ASSESSMENT OF GREENHOUSE GASES EMISSION IN SMALLHOLDER RICE PADDIES CONVERTED FROM ANYIKO WETLAND, WESTERN KENYA

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been submitted in part or whole for an award of a degree in any institution.

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Recommendation

This thesis has been submitted with our approval as supervisors for examination according to Egerton University regulations.

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DEDICATION

I dedicate this work to my loving daughters, for being an absentee mother, my dear husband for being an absentee wife and my entire family members for financial and moral support.

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ABSTRACT

Rice, (*Oryza sativa L.*) is an important food crop in Kenya and is the third most consumed cereal crop after maize (*Zea mays*) and wheat (*Triticum aestivum*). The high demand for rice has resulted in the conversion of wetlands to rice paddies, ultimately reducing the ability of wetlands to store carbon. Farmers have also increased use of fertilizer to improve productivity. Consequently, emissions from wetlands of three potent greenhouse gases (GHGs): methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) have increased. This study assessed the influence of fertilizer application on GHGs emission, organic carbon and nutrient stocks in rice paddies in papyrus dominated wetlands in the Nzoia River basin in Kenya. Sampling was done on a weekly basis for the first two months, and thereafter twice per month in the Anyiko rice paddies, which is a smallholder system partly converted from the Anyiko wetland. Two replicates of three fertilization treatments (standard, control and under fertilization) were assigned randomly in six rice plots. The static chamber method was used to collect the GHGs, which were then analyzed using gas chromatography. Soil samples were collected and analyzed for nitrogen and organic carbon stocks. Statistical tests revealed no significant differences in organic carbon and nitrogen stocks among the three fertilization treatments. The mean CH_4 fluxes did not differ significantly among the three treatments where mean flux for control plots were 8.30 ± 4.79 mg m^{-2} h^{-1}; under-fertilized plots had a mean of 6.93 ± 2.42 mg m^{-2} h^{-1} and standard fertilized plots mean fluxes were 4.00 ± 6.34 mg m^{-2} h^{-1}. Similarly, CO_2 mean fluxes were insignificantly different among the three treatments, where control plots had mean of 174.80 ± 26.81 mg m^{-2} h^{-1}, under-fertilized plots mean were 208.81 ± 36.20 mg m^{-2} h^{-1} and standard fertilized plots mean fluxes were 248.29 ± 41.22 mg m^{-2} h^{-1}. However, mean N_2O fluxes were significantly different among the three treatments, control plots had a mean of -3.59 ± 2.56 μg m^{-2} h^{-1}, followed by under-fertilized with mean of -0.59 ± 0.45 μg m^{-2} h^{-1} and standard fertilized plots with mean of 4.37 ± 3.18 μg m^{-2} h^{-1}. In this study, different fertilization scenarios had significant effects on N_2O emission but no significant effect on CO_2 and CH_4 emission, organic carbon and nutrient stocks. From the findings of the study, fertilizer application increases emission of N_2O. Therefore, there is need for sustainable use of wetlands and fertilizer in rice paddies to minimize greenhouse emissions and wetland degradation.

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LIST OF ABBREVIATIONS AND ACRONYMS

ECD	Electron Capture Detector
FAO	Food and Agriculture Organization
FID	Flame Ionizing Detector
GHGs	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
N	Nitrogen
NIB	National Irrigation Board
OC	Organic Carbon
SDG	Sustainable Development Goals
SOC	Soil Organic Carbon
TN	Total Nitrogen
UNFCCC	United Nations Framework Convention on Climate Change

CHAPTER ONE
INTRODUCTION

1.1 Background information

Wetlands occupy about 6% of the earth's surface; covering about 7% of Africa, 10% of North America, 20% of South America, 10% of Russia ,7% of China ,3% of tropical and subtropical Asia, 3% of Australia and 5% of Europe (Junk *et al.,* 2012). In Kenya, wetlands cover approximately 14,000 km^2 (2.5% of the surface area of the country) and fluctuates up to 6% during rainy seasons (Crafter *et al.,* 1992, MEMR, 2012). Wetland drainage and land reclamation (conversion of wetlands to arable lands) for crop production, papyrus harvesting and drainage of wastewater into the wetland have been reported to be the major threats leading to wetland degradation in Kenya (Morrison *et al.,* 2011). Mironga (2005) also noted that drainage and conversion to arable land have been the key drivers to degradation of wetlands in Kenya.

Rice is one of the essential cereal crops grown globally, in Africa (Balasubramanian *et al.,* 2007). The role of rice as a current and future global food security is inevitable, since it is one of the three most important food crops after wheat and maize (Food and Agriculture Organization, 2016). Food and Agriculture Organization 2017 had predicted the global rice production to reach 758.9 million tonnes (503.8 million tonnes, milled basis) by 2017. In Africa, 2016 season rice output records put the production at 30.8 million tonnes (20.1 million tonnes, milled basis) (Food and Agriculture Organization, 2017). In Kenya, rice cultivation was introduced in 1907 from Asia (Republic of Kenya, 2008). The annual rice consumption rate in Kenya is estimated at 949,000 metric tons whereas the annual production rate is 180,000 metric tons (International Rice Research Institute, 2018). Rice is either grown in upland areas or in lowland areas where then field can either be rain fed or irrigated. About 75% of the global rice production comes from irrigated rice systems because most rice varieties express their full yield potential when water supply is adequate (Haifa Group, 2019). Kenya's major irrigation schemes include Mwea, Yatta, Ahero, Bunyala and west Kano. These schemes are operated by National Irrigation Board (NIB) and produce about 80% of the rice while the remaining 20% is produce from the rain fed fields (Republic of Kenya, 2008). The growing population and socioeconomic changes have stimulated the need for more agricultural productive land in pursuit to improve food security (Junk *et al.,* 2012, Mitchell, 2013). To meet the high demand for rice caused by population pressure, there is increased conversion of natural wetlands to rice paddies and increased use of fertilizer to increase yield.

