising of four harvest seasons of 10 weeks each: short rains (SR, October 2018 to January 2019), hot dry season (HD, January 2019 to March 2019), long rains (LR, March 2019 to June 2019), and short rain 2; cold dry season (CD, June 2019 to August 2019).

Treatment and season significantly influenced daily CH_4 uptakes ($p < 0.01$ and $p = 0.009$) but did not show significant interaction ($p = 0.093$). Methane uptake was similar across all the treatments following the order of Control > Lablab > FYM > FYM-BC > NPK, except for Bioslurry which exhibited significantly lower (-2.69±4.47) CH_4 uptake ($p < 0.01$). Within the

seasons, significantly lower (-11.43±4.42) and higher (-21.23±1.11) CH_4 uptakes were recorded during the HD and CD seasons, respectively while SR and LR seasons had similar CH_4 uptake. Treatment and season had significant ($p < 0.01$ two-way ANOVA) effect on CO_2 emissions. CO_2 emissions in FYM-BC and FYM alone were on average lower by 61.6% compared to the control which had the highest (94.76±19.32). Seasonal CO_2 emissions followed the order of CD>HD>LR>SR seasons, respectively. Treatment and season also interacted significantly ($p<0.01$ two-way ANOVA) to influence CO_2 emissions. Lower (44.33±15.67) emissions occurred under FYM alone during the HD season while the highest (157.54±2.77) CO_2 emissions was recorded under the control treatment during the SR season. FYM-BC and FYM alone had significantly ($p < 0.01$ two-way ANOVA) lower (6.70±14.48 and 8.20±15.67 respectively) N_2O emissions compared to the control which had the highest (12.95±3.61). Significantly higher N_2O emissions were recorded during the SR season while HD, LR and CD seasons had similar emission rates. Significant ($p < 0.01$ two-way ANOVA) interaction between treatment and season was also observed with NPK recording the lowest (4.21±0.83) emissions during the second season relative to control which had the highest (27.16±0.90) N_2O emissions during the first season. Furthermore, fertilizer treatments significantly influenced NH_4^+ and NO_3^- availability in the soil ($p < 0.001$). The highest NH_4^+ concentration was recorded in the NPK treatment 14 days after fertilization (21.20±27.01 µg g^{-1} DM), while the lowest NH_4^+ concentration was recorded in the Lablab treatment (6.62±8.02 µg g^{-1} DM). Similar to NH_4^+, significantly higher NO_3^- -N concentration was observed in the NPK plots 14 days after fertilization (61.41±38.81 µg g^{-1} DM), while the lowest NO_3^- concentration was found in the Lablab plots 14 days after the last harvest (37.09±25.10 µg g^{-1} soil). *Brachiaria brizantha cv. xaraes* yields for the four harvests followed the order Control > FYM > NPK > FYM-BC > Bioslurry > Lablab, but these differences were not significant ($p = 0.957$). There were, however, significant differences in

yields of Brachiaria across the four seasons ($p<0.01$), with highest yields recorded in the long rains at 4.72±1.47 Mg DM ha^{-1} and lowest yields recorded in the cold dry season at 1.54±0.51 Mg DM ha^{-1}. The total mean biomass for the entire study period (8 months) was 10.4t ha^{-1}±1.3. Taken together, our findings do not show any significant effect of different soil fertilizers on *Brachiaria brizantha cv. xaraes* yields. This could partly be attributed to the short study period of eight months in a newly established area. Furthermore, the soil had been ploughed before grass planting, which could have mobilized N and other nutrients from soil organic matter mineralization and therefore might have masked a potential fertilizer effect. Whether fertilizer effects become more clearly distinguishable in the long term requires long-term measurements. Concerning soil GHG emissions, the findings have shown that at the applied fertilization rate, organic fertilizers did not increase soil N_2O emissions in this tropical site, indicating a potential option for low-emission forage grass production in SSA.

Key words: Soil fertilization, Forage grass, Greenhouse gas, legume intercropping, emissions.

CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background information

Traditionally, The global human population has been increasing rapidly since 1960 and is estimated to reach 10 billion people by the year 2050 (Cohen, 2003), with an estimated 16.6 % of the population to occur in Africa (Bengtsson et al., 2006). This adds to the increased demand for livestock and their products like milk, meat, as well as hides (Herrero et al., 2014). Worldwide, livestock are important assets that contributes about $1.4 trillion to the global economy by directly supporting livelihoods of 1.3 billion people and offers support to 600 million small-scale farmers (Thornton, 2010). Within Sub-Saharan Africa (SSA), these smallholder farming systems contribute up to 75 % of agricultural production besides generating over 70 % of employment in rural areas (Livingston et al., 2011). In Kenya, livestock contributes 45 % of the agricultural GDP and is a major source of livelihood across the arid and semi-arid regions and in small-holder farming systems (Odero, 2017).

As the consumption of milk and meat is expected to triple by 2050 (Smith et al., 2013), the lack of quality and quantity of feeds as well as poor soil fertility are among the factors limiting livestock productivity across SSA. Moreover, anthropogenic activities have contributed to the rising levels of greenhouse gases (GHG) in the atmosphere that is associated with increasing mean global temperatures and climate change. Low quality livestock feeds exacerbate these trends by increasing emissions of enteric CH_4 from livestock fed such poor-quality feeds (McMichael et al., 2007).

Changes in climate in tropical regions are expected to reduce forage productivity mainly due to more erratic rainfall in some regions and increased frequency and duration of droughts in other regions, both of which have negative impacts on forage productivity (Thornton et al., 2009). For example, high rainfall intensity can increase soil nitrogen (N) leaching and lead to

water-logged soils, while greater drought incidents may inhibit plant growth and thereby reduce biomass yields. In addition, fertilizer rates in SSA are generally low, with mean rates <10 Mg N ha^{-1} for crops such as maize (Snyder et al., 2009), while forage plots are often not fertilized at all, which limits feed productivity and leads to soil nutrient mining and degradation of soil organic matter (SOM) (Vitousek et al., 2009). Hence, there is need to come up with innovative agronomic practices aimed at optimizing feed production while at the same time keeping GHG emissions low and reducing vulnerability to future climate change.

Different agricultural soil fertilization practices have been proposed for tropical regions. For example, the use of forage-legume intercropping in livestock production systems as one of the intensification strategies in East Africa has recently increased due to its multiple benefits (Speijers et al., 2004). Besides reducing soil erosion and runoff, the legume-rhizomic symbiosis is capable of converting atmospheric N_2 to plant-available N forms via biological nitrogen fixation (BNF) that are moved into the soil-plant system, thereby acting as natural fertilizer. The N fixed from the atmosphere by legumes offers smallholder farmers with a cheap N that is environmentally friendly. In Kenya, Dolichos Lablab (*Lablab purpureus*) has been widely used for this purpose and as a quality supplementary N livestock feed (Groteluschen, 2014). Another type of soil amendment is the use of biochar, which improves soil quality and help to lowers GHG emissions. Studies have shown that biochar can improve soil aeration, increase soil water holding capacity (WHC) and soil organic carbon (SOC), stimulate soil microorganisms, reduce leaching of fertilizer (Dai et al., 2014), increase nutrient retention (Fidel et al., 2019), and increase carbon sequestration (Deng, 2013).

Besides legume intercropping and application of biochar, the fertilization of soil using organic fertilizers is highly recommended to enhance forage productivity in SSA (Chianu et al., 2012). The use of organic resources (ORs) and synthetic fertilizers is among the most

viable options proposed for smallholder farms in SSA. Since mineral N is one of the most important soil nutrient affecting production in Kenyan soils, the use of N-based fertilizers is among the intensification strategies proposed to increase pasture production not only in the country but across the region (Vanlauwe et al., 2014).

However, it should be kept in mind that regardless of the source of N, the added N may be leached from the soil or lost in gaseous form of nitric oxide (NO), ammonia (NH_3), nitrous oxide (N_2O) and di-nitrogen (N_2) (Millar et al., 2014). Organic soil fertilization can also contribute to the emissions of CO_2 and CH_4 (Sherlock et al., 2002). Approximately 50 % of global N_2O emissions in the post-industrial era resulted from human activities, with increase in fertilizer use and expansion of agricultural land being the key contributors. Currently, burning of biomass, industries, agriculture and indirect emissions from N leaching and run-off are the key N_2O emitters in SSA (Smith et al., 2014; Reddy, 2015). Of these, emissions from agricultural soils dominate (Mosier et al., 1997), with extensive use of N fertilizers and growing manure input interacting to drive the N_2O emission increase. The use of mineral and organic fertilizers may also accelerate the processes that lead to emissions of CO_2 and CH_4 from the soil, for example with increased CH_4 emissions occurring when organic fertilizers such as manure and bioslurry are applied (Sherlock et al., 2002).

As agricultural intensification increases due to rising demand for food and livestock products, N_2O, CO_2 and CH_4 emissions are, consequently, projected to increase in SSA in the coming decades (McMichael et al., 2007). Hence, livestock production systems will need to adapt. This will require significant changes in feed production methods and quantification of GHG emissions from diverse soil fertilization approaches. Furthermore, current feed production approaches often lack any fertilization leading to continuous nutrient mining of already depleted tropical soils and are therefore not sustainable. In SSA, common forage grasses are C4 species such as *Brachiaria spp*., *Pennisetum purpureum* (Elephant grass/Napier), and

Chloris gayana (Rhodes grass). These grasses can have high productivity, with *Pennisetum purpureum* (Napier) reaching up to 3 m height, but they also require substantial supply of nutrients like N and phosphorus (P) from the soil (Da Silva and de F. Carvalho, 2005). The newly improved and introduced Brachiaria grass species, formerly native to Africa, is being extensively promoted in the tropical areas of Eastern Asia and South America as forage grass for ruminants due to its adaptations to various ecological zones and high nutritive value, reaching yearly dry matter yields of 17 t ha^{-1} (Thornton and Herrero, 2010). This study assessed the direct impact of soil fertilization (inorganic fertilizer, Lablab intercropping and organic fertilizers) on the yields of *Brachiaria brizantha cv. xaraes* and soil GHG emissions. More specifically, the soil fertilizers were mineral N fertilizer (NPK), farm-yard cattle manure (FYM), Lablab intercropping (Lablab), FYM converted to Bioslurry in a biogas digester (Bioslurry), and farm-yard manure mixed with 10 % Biochar (FYM-BC), which were compared to soils without any fertilization (Control).

1.2 Statement of the problem

Increasing demand for livestock feed due to growing animal numbers and a higher demand for animal products underlie attempts to intensify feed production. Soil fertilization is a viable option for smallholder farmers in Sub-Saharan Africa (SSA) to enhance and maintain soils rich in nutrients and increase feed production. However, besides yield increases, agricultural intensification can simultaneously increase soil greenhouse gas (GHG) emissions due to higher soil nutrient availability, thereby contributing to climate change. Field studies on environmental effects including GHG emissions of different soil fertilization strategies such as organic and inorganic soil fertilization in SSA remain scarce. As the consumption of milk and meat is expected to triple by 2050 (Smith et al., 2013), the lack of quality and quantity of feeds as well as poor soil fertility are among the factors limiting livestock productivity across SSA. To supply quality and adequate feeds will require transformation of

current production systems, with emphasis on sustainable agricultural intensification amid rising effects of climate variability and change (Herrero et al., 2010). Use of various soil fertilization strategies offer a pathway to sustainable agricultural intensification. However, excessive use of soil fertilization can increase GHG emissions, which can further exacerbate climate change and thereby negatively affect feed and food production. Despite the fact that Africa's GHG emissions contribute to the global GHG budget (Valentini et al., 2014), field data on GHG emissions from different African land use systems remain scarce, leading to high uncertainties in global GHG budgets.

Application of mineral fertilizers like NPK is increasing mostly in African regions in the past four decades and the number of livestock kept including their waste materials have risen in SSA (Thornton, 2010). By 2050, the rising utilization of mineral N in cultivated soils of SSA, is projected to double amount of N2O released from the agricultural sector (Hickman et al., 2011). The current issue is that, in spite of the rising GHG emissions, livestock forages and food productivity have to be improved and maintained to support the existing and future populations. This requires sustainable use of farming inputs to increase productivity, while reducing the environmental footprint in terms of GHG emissions. Furthermore, this requires a focus on small-holder farmers given that they are the major agricultural producers in SSA (Bryceson, 1999).

1.3 Justification

Generally, convenient access to accurate and authentic GHG emission data is limited for tropical grasslands (Ciais et al., 2010), especially in SSA. It is therefore vital to evaluate the contribution of smallholder livestock farming practices to accurately determine GHG emission baselines, and to develop techniques to reduce GHG emissions in these systems. Insufficient knowledge of the magnitude and dynamics of GHG emissions from smallholder livestock systems results from a failure to consider spatial heterogeneity and environmental variations, as well as system-specific factors including soils, plant and animal breeds (Pelster et al., 2017). This leads to a challenge regarding policy formulation to help manage forage

and livestock productivity with an aim of safeguarding the environment from GHG emissions and ensuring continuing soil health, besides providing local farmers with a functional livelihood (Pelster et al., 2017).

The study will contribute to the Sustainable Development Goals (SDGs) by ensuring reduction in hunger (Goal 2), combating climate change and it impacts (Goal 13), supporting land rehabilitation frameworks (Goal 15), and natural resource conservation (Africa Agenda 2023). It also contributes to the Kenya Climate Smart Agricultural Strategy whose objective is to adapt to climate change, build resilience of agricultural systems while minimizing emissions for enhanced nutritional and food security that will result to improved peoples' livelihood. Understanding impacts of fertilization on soil-GHG emissions in SSA is imperative to offer management choices for local smallholder livestock farmers (Zuorro et al., 2016). The findings of this study aim to close this knowledge gap to help improve forage grass production while managing the impacts on the climate in the context of smallholder systems in SSA. The present study findings are geared towards providing baseline GHG emission data and dry matter (DM) yields in *Brachiaria brizantha cv. xaraes* production within the Climate-Smart Livestock projects (PCSL) across the regions in the tropics.

1.4 Objectives

1.4.1 Broad objective

To contribute to sustainable livestock production and climate change mitigation in Kenya via soil fertilization practices that improve forage grass yields and reduce soil GHG emissions.

1.4.2 Specific objectives

The specific objectives of the study were to:

1. Evaluate availability of mineral N in differently-fertilized humic -nitisols planted with *Brachiaria brizantha cv. xaraes.*
2. Determine Effects of different organic and inorganic fertilizer treatments on biomass yields of Brachiaria brizantha cv. Xaraes grown on humic -nitisols.

3. Determine the effects of inorganic and organic fertilizers on emissions of GHG (CO_2, CH_4 and N_2O) from plots planted with *Brachiaria brizantha cv. xaraes*.
4. Determine the effects of organic and inorganic soil fertilizers on yield-scaled N_2O emissions from *Brachiaria brizantha cv. xaraes* plots.

1.5 Hypotheses
1. Soil plant-available N (NH_4^+ and NO_3^-) is similar across fertilized humic -nitisol plots planted with *Brachiaria brizantha cv. Xaraes*.

2. *Brachiaria brizantha cv. xaraes* biomass yields is similar across humic-nitisols with different organic and inorganic fertilizer treatments.

3. Emissions of CO_2, CH_4 and N_2O is similar across humic -nitisol fertilized with organic and inorganic fertilizer treatments.
4. Yield-scaled nitrous oxide emissions from *Brachiaria brizantha cv. xaraes* plots are similar across fertilizer treatments

1.5 Thesis format
This thesis comprises of six chapters. Chapter one contains a general introduction, the problem statement, justification of the study, objectives, and study hypotheses. Chapter two presents a general literature review of previous studies. Chapter three, four and five are chapters based on the specific objectives whereby objective three and four have been combined into one chapter. Chapter six is consisted the general discussion of the findings, conclusions and research recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Livestock production in Sub-Saharan Africa

In developing countries, livestock keeping has a substantial contribution in the nutrition and economy of rural populations. It provides revenue to millions of smallholder households from sale of animal products such as meat or milk, employment opportunities in form of family labour, source of nutritive food for elderly and children, as well as provision of draft power and manure for crop production (Sinha, 2007). Most of the ruminant production in developing countries is dominated by medium- and small scale farmers (Herrero et al., 2013). However, poor animal nutrition has led to low productivity with delayed maturity time, which is approximately 50 % slower (36 months) in SSA compared to the time it takes to achieve the same weights in developed countries (22 months) (Tarawali et al., 2011a, b). This has been attributed primarily to low- and poor-quality feeds and inadequate supply of these feeds especially during drought periods (Tolera et al., 2000).

Forage production in developing countries depends largely on rainfall and is further constrained by decreases in land sizes. In addition, low farm inputs and poor soil management have led to soil degradation and soil nutrient mining, which negatively impacts fodder production (Kariuki et al., 2001; Bayble et al., 2007; Kabirizi et al., 2007). In tropical Africa, farmers mine soil nutrients, especially nitrogen (N), from pasture and forage lands, because nutrients that are removed from the soil via the plant biomass are rarely or not at all replenished, as the manure from the animals is used elsewhere (for example in arable lands for crop production). This leads to a depletion of essential soil nutrients such as N over time at the site of fodder production, leading to a compromised quality and quantity of livestock feeds. Furthermore, rainfall seasonality affects livestock feed production, with very low fodder yields achieved during dry seasons because irrigation systems are rarely in place and water is scarce. Due to this seasonal patterns of low feed availability and poor nutrient

content, productivity of ruminants is low while GHG emission intensities of livestock products (i.e. GHG released in each unit of animal product) are high compared to developed countries (Desjardins et al., 2012). Worldwide, the net GHG emission intensities range from 58 to over 1000 kg CO_2 eq. per kg edible animal protein, and higher values are primarily a result of extensive and low-productive ruminant production systems of tropical and sub-tropical Africa (Herrero et al., 2013).

Today, livestock production systems of SSA are changing due to several drivers, among them population increase and urbanization. Worldwide, the population of people is anticipated to increase from about 6.5 billion to 10 billion by the year 2050 (Bongaarts, 2009). About one billion of the increase in population will occur in Africa (Gerland et al., 2014). Urbanization is also rapidly increasing in developing countries and is expected to significantly rise in the future (Delgado, 2003). These developments continue to alter food consumption patterns, particularly the demand for livestock products. For example, urbanization normally stimulates infrastructural development as well as cold chains that allow fresh and perishable goods including livestock products to be widely traded (Tschirley, 2010).

Meat production in developing countries the number of tons produced is reported to have tripled from 45 to 134 million tons between 1980 and 2002 (Thornton and Herrero, 2010). These changes have been associated with increase in land used for pasture and forage production and substantial land-use changes (Thornton and Herrero, 2010). Pasture and arable lands in SSA have been significantly expanding since the year 1960, although the expansion rate is currently declining (Kanianska et al., 2014). In SSA, N is the main limiting nutrient to agricultural production because most small holder farmers do not apply N fertilizers in their farming systems (Vanlauweand and Giller, 2006). In addition, studies that have documented the yields of newly acquired forage species such as the newly introduced Brachiaria under different fertilization regimes are scarce. Brachiaria is regarded to possess

carbon (C) sequestration, implying its production can improve soil health and animal productivity (Desjardins et al., 2012), and is therefore being widely promoted. This study has therefore addressed a crucial knowledge gap by evaluating biomass yields of *Brachiaria brizantha cv. xaraes* forage grass in Kenya in relation to different fertilizer treatments.

2.2 Livestock production systems in high potential areas in Kenya

In Kenya, dairy production is the second major contributor of Kenyan agricultural sector's Gross Domestic Product (GDP) (Kosgey et al., 2011). It contributes around 13.4 % (USD 3.1 Bn.) to the agricultural sector, with dairy cattle being the key player (Behnke and Muthami, 2011). Kenya produced over 4.48 Bn. litres of milk in the year 2014 estimated at KES 243 Bn. (approx. USD 2.4 Bn.), of which 76 % is from cows and the rest from dairy goats and camels (Metaferia et al., 2011). Consumption is roughly 117 litres of milk for each household yearly – representing one of the highest milk consumptions in SSA (Siekmann et al., 2003). The dairy sector is one of the main source of jobs in rural areas across Kenya (Muriuki et al., 2001), mainly in small-scale farms that produce about 56 % of the total milk in the entire country (Odero, 2017). There are three major livestock systems in Kenya: extensive, intensive and semi-intensive systems. Semi-intensive and extensive systems make up to 85 % of the entire livestock production systems (Omore et al., 1999).

Despite its importance, the livestock sector has and continues to face a vast range of problems such as diseases, droughts, low nutritive quality feeds and feeds shortage. Feed shortage is the main challenge facing small-scale farmers in high potential areas. While trying to cope with feed shortage, most farmers are opting to use inorganic and organic soil fertilization strategies as well as improved forage grasses such as *Brachiaria brizantha cv. xaraes* to improve yields and nutritive quality. However, the effects of these soil fertilization strategies on GHG emissions are not well documented. Therefore, this study sought to fill these gaps by

evaluating the effects of various soil fertilization strategies on GHG emissions and yields of *Brachiaria brizantha cv. xaraes.*

2.3 Commonly used organic and inorganic fertilizers in tropical Africa

This section discusses various organic and inorganic soil fertilization used by smallholder farmers in tropical Africa, across soil types including humic- nitisol. Nitisols are well-drained, deep red tropical soils with turgid horizon borders and a subsurface horizon with above 30 % clay besides adequate to strong angular blocky arrangement features that easily fall apart into distinctive shiny, polyhedric ('nutty') elements (Kögel-Knabner & Amelung, 2021).

2.3.1 Biochar

It is a malleable, charcoal-like material made of 96 % C, dependent on the kind of material used and pyrolysis temperatures (Sohi et al., 2009). It is widely promoted by the International Biochar Initiative (IBI) due to vast benefits to the soil (Sohi et al., 2009). Sohi et al. (2009) also stated that biochar (BC) is made from barks of trees, woody-plant remains, crop residues, or poultry litter and dairy manure. Burning environments and feedstock affect the structure and inflexibility of BC that is formed by the pyrolysis of vegetal remains under anaerobic conditions (Sohi et al., 2009).

Biochar stability can lead to soil C sequestration, reducing SOM decomposition and emissions of CO_2 or CH_4 (Spokasand and Reicosky, 2009). Increasing temperature for pyrolysis increases the firmness of biochar as a result of the production of aromatic C disc constituents (Kan et al., 2016). Biochar burned at 500 °C or above has an exceedingly stable form and it might not likely decay (Woolf et al., 2010). The proportion of O:C and H:C is a feature used to assess aromaticity of biochar and influencing biochar's firmness. According to Enders et al., (2015), BC formed below 500 °C developed a H:C ratio beyond 0.5 whereas BC formed at over 500 °C had a H:C lower than 0.5. Owing to its biochemical resistance, BC

gradually decays and may consequently help to absorb soil C for a prolonged period. The potential negative effects of BC have also been reported. This include depression of plant-available nutrients that are needed by plants (Gaskin, et al., 2010), toxicity of some of the compounds that are formed during pyrolysis (Bussand and Mašek, 2014), competition with organic matter needed for burning (Lehmann and Rondon, 2006) and energy losses which could have been used for other purposes such as for cooking.