Rice paddies are important source of GHG emission (Garthorne-Hardy, 2013). The three potent and long lived GHGs emitted from the rice fields include; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Arunrat & Pumijumnong, 2017). The major processes responsible for production and emission of these GHGs are oxic respiration (decomposition), methanogenesis, nitrification and denitrification (Zhang *et al.,* 2006). In the soils in the rice paddies, CH_4 is produced through methanogenesis under anoxic conditions (Jain *et al.,* 2004). Nitrous oxide production occurs through nitrification and denitrification processes under oxic and anoxic conditions respectively whereas, when oxygen is supplied into the soil, organic carbon undergoes decomposition leading to CO_2 production (Ishii *et al.,* 2011). Rice paddy substrate undergoes variability between anoxia and oxic conditions due to the presence of rhizospheric zone and that there can never be complete anoxic even when the field is waterlogged.

Hydrological modifications in wetlands to pave way for crop production have implication on the greenhouse gas dynamics. Draining of wetlands to convert them to agricultural land exposes soil organic matter to oxygen leading to its oxidation and release of CO_2 to the atmosphere (Moomaw *et al.,* 2018). Consequently, the wetlands' ability to sequester carbon is impaired and this leads to increased GHGs emission to the atmosphere and the ultimate impact is climate change (Mitchell, 2013). Wetlands are usually waterlogged and therefore provide similar conditions as required in paddy soils for rice growth. Apart from wetland drainage and clearing to expand production area, farmers employ other management practices like fertilizer application to increase crop yield (Singh & Singh, 2017). There are different fertilizer application management practices that influence the emission of GHGs for example: method of placement, type of fertilizer, level and form of fertilizer used (Linquist *et al.,* 2012). Fertilizer application has been found to affect CH_4 and N_2O but have less impact on CO_2 emissions (Linquist *et al.,* 2012). Wang *et al.* (2017) reported that application of nitrogen fertilizer in rice paddies showed variability (increase or decrease) in CH_4 emissions but led to increase in N_2O emission. Generally, N fertilizer application increases the global warming potential (GWP) of N_2O by 78% (Sun *et al.,* 2016). The nitrogen electron donors and acceptors can be nitrified or denitrified to N_2O when fertilizer is applied to the soil (Wang *et al.,* 2017). Emissions of CO_2 from rice paddies is however low (less than 1%) since CO_2 emissions are largely offset by primary productivity and atmospheric fixation by plants (Linquist *et al.,* 2012).

The Intergovernmental Panel on Climate Change (IPCC) technical guidelines on climate policy agreements requires that GHGs emission from industrial and agricultural sectors be recorded and then submitted via national GHG inventories to the United Nations Framework Convention on Climate Change (UNFCCC) (Food and Agriculture Organization, 2015). Emission of GHGs is growing rapidly leading to increased global warming and thus climate change (Intergovernmental Panel on Climate Change, 2007). Global warming is also being affected by the residence time a given gas has been in the atmosphere (Solomon *et al*., 2007). Carbon dioxide, CH_4 and N_2O have been reported to have long residence time in the atmosphere and therefore contribute highly to global warming (Arunrat & Pumijumnong, 2017). Climate change is associated with natural hazards such as flooding, storms and drought which pose a continuous threat to agriculture and living beings (Intergovernmental Panel on Climate Change, 1992). Arunrat and Pumijumnong (2017) noted that rice cultivation has raised many concerns because rice fields have been reported to emit the three most potent and long-lived GHGs; CO_2, CH_4 and N_2O which stimulates climate change.

Atmospheric concentration of CO_2 has increased from a pre-industrial value of 278 parts per million (ppm) to 379 ppm in 2005 (Government of Kenya, 2017). The Kenyan government through the initiative like National Climate Change Action Plan (NCCAP), National Climate Change Response Strategy (NCCRS) and National Adaptation Plan (NAP) is putting efforts to combat climate change by investing in low carbon climate resilient technology and industries such as water resource management, renewable energy and agroforestry (Government of Kenya, 2012). In order to reduce global warming and temperature rising, it is essential to have "negative emissions" of GHGs, a necessecity in achieving the goal of the Paris Climate Agreeement (Sanderson *et al.,* 2016). Studies on GHGs emissions and trends is thereore necessary in order for individual countries to develop GHGs inventory records.

1.2 Statement of the problem

Global demand for food due to increased population leads to conversion of natural wetlands into rice paddies and increased use of fertilizer in order to increase yield. Increased rice production is fundamental in bridging the gap between demand and supply of rice. To meet the global and local demand for rice, production rate has to be increased way above the consumption rate. In Kenya however, the current rice production rate is below the consumption rate. Generally optimal production of rice requires maintenance of high soil moisture that consequently favors release of GHGs. This leads to increased conversion of wetlands into rice paddies since wetlands provide such soils. Also, to sustain productivity farmers fertilize the field. However, the downside to conversion of wetlands to rice paddies is increased GHGs emission since the wetlands' ability to sequester carbon is reduced. In addition, fertilizer has the potential to intensify emission of GHGs by providing more nitrogen substrate for N_2O and carbon substrates for CO_2 and CH_4 production respectively. Fertilization also enlarges the rice aerenchyma which acts as a pathway and in turn increases GHGs emissions. The consequence of increased GHGs emission is climate change which has various negative impacts on human lives.

1.3 Objectives

1.3.1 General Objective

To contribute to understanding how intensification of rice production by fertilizer use affects GHG emission for sustainable management practices.

1.3.2 Specific Objectives

I. To determine the effect of different fertilizer application scenarios on the standing stocks of organic carbon and nitrogen in rice paddies.

II. To determine CO_2, CH_4 and N_2O emissions in rice paddies under standard fertilization (basal, first and second topdressings), under-fertilization (first and second topdressings) and no fertilization (control) each during the rice growing season.

1.4 Hypotheses

I. Different fertilizer application scenarios have no significant effect on the standing stocks of organic carbon and nitrogen in rice paddies.

II. Standard fertilization (basal, first and second topdressings) and under-fertilization (first and second topdressings) has no significant effect on CO_2, CH_4 and N_2O emission in rice paddies.

1.5 Justification

All countries are required by the December 2015 Paris Agreement to make significant commitments to address climate change by strengthening their emissions reduction targets by 2030 (United Nations Framework Concept on Climate Change, 2015). The Paris 2015 agreement was revised and enforced by the 2019 UN climate action summit. Both agreements require its member countries to lower and hold global warming to well below 1.5° C and keep it there. Anthropogenic climate change is caused by human activities like deforestation, industrialization and agriculture which enhance GHGs emission to the atmosphere thus causing global warming. The world population however is growing, increasing the need for production of more rice to meet the growing demand. Consequently, there is enhanced conversion of wetlands to rice paddies and increased use of fertilizer to increase rice yield. Conversion of wetlands to smallholder rice paddies lowers their ability to sequester carbon and instead results to increased GHGs emission. Fertilizer application also leads to enhanced emission of GHGs due to increased supply of carbon and nitrogen substrates for soil microbes responsible for GHGs production. The contribution of agriculture and more so rice production to GHG may be insignificant compared to other sources especially industry in case of CO_2. Furthermore, Kenya contributes a mere less than 0.1 % of global GHGs. However, Kenya has to show global commitment as Climate Change will and continues to adversely impact Kenya’s socio-economic sectors. This study aimed at understanding how conversion wetlands and intensification of rice production by use of fertilizer can affect GHGs emission with the view of sustainable management practices. In addition, this study is in line with Sustainable Development Goals (SDG) 2 which is to end hunger, achieve food security and improved nutrition and promote sustainable agriculture and SDG 13 which is to take urgent action to combat climate change and its impacts. Food security is one of the Kenya’s big four agenda and one of the targets of the vision 2030. This can be achieved through reduced GHGs emission and sustainable agricultural practices.

CHAPTER TWO
LITERATURE REVIEW

2.1 Rice Production in Kenya

Rice (*Oryza sativa L.*) belongs to the genus *Oryza* and family Gramineae (Poaceae), where genus *Oryza* has about 25 species out of which 23 species are wild whereas only 2 species are cultivated (Vaughan, 1994). According to Vaughan (1994) the two cultivated species are *Oryza satiza* and *Oryza glaberrina* where *Oryza sativa* is the most widely grown. Lowland rice grows in water logged (moist) soils where land preparation requires at least two rounds of ploughing and levelling of the rice fields (International Rice Research Institute, 2015). It is an annual crop whose life cycle approximately ranges between 80- 200 days from germination to maturity. Mature rice consists of panicle, roots, and leaves, main stem and tillers as indicated in figure 1.

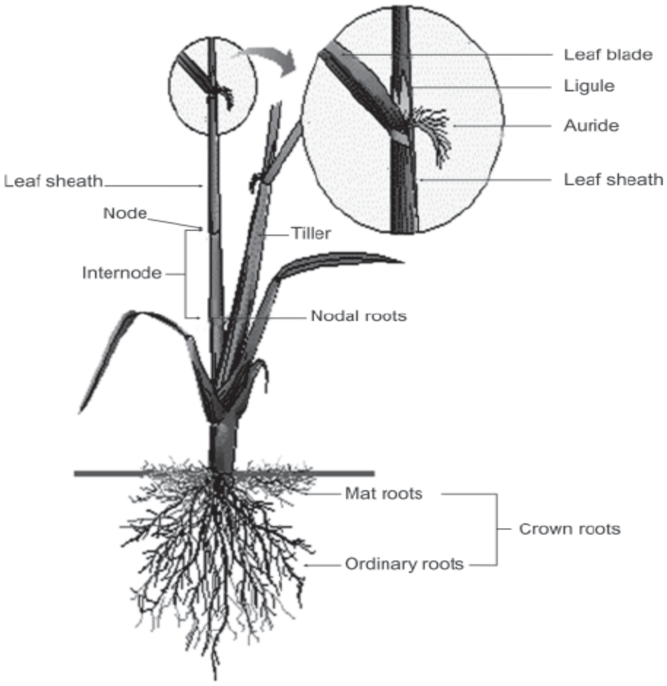

Figure 1: A picture of a rice plant showing various parts

Source: Department of Biotechnology, Ministry of Science & Technology & Ministry of Environment and Forests, Govt. of India (2011)

Globally, rice cultivation is estimated to cover 150 million hectares (ha), leading to about 500 million metric tons annual production which represent about 29% of the total output of grain crops worldwide with Africa accounting for about 10 to 13% (Nguyen, 2006, Onyango, 2006). According to Dunna and Roy (2013), rice is classified as the most important food crop since over 40% of the world's population consumes rice as the major staple food. However, rice production is an important source of GHGs emission (Garthorne-Hardy, 2013). Onyango (2014) and Balasubramanian *et al*. (2007) noted that increased population, (4% per annum), rising incomes, a shift in consumer preferences in favour of rice especially in urban areas and the fact that rice is no longer considered a luxury food but the main source of calories for most households has resulted to demand for more rice and increased rice import in Africa. Furthermore, increase in rice consumption can also be attributed to changing dietary habits which have led to production of more rice in the country in the recent years (Africa Rice Center, 2008, Balasubramanian *et al.,* 2007). In Kenya, annual rice consumption is estimated at 949,000 metric tons compared to an annual production of 180,000 metric tons (International Rice Research Instituture, 2018). However, despite the low production rate, the Kenyan annual rice consumption is increasing at a rate of 12% compared to 4% for wheat and 1% for maize which is the main staple food (Republic of Kenya, 2008). The low rice production has led to deficit in rice and hence wide gaps between production and consumption of rice as illustrated in figure 2.

The low rice production is attributed to various factors such as nutrient depletion, loss of organic matter, drought, pests, diseases (rice blast, leaf blast) and weeds (Bruce, 2010, Evans *et al.,* 2018). The government of Kenya has therefore put in place several remedial measures like: improving rice varities, rehabilitation of irrigation schemes, provision of incentives to farmers, expansion of irrigation schemes and provision of subsidized fertilizers to farmers to narrow the gap between production and import of rice (Evans *et al.,* 2018). In Kenya, 80% of rice production system is through irrigation schemes which require a continous supply of water for irrigation and soils with high water holding capacities. During drought however, theses rice production systems receive rationed water thus lowering productivity. The urge for high productivity has resulted to wetland conversion to rice paddies and increased use of fertilizers.