2.3.2 Bioslurry

Organic materials such as bioslurry derived from animal excreta have been applied in small scale farms as nutrient sources for plants (Tambone et al., 2010). Additional advantages comprise boosting the soil organic matter (SOM); leading to better-quality soil physical properties such as water infiltration; as well as soil water retention and soil aeration (Ngubo, 2016). However, the key limitation of using carbon-based fertilizers like bioslurry is the lower mineral N composition as contrasted to inorganic fertilizers (Shahbaz et al., 2014). This could require labor-intensive management due to large volumes required to meet the nutrients requirements for crops. This is very expensive particularly if huge volumes of animal dung are needed to be moved to distant farms (Holm-Nielsen et al., 2009). The difficulty of transporting large quantities of natural fertilizers can be minimized if, bioslurry formed in farms is re-used as livestock fodder plots in the same area, reducing transportation expenses. Small-holder farmers may equally make the investment by saving wood and time for wood collection, or money to buy gas. Some biogas systems are even mobile and allow to sell the biogas to neighbors in big balloons to provide additional income.

Bioslurry which is being adopted widely in SSA is regarded to be a slow-nutrient releasing fertilizer, enabling plant development at dire periods of growth, when crops are significantly affected by mineralization rates, temperature, pH, and the soil microbial activity (Chiyoka et al., 2011). The amount of nutrients in bioslurry and their subsequent absorption by plants

may vary significantly from field to field depending on soil properties (Drosg et al., 2015). Nutrient availability depends on feeds composition, amount of water put in the feed, procedures of dung collection and storage, soil addition timing, soil properties, crop type to which the bioslurry is applied, and environmental conditions.

2.3.3 Farm yard manure

Farm yard manure (FYM) has been used by smallholder farmers in crop production in tropical Africa (Opala, et al., 2015). FYM has proved to be the best strategy for soil fertility recovery in tropical Africa due to their availability, cheap compared to synthetic fertilizers and readily available to farmers (Reddy, 2010). FYM is a slow nutrients releasing organic fertilizers with longer residual effect in the soil compared to inorganic fertilizers (Babhulkar et al., 2000). It has been adopted widely in SSA and its quality is significantly affected by the rate of mineralization, PH, temperatures and soil microbial activity (Bhattacharyya, et al., 2007). Studies have reported improved forage yields when manure is applied in forage crops proving to be a better and affordable organic fertilizer for soil nutrients replenishment in tropical Africa (Mafongoya et al., 2006; Place et al., 2003; Sanchez et al., 1997). Contingent on the type of fodder, nearly 70-80 percent of N, 60-85 percent of P and 80-90 percent of potassium (K) fed by livestock is removed through manure (Koga et al., 2006). Nutrient availability in FYM rely on feed composition, amount of water put in the feed, approaches of dung collection, storage and time of application.

2.3.4 Legume intercropping

Legume-forage intercropping is a multifaceted system that relies on biological Nitrogen fixation. They fix it via microbial symbiosis in their root nodules to use in the plant. The transfer from plant to soil is secondary via decomposing roots or via using legume biomass as mulch (Zahran, 1999). Decaying leaves falling from the legumes and decomposing roots complement N to the soils that is used by the forage grasses (Stevenson and Cole, 1999).

Biological N fixation depends on the growth potential of the legume, inorganic soil N levels, grass competition and other environmental factors such as soil moisture level. Forage-legume intercropping has gained popularity in SSA. Annual N fixation levels of about 113 kg N ha^{-1} have been attained in forage legumes based on a report by Ledgard and Steele (1992). Harish et al. (2002) reported 150 kg of N fixed in a Lablab- Napier grass intercrop system in Ethiopia.

2.3.5 Lablab

This is a drought tolerant legume and is being promoted in Kenya's semi-arid land to improve soil fertility as well as forage production as reported by Macharia et al. (2010). Lablab remains productive with rainfall of between 650 mm and 2100 mm per annum and survives in diverse soils including deep-sands to heavy-clays, when seepage is effective, and pH of 4.5-7.5 as reported by Foyer et al. (2016). Lablab is generally grown from sea level to 2000 m altitude.

The DM harvests of this legume are quantified at 1.61 tons ha^{-1} $year^{-1}$ as a unmixed crop or after intercropping with forage grasses, and has a CP content of ranging from 190-260 g kg^{-1} DM harvested between the 6th and 9th week. Feed digestibility varies between 55-76 % and which decreases with harvesting stage and unfavorable growth conditions such as dry seasons. It yields seed at a rate of 15 kg ha^{-1}. The summary of Brachiaria and Lablab attributes is presented in table 2.1.

Table 2.1: Summary of Brachiaria and Lablab attributes

Attributes	Brachiaria	Lablab
DM yield (tons ha^{-1} $year^{-1}$)	7.1-17.0	1.6-10.4
Crude protein (g kg^{-1} DM)	54-175	190-260
In vitro digestibility (%)	56.4-78.7	55.2-76.4

Source: (Sanchez, et al., 2019)

2.3.6 NPK fertilizer in tropical forage production

Despite the potential for increased forage yields as recorded by use of fertilization in tropical Africa, most farmers still use inadequate levels of inorganic fertilizers application rates. Compared to other countries, the use of fertilizers in tropical Africa has remained low. For example, from the 1960s to 1990s, mean fertilizer use increased from only 5 kg ha^{-1} to 8 kg ha^{-1} compared to the rise from 10 kg ha^{-1} to 110 kg ha^{-1} in India; and 180 kg ha^{-1} to 240 kg ha^{-1} in China (Srinivasarao et al., 2013). Despite potential negative environmental effects, soil fertilization by use of synthetic fertilizers at the correct application rates is a potential method to avoid further nutrient depletion in soils and increase agricultural productivity in African smallholder farms (Gruhn et al., 2000) Therefore, this study used synthetic NPK fertilizer as an additional treatment and compared it to the abovementioned organic fertilizers (FYM, Bioslurry, FYM+10% BC and Lablab intercrop). All treatments used at a rate of 45 kg N ha^{-1}, which is based on amount of N mined from the soil by the forage grass in order to replenish the N removed from the soil by the grass biomass while avoiding over fertilization (Viljoen et al., 2020).

2.4 Brachiaria production

The newly introduced Brachiaria grass species, formerly inborn to Africa, has been extensively promoted as forage grass for ruminants because of its high nutritient value and adaptation potential to various ecological zones, with yearly dry matter yields of 17 t ha^{-1} (Thornton and Herrero, 2010). It is also known to contribute to carbon sequestration, reducing soil erosion and lowering GHG and losses of soil N through excretion of biological nitrification inhibiters (BNI) (Philippot et al., 2009). In its initial growth stage of 2–5 weeks, available N ranges between 62.5–175 g CP kg^{-1} DM, decreasing to 43.9 to 93.6 g CP kg^{-1} DM in the subsequent 12 weeks (Santos et al., 2014). The *In vitro* dry matter digestibility (DMD) in early growth stages has ranges between 56 %–78 % after 5 weeks of growth and

declines to 41.6 % on upon maturity (Merkel et al., 1999). The *in vitro* DMD of *Brachiaria brizantha cv. xaraes* forage grasses is highly variable amongst harvested trials at diverse maturity levels. Differences in CP levels and *in vitro* digestibility are related with fertilization, growth conditions and seasonality (wet vs dry) (Low, 2015). An evaluation by Low (2015) relating stocking rates, forage composition, and rate of growth in ruminants, resolved that *Brachiaria brizantha cv. xaraes* was equivalent to additional tropical forages (*Panicum maximum*) while in other cases overtook them with between 0.46 and 0.78 kg daily weight gain, compared to 0.49 and 0.61 kg in beef cattle.

2.6 Soil fertility under organic and inorganic Soil Fertilization

Soil health, "entails the capacity of a particular type of soil to operate within managed or natural environmental limits, enabling plant and animal productivity, sustaining and boosting air and water purity, as well as sustenance of human habitation and health" (Doran and Zeiss, 2000). In this section, the benefits of organic soil amendments in enriching the physical, chemical and biological components of the soil will discussed.

2.5 GHG emissions from soils with and without Fertilizer

Organic soil fertilization can promote GHG emissions with other methods for example, methanogenesis, priming effect, denitrification and nitrification, and soil respiration through autotrophic (roots and root-associated microorganisms) versus heterotrophic (decomposer microorganisms) respiration – this are also the most important process leading to soil CO_2 emissions. Priming is the process where disintegration of SOM is stimulated by addition of labile C, for example through the incorporation of organic fertilizers, which can lead to CH_4, CO_2 and N_2O soil emissions (Thangarajan et al., 2013). The process of methanogenesis is where CH_4 is formed by microorganisms belonging to the kingdom of archaea (methanogens) through anaerobic respiration.

Nitrification and denitrification, by two distinct soil microbial activities through soil N cycle can result in emission of N_2O. They also contribute directly to emissions of GHG in the forms of N_2O from N compounds within the organic materials, and indirectly through the effect on soil properties which may stimulate soil-borne GHG fluxes (Thangarajan et al., 2013). Several research has been conducted confirming the profitability of organic soil fertilization (Zebarth et al., 1999; Spiertz and Ewert, 2009). But little is known on the contribution of organic soil fertilization to global warming and GHG emissions particularly N_2O and how it relates to organic matter mineralization in tropical Africa. (Kim et al. (2016) observed that N_2O fluxes from SSA soils fertilized with compost manure were less than those applied with urea.

2.6.1 Physical fertility

Supplementing of organic fertilizers in the soil can relatively increase soil organic matter (SOM) (Zerzghi et al., 2010; Zhao et al., 2009). The added SOM improves the quality of the soil by increasing stability of soil aggregates and improving soil physical properties such as water holding capacity (WHC), water infiltration, percolation and the porosity of soil (Evrendilek et al., 2004; Leroy et al., 2008). However, soil fertilization by use of carbon-based ingredients has been proved to lower bulk density and soil crusting that are important for the health of the soil (Zhao et al., 2009).

2.6.2 Chemical fertility

Overall, repetitive application of only inorganic fertilizers is pointed out to reduce yield of crops because of increased nutrient imbalance and soil acidity (Mbah and Mbagwu, 2006). Organic soil fertilization can increase SOC stocks which subsequently raises the soil cation exchange capacity (CEC), which is necessary in absorbing important nutrient cations and anions, and availing them for plant uptake. Augmented SOM content attributable to organic soil fertilization can furthermore improve electrical conductivity (EC), pH, and

concentrations of vital nutrients for growth of plants, mainly N, P, and K (Bulluck Iii et al., 2002).

2.6.3 Biological fertility

Soil microorganisms are vital in disintegration of organic matter (OM), nutrient cycling, nutrient immobilization in plant cells, and various soil chemical and physical changes (Abbott and Murphy, 2007). Therefore, the microbial population has an important role as energy and nutrient change regulator, source and sink. A variety of soil microorganisms direct the degree of SOC mineralization, thus enhancing soil vigor and sustainability of agricultural activities (Scotti et al., 2015). Enzymes excreted by soil microorganisms control the decomposition process and the cycling of soil nutrients. Addition of organic amendments to the soil can promote increased diversity and growth of soil microbial populations (Chakraborty et al., 2011). Continuous application of manure is also known to significantly increase the soil microbial groups as well as enzyme activities (Meyer et al., 2004).

CHAPTER THREE: SOIL MINERAL NITROGEN UNDER DIFFERENT ORGANIC AND INORGANIC FERTILIZATION TREATMENTS

3.1 Abstract

As part of an agricultural intensification strategy to increase livestock feed productivity, an agronomic trial was set up at ILRI campus, Nairobi, Kenya. The agronomic trial followed a completely randomized block design with three replicate plots per treatment (4 m × 2 m). The treatments comprised of NPK fertilizer, FYM, FYM-BC, Bioslurry (all at 45 kg N ha^{-1}), Lablab intercropping (biological N fixation), and Control treatment (no fertilizer). Treatments significantly influenced ammonium ($NH_4^{+)}$ and nitrate (NO_3^-) availability in the soil ($p < 0.001$). Highest NH_4^+ concentration was recorded under NPK (21.20±27.01 µg g^{-1} DM), while the lowest NH_4^+concentration was recorded under Lablab treatment (6.62±8.02 µg g^{-1} soil). Like NH_4^+, significantly higher (61.41±38.83 µg g^{-1} DM) NO_3^- concentration was observed under NPK plots while the lowest concentration (37.09±25.15 µg g^{-1} soil) was recorded under Lablab. These findings indicate that NPK releases plant-available mineral N faster into the soil compared to organic fertilizers (FYM, FYM-BC and Bioslurry), which could lead to faster plant growth but also to higher N leaching losses compared to the slow-release organic fertilizers.

Key words: Nitrogen fertilizers, mineral N, organic fertilizers, inorganic fertilizers.

3.2 Introduction

Nitrogen is a soil nutrient important for the development and nourishment of plants. The increasing demands for livestock feeds and human food have led to an increase in use of N fertilizers in agricultural fields. Worldwide, approximately 103 to 112 million tonnes of artificial N fertilizers are applied annually to farms (Heffer and Prud'homme, 2010),

representing a potential hazard for ecosystem health when this reactive N is not taken up by plants but released to the environment. The amount of the added N that is found in the harvested crop products (the fertilizer N use efficiency, NUE), is at only 33 % in cereals (Raun and Johnson, 1999; Glass, 2003). Of the remaining 67 %, apart from what remains in soils, much is lost through leaching or run-off, or as gaseous emissions such as N_2O, NH_3 and N_2 (Jambert et al., 1997).

As the costs of inorganic N fertilizers increase and as the demands for agricultural intensification picks up in East Africa, smallholder farmers are opting to use organic fertilization as alternative nutrient sources. Organic fertilization includes livestock by-products such as FYM, Bioslurry as well as recycled agricultural crop by-products. These fertilizers are applied either in raw forms or modified such as composted materials or with addition of biochar (BC).

Organic fertilizers are normally low in nutrient supply such as N concentrations ranging between 7-28 mg N kg^{-1} on DM basis (Quilty and Cattle, 2011), and they should therefore be applied at relatively high rates to meet plant nutrient demands. In addition, the release of N from organic fertilizers relies on the rates of mineralization and immobilization via soil microorganisms, which are hard to precisely envisage when determining N supply to the crops. Organic fertilizers with relatively higher labile C contents promote N losses through denitrification (Robertson et al., 1988); while those with high C/N ratio lead to immobilization of N which reduces availability of N according to figure 3.1 (Ramirez et al., 2010; Bruun et al., 2012). This study therefore evaluated the effects of various organic (FYM, FYM + 10% BC, Bioslurry) and inorganic (NPK) fertilizers, and Lablab intercrop on the soil mineral N availability in a humic-nitisol planted with *Brachiaria brizantha cv. xaraes.*

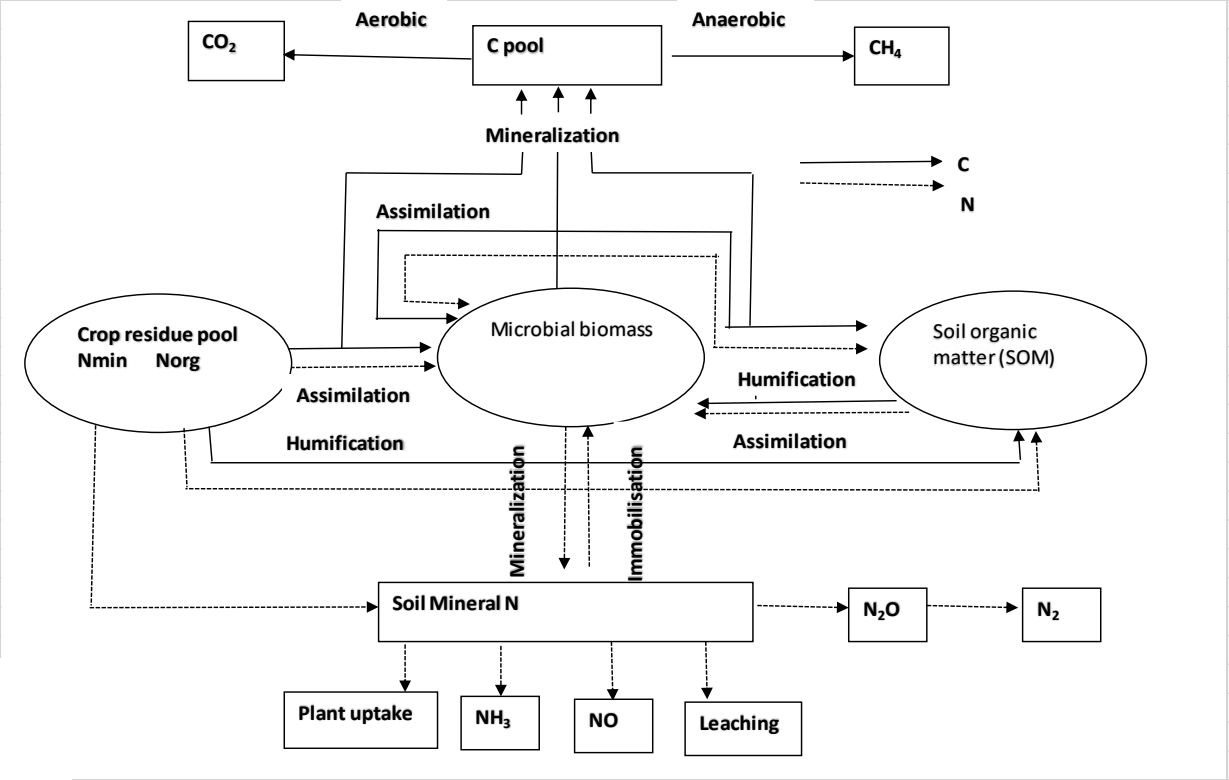


Figure 3.1: Soil C and N changes

Source: Mungoche, 2020

3.3 Materials and methods

3.3.1 Description of the study site

The study was conducted at the International Livestock Research Institute (ILRI)-Nairobi campus at elevation 900 m above sea level. It is a research Centre located in Nairobi County. It lies between latitude 1° 16' 11.73’ South and longitude 36° 43' 26.0472" East. Mean annual temperature is 17 ºC and mean daily minimum and maximum temperatures are 12 ºC and 23 ºC. Mean annual rainfall is 875 mm and varies between 500-1500 mm. The total rainfall amount during the experimental period (eight months) was 802 mm. Soil temperature at the study site ranged between 16.6 ° C in the wet season to 50.8 ºC in the dry season, with a mean of 34ºC.

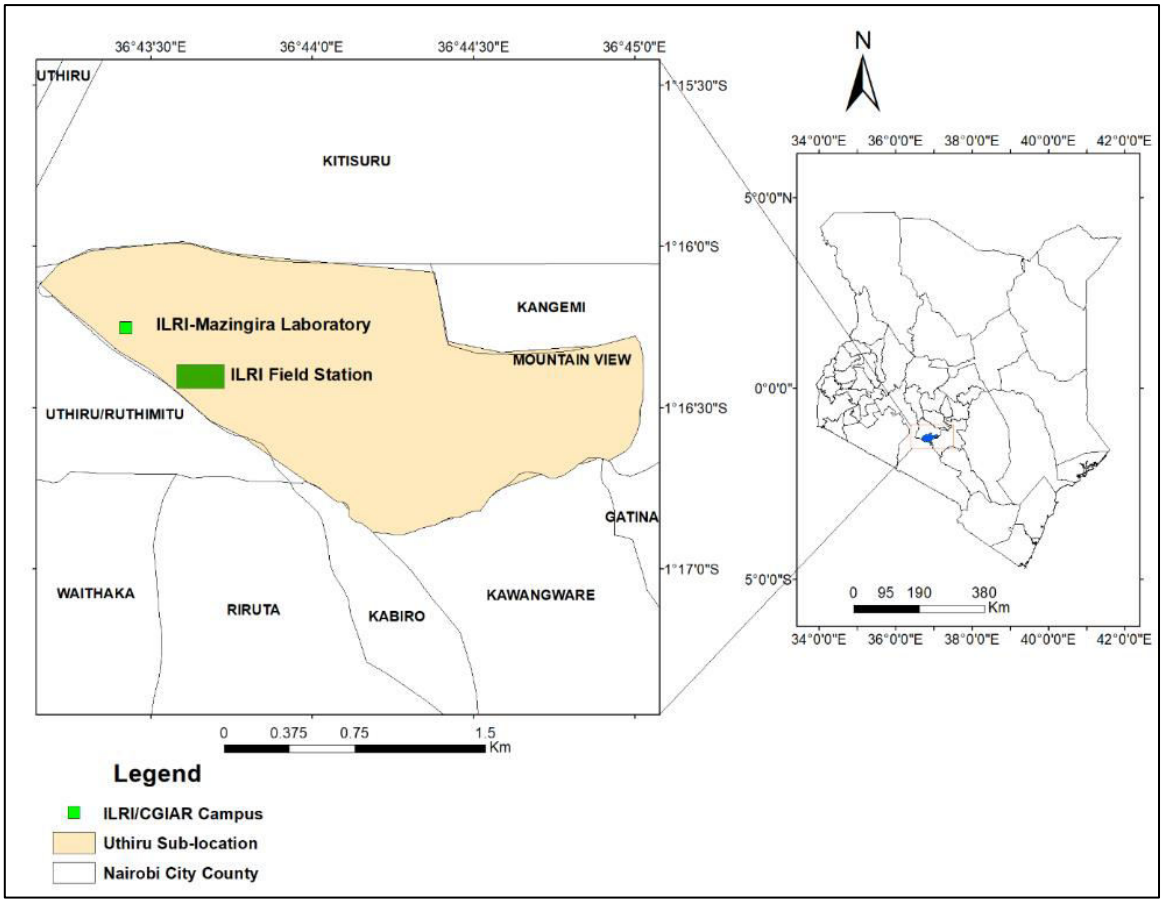


Figure 3.2: The study area (ILRI-Campus)

Source: Mungoche, 2020

3.3.2 Experimental design and agronomic management

The experiment followed a Complete Randomized Block Design (CRBD) replicated three times (n=3). The treatments applied were Control (no fertilizer), farm-yard cattle manure (FYM), FYM + 10 % biochar (FYM-BC), and FYM digested in a bio digester (Bioslurry), mineral fertilizer (NPK), and legume intercrop (Lablab). FYM was collected from the ILRI farm. Bioslurry was produced in two biogas digesters located at ILRI's Mazingira Centre. Before application, FYM and bioslurry were homogenized manually and analyzed for N content to adjust the applied quantity. Part of the FYM was mixed with 10 % (w/w) of chopped biochar. Fertilization was applied at 45 kg N ha^{-1} for all the organic and inorganic fertilizer treatments after every harvest except for Lablab intercrop that dependent on biological N fixation (BNF) that was not measured in this agronomic trial. All the agronomic

management practices emulated those commonly found on smallholder farms in Kenya (Figure 3.2).