2.2 Wetland conversion and greenhouse gases emission

The Ramsar classification systems for wetlands types provides three broad categories of wetlands: marine/coastal, inland and human-made wetlands; and these are subdivided into 42 types of wetlands (Ramsar Convention, 2007). Human-made wetlands are as important as natural wetlands and the largest human-made wetland is a rice paddy field (130,000,000 hactares) taking about 18% of the total global wetland which is approximately 570 million hactares (Yoon, 2009). Other human made wetland types include: fish and shrimp ponds, farm ponds, irrigated agricultural land including rice paddies, salt pans, dams, reservoirs, gravel pits, wastewater treatment ponds and canals (Ramsar Convention Secretariat, 2016). Rice paddies just like natural wetlands plays important roles like flood control, reduction of soil erosion, groundwater recharge and nutrient removal (Yoon, 2009). However, human activities within the wetlands (eg drainage, agriculture, forestry, peat extraction, aquaculture) have significant effect on carbon and nitrogen balance and thus GHGs emissions and removals from these lands (Intergovernmental Panel on Climate Change, 2014).

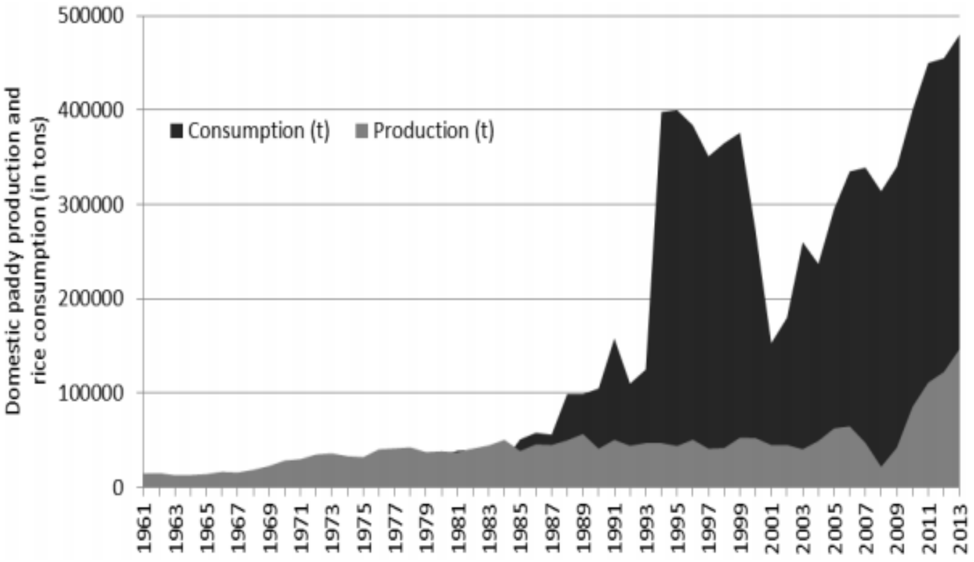

Figure 2: Gaps between domestic rice production (paddy) and consumption in Kenya. Source: Evans *et al.* (2018)

Wetlands have many functions and services like; water supply, fisheries, agriculture, timber production, biodiversity conservation, nutrient sink (carbon sequestration), source of raw materials for basketry, wildlife habitat, tourism attraction and cultural activities (Okech, 2016). However, despite the diverse benefits of wetlands, the growing world population has led to wetlands degradation and loss due to unsustainable activities like overexploitation of wetlands natural resources, converting wetlands to agricultural and grazing lands and use as waste disposal sites (Okech, 2016). Globally, wetlands losses due to conversion to arable cropping have been the key drivers to degradation of wetlands and increased emission of greenhouse gases (Tangen *et al.,* 2015). Studies in North America have indicated that least disturbed wetland catchments along native grasslands have relatively high carbon compared to agricultural settings (Tangen *et al.,* 2015). Land use change has resulted in wetland destruction and the largest effect is on the carbon fluxes. The high rate of land use change is occurring in the tropics where wetlands are being converted to agricultural lands so as to increase crop production particularly rice to ensure food security (Safary, 2016). This has resulted to degradation of important wetland functions like carbon sequestration thus increasing amounts of GHGs emission (Mitchell, 2013).

The processes responsible for emission of three potent GHGs include aerobic decomposition of organic matter in wetland soils (decomposition), methanogenesis and denitrification (Zhang *et al.,* 2006). These processes are carried out by microbes and therefore are sensitive to substrate characteristics in this case nitrogen and carbon stock. Microbes utilize the substrates for energetic gains and consequently produce GHGs. Wetlands can either be source or sink of GHGs, depending on weather conditions, time and dominant biological processes especially for CO_2 (respiration and photosynthesis). Due to their ability of carbon sequestration (accumulation of carbon as organic matter in soil and as plant biomass), wetlands have been found to act as CO_2 sink (Johnson *et al.,* 2007). However, wetlands are a source of CH_4, when carbon is lost through methanogenesis process in anoxic soil conditions (Whiting & Chanton, 2001). When the wetlands are drained, they act as source of CO_2 where organic matter is oxidized due to presence of oxygen (Zhu *et al.,* 2010). Veber *et al.* (2017) also reported that drainage of wetlands increases decomposition rates because of increased oxygen supply into the soils, thus resulting to increased CO_2 emissions and reduced CH_4 emissions due to oxidation of organic matter. Natural wetlands converted to rice paddies enhance emissions of N_2O due to use of N fertilizer during planting and top-dressing (Mitchell, 2013).

Since wetlands act as both sink for CO_2 and source for CH_4, it is difficult to determine the contribution of wetlands to greenhouse effect. A study that was done on carbon balance of wetlands by incorporating the aspect of time reported that over short time horizon (20 years), wetlands function as a net source of GHGs (Intergovernmental Panel on Climate Change, 1996). This is because CH_4 has a 21.8-fold greater infrared absorptivity relative to that of CO_2, indicating that CH_4 emission contributes to the overall greenhouse effect (Whiting & Chanton, 2001). However, over a long-time horizon (100-500 years) as suggested by IPCC, the global warming potential (GWP) of methane decreases to about 7.6, whereby in this circumstance wetlands acts as sink and hence attenuates the greenhouse effect (Intergovernmental Panel on Climate Change, 1996).