Figure 3.3: a). Field layout after ploughing and before planting in September 2018. b) Homogenized farm-yard manure ready for application c) Bioslurry collected from the biogas digesters at Mazingira.

3.3.3 Experimental set up

The study was conducted between October 2018 and August, 2019 comprising of four harvest seasons of 10 weeks each: short rains (SR, October 2018 to January 2019), hot dry season (HD, January 2019 to March 2019), long rains (LR, March 2019 to June 2019), and cold dry season (CD, June 2019 to August 2019). The setup consisted of 3 replicate blocks with 18 plots each (3 forage grass species and 6 fertilizer types), giving a total of 54 plots (4 m x 2 m) (Table 3.1).

Table 3. 1: Experimental set up for the agronomic forage grass fertilizer trial

Treatment Number.	Forage grass species	Fertilizer type	Fert. rph (kg N ha^{-1})
	Brachiaria ***Brachiaria brizantha cv. Xaraes***	Control (Control)	0
		Legume intercropping (Lablab)	-
		Farmyard manure (FYM)	45
		Farmyard manure + 10 % biochar (FYM-BC)	45
		Manure bioslurry (Bioslurry)	45
		Mineral NPK fertilizer (NPK)	45

The preliminary measurements of the soil attributes was conducted prior to planting of the forage grass. The organic manures and bioslurry were also evaluated on the basis of the available mineral Nitrogen, organic Carbon and the PH levels before application in the field (table 3.2).

Table 3.2: The available mineral Nitrogen and moisture contents in the organic fertilizers before application

Treatment	Water content (%)	Ammonium (µg NH_4-N g^{-1} DW)	Nitrate (µg NO_3-N g^{-1} DW)
Bioslurry	89.8688	1912.731	82.64069
Manure	70.7461	297.0754	423.8709

The soil samples were taken from each of the plots before planting to test for the preliminary soil attributes (% Nitrogen, % Carbon, Total Nitrogen and Total Carbon) as presented in

Table 3.3: The preliminary soil attributes in the field before planting

Soil attributes	Unit of measurement
% Total Nitrogen	0.188426667
% Total Carbon	1.803746667
P.H	6.8724
Total N	18.84266667
Total C	180.3746667
C:N ratio	9.683846891

Source: Data, 2018

3.3.4 Soil sampling and analysis

This section discusses the procedures followed when sampling the soil as well as the analysis for pH and mineral N.

3.3.4.1 Mineral N

Soil sampling at 0 to15 cm depth was conducted following transplanting and fertilization, harvests and then after 15 days of each harvest. This was done by using a soil auger with inner diameter of 3 cm. Fresh soil samples were put in labelled bags and immediately taken to the Mazingira Centre for analyses. In the laboratory, the soil samples were sieved using a 2 mm sieve, after which extraction of the field-moist soil (8g) with 40 ml of 1 M KCl for calorimetrically determined mineral nitrogen (NH_4^+ and NO_3^-) was done. Samples were put on an orbital shaker for 60 min and afterwards filtered on ash-free filter paper (What man No. 42) to spectrophotometrically to determine NO_3^- -N and NH_4^+-N (Hood-Nowotny, et al., 2010).

3.3.4.2 PH

Determination of soil pH was done using 10 g of dry soil mixed with 25 ml of high-purity H_2O. The mixture was shaken for 60min at speed of 144 rpm. After settling for 2-3 hours, pH value was measured using a pH-electrode (Model, Brand).

3.3.5 Statistical analyses

All mineral N data was analyzed statistically using Genstat Discovery 15th edition statistical software package for Windows. Two-way analysis of variance (ANOVA) was done to determine if the measured soil NO_3^- and NH_4^+ pools were significantly different among the fertilizer treatments. Significant differences for the analysis of variance were accepted at $P \leq 0.05$. Tukey's HSD post hoc test was used to separate means of the measured soil attributes under the influence of fertilizer treatments. Significance differences were confirmed using a two-way ANOVA at $P < 0.05$.

3.4. Results

3.4.1 Effects of treatments on soil ammonium and nitrate availability

Treatments significantly influenced NH_4^+ and NO_3^- availability in the soil ($p < 0.001$). Higher NH_4^+ concentration was recorded under Brachiaria treated with NPK (21.20±27.01 µg g^{-1} soil) while the lowest NH_4^+ concentration was recorded under *Brachiaria brizantha cv. Xaraes*- Lablab intercrop (6.62±8.02 µg g^{-1} soil) (Figure 3.3, bars with different letters represent significance difference between treatments). Generally, the temporal trends of NH_4^+ concentration were similar across all the treatments during the study period except under NPK, which exhibited higher NH_4^+ concentration two weeks after 2nd and 3rd fertilizations, respectively (Figure 3.3 and 3.4).

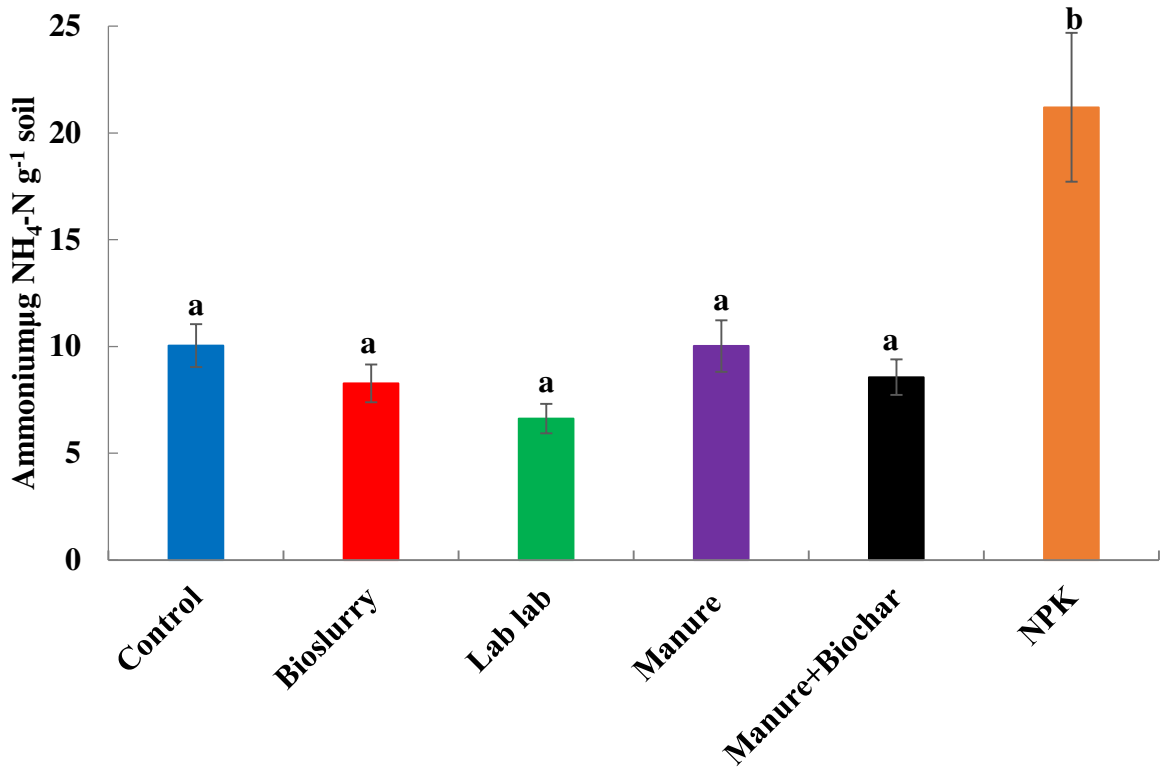


Figure 3. 3: Effect of treatments on availability of ammonium in soil under *Brachiaria brizantha cv. xaraes* in central Kenya

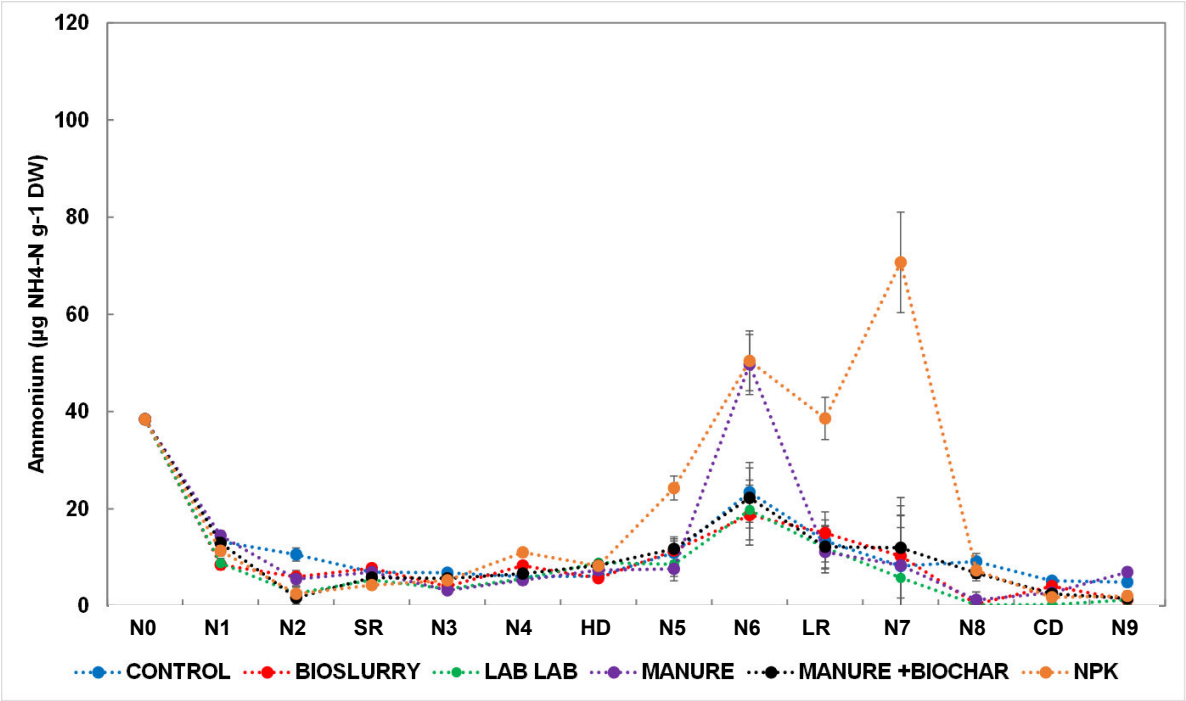


Figure 3. 4: Variations of soil ammonium concentration during the experiment period under *Brachiaria brizantha cv. xaraes* in central Kenya

Key: N0 (at planting), N1 (1st fertilization), N2 (2 weeks after planting), SR (Short rains - October 2018-January 2019), N3 (fertilization after 1st harvest) N4 (2 weeks after fertilization) HD (January 2019-March 2019) N5 (fertilization after 2nd harvest), N6 (2 weeks after fertilization), LR (Long rains-March 2019-June 2019), N7 (fertilization after 3rd harvest), N8 (2 weeks after fertilization), CD (short rains 4-June-August 2019), N9 (fertilization after 4th harvest).

Significantly higher (61.41±38.83 µg g^{-1} soil) NO_3^- concentration was observed under NPK plots while the lowest concentration (37.09±25.15 µg g^{-1} soil) was found in Lablab (Figure 3.5). However, the NO_3^- concentration in the Control (50.86±29.66 µg g^{-1} soil) treatment was higher than NO_3^- concentration in Lablab (37.09±25.15 µg g^{-1} soil), FYM (39.10±21.38 µg g^{-1} soil), FYM + 10% BC (40.78±22.26 µg g^{-1} soil), and Bioslurry (41.04±25.81 µg g^{-1} soil) (Figure 3.5 Figure 3.6).

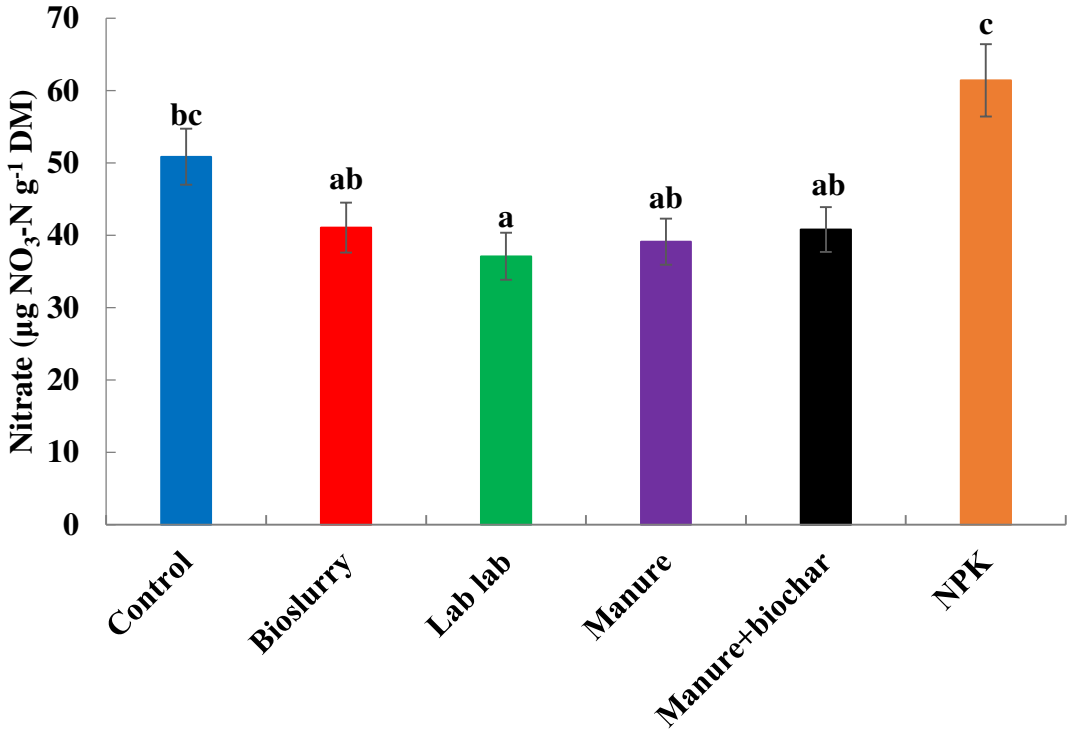


Figure 3. 5: Effect of treatments on availability of nitrate in soil under *Brachiaria brizantha cv. xaraes* in central Kenya. Bars with different letters represent significance difference between treatments.

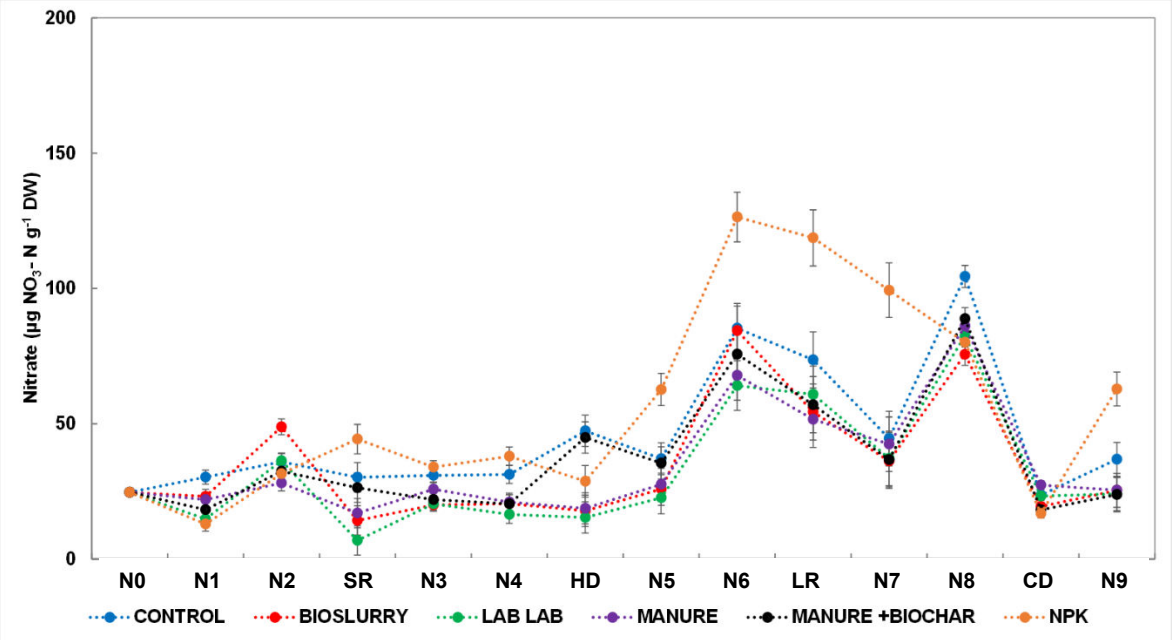


Figure 3. 6: Variations of soil nitrate during the experiment period under *Brachiaria brizantha cv. xaraes* in central Kenya

Key: N0 (planting and), N1 (1st fertilization), N2 (2 weeks after planting), SR (Short rains - October 2018-January 2019), N3 (fertilization after 1st harvest) N4 (2 weeks after fertilization) HD- January 2019-March 2019) N5 (fertilization after 2nd harvest), N6 (2 weeks after fertilization), LR (Long rains-March 2019-June 2019), N7 (fertilization after 3rd harvest), N8 (2 weeks after fertilization), CD (short rains 4-June-August 2019), N9 (fertilization after 4th harvest).

Soil nutrients including mineral N availability to plants are also influenced by soil moisture content. It presents the medium for soil nutrient mineralization and nutrient flow to plant roots. Figure 3.7 below present's trends in gravimetric water content across the treatments.

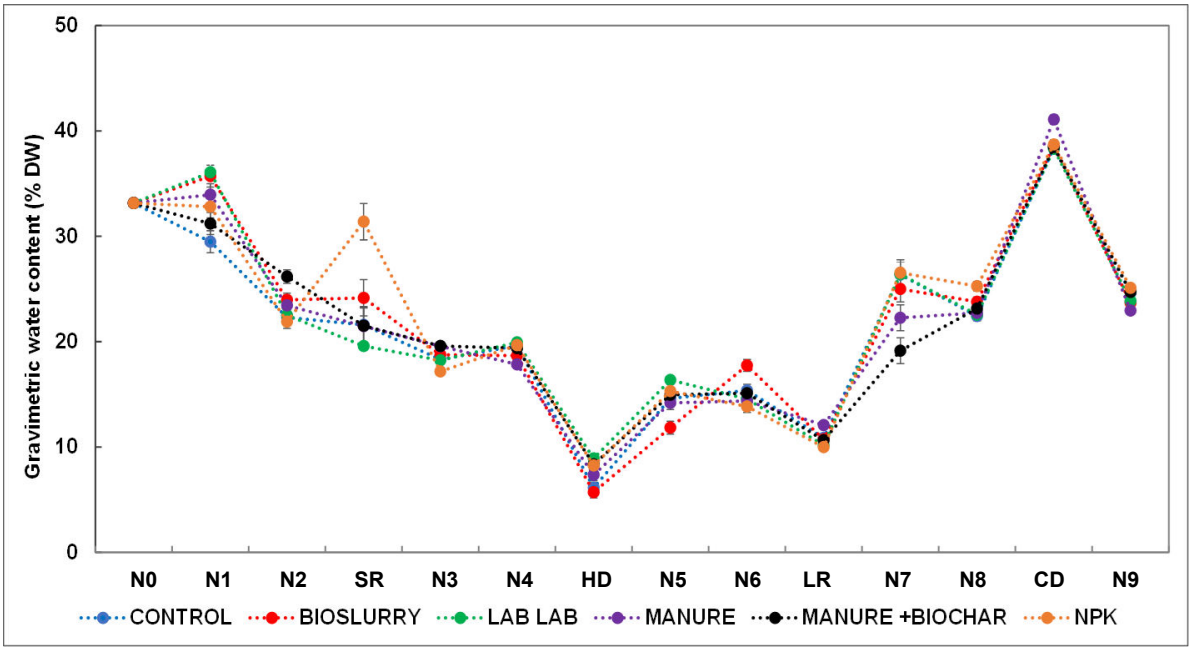


Figure 3. 7: Soil gravimetric water content from Brachiaria plots

Key: N0 (planting and), N1 (1st fertilization), N2 (2 weeks after planting), CD (October 2018-January 2019), N3 (fertilization after 1st harvest) N4 (2 weeks after fertilization) SR (January 2019-March 2019) N5 (fertilization after 2nd harvest), N6 (2 weeks after fertilization), LR (March 2019-June 2019), N7 (fertilization after 3rd harvest), N8 (2 weeks after fertilization), HD (June-August 2019), N9 (fertilization after 4th harvest).

3.5 Discussion

An increased mineral N concentration was observed at the beginning of the seasons, after the fertilization events. The mineral N concentration dropped afterwards, potentially due to increased crop N-uptake and due to leaching below the root surface. The increased concentrations of NH_4-N in the soil relative to the control may be due to increased release under NPK treatments. Nitrogen response is affected by soil moisture (Ageharaand and Warncke, 2005). When soil moisture is adequate N response is expected. NH_4-N can be fixed by soil organic matter and clay minerals as they are negatively charged, which can result in adsorption on NH_4^+ and slower release (Kissel et al., 2008). On the other hand, NO_3-N, which

is negatively charged, is not well retained by the soil and can be leached more easily, representing a potential hazard because NO_3^- is a groundwater pollutant (Lodhi, 1979). In respect to this when high rainfall is experienced NH_4-N gives a better yield response compared to NO_3-N in the soil (Gallardo, et al., 2006). The differences in bioavailability of NO_3-N and NH_4-N has been studied and reported that NH4-N can be directly assimilated into amino acids whereas NO_3-N has to be reduced first into NH_4-N before the assimilation process (Careyand and Migliaccio, 2009; Fernandesand and Rossiello, 1995). Whenever the proteins present in inorganic fertilizers are depolymerized and decomposed to NH_4-N, the NH_4-N concentrations in the soil will increase (Chantigny et al., 2010; Noll et al., 2019). Furthermore, nitrification process can only produce NO_3-N in presence of enough NO_3-N to stimulate the process of denitrification to release N_2O and N_2 (Azam, et al., 2002).

NH_4^+ and NO_3^- are more rapidly taken up by plants when applied during the period of growth (Steiner et al., 2007). During this time, water availability is key for nutrient fluxes from the soil to plant roots (Christophe, et al., 2011). Without addition of N fertilizers, the inorganic N concentration of the soils planted with forage grasses become low throughout the whole year (Sommer et al., 2004). In this study, values for NH_4^+ concentrations , 21.20±27.01 µg g^{-1} for NPK and 6.62±8.02 µg g^{-1} for Lablab were consistent with the numbers reported previously in Kenya (Sommer et al., 2004). However, the NO_3^- concentrations were higher at 61.41±38.83 µg g^{-1} for NPK and 50.86±25.15 µg g^{-1} in Lablab intercrop. Soil NH_4^+ and NO_3^- were lower in FYM, FYM-BC which could be attributed to low mineralization rates of organic materials. This might have slowed soil microbial action and maintained a mineralization process that allows for gradual release of C and N in soils over time (Kemmitt, et al., 2006). A study by Prasadand and Singh (1980) when applying FYM and NPK in maize plantation noted that there was 55 % increase in NH_4^+ concentrations over the Control treatment which is a higher value than that recorded in this study (40 %). Similarly, like this

case high NO_3^- concentrations in treatment containing FYM has been previously reported by N'Dayegamiye et al. (1997).

3.6 Conclusions and recommendations

In conclusion, in this study, NPK (inorganic fertilizer) releases the N-minerals faster (NH_4^+ and NO_3^-) in the soil. Unlike FYM, Bioslurry, FYM-BC (organic fertilizers) which are slow-release fertilizers for mineral N, and they can stay in the soil for longer period as their mineralization is gradual. Added inorganic N fertilizer is more effective in low soil N conditions in order to maximize the yields of forage grass production, however, the gradual mineralization of organic fertilizers particularly FYM and FYM-BC, which eventually have a long-term residual effect in the soil are a promising strategy for improving forage grass production in SSA overtime.

It is recommended that when discussing the effects of organic and inorganic fertilizers on mineral N, besides quantifying N concentrations, escape pathways such as through leaching should be evaluated. This will add more insights in understanding the exact quantities of mineral N utilized from various organic fertilizers by forage grasses for improved yields. This will also form a basis for calculation of nutrient balances in forage grass fields. It will also help in understanding the nutrient uptake by forage grasses and in measuring the contribution of organic and inorganic fertilizers to forage grass biomass yield.

CHAPTER FOUR: YIELDS OF *BRACHIARIA BRIZANTHA CV. XARAES* UNDER DIFFERENT ORGANIC AND INORGANIC SOIL FERTILIZATION TREATMENTS

4.1 Abstract

With the ongoing growth of the global population, there is an increased demand for food and particularly livestock products. Simultaneously, and specifically for the African continent, livestock production remains limited due to the lack of adequate feeds, poor soil fertility and ongoing climate change. Interventions that provide a way out of this situation include the introduction of improved forage grasses such as *Brachiaria brizantha cv. xaraes* due to its high potential yield and tolerance to drought effects. Still, and independent of which grass one uses, soil fertilization is necessary to avoid nutrient depletion and degradation of soils. This study evaluated the effects of organic and inorganic soil amendments on *Brachiaria brizantha cv. xaraes* yields in a Humic Nitisol. A field experiment was set up at the International Livestock Research Institute in Nairobi, Kenya between October 2018 and August 2019. The experimental design followed a completely randomized block design with three replications and individual forage plots measuring 4 m × 2 m. Treatments comprised of NPK fertilizer, Lablab intercrop (biological N fixation), FYM-BC, Bioslurry, FYM and Control (zero fertilization). Except Lablab intercrop, all other treatments were applied at a rate of 45 kg N ha^{-1}. Sampling included biomass yield measurements after every 70 days growth period and subsequent analysis of soil mineral N and GHG emissions. Brachiaria yields followed the order FYM > NPK > FYM-BC > Bioslurry > Lablab, however, the differences were not significant ($p<0.957$). There were significant differences in yields of Brachiaria across the four seasons ($p<0.01$), with highest yields (4.72±1.47 Mg DM ha^{-1}) in the long rains (March-June) and lowest yields (1.54±0.51 Mg DM ha^{-1}) recorded CD (June-August). Based on these findings, Brachiaria can do well during rainy season but is negatively affected by water limitation during dry periods. Compared to other soil fertilizers

applied, FYM recorded highest DM yields partly due to its slow nutrient release rate that is not affected by rapid changes in soil moisture and thus is recommended to improve *Brachiaria brizantha cv. xaraes* yields.

Key words: Biomass yields, changes in climate, soil fertilization, quality feeds

4.2 Introduction

As demands for livestock products increases in tropical Africa, there has been an increase in agricultural intensification strategies including introduction of new forage grasses. Improved Brachiaria forage grass, whose native ecological region is Africa, has been re-introduced from South America and is widely promoted in Southern and Eastern Africa among smallholder livestock farmers. It has good nutritive value for livestock and agronomic performance when sampled at the right time (Djikeng et al., 2014; Njarui et al., 2016). There are also indications that Brachiaria enhances soil Carbon sequestration. Having these vital attributes, Brachiaria could enhance the health of the soil as well as animal productivity (Desjardins et al., 2012). In addition, improvement of the livestock diet nutritive quality can indirectly reduce enteric CH_4 emissions by enhancing feed utilization efficiencies and thereby lowering GHG intensities for each animal product produced. The full potential of forage grasses may, however, not be achieved in tropical Africa under the current forage management practices, where there is little or no fertilizer returned to the pasture. Another viable option if organic or inorganic fertilizer is unavailable is the intercropping of forage grasses with legume fodder plants such as Lablab, Desmodium, Lucerne or Clover, all of which supports symbiotic N fixation of atmospheric N via microorganisms living in their root nodules (Giller, 2001). Grass-legume intercropping has proved to be sustainable in terms of higher fodder productivity in situations where there is no fertilizer application to the soil and during drought periods because some legumes have drought resilient attributes (Mugerwa et al., 2012). This may offer an affordable strategy to improve quality and yields of the grasses

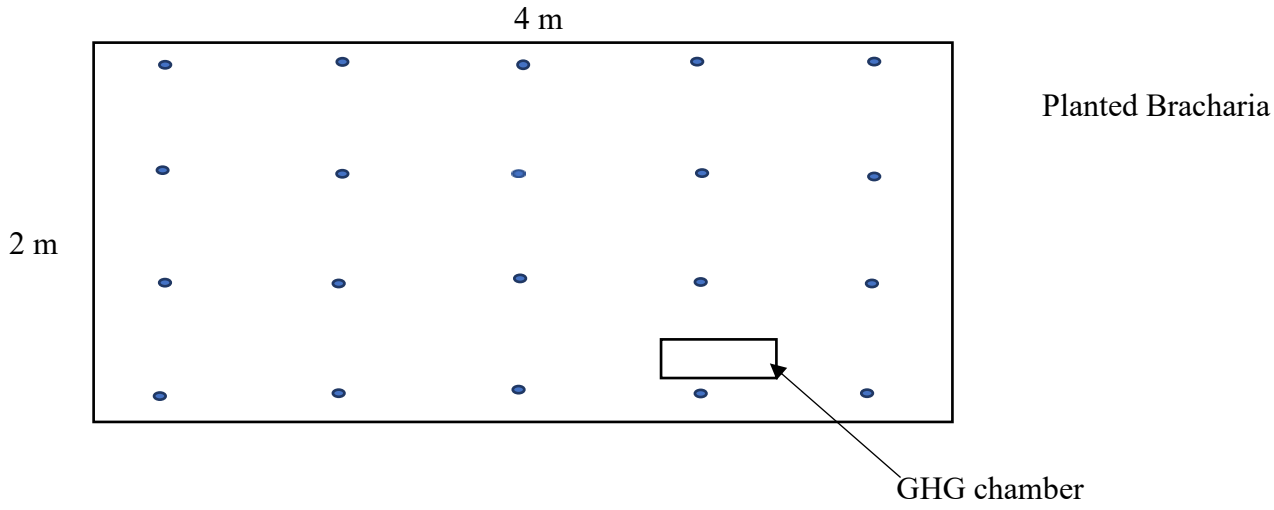
in the long run, while still allowing the smallholder farmers to channel organic fertilizers such as FYM and Bioslurry from animals, to improve forage and crop production. In addition, legumes themselves are high-quality animal feed and can improve animal production. This study evaluated the use of organic and inorganic fertilizers as well as Lablab intercrop on the yields of *Brachiaria brizantha cv. Xaraes.*

4.3 Materials and methods

4.3.1 Description of the study site

The study was conducted between October 2018 and August, 2019 comprising of four harvest seasons of 10 weeks each: short rains (SR, October 2018 to January 2019), hot dry season (HD, January 2019 to March 2019), long rains (LR, March 2019 to June 2019), and cold dry season (CD, June 2019 to August 2019). The setup consisted of 3 replicate blocks with 18 plots each (3 forage grass species and 6 fertilizer types), giving a total of 54 plots (4 m x 2 m).

4.3.2 Planting scheme for Brachiaria plots



Figu

The study was conducted in the context of a newly established agronomic trial at ILRI's Mazingira Centre for Environmental Research and Education in Nairobi, Kenya. A total of 6 plots for each block, and each plot measuring 4 m×2 m (Figure 4.1) were used. For the experimental set up and field lay out, refer to Chapter 3 for more details.

4.3.3 Biomass harvesting and yield determination

Each Brachiaria plot was harvested down to a stubble height of 10 cm and the entire fresh biomass was weighed directly in the field. Then, approximately a quarter of the biomass was chopped into 5 cm pieces using a machete, and three aliquots from each plot were then taken to the Mazingira Centre for dry matter determination. The fresh weight of each aliquot was determined in the lab, and then plant biomass was dried at 50 °C for 96 hours. Water content was determined by getting the difference between the fresh and dry weight.

Equation 1: Dry matter yield determination

Dry matter yield (DM) was determined using the formula below:

$$\text{DM (t ha}^{-1}) = \frac{\text{kg ha}^{-1}}{1000}$$

$$\text{DM in total harvested (kg plot}^{-1}) = \frac{\text{Total fresh biomass (kg)} \times \text{\% DM}}{100}$$

$$\text{DM in total harvested (t ha}^{-1}) = \frac{\text{DM in total harvest (kg plot}^{-1})}{\text{Plot size (8 m}^2) \times 10000}$$

4.3.4 Statistical analysis

Two-way Analysis of Variance (ANOVA) based on fertilizer and season effects was conducted to determine if the harvested *Brachiaria brizantha cv. xaraes* yields were significantly different among the fertilizer treatments. Significant differences for the analysis of variance were accepted at $P \leq 0.05$. Tukey‘s HS post hoc was used to separate means of the determined *Brachiaria brizantha cv. xaraes* yields under the influence of various soil fertilization.

4.4 Results

4.4.1 The Rainfall patterns in the study area

The total rainfall amount during the experimental period was about 802 mm with long rains (LR) lasting from March-June while the short rains (SR) were recorded in the months between October 2018 to January 2019, January 2019 to March 2019 and October 2019 to December 2019. Due to the effects of climate change, the rainfall patterns changed leading to high rainfall being experienced in October, November and December (Figure 4.2).

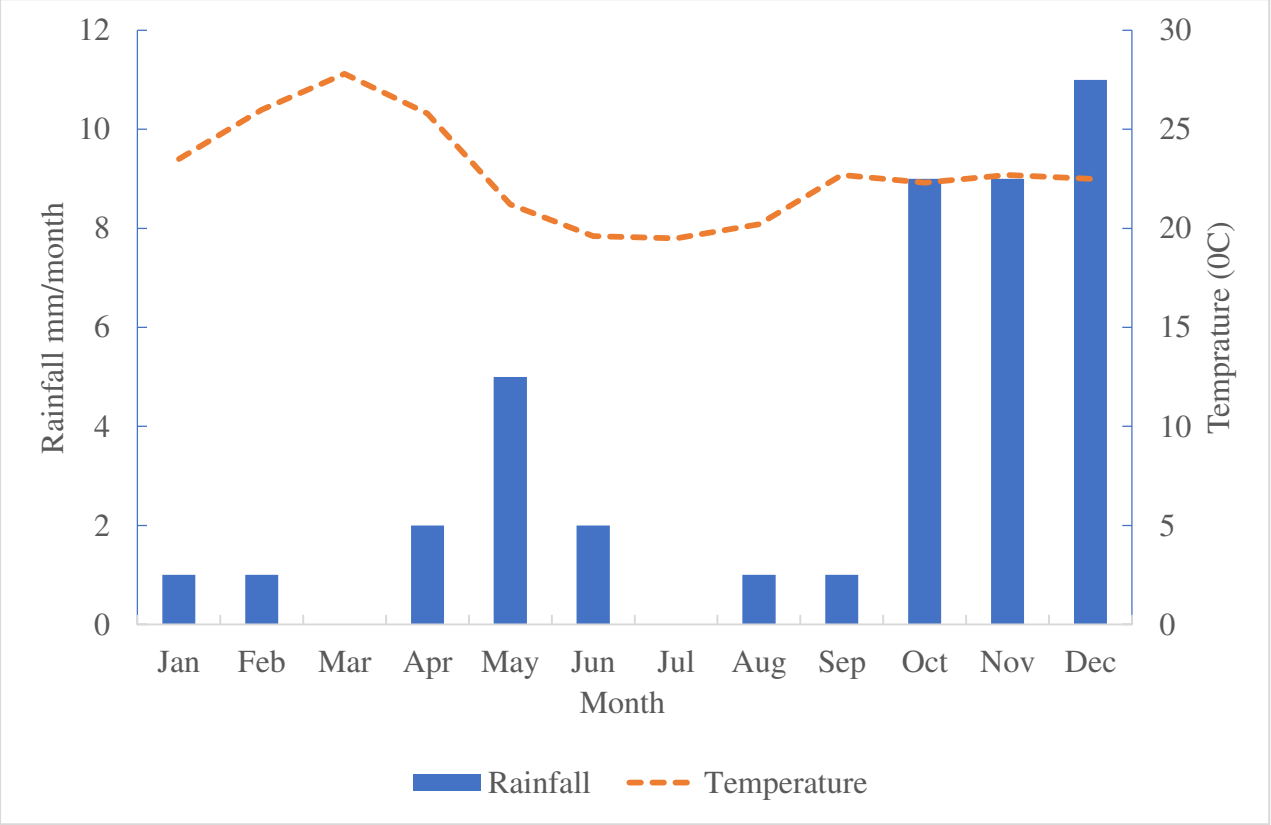


Figure 4. 2: Rainfall trends in the year 2019

4.4.2 Treatments effects on the yields of *Brachiaria brizantha xaraes*

The yields of Brachiaria exhibited similarity across all treatments and ranged between 0.94±0.50 and 4.72±1.46 Mg DM ha^{-1}. However, significant ($p<0.001$) seasonal effects were observed with the lowest (1.54±0.51 Mg DM ha^{-11}) and highest yields (4.72±1.46 Mg DM ha^{-}

[1]) recorded under cold season CD (June-August 2019) and LR (March-June 2019) respectively (Table 4.1).

Table 4. 1: *Brachiaria brizantha cv. xaraes* yields across treatments and seasons

Treatment	Season				p-value	L.S.D.
	SR	HD	LR	CD		
Bioslurry	2.15 ± 0.15^{ABa}	1.42 ± 0.25^{Aa}	4.46 ± 1.46^{Ba}	1.50 ± 1.46^{Aa}	0.036	2.083
Control	1.64 ± 1.16^{Aa}	2.24 ± 0.57^{Aa}	4.40 ± 1.32^{Aa}	2.05 ± 1.32^{Aa}	0.455	4.014
Lablab	1.96 ± 0.47^{Aa}	1.27 ± 0.38^{Aa}	4.70 ± 1.21^{Aa}	1.20 ± 1.21^{Aa}	0.074	2.893
FYM	3.31 ± 1.04^{Aa}	1.90 ± 1.44^{Aa}	4.48 ± 2.29^{Aa}	1.44 ± 2.29^{Aa}	0.812	3.017
FYM -BC	2.16 ± 0.55^{Aa}	2.17 ± 0.72^{Aa}	4.26 ± 1.03^{Aa}	1.79 ± 1.03^{Aa}	0.281	2.506
NPK	0.94 ± 0.50^{Aa}	3.55 ± 1.58^{Aa}	4.74 ± 1.47^{Aa}	1.25 ± 1.47^{Aa}	0.156	4.008
Pooled mean	2.03 ± 0.64^{A}	2.09 ± 0.83^{A}	4.72 ± 1.46^{B}	1.54 ± 0.51^{A}	<0.001	1.29

Different uppercase letters across the row represent significant difference between seasons. Different lowercase letters within the same column represent significant difference between treatments. (Values are mean ± SE).

Key: SR-Short rains season (October 2018 to January 2019)
HD- short rains season (January 2019 to March 2019)
LR- long rains season (March 2019 to June 2019)
CD- short rains (June 2019 to August 2019).

There were no significant differences in the total yields of Brachiaria for the control and the rest of the treatments (Figure 4.3). The total mean biomass for the entire study period (8 months) was 10.4t ha^{-1}±1.3 SE.

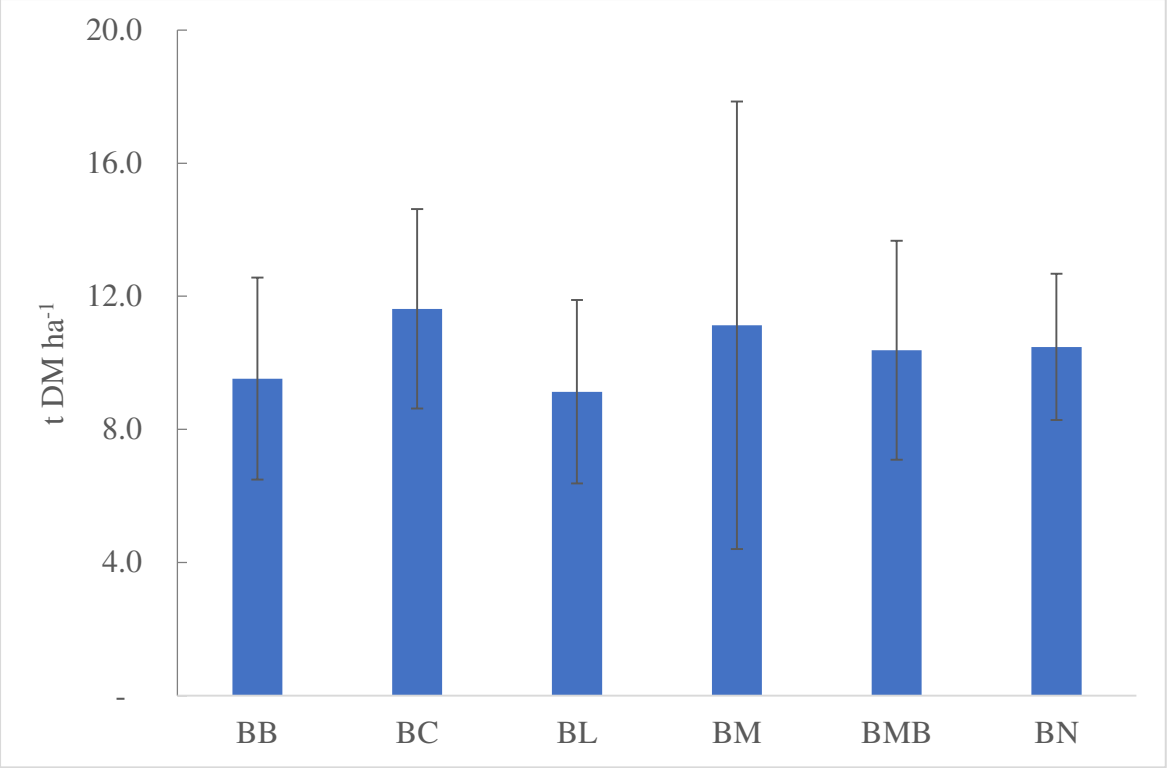


Figure 4. 3: The Total Grass yield sum for 8 months (means yields for all the 3 blocks)

(Where: **BB** (Brachiaria Bioslurry), **BC** (Brachiaria Control), **BL** (Brachiaria Lablab), **BM** (Brachiaria Manure), **BMB** (Brachiaria Manaure+10% Biochar) and **BN** (Brachiaria NPK))

4.5 Discussions

4.5.1 Effects of fertilization on Brachiaria yields

In this study , the highest yield of 4.74±1.47 t ha^{-1} was recorded under NPK during the long rains (April-June 2019, LR3), and the lowest yield under FYM+10% BC (4.26±1.03 t ha^{-1}) although the differences were not significant across the treatments. The higher DM yields during the rainy season in this study suggest that Brachiaria grows better during the rain seasons, indicating high water requirements and a potential drought sensitivity of the yields. However, since this trial was short-term, to affirm the results a long-term performance monitoring trial of Brachiaria under the tested treatments is recommended. The fertilizer treatments did not show any significant effects on the yields of Brachiaria which can be attributed to short duration of the study period. The study site was left fallow for a long period of time without any ploughing; this can lead to a delay in the process of mineralization (Francis, 1995). Historically, the field was only used for livestock grazing which deposited

lots of manure and urine which could potentially lead to increased phosphorus (P) levels in the soil (Park, et al., 2011). Excessive soil P has been reported to cause plant toxicity as well as immobilization of trace metals in the soil (Herath et al., 2015). This further leads to ground and surface water pollution through runoff that is unhealthy for plant growth (Carpenter et al., 1998).

4.6 Conclusions and recommendations

The results demonstrate that *Brachiaria brizantha cv. xaraes* can perform well when grown under enough rainfall conditions.to realize high yields. The treatments used did not influence DM yields of Brachiaria since the trial was newly established. The study period of eight months was relatively short for a newly established trial with a perennial plant, and therefore it is not possible to rule out potential medium- or long-term effects of these organic and inorganic fertilizers on yields. Furthermore, in the present study nutritional quality of the grass was not measured, but it is possible that the fertilized plants contain higher CP concentrations and are therefore of better nutritional quality. Hence, long-term studies that look at yields together with nutritional quality are required to effectively evaluate the agronomic performance of *Brachiaria brizantha cv. xaraes* and understand the influence of organic decomposition period on plant soil nutrient availability.