2.3 Global trends of Greenhouse gases

Concentrations of GHGs in the atmosphere have been rising steadily since the industrial revolution (Olivier *et al.,* 2017). Sources of GHG emissions are broadly categorized into natural which accounts for approximately 44.54% whereas anthropogenic accounts for 55.46% of the global annual GHG emissions (Xi-Liu & Qing-Xian, 2018). Wetlands being one of the natural sources accounts for 17.2% after forest fires, oceans and permafrost at 37.8%, 21.05% and 20.64% of GHGs respectively. Natural resources emit 30-40% of global methane (150-237 Tg CH_4 yr^{-1}) and 44-54% of N_2O (9.6-10.8 Tg N_2O yr^{-1}); of which tropical wetlands contribute 22-27% of N_2O and 24% of CH_4 (Garthorne-Hardy, 2013). Greenhouse gas emissions lead to climate change and this has been evidenced in the recent years through: rise in mean global temperature, decreasing snow and ice in the northern hemisphere, ocean warming, extreme weather conditions, hence CO_2 concentration in the atmosphere has increased by 40% since the pre-industrial era (Cubasch *et al.,* 2013). An additional warming of 1.1 to 6.4° Celsius (C) is anticipated by future climate change projections (National Research Council, 2010). To attain SDS 13 (take urgent action to combat climate change), the 2015 Paris agreement on climate change and UN climate action summit require member countries to reduce global warming to 1.5° C to combat climate change.

There are various subcategories of GHGs sources globally. Greenhouse gas emission from different sources: agricultural practices (rice production, cattle stock, animal manure, synthetic fertilizer); energy combustion (coal, oil, natural gases); landfills, wastewater, use of hydro-fluorocarbons have been recorded over the years (Olivier & Peters, 2018). However, GHG emissions from land use, land use change and forestry (LULUCF) are rarely documented since they show large temporal variations (Olivier *et al.,* 2017). Carbon dioxide emissions contribute the largest percentage of GHG to the atmosphere (about 73 %) whereas CH_4, N_2O and fluorinated gases (F gases) contribute 18 %, 6 %, and 3 % respectively (Olivier *et al.,* 2017). The major source of CO_2 is combustion of fossil fuels however, by 2010, CO_2 emissions including land use change comprised over 75 % (38 ± 3.8Gt CO_2 eq/yr) of 100-year GWP weighted anthropogenic GHG emissions (Blanco *et al.,* 2014). Rice cultivation on flooded rice fields is the second largest anthropogenic source of CH_4 (10 %) after cattle stock (Olivier & Peters, 2018). The same study noted that agricultural activities are the main source of N_2O where synthetic fertilizer (nitrogen content) account for 18 % of N_2O emissions after cattle stock (21 %). In the year 2017, the total GHG emission (land use change excluded) was at rate of 1.3% (± 1%) per year, and the total emissions reached a record of 50.9 gigatonnes of CO_2

equivalent (United Nations Environment Program, 2018). The top four emitters of GHG include: China (about 27 %), United States of America (13 %), European Union (9 %) and India (7.1%) of the global GHG emissions as shown in figure 3 (United Nations Environment Program, 2018).

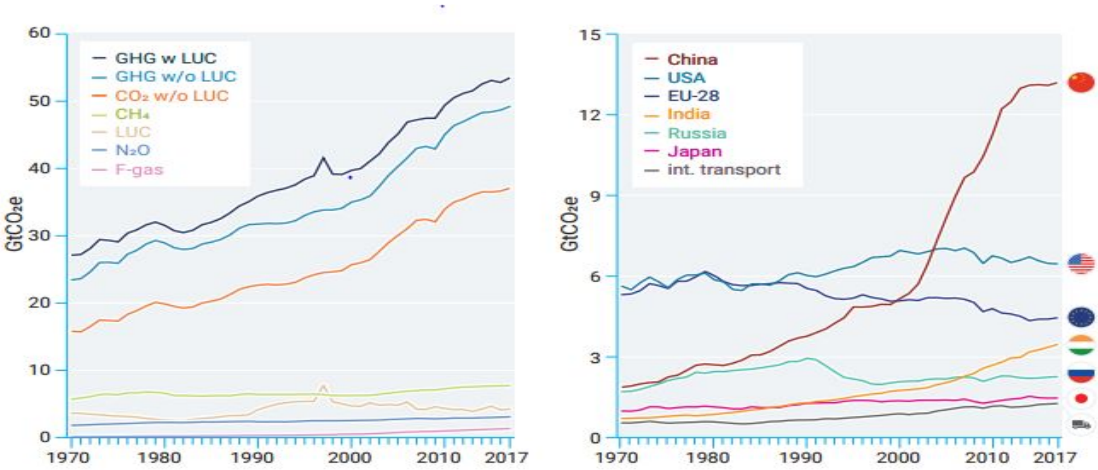

Figure 3: Global greenhouse gas emissions, per type of gas and top greenhouse gas emitters. (This excludes land-use change emissions due to lack of reliable data.)

Source: Crippa *et al.* (2018) and Le Quéré *et al.* (2018)

2.4 Emission of Greenhouse gases from rice paddies

Rice paddies are in most cases waterlogged; a similar condition experienced in natural wetlands. In rice paddies just like in natural wetlands, methanogenesis is responsible for production of CH_4 under anoxic conditions (Jain *et al.,* 2004). Denitrification also occurs under anoxic conditions leading to emission of N_2O whereas CO_2 is produced through respiration process under oxic conditions and released to the atmosphere (Ishii *et al.,* 2011). Rice cultivation is ranked the third with respect to CH_4 emission (112 Tg CH_4 yr^{-1}) after ruminants (189 Tg CH_4 yr^{-1}) and natural wetlands (145 Tg CH_4 yr^{-1}) (Garthorne-Hardy, 2013). Land use change impacts on the net GHG emission, for example drainage of natural wetlands for agriculture result to increased N_2O and CO_2 emissions and decreased CH_4 emission (Smith & Conen, 2004). Arable lands converted to wetlands may require application of fertilizers to sustain productivity, particularly nitrogen input and this enhances the potential of the land to emit N_2O which is a powerful GHG (Tangen *et al.,* 2015). Rice paddies however emit more GHGs, especially CH_4 due to flooded conditions compared to other crop lands like maize and wheat (Rosenstock *et al.,* 2016).

The greenhouse gases have different global warming potential (GWP) irrespective of their concentration in the atmosphere. The GWP of a greenhouse gas is an index computed to measure its radiative force following an emission of a unit mass of the specific gas, accumulated over a specific time period using CO_2 as a reference (Boateng *et al.,* 2017). Carbon dioxide has a GWP of 1 compared to that of CH_4 and N_2O which are 25 and 298 respectively (Solomon *et al.*, 2007). Therefore, GWP represents the combined effect of the differing times these substances remain in the atmosphere and their effectiveness in causing radiative force. Despite having lower GWP, CO_2 is present in higher concentration in the atmosphere at about 400 parts per million (ppm) compared to CH_4 and N_2O at concentrations of around 2 and 0.3 ppm respectively (Ventura, 2014). Consequently, CO_2 contributes about 50% of the GHGs effect because of its high concentration in the atmosphere followed by CH_4 and N_2O contributing about 19% and 7 % respectively (Collier *et al.,* 2014).

2.4.1 Nitrous oxide emissions in rice paddies

Atmosphere-biosphere N_2O fluxes is a by-product of two microbial processes, nitrification and denitrification. Nitrous oxide is released into the atmosphere through denitrification process. This process is carried out by anoxic facultative bacteria like the pseudomonas, in anoxic conditions (Hernandez & Mitsch, 2007). The absence of oxygen as an electron acceptor makes the microbes to use the available alternative acceptors. When denitrifying bacteria uses nitrate as a terminal electron acceptor, one of the resulting products is N_2O (Bateman & Baggs, 2005). Agricultural activities such as use of green and/or livestock manure, inorganic fertilizers and livestock grazing are some of the sources of N_2O and contribute to nitrogen cycling in paddy rice farms (Intergovernmental Panel on Climate Change, 2007). The main factors that influence emissions of N_2O include soil properties; nitrogen availability (in the form of ammonium and nitrate), availability of organic carbon, oxygen supply and pH (Bateman & Baggs, 2005). Its emission is driven mainly by application rates of N fertilizers, type of fertilizer used, temperature and organic carbon supply (Arunrat & Pumijumnong , 2017). Nitrogen fertilizer application increases N_2O emission since N fertilizer acts as a substrate for the nitrifying and the denitrifying bacteria (Akiyama *et al.,* 2006).

Nitrification and Denitrification

Nitrification involves oxidation of ammonium (most reduced state) to nitrate, (most oxidized state) (Kurgat *et al.,* 2017). It occurs in oxic zones and the magnitude is controlled by oxygen diffusion rates, the thickness of rhizospheric zones, ammonium-N concentration and levels of inorganic carbon (Reddy, 1982). This process occurs in two stages each mediated by bacteria.

First stage is oxidation of ammonium to nitrite mediated by the *Nitrosomonas and Nitrospira species* and the second stage is oxidation of nitrite to nitrate mediated by the *Nitrobacter species* (Ishii *et al.,* 2011).

Denitrification is a microbial respiratory process where NO_3^- and NO_2^- are reduced to gaseous forms (NO_2, N_2O and N_2) under anoxic conditions (Figure 4). Since O_2 is lacking, the nitrogen oxides are used as alternative electron acceptors leading to their reduction (Ishii *et al.,* 2011). The nitrate formed in oxic layer is then supplied to anoxic zone where N is removed by denitrification by bacteria like *Pseudomonas*, *Achromobacter*, and *Micrococcus* (Bateman & Baggs, 2005). In rice fields, nitrification occurs when soils are drained thus reducing the levels of N_2O emission; whereas in flooded conditions, the accumulated NO_3^- is denitrified to N_2O (Reddy, 1982).

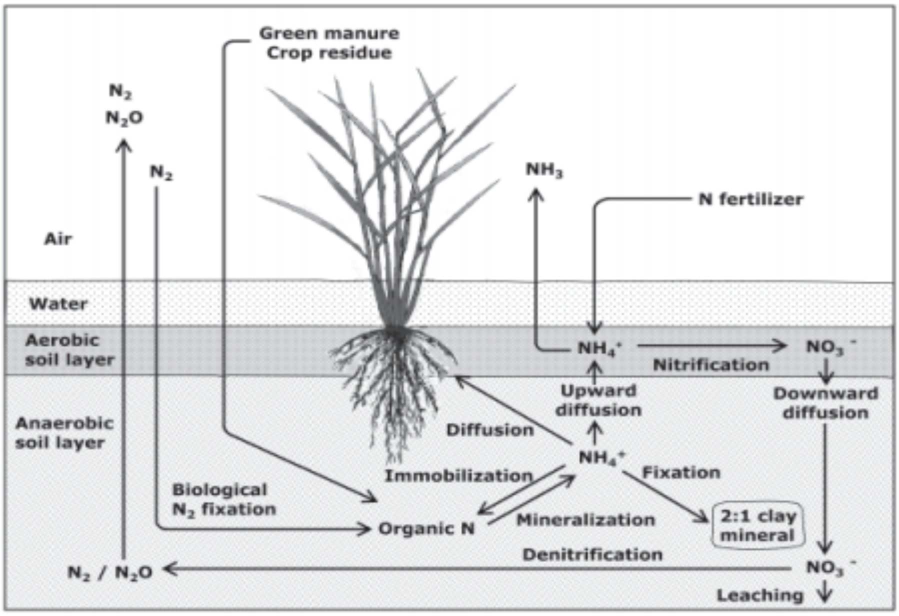

Figure 4: A schematic diagram of N transformations in a submerged soil
Source: Buresh *et al.* (2008)

2.4.2 Carbon dioxide emissions in rice paddies

Carbon dioxide has higher concentrations in the atmosphere compared to N_2O and CH_4 (Ventura, 2014). However, CO_2 has lower global warming potential of 1, (reference point) compared to N_2O and CH_4 which has 298 and 25 times more than that of CO_2 respectively (Solomon *et al.*, 2007). It's emission to the atmosphere in rice paddies occur through respiration, burning of rice straws and microbial decomposition under oxic conditions as indicated in figure 5 (Whiting & Chanton, 2001). It is however removed from the atmosphere through the process of photosynthesis by plants which acts as a sink of CO_2 thus reducing its concentration in the atmosphere (Whiting & Chanton, 2001). In rice paddies, CO_2 emission occurs under oxic conditions like soil-water interface, in the rhizospere and when the farm is drained (Figure 5) (Boateng *et al.,* 2017). It would be expected that N fertilizer would increase CO_2 emissions by providing more carbon substrate for decomposers either directly or indirectly through stimulating productivity. However, studies have shown variable results on CO_2 emissions for example, increased CO_2 emissions with use of N fertilizer from rice paddy farms was observed in studies done by (Iqbal *et al.,* 2009; Xiao *et al.,* 2005). Nevertheless, in a study done by Burton *et al.* (2004), there was decrease in CO_2 emission with use of N fertilizer. A study done by Cheng-Fang *et al.* (2012) on the other hand showed no significance effect of N fertilizer application on cumulative CO_2 emissions. These emissions are essential in calculating the CO_2 fluxes and hence estimation of potential effect of greenhouse gas emissions from rice paddies (Caro *et al.,* 2014).