CHAPTER FIVE: CUMULATIVE AND YIELD-SCALED GREENHOUSE GAS EMISSIONS UNDER DIFFERENT ORGANIC AND INORGANIC SOIL FERTILIZATION TREATMENTS

5.1 Abstract

Demand for livestock products in East Africa is anticipated to triple by 2050. Therefore, sustainable intensification of livestock production systems for increased productivity is necessary in line with minimal negative environmental consequences. An agronomic field experiment was set up at the International Livestock Research Institute in Nairobi, Kenya, and the effects of organic and inorganic soil amendments on greenhouse gas emissions (particularly N_2O) from a Humic Nitisol planted with *Brachiaria brizantha cv. xaraes* were evaluated between October 2018 and August 2019. The treatments comprised mineral NPK fertilizer, Lablab intercrop, FYM, FYM-BC, Bioslurry, and control. Fertilizer treatments were applied at a rate of 45 kg N ha^{-1} following each harvest. GHG emissions were measured using the static vented chamber technique. Treatment and season significantly influenced daily N_2O emissions. The lowest (4.51±3.30 µg N m^{-2} h^{-1}) and highest (27.16±3.61 µg N m^{-2} h^{-1}) mean N_2O emissions were recorded under NPK and Control treatments during the short rains and dry seasons, respectively. Cumulative N_2O emissions and the corresponding yield-scaled emissions were similar across all the treatments but varied significantly ($p < 0.001$) between the wet and dry seasons. Cumulative N_2O emissions were 0.31±1.49, 0.33±1.47, 0.33±1.74, and 0.37±1.74, 0.38±2.3 and 0.42±1.81 Kg N ha^{-1} under FYM-BC, Lablab, NPK fertilizer, and FYM, Bioslurry and control treatments respectively. The corresponding yield-scaled emissions were also higher during the wet (0.23±1.16 g N kg^{-1} DM) than in the dry seasons (0.16±0.50 g N kg^{-1} DM). Higher (-21.86±4.47 mg CH_4-Ch^{-1}) CH_4 uptake was recorded under the control treatment whereas the lowest (-2.69±17.97 mg CH_4-Ch^{-1}) uptake

was recorded under Bioslurry ($P < 0.01$). Treatment and season exhibited individual effects on daily CO_2 emissions ($P < 0.001$), with a significant interaction effect ($P < 0.001$). The highest (157.5±28.76 mg CO_2-C $m^{-2}h^{-1}$) and lowest (44.33±8.37 mg CO_2-C $m^{-2}h^{-1}$) CO_2 emissions were recorded under Control and FYM treatments during the October 2018-January 2019 and January-March 2019 HD. Since the experiment was newly established via ploughing a field which had been used as a permanent pasture during previous years, did not expect considerable yield differences between treatments. Yet, it is interesting to see first effects of fertilizer amendments, pointing to their potential as climate-smart forage intensification strategies. Manure + biochar seems to be a better strategy for forage soil amendments in mitigating soil N_2O emissions.

Key words: GHG emissions; Nitrous oxide; organic and inorganic fertilizers; forage quality.

5.2 Introduction

5.2.1 Carbon mineralization and CO_2 emissions

During decomposition, organic matter (plant and microbial biomass, soil organic matter) is broken down and biochemically changed, processes during which CO_2 under aerobic conditions (heterotrophic respiration) and CH_4 under anaerobic conditions (methanogenesis) are produced. The soil microbial community is crucial for the turnover of nutrients, such as the incorporation of carbon into microbial biomass (the primary pathway of SOM formation), or the mineralization and immobilization of N. Soil microorganisms are driving the so-called C and N "humification", a term describing the production and decomposition of SOM. Humus affects soil parameters due to its slow decomposition rate, improving soil aggregate stability, and increasing cation exchange capacity (CEC) (Bot and Benites, 2005). Decomposition involves the physical breakdown and chemical amendment of organic fragments (e.g. cellulose, protein) from dead organic resources into shorter mineral and

organic units (for example sugars, peptides and amino acids) (Janzen et al., 1998; Bot and Benites, 2005).

Organic material supplemented to the soil can increase microbial activity and accelerate turnover of C in the soil, a procedure in which inorganic and organic C compounds are continuously transformed by connections between various organic components, vegetation and atmosphere (Bengtsson et al., 2005; Bot and Benites, 2005). This process releases CO_2, energy, water, nutrients and C compounds.

In addition to soil microorganisms, soil properties and conditions are also affected by plant roots, for example via excretion of root exudates. Furthermore, microorganisms and plant roots compete for Oxygen (O_2), with high O_2 use creating anoxic conditions (Hynes and Knowles, 1984). In cases of insufficient O_2, microorganisms have to use alternative respiration pathways, e.g. denitrifying bacteria that utilize NO_3^- instead of O_2 as electron acceptor during respiration (Robertson and Groffman, 2007), or methanogenic archaea that use CO_2 as electron acceptor and produce CH_4.

Variations in temperatures, rainfall and organic matter composition influence decomposition rates, which can be more rapid in tropics compared to temperate regions if moisture is not limiting. An increase in the level of yearly rainfall usually increases the rate of decomposition. Increased rate of decomposition and bacterial activity occur at 60 percent water-filled pore space (WFPS) (Linn and Doran, 1984). Though, periods of saturation and poorly aerated soil slows downs the rate of decomposition (Bot and Benites, 2005).

Higher soil temperatures too are associated with higher soil respiration rates by accelerating the rates of Carbon cycling through autotrophic respiration and providing a powerful positive feedback to climatic warming through the heterotrophic respiration of the soil organic Carbon (Hamdi et al., 2013). Other factors that have been reported to influence the rate of soil

respiration are soil moisture, the levels of nutrients content and Oxygen levels in the soil (Moyano et al., 2013). Ploughing and soil disturbance too increase the rate of soil respiration through opening of the soil air spaces that accelerate the rate of microbial activity in the soil (Yiqiand and Zhou, 2010).

The quantity and quality of organic matter added also affects the rate of decomposition in numerous ways. CO_2 emissions are stimulated whenever sources of C-based material hold easily decomposable C and N compounds. In tropical Africa, the use of organic substances possessing narrow C/N ratios such as manure and legume plant remnants, increases decomposition whereas the input of crop residues with high C/N ratios, like cereals and forage grasses, increases soil nutrient immobilization, the build-up of organic matter, and humus formation (Nicolardot et al., 2001; Bot and Benites, 2005). CO_2 is formed when autotrophic and heterotrophic organisms respire. CO_2 formation via heterotrophs occurs when O_2 is available. CO_2 is emitted from soils that are readily formed, more porous, leading to around 10 percent of CO_2 collects in the atmosphere annually (Raich and Tufekciogul, 2000). The soil carbon element is reduced through the process of heterotrophs that uses O_2 and emit CO_2 as a by-product (Cambardella, 2005).

5.2.2 Methane consumption and emissions

Methane is a GHG with a global warming potential 28 times larger compared to CO2 calculated over a 100-year time horizon (Myhre et al., 2013). Globally, the level of CH_4 in the atmosphere rose up from 750 ppb in the year 1800 up to 1,803 ppb by the year 2011 (Myhre et al., 2013). Segers (1998) reported that formation of CH_4 and its consumption are changes supported by organic matter mineralization in the soil.

Soil conditions such as temperature, pH and inhibitory materials influences CH_4 production. High differences in absolute rise in microbial activity when temperature rises by 10 °c leads to values of CH_4 emissions of 1.3–28 (Segers, 1998). The pH of the soil is a factor that

influences CH_4 formation. A lot of methanogenic microorganisms' work at optimum pH of seven and raising the pH of anaerobically induced soils raises CH_4 emissions. Methanogens are strictly anaerobic and can only survive under continuously O2-depleted conditions (for example wetlands, rice paddies). In anaerobic circumstances, the availability of organic materials is a limiting aspect for CH_4 release. Many studies have reported that addition of straight methanogenesis materials such as acetate and hydrogen or others like leachate and glucose promotes CH_4 emissions (Segers, 1998).

Methane consumption is a process whereby CH_4 is disintegrated by methanotrophic microorganisms (Segers, 1998). Le Mer and Pierre (2001) reason that these microorganisms use CH_4 as C and energy sources. They highlight that about 90 % of the CH_4 produced in low O2 environments may be broken down by methanotrophs in adequate supply of O2, for example in different layers of the same soil (methanogenesis in water-logged deep soil layers, methanotrophy in well-aerated topsoil) (Segers, 1998). Aerobic upland soils are vital sinks for CH_4, resulting to 15 % of the annual global CH_4 oxidation (Van den Pol-van Dasselaar et al., 1998). CH_4 usage is influenced by soil temperature, soil water levels, and soil N availability. When the temperature increases from 4 - 12 °C, the CH_4 absorption is doubled; however, additional temperature rises to 20 ° Celsius displays a smaller CH_4 usage. Van den Pol-van Dasselaar et al., (1998), outlined that the optimum temperature for CH_4 usage is within 20 to 25 °Celsius, moderately low compared to its production.

Methane consumption increases whenever H_2O levels rises from 22.5 % - 37.5 % w/w and decreases when water level is more than 45 % w/w. When H_2O level is less than 5 % and more than 50 % w/w, CH_4 absorption is stopped (Van den Pol-van Dasselaar et al., 1998), implying that wet or dry soil environments can stop CH_4 oxidation. It is also reported that the use of N fertilizer prevents the breakdown of CH_4 in soil because of competition between NH_3 and CH_4 for the CH_4 monooxygenase enzyme.

5.2.3 Soil N turnover

Soil N_2O and NO are by-products of N-transformation processes (e.g. nitrification, denitrification, and many others) that are environmentally harmful (Figure 5.1) (Dhondt et al.,

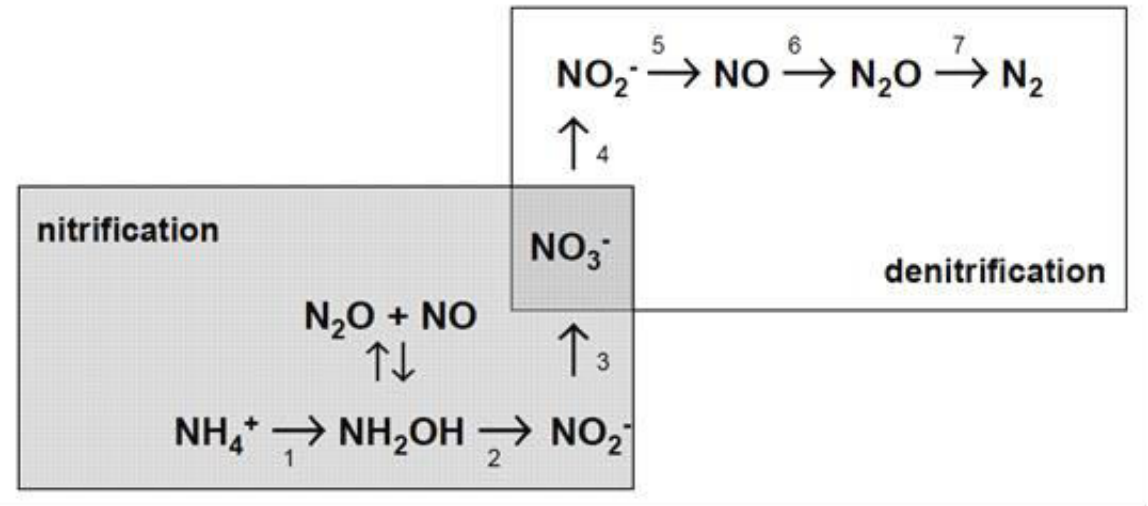


Figure 5. 1: Processes of denitrification and nitrification (adapted from; (Kotsyurbenko et al., 2001; Dhondt et al., 2004).

2004).

The process of nitrification requires enough O_2 supply because it is an aerobic process. Subsequently, H_2O level in soil is one of the processes controlling the speed of nitrification process since soil H_2O stops air movement in the soil. The process of Nitrification ends when the levels of soil water hits the point of saturation due to lack of O2. The high rates of the process are projected when the soil attains field capacity or 60% water filled pore spaces (WFPS) (Dhondt et al., 2004). The main complex bacteria to water stress are Nitrobacter species, therefore NH_4^+ and nitrite ions accumulate in drier soils. The process of Nitrification is slow when pH levels are low and increases when the pH goes up. However, in normal conditions, accumulation of nitrite happens as Nitrobacter species is thought to be immobile by NH_4^+, that build-up in alkaline conditions (Dhondt et al., 2004).

5.3 Materials and methods

5.3.1 Description of the study site

The study area is as described in section 3.1. This section presents the GHG gas measurements and analysis protocol.

5.3.2 Treatments and experimental design

The study was conducted between October 2018 and August, 2019 comprising of four harvest seasons of 10 weeks each: short rains (SR, October 2018 to January 2019), hot dry season (HD, January 2019 to March 2019), long rains (LR, March 2019 to June 2019), and cold dry season (CD, June 2019 to August 2019). The setup consisted of 3 replicate blocks with 18 plots each (3 forage grass species and 6 fertilizer types), giving a total of 54 plots (4 m x 2 m).

5.3.3 Greenhouse gas sampling and analysis

The soil-atmosphere fluxes of CH_4, CO_2 and N_2O were measured using the static chamber approach (Rosenstock et al., 2016). All sampling points followed the same scheme, between the plant rows at a specific distance from the borders, an opaque chamber was mounted for gas sampling (one chamber per plot). These chambers consisted of a plastic lid (0.27m×0.372m×0.125m) and a collar (0.27 m × 0.372 m × 0.1 m) (Figure 5.2). The collars were inserted up to 10 cm in the soil a week prior to the first GHG flux measurements and were left in place throughout the entire sampling period. The lids contained 50 cm long vent tubes with an inner diameter of 0.6 cm, thermometer ports to measure chamber headspace temperature during sampling, a fan to ensure headspace air mixing, and a sampling port with a rubber septum for collecting gas samples. When collecting the gases, the lid was put on the collar and tied with clamps with a seal between the lid and the collar for airtight closure. When collecting the gases, chamber closing was for 30 minutes, and four gas samples were drawn from each chamber at an interval of 10 minutes at 0, 10, 20, and 30 min for each plot.

A 60 ml propylene syringe with Luerlocks was used to sample the gas and instantly put into pre-evacuated 10 ml gas chromatography glass vials fixed with crimp seals (Butterbach-bahl et al., 2011). The gas samples were analyzed within one week after every sampling campaign as described below in the Mazingira Centre.

Concentrations of CO_2, N_2O, and CH_4 were analyzed by use of a gas chromatograph (GC, model 8610C, SRI, Germany) equipped with two detectors: a flame ionization detector (FID) comprising of a Platinum catalyzed methanizer for catalytic conversion of CO_2 to CH_4 and for subsequent detection of CH_4 and CO_2, and an electron capture detector (ECD) to detect N_2O. A 5% CO_2-in-N_2 mixture was used as the ECD Make-up gas to improve on the detector sensitivity. The analytes were separated on chromatographic columns (Hayesep D, 3 m, and 1/8″) as the stationary phase at an isocratic oven temperature (70 °C). ECD and FID detector temperatures were set at 350 °C. High-purity N_2 was used as carrier gas at flow rates of 25 ml min^{-1} on both FID and ECD. Gas concentrations of the samples were calculated as the peak areas measured by the GC comparative to the peak areas measured from standard gases of known concentrations run at four calibration levels. Calibration gases ranged from 2.03 to 49.8 ppm for CH_4, 403 to 2420 ppm for CO_2 and 329 to 2530 ppb for N_2O. Concentrations in ppm or ppb were then changed to mass per volume by using the Ideal Gas Law (PV = nRT) using the chamber volume and area, internal chamber air temperature, and atmospheric pressure determined during sampling. GHG fluxes were calculated using linear regression of gas concentrations versus chamber closure time (that is change of concentration over time). The limit of detection (LOD) were as follows: CH4 (R-squared R2=0.7), CO_2 (R2=0.9) and N_2O (R2=0.7). Data quality checks and cleaning was performed whereby 5% of the data were discarded since they were below the LOD.

Figure 5. 2: The plots before planting. b) The complete set of static GHG sampling assemblage. c) The inter-row positioning of the static chamber in the field in newly planted Brachiaria plots (approx. two weeks old).

5.3.4 Greenhouse gas measurements and analysis

Greenhouse gases were measured by use of static chamber approach and analyzed using GC machines at the Mazingira Laboratory (refer to chapter 3).

5.3.5 Yield scaled emissions

The yield-scaled GHG emissions were estimated using the cumulative fluxes over the 8 months sampling period divided by the yield data for the 4 harvests.

Equation 2: Yield-scaled GHG emissions.

$$\textbf{Yield scale emissions (g N kg}^{-1}\textbf{)} = \frac{\mathbf{N_2O\ \ emissons\ \ \ (kg\ ha^{-1})}}{\mathbf{Yield\ (t\ ha^{-1})}}$$

5.3.6 Brachiaria brizantha yields

Brachiaria brizantha cv. xaraes in individual plots was harvested after every 10 weeks down to a stubble height of 10 cm, and the entire aboveground biomass was collected and weighed. Maximum heights of Brachiaria (cm) was determined by use of a tape measure on separate plants per plot. All the biomass was weighed, and approximately a quarter of it was cut into 5 cm pieces using a machete. After cutting, 3 aliquots of about 300-500 g were selected from each plot and put into a pre-weighed and labelled bag. The samples were taken to the Mazingira Centre immediately after sampling and weighed (bag + fresh sample). The samples were then oven dried until constant weight (approximately. 96 hours) at 105 °C to determine dry matter content.

5.3.7 Statistical analysis

A two-way ANOVA was conducted to determine if the GHG fluxes were significantly different among the fertilizer treatments. Significant differences for the analysis of variance were accepted at $P \leq 0.05$. Tukey 's HSD post hoc test was used to separate means of the determined daily fluxes, cumulative fluxes and yield-scaled N_2O emissions under the influence of various soil amendments. Backward elimination regression analysis was conducted using Stata to determine the soil properties that influence N_2O and CO_2 emissions.

5.4 Results

This section discusses the effects of various soil amendments on soil GHG fluxes, cumulative N_2O, CO_2 and yield-scaled N_2O emissions.

5.4.1 Effects of soil fertilization on hourly CH_4 uptake

All the treatments acted as net sink for methane (Table 5.1, Figure 5.3), with treatment and season significantly influencing the uptake. Higher (-21.86±17.97mg CH_4-C h^{-1}) CH_4 uptake was recorded in the Control treatment whereas the lowest (-2.69±4.47mg CH_4-C h^{-1}) uptake was recorded in Bioslurry ($P < 0.01$).

Table 5. 1: Average CO_2, N_2O emissions and CH_4 uptake across the treatments during the experiment period.

Treatment	CH_4 (mg CH_4-C m^{-2} h^{-1})	CO_2 (mg CO_2-C $m^{-2}h^{-1}$)	N_2O (mgN_2O-N $m^{-2}h^{-1}$)
Control	-21.86±17.97b	94.76 ±19.32a	12.95±3.61a
Lablab	-18.32 ±5.04b	86.71±15.89a	10.51±2.93ab
Bioslurry	-2.69 ±4.47a	74.38 ±11.08b	12.87±4.29a
NPK	-16.67±3.69b	66.06 ±12.88bc	10.00±3.30ab
FYM_BC	-17.84 ±6.05b	58.43±14.48c	6.70±2.44b
FYM	-18.30 ±2.91b	58.39 ±15.67c	8.20±2.34b
p-value	<0.01	<0.01	<0.01
L.S.D.	8.85	6.37	3.13

Values are means ± standard error (SE). Different lowercase letters within the same column indicate significant differences between the treatments.

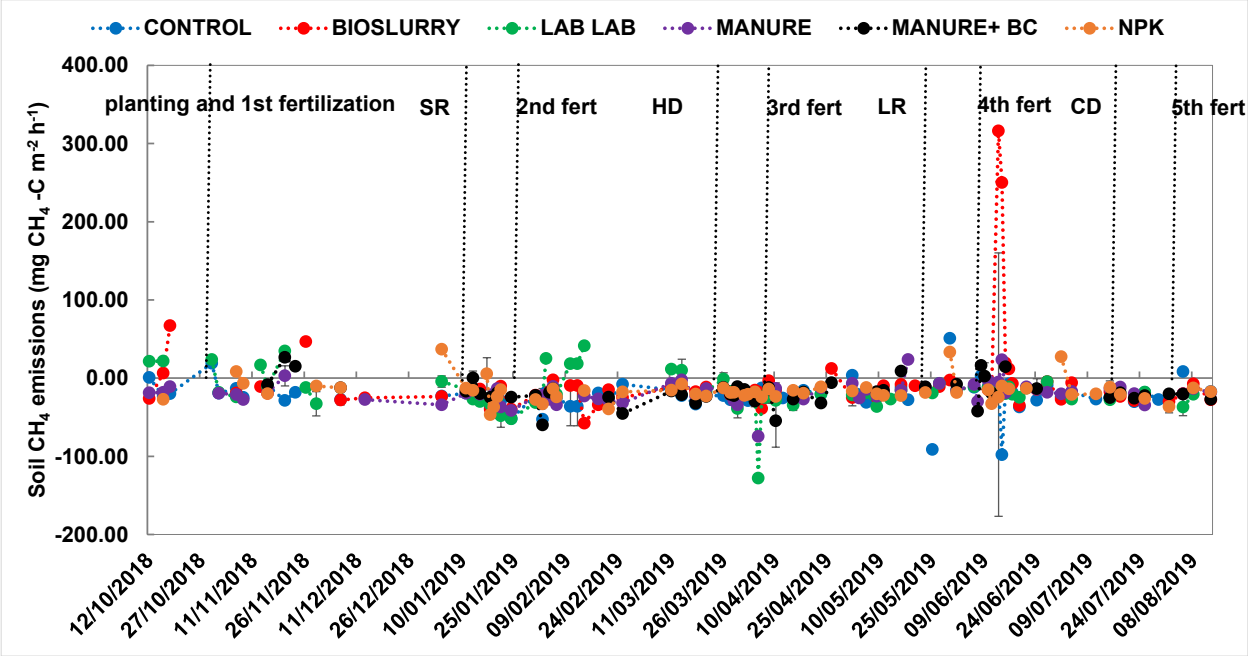


Figure 5. 3: Daily temporal CH_4 uptake during the entire study period

Key: Short rains season (October 2018 to January 2019) (SR), hot dry season (January 2019 to March 2019) (HD), long rains season (March 2019 to June 2019) (LR), cold dry season (June 2019 to August 2019) (CD).

Cumulative CH_4 uptake was 3.56% higher under FYM relative to the control, but the difference was not significant (Table 5.2). Daily and cumulative CH_4 uptake increased from season SR to HD and decreased in the subsequent seasons (Table 5.3 and Table 5.4).

Treatment and season significantly influenced daily CH_4 uptakes ($p < 0.01$ and $p = 0.009$ respectively) but did not show significant interaction ($p = 0.093$). Methane uptake was similar across all the treatments following the order of Control > Lablab > Manure > FYM-BC > NPK, except for Bioslurry which exhibited significantly lower (-2.69±4.47) CH_4 uptake ($p < 0.01$). Within the seasons, significantly lower (-11.43±13.87) and higher (-21.23±5.39) CH_4 uptakes were recorded during the cold

dry seasons and hot dry respectively whereas short rains and Long rains had similar CH_4 uptake.

Table 5. 2: Average CO_2 and N_2O emissions and CH_4 uptake across the four growing seasons.

Season	CH_4 (mg CH_4-C m^{-2} h^{-1})	CO_2 (mg CO_2-C $m^{-2}h^{-1}$)	N_2O (mgN_2O-N $m^{-2}h^{-1}$)
SR	-11.69 ±4.67ab	97.89 ±20.45a	18.40 ±5.41a
HD	-21.23 ±5.39b	65.22 ±14.16c	7.26 ±2.03b
LR	-19.07 ±6.42ab	73.78 ±16.17b	9.40 ±2.93b
CD	-11.43 ±13.87a	63.21 ±13.32c	7.36 ±0.20b
p-value	0.01	<0.01	<0.01
L.S.D.	7.67	5.25	2.46

Values are means ± standard error (SE). Different lowercase letters within the same column indicate significant differences between seasons.

Table 5. 3: Average CO_2 and N_2O emissions and CH_4 uptake of the different treatments across the four growing seasons.

Treatment	*Season*	*CH_4 (mg CH_4-C m^{-2} h^{-1})*	*CO_2 (mg CO_2-C $m^{-2}h^{-1}$)*	*N_2O (mgN_2O-N $m^{-2}h^{-1}$)*
Control	SR	-357±2.60a	157.54 ±17.90a	27.16 ±8.79a
	HD	-506 ±12.60a	86.1 ±11.08bcde	9.20 ±2.96c
	LR	-282 ±13.55a	82.86 ±10.72 bcdef	9.60 ±3.12c
	CD	-302 ±58.22a	70.67 ± defghi	7.07 ±2.01c
Lablab	SR	-340 ±6.09a	96.70 ±23.55 bc	11.63 ±3.87bc
	HD	-252 ±6.20a	82.11 ±15.06bcdefg	9.76 ±2.33bc
	LR	-273 ±4.35a	90.16 ±15.75bcd	11.82 ±3.95bc
	CD	-302 ±2.82a	79.82 ±13.01bcdefgh	8.57 ±2.89c
Bioslurry	SR	-292 ±3.83a	100.10 ±28.76b	24.37 ±5.69a
	HD	-275 ±3.08a	67.07 ±25.75efghij	8.61 ±3.28c
	LR	-297 ±4.41a	73.62 ±14.75cdefghi	11.23 ±3.37bc
	CD	-105 ±6.36a	63.26 ±13.06fghij	8.90 ±2.86c
NPK	SR	-88 ±1.45a	95.23 ±19.81bc	20.97 ±7.86ab
	HD	-354 ±4.35a	57.91 ±9.45hij	4.51 ±0.96c
	LR	-179 ±3.26a	64.94 ±12.92efghij	8.37 ±1.93c
	CD	-81 ±5.63a	52.71 ±11.94ij	5.76 ±2.24c
FYM-BC	SR	-76 ±5.06a	67.81± 14.79defghij	10.45 ±3.88bc
	HD	-337 ±2.52a	51.26±15.27ij	5.29 ±1.88c
	LR	-150 ±10.99a	62.60 ±18.16fghij	5.60 ±2.00c
	CD	-234 ±9.60a	52.84 ±14.08ij	5.23 ±1.91c
FYM	SR	-540 ±8.99a	63.81 ±17.92efghij	11.24 ±2.36bc
	HD	-431 ±3.59a	44.33±8.37j	4.95 ±0.79c
	LR	-260 ±1.97a	66.68 ±24.72efghij	8.50 ±3.21c
	CD	-268 ±0.57a	58.87 ±18.49ghij	7.74 ±2.94c
*p-value (Treatment * Season)*		0.093	<0.01	<0.01
L.S.D.			13.112	6.36

Values are means ± standard error (SE). Different lowercase letters within the same column indicate significant differences between the treatments and seasons. Different lowercase letters within the same column indicate significant differences between the treatments.

Key: SR-Short rains season (October 2018 to January 2019)

HD- short season (January 2019 to March 2019)

LR- long rains season (March 2019 to June 2019)

CD- short (June 2019 to August 2019).

5.4.2 Effects of soil fertilization on hourly and cumulative CO_2 fluxes

Treatment and season had significant ($p < 0.01$ respectively) effect on CO_2 emissions. CO_2 emissions in FYM-BC and FYM alone were on average lower by 61.6% compared to the CO_2 emissions in control which had the highest CO_2 emissions. Seasonal CO_2 emissions followed the order of CD>HD>LR>LR. Treatment and season also interacted significantly ($p<0.01$) to influence CO_2 emissions. Lower (44.33±8.37) emissions occurred under FYM alone during the HD season while the highest (157.54 ±17.90) CO_2 emissions were recorded under the control treatment during the 1st season. Figure 5.4 shows daily temporal CO_2 fluxes during the entire study period. Figure 5.5 presents hourly (A) and cumulative (B) CO_2 emissions of the different treatments during the four seasons.

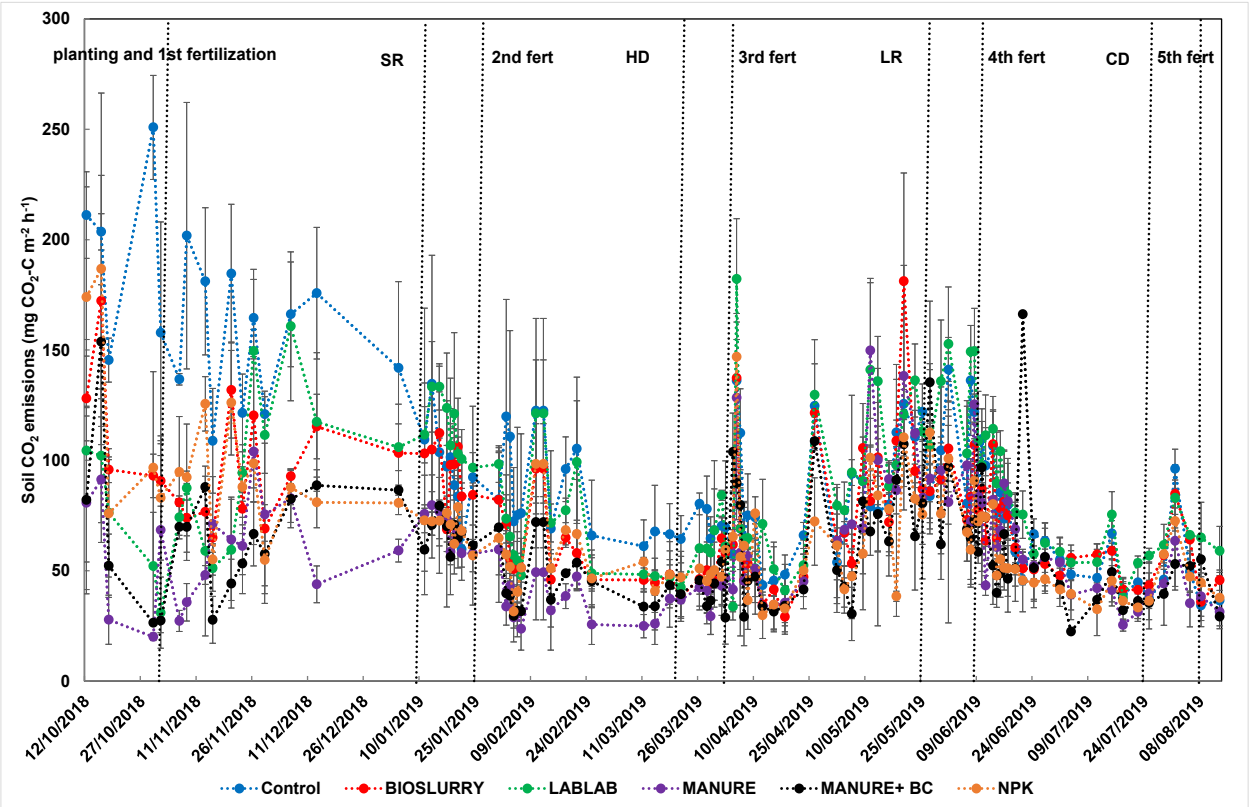


Figure 5. 4: Daily temporal CO_2 fluxes during the entire study period

Key: Short rains season (October 2018 to January 2019) (SR), short rains season (January 2019 to March 2019) (HD), long rains season (March 2019 to June 2019) (LR), and Cold Dry (June 2019 to August 2019) (CD).

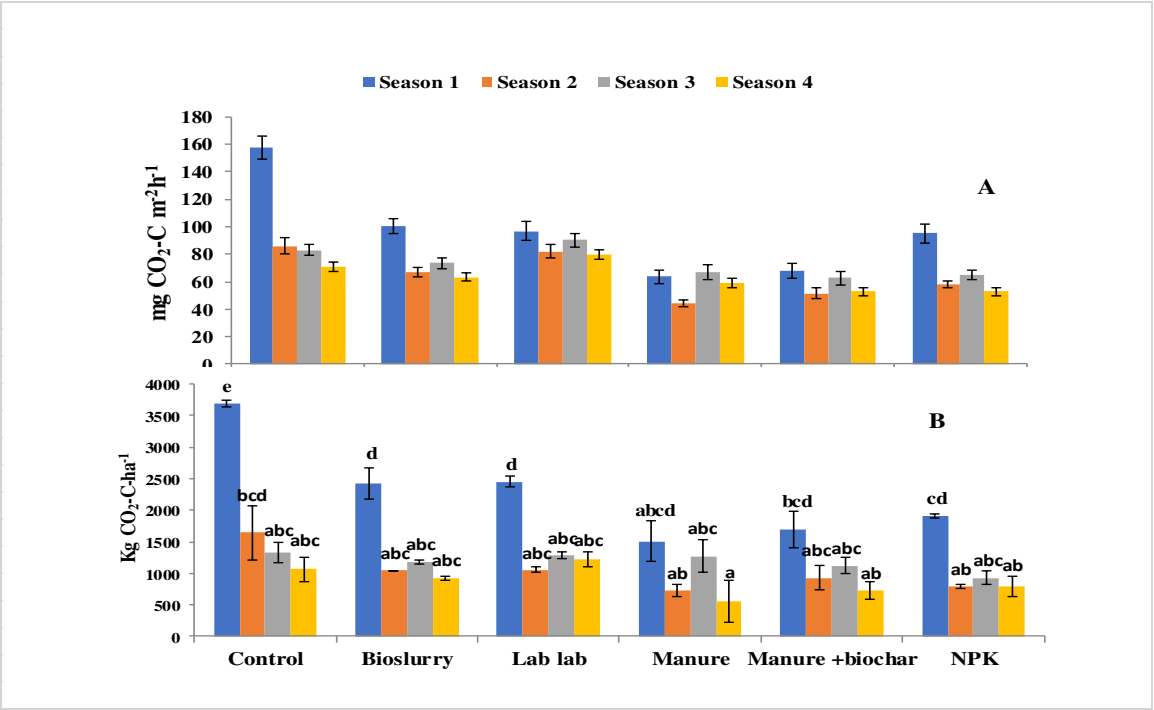


Figure 5. 5: Hourly (A) and cumulative (B) CO2 emission of different treatments during the four seasons. Vertical error bars represent standard error of the mean. Different lowercase letters indicate significant differences between treatments and seasons.

Key: Season 1-SR: SR (October 2018-January 2019), Season 2-HD (January 2019-March 2019), Season 3-LR (March 2019-June 2019), CD (June 2019-August 2019).

5.4.3 Effects of soil fertilization on daily and cumulative N_2O fluxes.

FYM-BC and FYM alone had significantly ($p < 0.01$) lower (6.70±2.44 and 8.20±2.34) N_2O emissions compared to the control which had the highest (12.95±3.61) N_2O emissions. Significant higher N_2O emissions were recorded during the first season while seasons 2, 3 and 4 had similar emission rates.

Significant ($p < 0.01$) interaction between treatment and season was also observed with NPK recording the lowest (4.51 ±0.96) emissions during the second season relative to control which had the highest (27.16 ±8.79) N_2O emissions during the first season. However, cumulative N_2O emissions were similar across all treatments ($P = 0.235$) and seasons ($P = 0.736$) (Table 5.4). Figure 5.6 shows daily temporal soil N2O fluxes during the entire period of study.

Table 5. 4: Cumulative CH_4 uptake and CO_2 and N_2O emissions under different treatments and seasons

		CH_4(g CH_4-C ha^{-1})	CO_2 (kg CO_2-C ha^{-1})	N_2O (Kg N_2O -N ha^{-1})
Treatment	Control	-361.90±21.74ab	1929±208.89c	0.233±4.24a
	Lablab	-291.80±4.87ab	1504±73.82b	0.141±3.26a
	FYM	-374.80±3.78a	1015±250.61a	3.801±2.32a
	FYM-BC	-199.10±7.05ab	1117±185.33ab	1.252±2.42a
	NPK	-175.30±3.67b	1106±84.69a	2.265±3.25a
	Bioslurry	-242.20±4.42ab	1393±78.09ab	0.26±3.80a
	P-value	0.013	<0.001	0.235
	L.S.D.	130.5	263.0	5.193
Season	SR	-282.4±4.67ab	2279±169.72c	0.32±5.41a
	HD	-359.1±5.39a	1030±134.05ab	0.12±2.03a
	LR	-240.0±6.42ab	1184±120.37b	0.16±2.93a
	CD	-215.3±13.87b	883±163.45a	2.14±0.2a
	P-value	0.048	<0.001	0.736
	L.S.D.	106.6	214.7	2.109

(Values are mean ± SE).

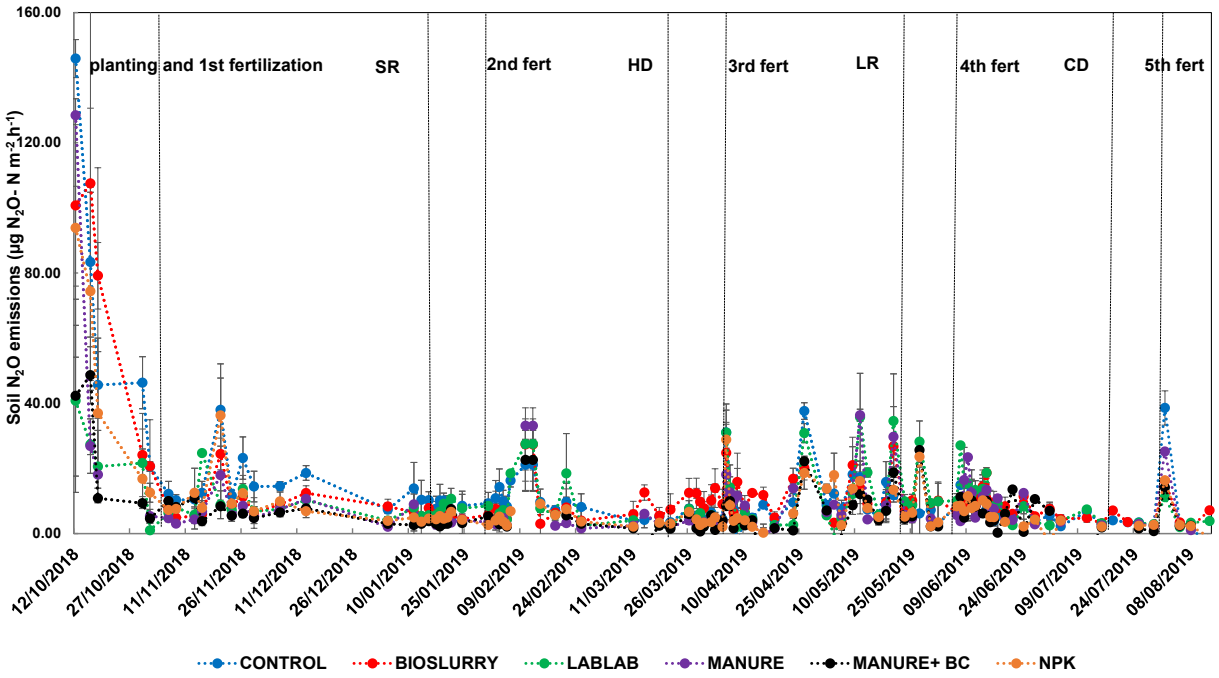


Figure 5. 6: Daily temporal soil N_2O fluxes during the entire period of study

Key: Short rains season (October 2018 to January 2019) (SR), short rains season (January 2019 to March 2019) (HD), long rains season (March 2019 to June 2019) (LR), and short rains (June 2019 to August 2019) (CD).

The total cumulative N_2O fluxes for the entire study period (8 months) was 1.4 Kg ha^{-1}±0.1. However, there was no significant differences recorded for the cumulative N_2O fluxes across the treatments for the entire study period (Figure 5.7).

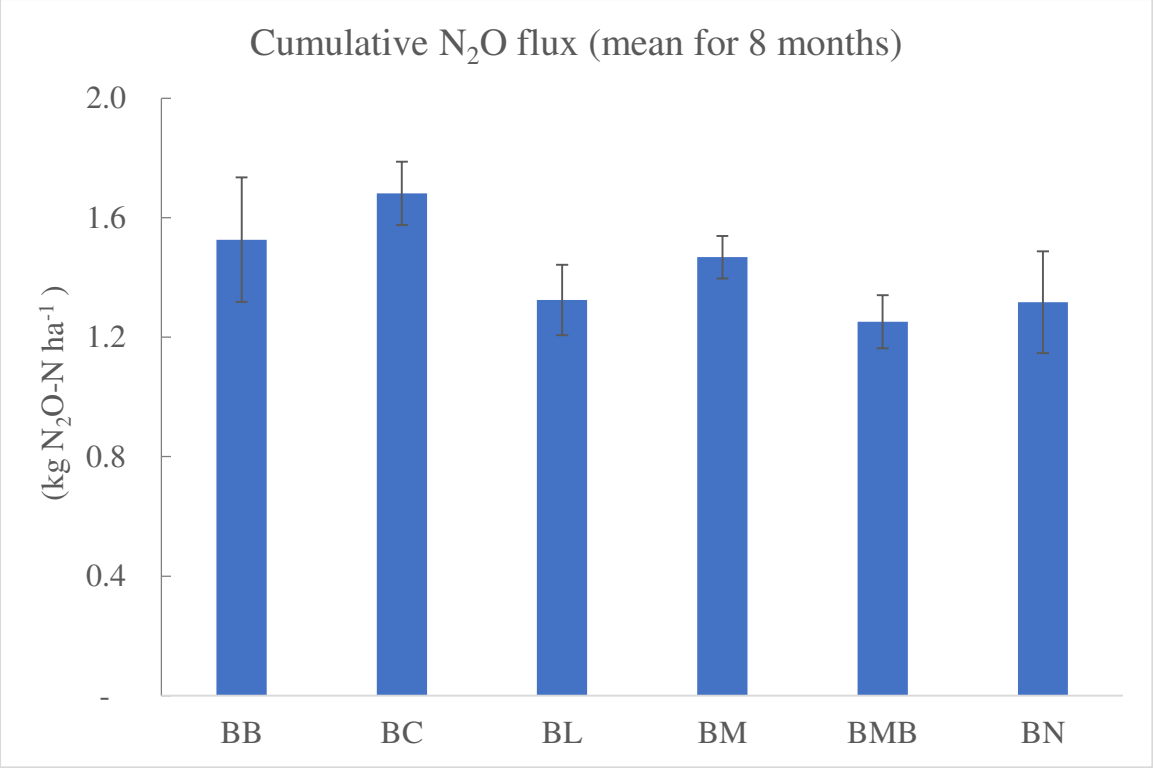


Figure 5. 7: The total cumulative N2O fluxes for the entire study period

5.4.4 Effects of soil fertilization on yield-scaled N_2O emissions

The treatments did not show significant effect on yield scaled N_2O emissions (P = 0.244) but interacted significantly with seasons to influence yield-scaled N_2O emissions (P = 0.026). Compared to Control, FYM-BC recorded a net N_2O uptake of 0.02±0.04 Kg N_2O-N kg^{-1} DM in the CD season whereas the highest (21.35±0.04 Kg N_2O-N kg^{-1} DM) N_2O emission was under Lablab in the SR season. The Yield-scaled N_2O emissions were generally higher in first season with the seasons 2, 3, and 4 exhibiting moderates to low yield-scaled N_2O emissions (Table 5.5).

Table 5. 5: Yield-scaled N2O emissions under different treatments during the four seasons

Treatment (Values are mean ± SE).	Season			
	SR	HD	LR	CD
	(g N_2O-N kg^{-1} DM yield)			
Control	4.47±0.05ab	0.08±0.01a	0.03±0.01a	0.03±0.05a
Bioslurry	7.05±0.04ab	0.12±0.02a	0.03±0.003a	0.07±0.003a
Lablab	21.35±0.04b	0.10±0.02a	0.07±0.01a	0.07±0.03a
FYM	0.74±0.01a	0.19±0.01a	0.02±0.01a	10.23±0.26a
FYM-BC	3.17±0.04ab	0.04±0.01a	0.02±0.01a	0.02±0.04a
NPK	2.77±0.15ab	0.06±0.01a	0.02±0.01a	6.89±0.05ab

Key: SR-Short rains season (October 2018 to January 2019)

HD- short rains season (January 2019 to March 2019)

LR- long rains season (March 2019 to June 2019)

CD- short rains (June 2019 to August 2019).

5.4.5. Effect of fertilization and harvesting on N_2O and CO_2 emissions

Soil ammonium concentration, soil moisture (Table 5.6), CN ratio and CO_2 emissions were the main drivers of N_2O emissions during the fertilization period ($P < 0.01$, Adjusted R^2 = 0.83-Pearson correlations), while N_20 emission was the only parameter that influenced CO_2 emission ($P < 0.01$, Adjusted $R^2 = 0.65$). At harvesting, the soil parameters did not exhibit any relationship with N_2O ($P = 0.62$), while CO_2 was significantly influenced by soil moisture content ($P = 0.01$, Adjusted $R^2 = 0.52$).

Table 5. 6: Factors affecting N_2O and CO_2 emissions during fertilization

(n = 36)		*Coefficients*	*Standard Error*	*t Stat*	*P-value*
N_2O	(Constant)	-486.46	177.10	-2.75	0.01
	Soil temperature	1.08	0.68	1.59	0.12
	C/N ratio	39.77	17.29	2.30	**0.03**
	Soil moisture	0.96	0.37	2.60	**0.01**
	Ammonium	1.18	0.29	4.01	**0.00**
	Nitrate	-0.04	0.13	-0.35	0.73
	CO_2 flux	0.43	0.07	6.62	**0.00**
CO_2	(Constant)	729.28	329.40	2.21	0.03
	Soil temperature	-1.28	1.24	-1.03	0.31
	C/N ratio	-59.07	31.84	-1.85	0.07
	Soil moisture	-0.95	0.72	-1.32	0.20
	Ammonium	-1.03	0.63	-1.64	0.11
	Nitrate	-0.04	0.23	-0.15	0.88
	N_2O flux	1.39	0.21	6.62	**0.00**

5.5 Discussions

5.5.1 Effects of soil moisture and temperature on soil GHG emissions

The primary drivers of biochemical processes including GHG emissions, are soil moisture and temperature (Zhang et al., 2012); (Butterbach-Bahl et al., 2013). The GHG fluxes temporal patterns followed rainfall trends (moisture fluctuations), which is consistent with Hickman et al., (2014), whose fluxes were high during rainfall seasons. This is similar to the findings of other studies (Ding et al., 2012); (Zhang et al., 2012). A study by Wei-xin et al., (2007) reported that the optimum temperature for N_2O emissions ranges should be between 25 to 40 ^{0}C which was within our temperature range for GHG emissions.