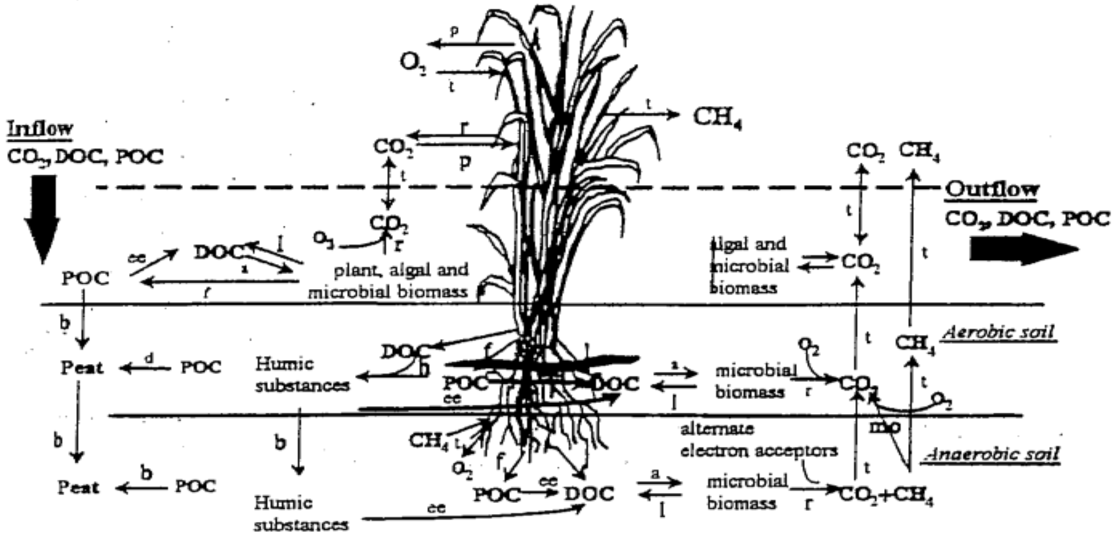

Figure 5: Carbon transformation in the soil-water-plant environment of wetlands
Source: Reddy *et al.* (2000)

POC= Particulate organic carbon; DOC= Dissolved organic carbon; a= accumulation; b= burial; ee= extracellular enzyme hydrolysis; f= fragmentation; h= humification; l= leaching; mo= methane oxidation; p= photosynthesis; r= respiration; t= transport

2.4.3 Methane emissions in rice paddies

Methane production is a microbial process strictly limited to anoxic conditions, and therefore its emission occurs in flooded paddy rice fields due to anoxic conditions (Ma *et al.,* 2009). Rice fields emit approximately 20% of CH_4 to the atmosphere (Khalil *et al.,* 1998). Methane accounts for 20–30% of the global warming effect and is second to CO_2 as the most significant GHG. The three principal processes that control CH_4 emission include, production, transport and oxidation of CH_4 in the rice soil-plant system (Conrad, 2002). Methane production from flooded rice paddies is carried out by methanogens (CH_4 producing bacteria) in soil and it is transported through aerenchyma of the rice plant to the atmosphere (Figure 6) (Jain *et al.,* 2004). This is because in anoxic conditions, alternative electron acceptors such as nitrates, metals oxides like ferric iron and sulphates are usually used (Frenzel *et al.,* 1999). If anoxic conditions persist, the alternatives are all mineralized and therefore microbes start using carbon sources through anoxic respiration resulting to CH_4 production as a by-product (equations 1 and 2). However, when oxygen is supplied from plant root exudates, atmosphere, or at soil-water interface, available CH_4 is oxidized by methanotrophic bacteria thus lowering its emission to the atmosphere (Intergovernmental Panel on Climate Change, 1996).

$$\mathrm{CH_2O + CH_2O \leftrightarrow CH_4 + CO_2} \qquad (1)$$

$$\mathrm{C_6H_{12}O_6 \leftrightarrow 3CO_2 + 3CH_4 + Energy} \qquad (2)$$

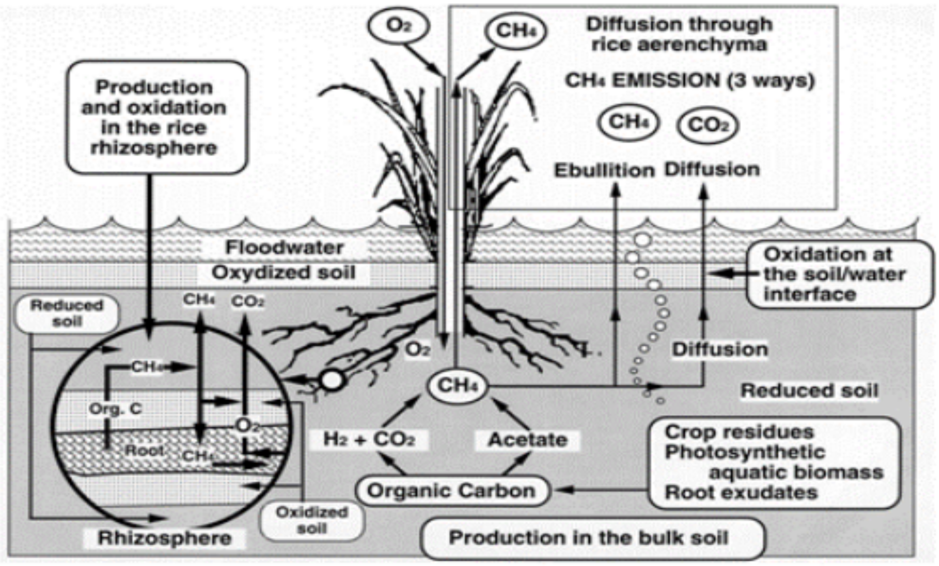

Figure 6: Schematic diagram of methane production, consumption and transfer pathways into atmosphere Source: Le Mer and Roger (2001)

2.5 Smallholder rice production and greenhouse gases emission

Rice is a source of livelihood to some smallholder farmers where rice can be grown either as cash or food crop all over the world (Food and Agriculture Organization, 2012). In developing countries, the smallholder farmers make about 80% of the farming community and they hold less than 10 hectares of land each (Food and Agriculture Organization, 2012). In Kenya, smallholder farming dominates the rice production landscape and accounts for 75% of total agricultural output (Ogada *et al.,* 2014). However, most of them have low to medium production efficiency (Magreta *et al.,* 2013). Some smallholder farmers also lack enough capital to invest on rice production and they also have small pieces of land which are not enough for maximum production output.