5.5.2 Effects of organic and inorganic fertilizers on cumulative N_2O fluxes

The cumulative N_2O fluxes observed in this research study were similar with those reported from some of the studies involving the use of organic and inorganic fertilizers (Baggs et al., 2003; Sarkodie-Addo et al., 2003; Millar, Ndufa, 2004). These cumulative N_2O fluxes are slightly lower than 0.45 kg N_2O-N ha^{-1} that was observed under fertilized agricultural soil in

sub-Saharan Africa (Dick et al., 2008); (Wanyama et al., 2018). These figures suggest that yearly N_2O fluxes from Kenyan agricultural soils is at the lower end of the global estimate at 1.0 kg N_2O ha^{-1} $year^{-1}$ (Bouwman, 1996).

However, manure recorded higher cumulative N_2O emissions (3.801 Kg N_2O -N ha^{-1}) compared to NPK (2.265 Kg N_2O -N ha^{-1}) although not significantly different. This finding is contradictory to other studies where inorganic fertilizers recorded higher cumulative N_2O emissions than the control and organic fertilizers (Ding et al., 2010; Frimpong and Baggs, 2010; Charles et al., 2017). Consequently, FYM + 10% BC recorded the least cumulative N_2O emissions (1.252 Kg N_2O -N ha^{-1}) which propose that FYM + 10% BC can be a viable strategy in mitigating N_2O emissions from agricultural soils. Nevertheless, N_2O emissions recorded in NPK plots increased after 15 days of fertilizer application. This was similarly recorded by Maljanen et al, (2003) who asserted that N_2O emissions from inorganic fertilizers is short-lived.

5.5.3 Yield-scaled N_2O emissions

Reducing yield-scaled N_2O emissions is vital in the realization of sustainable African agricultural systems rather than absolute N_2O emissions values for a given area (Scheer et al., 2012). Generally, yield-scaled N_2O emissions for this study showed a decline from harvest 1 to 4. FYM + 10% BC recorded the lowest values of N_2O yield-scaled emissions in harvest 2, 3 and 4, suggesting that the use of FYM-BC can be a good strategy in reducing N_2O yield scaled emissions. Other treatments recorded higher N_2O yield-scaled emissions from control and organic fertilizers compared to the inorganic fertilizer (NPK) which was in agreement to the findings reported by Nyamadzawo et al. (2014).

5.6 Conclusion

In conclusion, these results suggest that the use of FYM-BC can be a good strategy in reducing N_2O yield scaled emissions. From the study, the following recommendations can be made:

- Having recorded low N_2O emissions when *Brachiaria brizantha cv. xaraes* is grown at 45 kg N ha^{-1} $harvest^{-1}$ (or 225 kg N ha^{-1} yr^{-1} for 5 annual harvests) of fertilizer implies that this fertilization rate can be a good GHG mitigation strategy in tropical forage production.
- It is important to look at different rates of N fertilizer applications in evaluating the yields and emissions of GHG in forage crops. Further research can be conducted at varied fertilizer rates to evaluate the long-term effects of organic and mineral fertilizer on N_2O fluxes.
- Spatial variations in forage GHG emissions in tropical Africa need to be assessed further to understand how various ecological zones respond to varied organic and inorganic fertilizers in terms of yields and GHG emissions.

CHAPTER SIX: GENERAL DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

6.0 General Discussions

The study indicates that the main drivers for soil greenhouse gas emissions are the moisture and temperature. The rainfall seasons recorded higher soil CO_2, NH_4 and N_2O fluxes whereas the dry seasons recorded lower emissions of the GHGs. It is expected that the biomass production should be significantly higher for soils amended with inorganic fertilizers (NPK), however, for this study, the fertilizer amendments did not significantly affect biomass production for Bracharia brizantha xaraes. This is attributed to the fact that the field was initially used for livestock grazing leading to deposition of urine and dung. The urine and dung are full of mineral N and therefore it was no longer a limiting nutrient component in the soil.

6.1 Summary Conclusions

From the study, it was observed that *Brachiaria brizantha cv. xaraes* yields did not significantly respond to various organic and inorganic fertilization regimes. The rainfall patterns changed from the normal patterns due to the effects of climate change. The usual hot dry (January-March) and cold dry seasons (June-September) increasingly received more rainfall. The field had overstayed without ploughing and farming activities and was only used for long grazing. Due to the grazing activities, there was more urine and manure deposits in the field and therefore, mineral N is no longer a limiting factor for plant growth in the field where the experiment occurred. This made Nitrogen availability not to significantly influence the yields of the *Brachiaria Brizantha xaraes.* Generally, Nitrogen fertilization events released more NO_2 than the other parameters. Additionally, due to higher N availability in the soil, it influenced the emissions of the CH_4, CO_2 and N_2O. Therefore, the data does not support conclusively on the potential of organic or mineral fertilizers for climate-smart forage grass production. Either way, we recommend the use of any type of fertilizer for forage grass

production to avoid soil nutrient mining and degradation of soil health over time. The study findings also clearly assert that:

- *Brachiaria brizantha cv. xaraes* performs well and gives higher yields when grown under enough rainfall conditions.
- N_2O emissions under NPK fertilizer (inorganic fertilizer) are generally higher compared to those of organic fertilizers.
- FYM-BC has shown a potential of minimizing soil N_2O emissions and therefore presents the best option for climate smart forage production.

6.3 General Recommendations

The following are the recommendations future studies;

- The differences in spatial variation in the Brachiaria yields and soil GHG emissions which cannot be explained by the data should be researched in detail, especially on the influence of soil properties to soil N_2O emissions.
- Inorganic fertilizer (NPK) recorded higher soil Ammonium and Nitrates compared to the organic fertilizers across the study period. Similar agronomic studies need to be examined for a longer period of time to fully assess the mineralization potentials of various organic fertilizers used in forage production.

REFERENCES

Abbott, L.K., Murphy, D.V. (2007). What is soil biological fertility? Soil biological fertility. Springer, pp. 1-15. Applied nitrogen, (3), 54–61. https://doi.org/10.1007/s00374-001-0441-5.

Agehara, S. and Warncke, D.D. (2005). Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. Soil Science Society of America Journal. 69(6), 1844-1855.

Aydin, I. and Uzun, F. (2005). Nitrogen and phosphorus fertilization of rangelands affects yield, forage quality and the botanical composition. European Journal of Agronomy, 23(1), 8-14.

Azam, F., Müller, C., Weiske, A., Benckiser, G. and Ottow, J. (2002). Nitrification and denitrification as sources of atmospheric nitrous oxide–role of oxidizable carbon and applied nitrogen. Biology and Fertility of Soils, 35(1), 54-61. 35(1), 54–61.

Babhulkar, P.S., Wandile, R.M., Badole, W.P. and Balpande, S.S. (2000). Residual effect of long-term application of FYM and fertilizers on soil properties (Vertisols) and yield of soybean. Journal of the Indian society of soil science, 48(1), 89-92.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. and Cadisch, G. (2003). Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. 1(1998), 361–370.

Bayble, T., Melaku, S., Prasad, N. (2007). Effects of cutting dates on nutritive value of Napier (Pennisetum purpureum) grass planted sole and in association with Desmodium (Desmodium intortum) or Lablab (Lablab purpureus). Livestock Research for Rural Development 19, 120-136.Behnke, R., Muthami, D., 2011. The contribution of livestock to the Kenyan economy.

Bengtsson, J., Ahnström, J., WeibulL, A.C. (2005). The effects of organic agriculture on biodiversity and abundance: a meta-analysis. Journal of applied ecology 42, 261-269.

Bengtsson, M., Shen, Y. and Oki, T. A. (2006). SRES-based gridded global population dataset for 1990–2100. Population and Environment, 28(2), 113-131. 28(2), 113-131.

Bongaarts, J. (2009). Human population growth and the demographic transition. Philosophical Transactions of the Royal Society B: Biological Sciences 364, 2985-2990.Bot, A., Benites, J., 2005. The importance of soil organic matter: Key to drought-resistant soil and sustained food production. Food and Agriculture Org. Accessed 19 Nov 2019.

Bouwman, A. F. (1996). Direct emission of nitrous oxide from agricultural soils. 53–54.

Bruun, E.W., Ambus, P., Egsgaard, H., Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biology and Biochemistry 46, 73-79.

Bryceson, D.F. (1999). African rural labour, income diversification and livelihood approaches: a long-term development perspective. Review of African Political Economy 26, 171-189.

Bulluck Iii, L., Brosius, M., Evanylo, G., Ristaino, J. (2002). Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Applied soil ecology 19, 147-160. Accessed 17 Nov 2019

Buss, W. and Mašek, O. (2014). Mobile organic compounds in biochar–a potential source of contamination–phytotoxic effects on cress seed (Lepidium sativum) germination. Journal of Environmental Management, 137, 111-119.

Butterbach-bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-boltenstern, S. and Butterbach-bahl, K. (2013). Nitrous oxide emissions from soils: how well do we understand the processes and their controls?

Butterbach-bahl, K., Kiese, R. and Liu, C. (2011). Measurements of Biosphere – Atmosphere Exchange of CH 4 in Terrestrial Ecosystems. In Methods in Methane Metabolism, Part B (1st ed., Vol. 495). Elsevier Inc. https://doi.org/10.1016/B978-0-12-386905-0.00018-8

Cambardella, C. (2005). Aggregation and Organic Matter. Encyclopedia of Soil Science, Rattan L. CRC Press.

Carey, R. O. and Migliaccio, K. W. (2009). Contribution of wastewater treatment plant effluents to nutrient dynamics in aquatic systems: A review. Environmental Management. 44(2), 205–217.

Carpenter, S.R., Caraco, N.F., Correll, D. L., Howarth, R.W., Sharpley, A.N. and Smith, V.H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological applications, 8(3), 559-568. 8(3).

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B. and Misselbrook, T. (2011). Manure management: Implications for greenhouse gas emissions. Animal Feed Science and Technology, 166–167, 514–531. https://doi.org/10.1016/j.anifeedsci.2011.04.036

Chakraborty, A., Chakrabarti, K., Chakraborty, A., Ghosh, S. (2011). Effect of long-term fertilizers and manure application on microbial biomass and microbial activity of a tropical agricultural soil. Biology and Fertility of Soils 47, 227-233.

Chantigny, M.H., Curtin, D., Beare, M.H. and Greenfield, L.G. (2010). Influence of temperature on water-extractable organic matter and ammonium production in mineral soils. Soil Science Society of America Journal, 74(2), 517-524. 74(2), 517–524.

Charles, A., Rochette, P., Whalen, J.K., Angers, D.A., Chantigny, M. H. and Bertrand, N. (2017). Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. Agriculture, Ecosystems and Environment, 236(3), 88–98. https://doi.org/10.1016/j.agee.2016.11.021. Accessed 13 Dec 2019.

Chianu, J.N., Chianu, J.N., Mairura, F. (2012). Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agronomy for sustainable development 32, 545-566.

Chiyoka, W., Hao, X., Zvomuya, F., Li, X. (2011). Nitrous oxide emissions from Chernozemic soils amended with anaerobically digested beef cattle feedlot manure: A laboratory study. Animal feed science and technology 166, 492-502.

Christophe, S., Jean-Christophe, A., Annabelle, L., Alain, O., Marion, P. and Anne-Sophie, V. (2011). Plant N fluxes and modulation by nitrogen, heat and water stresses: A review based on comparison of legumes and non-legume plants. Abiotic Stress in Plants–Mechanisms and Adaptations. Intech Open Access Publisher, Rijeka, Croatia. 79-118.

Ciais, P., Soussana, J., Vuichard, N., Luyssaert, S., Don, A., Janssens, I., Piao, S., Dechow, R., Lathière, J., Maignan, F. (2010). The greenhouse gas balance of European grasslands. Biogeosciences Discussions 7, 5997-6050.

Cohen, J.E. (2003). Human population: The next half century. Science, 302(5648), 1172-1175. 302(5648), 1172-1175.

Da Cunha, F.F., Ramos, M.M., de Alencar, C. A.B., de Oliveira, R.A., Cóser, A. C., Martins, C.E., and Araújo, R. A. S. (2012). Yield of Brachiaria brizantha cv. Xaraes in different management and levels of fertilization, rest periods and seasons. IDESIA, 30(1), 75-82.

Da Silva, S.C. and Carvalho, P.D.F. (2005). Foraging behaviour and herbage intake in the favourable tropics/sub-tropics. Grassland: a global resource, 1, 81-95.

Dai, Z., Wang, Y., Muhammad, N., Yu, X., Xiao, K., Meng, J., Liu, X., Xu, J., Brookes, P.C. (2014). The effects and mechanisms of soil acidity changes, following incorporation of biochars in three soils differing in initial pH. Soil Science Society of America Journal 78, 1606-1614. Accessed 10 Dec 2019.

Delgado, C.L. (2003). Rising consumption of meat and milk in developing countries has created a new food revolution. The Journal of nutrition 133, 3907S-3910S.

Deng, H.Y. (2013). Effect of biochar amendment on soil nitrous oxide emission. McGill University Libraries.

Desjardins, R.L., Worth, D.E., Vergé, X.P., Maxime, D., Dyer, J., Cerkowniak, D. (2012). Carbon footprint of beef cattle. Sustainability 4, 3279-3301.

Dhondt, K., Boeckx, P., Hofman, G., Van Cleemput, O. (2004). Temporal and spatial patterns of denitrification enzyme activity and nitrous oxide fluxes in three adjacent vegetated riparian buffer zones. Biology and Fertility of Soils 40, 243-251.

Dick, J., Kaya, B., Soutoura, M., Skiba, U., Smith, R., Niang, A. and Tabo, R. (2008). The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. September, 292–301. https://doi.org/10.1111/j.1475-2743.2008.00163.x

Ding, W., Luo, J., Li, J., Yu, H., Fan, J. and Liu, D. (2012). Science of the Total Environment Effect of long-term compost and inorganic fertilizer application on background N 2 O and fertilizer-induced N 2 O emissions from an intensively cultivated soil. Science of the Total Environment, 465, 115–124. https://doi.org/10.1016/j.scitotenv.2012.11.020. Accessed 1 Nov 2019.

Ding, W., Yagi, K., Cai, Z. and Han, F. (2010). Impact of long-term application of fertilizers on N2O and NO production potential in an intensively cultivated sandy loam soil. Water, Air, and Soil Pollution, 212(1–4), 141–153. https://doi.org/10.1007/s11270-010-0328-x

Djikeng, A., Rao, I.M., Njarui, D., Mutimura, M., Caradus, J., Ghimire, S.R., Johnson, L., Cardoso, J.A., Ahonsi, M., Kelemu, S. (2014). Climate-smart Brachiaria grasses for improving livestock production in East Africa. Tropical Grasslands-Forrajes Tropicales 2, 38-39.

Doran, J.W., Zeiss, M.R. (2000). Soil health and sustainability: managing the biotic component of soil quality. Applied soil ecology 15, 3-11.

Drosg, B., Fuchs, W., Al Seadi, T., Madsen, M., Linke, B. (2015). Nutrient recovery by biogas digestate processing. IEA Bioenergy Berlin, Germany.

Enders, A., Hanley, K., Whitman, T., Joseph, S., Lehmann, J. (2012). Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresource technology 114, 644-653.

Estefan, G., Sommer, R., Ryan, J. (2013). Methods of soil, plant, and water analysis. A manual for the West Asia and North Africa region, 170-176.

Evrendilek, F., Celik, I., Kilic, S. (2004). Changes in soil organic carbon and other physical soil properties along adjacent Mediterranean forest, grassland, and cropland ecosystems in Turkey. Journal of Arid Environments 59, 743-752.

Fateh, E., Chaichi, M.R., Sharifi Ashorabadi, E., Mazaheri, D., Jafari, A.A. and Rengel, Z. (2009). Effects of organic and chemical fertilizers on forage yield and quality of globe artichoke (Cynara scolymus L.). Asian Journal of Crop Science, 1(1), 40Y48.

Fernandes, M.S. and Rossiello, R. O.P. (1995). Mineral nitrogen in plant physiology and plant nutrition. Critical Reviews in Plant Sciences. 14(2), 111–148.

Fidel, R.B., Laird, D.A., Parkin, T.B. (2019). Effect of biochar on soil greenhouse gas emissions at the laboratory and field scales. Soil Systems 3, 8.

Foyer, C.H., Lam, H.-M., Nguyen, H.T., Siddique, K.H., Varshney, R.K., Colmer, T.D., Cowling, W., Bramley, H., Mori, T.A., Hodgson, J.M. (2016). Neglecting legumes has compromised human health and sustainable food production. Nature plants 2, 16112.

Francis, G.S. (1995). Management practices for minimizing nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. Journal of Contaminant Hydrology, 20(3–4), 313–327.

Frimpong, K.A. and Baggs. (2010). Do combined applications of crop residues and inorganic fertilizer lower emission of N 2 O from soil? August. https://doi.org/10.1111/j.1475-2743.2010.00293.

Gallardo, A., Paramá, R. and Covelo, F. (2006). Differences between soil ammonium and nitrate spatial pattern in six plant communities. Simulated effect on plant populations. Plant and soil, 279(1-2), 333-346. 279, ((1-2)), 333–346. Accessed 31 Oct 2019

Gaskin, J.W., Speir, R.A., Harris, K., Das, K.C., Lee, R.D., Morris, L.A. and Fisher, D.S. (2010). Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agronomy Journal, 102(2), 623-633.

Gerland, P., Raftery, A.E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., .and Bay, G. (2014). World population stabilization unlikely this century. Science, 346(6206), 234-237.

Giller, K.E. (2001). Nitrogen fixation in tropical cropping systems. Cabi.

Glass, A.D. (2003). Nitrogen use efficiency of crop plants: physiological constraints upon nitrogen absorption. Critical reviews in plant sciences 22, 453-470.

Grafton, R.Q., Daugbjerg, C., Qureshi, M.E. (2015). Towards food security by 2050. Food Security 7, 179-183.

Groteluschen, K. (2014). Lablab purpureus (L.) Sweet: A promising multipurpose legume for enhanced drought resistance and improved household nutritional status in smallholder farming systems of Eastern Kenya. M. Sc. thesis submitted to Georg-August-University Göttingen, Germany.

Hamdi, S., Moyano, F., Sall, S., Bernoux, M. and Chevallier, T. (2013). Synthesis analysis of the temperature sensitivity of soil respiration from laboratory studies in relation to incubation methods and soil conditions. Soil Biology and Biochemistry. 58, 115–116.

Harish, C.T., Asmono, D., Guduru, S., Hassena, M., Sumbula, M., Esmira, L. (2002). Opportunities for crop diversification and better crop-livestock integration in the highlands of Arsi, Ethiopia.

Haug, R.T. (1980). Compost engineering. Ann Arbor Science Publishers.

Heffer, P., Prud'homme, M. (2010). Fertilizer outlook 2010–2014. 78th IFA annual conference, Paris.

Herath, I., Kumarathilaka, P., Navaratne, A., Rajakaruna, N. and Vithanage, M. (2015). Immobilization and phytotoxicity reduction of heavy metals in serpentine soil using biochar. Journal of Soils and Sediments. 15(1), 126–138.

Herrero, M., Havlik, P., McIntire, J., Palazzo, A., Valin, H. (2014). African Livestock Futures: Realizing the potential of livestock for food security, poverty reduction and the environment in Sub-Saharan Africa.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences 110, 20888-20893.

Herrero, M.T., Ringler, C., Steeg, J.V.D., Thornton, P.K., Zhu, T., Bryan, E., Omolo, A., Koo, J., Notenbaert, A.M.O. (2010). Climate variability and climate change and their impacts on Kenya's agricultural sector.

Hickman, J. E., Palm, C. A., Mutuo, P., Melillo, J. M. and Tang, J. (2014). Nitrous oxide (N_2O) emissions in response to increasing fertilizer addition in maize (Zea mays L.) agriculture in western Kenya, (3), 177–187. https://doi.org/10.1007/s10705-014-9636-7

Hickman, J.E., Havlikova, M., Kroeze, C., Palm, C.A. (2011). Current and future nitrous oxide emissions from African agriculture. Current Opinion in Environmental Sustainability 3, 370-378.

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. Bioresource technology 100, 5478-5484.

Hynes, R.K., Knowles, R. (1984). Production of nitrous oxide by Nitrosomonas europaea: effects of acetylene, pH, and oxygen. Canadian Journal of Microbiology 30, 1397-1404.

Jambert, C., Serca, D., Delmas, R. (1997). Quantification of N-losses as NH 3, NO, and N_2O and N 2 from fertilized maize fields in southwestern France. Nutrient Cycling in Agroecosystems 48, 91-104.

Janzen, H., Campbell, C., Izaurralde, R., Ellert, B., Juma, N., McGill, W., Zentner, R. (1998). Management effects on soil C storage on the Canadian prairies. Soil and Tillage Research 47, 181-195.

Kabirizi, J., Mpairwe, D., Mutetikka, D. (2007). The effect of integrating forage legumes in smallholder crop/livestock farming systems on food, fodder and animal performance. Conf. Int. Agr. Res. Dev., October, pp. 9-11.

Kan, T., Strezov, V., Evans, T.J. (2016). Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. Renewable and Sustainable Energy Reviews 57, 1126-1140.

Kanianska, R., Kizeková, M., Nováček, J., Zeman, M. (2014). Land-use and land-cover changes in rural areas during different political systems: A case study of Slovakia from 1782 to 2006. Land Use Policy 36, 554-566.

Kariuki, Tamminga, S., Gachuiri, C., Gitau, G., Muia, J. (2001). Intake and rumen degradation in cattle fed napier grass (Pennisetum purpureum) supplemented with various levels of Desmodium intortum and Ipomoea batatus vines. South African Journal of Animal Science 31, 149-157.

Karl, T.R., Trenberth, K.E. (2003). Modern global climate change. Science 302, 1719-1723.

Kemmitt, S.J., Wright, D., Goulding, K. W. and Jones, D. L. (2006). pH regulation of carbon and nitrogen dynamics in two agricultural soils. Soil biology and biochemistry, 38(5), 898-911. 38(5), 898-911

Kim, D. G., Thomas, A., Pelster, D., Rosenstock, T.S. and Sanz-Cobena, A. (2016). Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Agrica: Synthesis of available data and suggestions for further research. Biogeosciences, 13(16), 13(16), 4789-4809.

Kissel, D.E., Cabrera, M.L. and Paramasivam, S. (2008). Ammonium, ammonia, and urea reactions in soils. Nitrogen in agricultural systems. 101–155.

Koga, N., Sawamoto, T., Tsuruta, H. (2006). Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, northern Japan. Soil Science and Plant Nutrition 52, 564-574.

Kögel-Knabner, I., & Amelung, W. (2021). Soil organic matter in major pedogenic soil groups. *Geoderma*, *384*, 114785.

Kosgey, I., Mbuku, S., Okeyo, A., Amimo, J., Philipsson, J., Ojango, J. (2011). Institutional and organizational frameworks for dairy and beef cattle recording in Kenya: a review and opportunities for improvement. Animal Genetic Resources/Resources génétiques animales/Recursos genéticos animales 48, 1-11.

Kotsyurbenko, O.R., Glagolev, M.V., Nozhevnikova, A.N., Conrad, R. (2001). Competition between homoacetogenic bacteria and methanogenic archaea for hydrogen at low temperature. FEMS microbiology ecology 38, 153-159.

Le Mer, J., Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: a review. European journal of soil biology 37, 25-50.

Ledgard, S., Steele, K. (1992). Biological nitrogen fixation in mixed legume/grass pastures. Plant and soil 141, 137-153.

Lehmann, J., Gaunt, J. and Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems–a review. Mitigation and adaptation strategies for global change, 11(2), 403-427.

Leroy, C., Delbarre, C., Ghillebaert, F., Compere, C., Combes, D. (2008). Influence of subtilisin on the adhesion of a marine bacterium which produces mainly proteins as extracellular polymers. Journal of applied microbiology 105, 791-799.

Linn, D.M., Doran, J.W. (1984). Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils 1. Soil Science Society of America Journal 48, 1267-1272.

Livingston, G., Schonberger, S. and Delaney, S. (2011). Sub-Saharan Africa: The state of smallholders in agriculture. In Paper presented at the IFAD Conference on New Directions for Smallholder Agriculture (Vol. 24, p. 25). 24, 25.

Lodhi, M.A.K. (1979). Inhibition of nitrifying bacteria, nitrification and mineralization in spoil soils as related to their successional stages. Bulletin of the Torrey Botanical Club, 284-289. 284–289.

Macharia, P.N., Gachene, C., Mureithi, J., Kinyamario, J., Ekaya, W., Thuranira, E. (2010). The effect of introduced forage legumes on improvement of soil fertility in natural

pastures of semi-arid rangelands of Kajiado District, Kenya. Tropical and Subtropical Agroecosystems 14, 221-227.

Mafongoya, P. L., Bationo, A., Kihara, J. and Waswa, B.S. (2006). Appropriate technologies to replenish soil fertility in southern Africa. Nutrient Cycling in Agroecosystems, 76(2-3), 137-151.

Maljanen, M., Liikanen, A., Silvola, J. and Martikainen, P. J. (2003). Measuring N_2O emissions from organic soils by closed chamber or soil / snow N 2 O gradient methods. September, 625–631.

Mandal, K.G. and Sinha, A.C. (2004). Nutrient management effects on light interception, photosynthesis, growth, dry-matter production and yield of Indian mustard (Brassica juncea). Journal of Agronomy and Crop Science, 190(2), 190(2), 119-129.

Mapanda, F., Wuta, M., Nyamangara, J. and Rees, R. M. (2012). Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. Nutrient Cycling in Agroecosystems, 94(1), 85–96. https://doi.org/10.1007/s10705-012-9528-7. Accessed 14 Nov 2019

Mbah, C., Mbagwu, J. (2006). Effect of animal waste on physicochemical properties of a Dystric Leptosol and maize yield in southeastern Nigeria. Nigerian Journal of Soil Science 16, 96-103.

Mbugua, J., Njonge, F. (2017). report on cow milk value chain project.

McMichael, A.J., Powles, J.W., Butler, C.D. and Uauy, R. (2007). Food, livestock production, energy, climate change, and health. The lancet, 370(9594). 1253–1263.

McMichael, A.J., Powles, J.W., Butler, C.D., Uauy, R. (2007). Food, livestock production, energy, climate change, and health. The lancet 370, 1253-1263.

Metaferia, F., Cherenet, T.G., Abnet, F., Tesfay, A., Abdi, J., Gulilat, W. (2011). A review to improve estimation of livestock contribution to the national GDP.

Meyer, V., Redente, E., Barbarick, K., Brobst, R., Paschke, M., Miller, A. (2004). Plant and soil responses to biosolids application following forest fire. Journal of Environmental Quality 33, 873-881.

Millar, N., Doll, J.E., Robertson, G.P. (2014). Management of nitrogen fertilizer to reduce nitrous oxide (N2O) emissions from field crops. Climate Change and Agriculture Fact Sheet Series, MSU Extension Bulletin E 3152.

Millar, N.K. Ndufa, G.C. and E.B. (2004). Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. 18, 1–9. https://doi.org/10.1029/2003GB002114

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput, O. (1997). Closing the global atmospheric N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. (OECD/IPCC/IEA Phase II Development of IPCC Guidelines for National Greenhouse Gas Inventories). Dissipation of N from the human N-cycle, and its role in present and future N2O emissions to the atmosphere. Int. Workshop, Oslo, Norway, pp. 4-4.

Moyano, F.E., Manzoni, S. and Chenu, C. (2013). Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. Soil Biology and Biochemistry. 59, 72–85.

Mugerwa, S., Kabirizi, J., Njarui, D., Mpairwe, D. (2012). Utilization of introduced forages by smallholder dairy farmers in Uganda. International Journal of Biosciences 2, 36-45.

Muriuki, H., Mwangi, D., Thorpe, W. (2001). How smallholder dairy systems in Kenya contribute to food security and poverty alleviation: results of recent collaborative studies.

Myhre, G., Samset, B.H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T.K., Bian, H., Bellouin, N., Chin, M., Diehl, T. (2013). Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. Atmospheric Chemistry and Physics 13, 1853.

N'Dayegamiye, A., Royer, R. and Audesse, P. (1997). Nitrogen mineralization and availability in manure composts from Quebec biological farms. Canadian journal of soil science, 77(3), 345-350. 77(3), 345-350.

Ngubo, N. (2016). The effect of bioslurry, grass clippings and pumpkin live mulch on soil water content and maize production.

Nguku, S.A., Donald, M.G., Musimba, N.K., Amwata, D. and Kaindi, E.M. (2016). Primary production variables of brachiaria grass cultivars in kenya dry lands. Tropical and Subtropical Agroecosystems, 19(1).

Nicolardot, B., Recous, S., Mary, B. (2001). Simulation of C and N mineralisation during crop residue decomposition: a simple dynamic model based on the C: N ratio of the residues. Plant and soil 228, 83-103.

Nielsen, K.F. and Cunningham, R.K. (1964). The effects of soil temperature and form and level of nitrogen on growth and chemical composition of Italian ryegrass. Soil Science Society of America Journal, 28(2), 28(2), 213–218.

Njarui, D.M., Gichangi, E.M., Ghimire, S.R., Muinga, R.W. (2016). Climate Smart Brachiaria Grasses for Improving Livestock Production in East Africa–Kenya Experience.

Noll, L., Zhang, S. and Wanek, W. (2019). Novel high-throughput approach to determine key processes of soil organic nitrogen cycling: Gross protein depolymerization and microbial amino acid uptake. Soil Biology and Biochemistry, 130, 73-81. 130, 73–81.

Nyamadzawo, G., Wuta, M., Nyamangara, J. and Rees, B. (2014). Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic. https://doi.org/10.1007/s10705-014-9634-9

Odero, W.J.A., Odero-Waitituh J.A. (2017): Smallholder dairy production in Kenya; a review. Livestock Research for Rural Development. Volume 29, Article #139. Retrieved May 15, 2020, fromhttp://www.lrrd.org/lrrd29/7/atiw29139.html.http://lrrd.cipav.org.co/lrrd29/7/atiw29139.html.

Omore, A.O., Muriuki, H., Kenyanjui, M., Owango, M., Staal, S.J. (1999). The Kenya dairy sub-sector: a rapid appraisal.

Oorts, K., Ghesquiere, U., Swinnen, K., Smolders, E. (2006). Soil properties affecting the toxicity of CuCl2 and NiCl2 for soil microbial processes in freshly spiked soils. Environmental Toxicology and Chemistry: An International Journal 25, 836-844.

Opala, P.A., Kisinyo, P.O. and Nyambati, R.O. (2015). Effects of Tithonia diversifolia, farmyard manure and urea, and phosphate fertiliser application methods on maize yields in western Kenya. Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS), 116(1), 1-9.

Pelster, D., Rufino, M., Rosenstock, T., Mango, J., Saiz, G., Diaz-Pines, E., Baldi, G., Butterbach-Bahl, K. (2017). Smallholder farms in eastern African tropical highlands have low soil greenhouse gas fluxes. Biogeosciences 14, 187-202.

Place, F., Barrett, C.B., Freeman, H.A., Ramisch, J. and Vanlauwe, B. (2003). Prospects for integrated soil fertility management using organic and inorganic inputs: evidence from smallholder African agricultural systems. Food policy, 28(4), 365-378.

Prasad, B. and Singh, A.P. (1980). Changes in soil properties with long-term use of fertilizer, lime and farmyard manure. Journal of the Indian Society of Soil Science, 28(4), 28(4), 465-468.

Quilty, J., Cattle, S. (2011). Use and understanding of organic amendments in Australian agriculture: a review. Soil Research 49, 1-26.

Raich, J.W., Tufekciogul, A. (2000). Vegetation and soil respiration: correlations and controls. Biogeochemistry 48, 71-90.

Ramirez, K.S., Craine, J.M., Fierer, N. (2010). Nitrogen fertilization inhibits soil microbial respiration regardless of the form of nitrogen applied. Soil Biology and Biochemistry 42, 2336-2338.

Raun, W.R., Johnson, G.V. (1999). Improving nitrogen use efficiency for cereal production. Agronomy journal 91, 357-363.

Reddy, P.P. (2015). Climate resilient agriculture for ensuring food security. Springer.

Richardson, H.L. (1938). The nitrogen cycle in grassland soils with special reference to the Rothamsted Parkg rasse xperiment.J .a gric.Sci., C amb.2 8:7 3-121.

Robertson, G.P., Groffman, P. (2007). Nitrogen transformations. Soil microbiology, ecology and biochemistry. Elsevier, pp. 341-364.

Robertson, G.P., Hutson, M.A., Evans, F.C., Tiedje, J.M. (1988). Spatial variability in a successional plant community: patterns of nitrogen availability. Ecology 69, 1517-1524.

Rosenstock, T.S., Mpanda, M., Pelster, D.E., Butterbach-Bahl, K., Rufino, M.C., Thiong'o, M., Mutuo, P., Abwanda, S., Rioux, J., Kimaro, A.A. (2016). Greenhouse gas fluxes from agricultural soils of Kenya and Tanzania. Journal of Geophysical Research: Biogeosciences 121, 1568-1580.

Sanchez, P.A., Korir, D., Ali, A.I.M., Goopy, J.P., Merbold, L., Schlecht, E.and and Dickhoefer, U. (2019). Feed intake, apparent total tract digestibility, and nitrogen balance in Boran steers fed with three grasses grown alone or intercropped with Lablab purpureus.

Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.M.N., and Woomer, P. L. (1997). Soil fertility replenishment in Africa: an investment in natural resource capital. Replenishing soil fertility in Africa, 51, 1-46.

Santos, G.O., Faria, R.T. De and Rodrigues, G.A. (2014). Yield and forage quality of Brachiaria fertigated with sew- age effluent. 2010, 6–10.

Sarkodie-Addo, J., Lee, H.C. and Baggs, E.M. (2003). Nitrous oxide emissions after application of inorganic fertilizer and incorporation of green. https://doi.org/10.1079/SUM2003203

Sass, R., Fisher, F., Harcombe, P., Turner, F. (1991). Mitigation of methane emissions from rice fields: Possible adverse effects of incorporated rice straw. Global Biogeochemical Cycles 5, 275-287.

Scheer, C., Grace, P.R., Rowlings, D.W. and Payero, J. (2012). Nitrous oxide emissions from irrigated wheat in Australia: Impact of irrigation management. Plant Soil. https://doi.org/10.1007/s11104-012-1197-4

Scotti, R., Bonanomi, G., Scelza, R., Zoina, A., Rao, M. (2015). Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. Journal of soil science and plant nutrition 15, 333-352.

Segers, R. (1998). Methane production and methane consumption: a review of processes underlying wetland methane fluxes. Biogeochemistry 41, 23-51.

Shahbaz, M., Akhtar, M.J., Ahmed, W., Wakeel, A. (2014). Integrated effect of different N-fertilizer rates and bioslurry application on growth and N-use efficiency of okra (Hibiscus esculentus L.). Turkish Journal of Agriculture and Forestry 38, 311-319.

Sherlock, R.R., Sommer, S.G., Khan, R.Z., Wood, C., Guertal, E.A., Freney, J.R., Dawson, C.O., Cameron, K.C. (2002). Ammonia, methane, and nitrous oxide emission from pig slurry applied to a pasture in New Zealand. Journal of Environmental Quality 31, 1491-1501.

Siekmann, J.H., Allen, L.H., Bwibo, N.O., Demment, M.W., Murphy, S.P., Neumann, C.G. (2003). Animal source foods to improve micronutrient nutrition and human function in developing countries.

Silva, D., Silva, W.J.D., Barreto, A.C., Oliveira Junior, A B.D., Paes, J.M.V., Ruas, J.R.M. and Queiroz, D.S. (2012). Dry matter yield, thermal sum and base temperatures in irrigated tropical forage plants. Revista Brasileira de Zootecnia, 41(3), 41(3), 574-582.

Sinha, O. (2007). Agro-industries characterization and appraisal: dairy in India. AGSF Working Document (FAO).

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S. and Herrero, M. (2013). Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. Animal Frontiers, 3(1), 6-13.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M. (2014). Agriculture, forestry and other land use (AFOLU). Climate change 2014: mitigation of climate change. Contribution of

Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L. and Fixen, P.E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. 133, 247–266. https://doi.org/10.1016/j.agee.2009.04.021. Accessed 19 Nov 2019

Sohi, S., Lopez-Capel, E., Krull, E., Bol, R. (2009). Biochar, climate change and soil: A review to guide future research. CSIRO Land and Water Science Report 5, 17-31.

Sommer, S.G., Schjoerring, J.K. and Denmead, O.T. (2004). Ammonia emission from mineral fertilizers and fertilized crops. Advances in agronomy, 82((557622)), 82008–4.

Speijers, M.H., Fraser, M.D., Theobald, V.J., Haresign, W. (2004). The effects of grazing forage legumes on the performance of finishing lambs. The Journal of Agricultural Science 142, 483-493.

Spiertz, J., Ewert, F. (2009). Crop production and resource use to meet the growing demand for food, feed and fuel: opportunities and constraints. NJAS-Wageningen Journal of Life Sciences 56, 281-300.

Spokas, K.A. and Reicosky, D.C. (2009). Impacts of sixteen different biochars on soil greenhouse gas production.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macêdo, J.L.V., Blum, W. E. and Zech, W. (2007). Long-term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant and soil, 291((1-2),), 275–290.

Steudler, P., Bowden, R., Melillo, J., Aber, J. (1989). Influence of nitrogen fertilization on methane uptake in temperate forest soils. Nature 341, 314.

Stevenson, F.J., Cole, M.A. (1999). Cycles of soils: carbon, nitrogen, phosphorus, sulfur, micronutrients. John Wiley and Sons.

Tambone, F., Scaglia, B., D'Imporzano, G., Schievano, A., Orzi, V., Salati, S., Adani, F. (2010). Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. Chemosphere 81, 577-583.

Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E., Blümmel, M. (2011a). Pathways for sustainable development of mixed crop livestock systems: Taking a livestock and pro-poor approach. Livestock science 139, 11-21.

Thangarajan, R., Bolan, N.S., Tian, G., Naidu, R., Kunhikrishnan, A. (2013). Role of organic amendment application on greenhouse gas emission from soil. Science of the Total Environment 465, 72-96.

Theron, J.J. (1963). The mineralization of nitrogen in soils under grass. South African J. agric. Sci. 6: 155-164.

Thornton, P.K. (2010). Livestock production: recent trends, future prospects. Philosophical Transactions of the Royal Society B: Biological Sciences 365, 2853-2867.

Thornton, P.K., Herrero, M, (2010). Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. Proceedings of the National Academy of Sciences 107, 19667-19672.

Thornton, P.K., van de Steeg, J., Notenbaert, A., Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. Agricultural systems 101, 113-127.

Tolera, A., Merkel, Goetsch, R.C., Sahlu, A.L.T, and Negesse, T. (2000). Nutritional constraints and future prospects for goat production in East Africa. Proceedings of the opportunities and challenges of enhancing goat production in East Africa. A conference held at Awassa College of agriculture, Debub University (pp. 10-12).

Tschirley, D. (2010). Opportunities and constraints to increased fresh produce trade in East and Southern Africa. 4th Video Conference under AAACP-funded Series of High Value Agriculture Seminars. Available at: http://citeseerx. ist. psu. edu/viewdoc/download. Citeseer.

Valentini, R., Arneth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., Ciais, P., Grieco, E., Hartmann, J., Henry, M. (2014). A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities. Biogeosciences 11, 381-407.

Vallejo, A., Skiba, U.M., García-Torres, L., Arce, A., López-Fernández, S., Sánchez-Martín, L. (2006). Nitrogen oxides emission from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. Soil Biology and Biochemistry 38, 2782-2793.

Van den Pol-van Dasselaar, A., Van Beusichem, M., Oenema, O. (1998). Effects of soil moisture content and temperature on methane uptake by grasslands on sandy soils. Plant and soil 204, 213-222.

Vanlauwe, B. and Giller, K. E. (2006). Popular myths around soil fertility management in sub-Saharan Africa. Agriculture, ecosystems and environment, 116(1-2), 34-46.

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., Van Asten, P. (2014). Sustainable intensification and the African smallholder farmer. Current Opinion in Environmental Sustainability 8, 15-22.

Viljoen, C., Van der Colf, J., & Swanepoel, P. A. (2020). Benefits are limited with high nitrogen fertiliser rates in kikuyu-ryegrass pasture systems. *Land*, *9*(6), 173.

Wanyama, I., Pelster, D.E., Arias-navarro, C., Butterbach-bahl, K., Verchot, L. and Ru, M.C. (2018). Management intensity controls soil N 2 O fl uxes in an Afromontane ecosystem. 624, 769–780. https://doi.org/10.1016/j.scitotenv.2017.12.081. Accessed 02 Jan 2019

Wei-xin, D., Lei, M., Zu-cong, C.A.I. and Feng-xiang, H.A.N. (2007). Effects of long-term amendment of organic manure and nitrogen fertilizer on nitrous oxide emission in a sandy loam soil. Journal of Environmental Sciences, 19, 185–193.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S. (2010). Sustainable biochar to mitigate global climate change. Nature communications 1, 56.

Yiqi, L. and Zhou, X. (2010). Soil respiration and the environment. Elsevier.

Zahran, H.H. (1999). Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. Microbiol. Mol. Biol. Rev. 63, 968-989.

Zebarth, B., Neilsen, G., Hogue, E., Neilsen, D. (1999). Influence of organic waste amendments on selected soil physical and chemical properties. Canadian Journal of Soil Science 79, 501-504. Accessed 11 May 2019

Zerzghi, H., Gerba, C.P., Brooks, J.P., Pepper, I.L. (2010). Long-term effects of land application of class B biosolids on the soil microbial populations, pathogens, and activity. Journal of Environmental Quality 39, 402-408.

Zhang, Y., Liu, J., Mu, Y., Xu, Z., Pei, S., Lun, X. and Zhang, Y. (2012). Nitrous oxide emissions from a maize field during two consecutive growing seasons in the North China Plain. Journal of Environmental Sciences, 24(1), 160–168. https://doi.org/10.1016/S1001-0742 (10)60594-3. Accessed 22 Jul 2019.

Zhao, X., Cheng, K., Liu, D. (2009). Organosolv pretreatment of lignocellulosic biomass for enzymatic hydrolysis. Applied microbiology and biotechnology 82, 815.

Zuorro, A., Maffei, G., Lavecchia, R. (2016). Reuse potential of artichoke (Cynara scolimus L.) waste for the recovery of phenolic compounds and bioenergy. Journal of cleaner production 111, 279-284.

Appendices

Appendix 1: ANOVA for CH_4 Daily Emissions

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
RESEARCH_ID	5	19812.5	3962.5	4.34	<.001
HARVEST	3	10592.6	3530.9	3.87	0.009
RESEARCH_ID.HARVEST	15	20825.9	1388.4	1.52	0.093
Residual	550	502237.6	913.2		
Total	573	553466.5			

Appendix 2: ANOVA for CO_2 Daily Emissions

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
TREATMENT	5	306461.	61292.	44.71	<.001
HARVEST	3	262690.	87563.	63.87	<.001
TREATMENT.HARVEST	15	171722.	11448.	8.35	<.001
Residual	1596	2187945.	1371.		
Total	1619	2928817.			

Appendix 3: ANOVA for N_2O Daily Emissions

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
RESEARCH_ID	5	5998.6	1199.7	4.89	<.001
HARVEST	3	23552.2	7850.7	32.03	<.001
RESEARCH_ID.HARVEST	15	9412.3	627.5	2.56	<.001
Residual	1169	286570.1	245.1		
Total	1192	325533.1			

Appendix 4: ANOVA for CH_4 cumulative fluxes

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
TREATMENT	5	414692.	82938.	3.28	0.013
Harvest	3	214556.	71519.	2.83	0.048
TREATMENT. Harvest	15	391210.	26081.	1.03	0.442
Residual	48	1213677.	25285.		
Total	71	2234134.			

Appendix 5: ANOVA for CO_2 cumulative fluxes

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
TREATMENT	5	283.75	56.75	1.42	0.235
Harvest	3	50.96	16.99	0.42	0.736
TREATMENT. Harvest	15	856.91	57.13	1.43	0.173
Residual	48	1921.11	40.02		
Total	71	3112.72			

Appendix 6: ANOVA for Brachiaria yields

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	2	50.685	25.342	8.05	
BLOCK.*Units* stratum					
TREATMENT	5	3.304	0.661	0.21	0.957
HARVEST_NO	3	112.059	37.353	11.86	<.001
TREATMENT.HARVEST_NO	15	21.201	1.413	0.45	0.954
Residual	46	144.844	3.149		

Total	71	332.092			

Appendix 7: ANOVA for Total Brachiaria yields over the entire study period (8 months)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	2	50.685	25.342	5.83	
BLOCK.*Units* stratum					
RESEARCH_ID	5	3.304	0.661	0.15	0.979
Residual	64	278.104	4.345		
Total	71	332.092			

Appendix 8: ANOVA for total N_2Ocumulative fluxes over the entire study period (8 months)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	2	0.18253	0.09126	1.89	
BLOCK.*Units* stratum					
Treatment	5	0.38858	0.07772	1.61	0.243
Residual	10	0.48199	0.04820		
Total	17	1.05310			

Appendix 9: ANOVA for Total N_2O yield-scaled emissions over the entire study period (8 months)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	2	0.15936	0.07968	3.76	
BLOCK.*Units* stratum					
Treatment	5	0.06841	0.01368	0.65	0.672
Residual	10	0.21212	0.02121		
Total	17	0.43990			