In Sub-Saharan Africa, there are very few studies that have been done to measure the amount of GHGs emitted from smallholder rice farms and therefore, there is limited data on the impact of smallholder farming on GHGs emission and on climate change (Rosenstock *et al.,* 2013). In Kenya, irrigated areas cover approximately 13,000 ha and include irrigation schemes in Nyanza; West Kano and Ahero (at 3,520 ha), Western; Bunyala scheme (at 516 ha) and Mwea irrigation scheme (at 9,000 ha) where production is done by smallholder farmers and managed by national irrigation board (NIB) (Indeche & Ondieki-Mwaura, 2015). With the growing population and increased rice consumption, area of rice cultivation is expected to grow and this will increase the amount of GHGs emitted from these rice farms. This is due to foreseen conversion of more natural wetlands to smallholder arable farms for crop production like rice and yams (Safary, 2016) and increased use of fertilizer to increase yields (Chirinda *et al.,* 2018).

2.6 Fertilizer management practices and greenhouse gases emission in rice paddies

Nitrogen fertilizer is usually applied to rice farms to increase yields; however, this may have effect on the amount of GHGs emitted from the rice farms (Chirinda *et al.,* 2018). Different fertilizer management practices like rates, type, source, placement and enhanced efficiency affects the amount of GHGs emitted (Chirinda *et al*., 2018). In a meta-analysis done by Linquist *et al.* (2012) for example, use of ammonium sulphate instead of urea led to 24% increased emission of N_2O and 40% decrease in CH_4 emission and this is because they have different denitrification rates. Nitrate based fertilizer is however not recommended in rice fields because it undergoes denitrification thus enhancing emission of N_2O, and leads to poor rice growth due to nitrogen limitation (Wang *et al.,* 1992).

Application of N fertilizer supplies more nitrogen substrate for decomposers which they attach on and degrade and the result is enhanced emission of GHGs especially N_2O (Chirinda *et al.,* 2018). In some cases, N fertilizer application increases the amount of CH_4 emitted (Cheng-Fang *et al.,* 2012). This is because N fertilizer increases plant biomass and hence provide carbon substrate for methanogens (Dunfield & Knowles, 1995). Fertilizer application also increases NH_4^+ in the soil and as a result, the mono-oxygenases uses NH_4^+ provided instead of CH_4; since NH_4^+ is similar in size and structure with CH_4; therefore, the reduced consumption of CH_4 increases its emission to the atmosphere (Zhang *et al.,* 2014). Fertilization also escalates growth of rice crops and thus enlarges aerenchyma, which is a pathway for gas exchange between plant parts by reducing resistance thus facilitates GHGs emission (Tang *et al.,* 2018). However, there are few studies on the effect of fertilizer placement methods on emission of GHGs (Linquist *et al.,* 2012).

Rice response to applied fertilizer varies depending on soil status and environmental conditions just like other crops. Also, different rates of fertilizer application for various crops, impact differently on the GHGs emissions. According to Linquist *et al.* (2012) rice farmers should use the recommended fertilizer application rates since it has minimum or even no significant effect on CH_4 and N_2O emissions. However, fertilizer application practices in smallholder farmers varies and this can be attributed to lack of enough capital, long distances between farmers and fertilizer retailers, different environmental factors and soil conditions (Carmen, 1968). Therefore, different studies have reported different fertilizer application rates for rice production. For example, in Mwea 25 kg NPK Ha^{-1} has been recommended as standard basal fertilization (Njinju, *et al.,* 2018). However, other application rates have also been reported for Mwea: 46 kg Ha^{-1} and 75 kg Ha^{-1} (Njinju *et al.,* 2018). Ministry of agriculture in Kenya however recommend 100 Kg/Ha for Di-Ammonium Phosphate (DAP), NPK and Calcium Ammonium Nitrate (CAN) and 180 Kg/Ha for ammonium sulphate (SA) (Oseko & Dienya, 2015). It is however important to note that the amount of fertilizer applied depends on fertility conditions of the soil, type of crop and site characteristics. Therefore, soil test should be done to determine the recommended fertilizer application rates and this was adopted in this study.

2.7 Relationship between organic carbon, nitrogen and greenhouse gases

Greenhouse gases (CO_2, N_2O and CH_4) emission in paddy rice farms depends on soil microbial activities; like methanogenesis, methane oxidation, nitrification, denitrification, respiration and photosynthesis (Wang *et al.,* 2017). Presence of soil organic carbon and nitrogen stocks act as electron acceptors and donors and as a result regulates GHGs consumption and production and hence emission levels (Wang *et al.,* 2017). Nitrate for example acts as electron acceptors under anoxic conditions leading to denitrification and release of N_2O (Reddy, 1982). Therefore, amplified N supply through increased fertilizer applications increases N_2O emissions. Fertilizer application increases SOC which is a substrate for microbes, where under oxic conditions leads to CO_2 emission and CH_4 emission under anoxic conditions (Le Mer & Roger, 2001).

Carbon and nitrogen (C/N) stock ratios affect the microbial activities in the soil and as a result affect the GHG fluxes. Soil microorganisms may adjust their stoichiometry with that of the substrate and release or immobilize N depending on the C/N ratio on substrate (Ding *et al*., 2013). Addition of N as fertilizer for example causes higher N content in plant tissue, leaves and the litter fall, which in turn accelerates the assimilation and dissimilation processes of CO_2 and also intensifies the substrate for N_2O emission from soil (Allison *et al.,* 2010). Nitrous oxide negatively correlates with the C/N ratio (Pilegaard *et al.,* 2006); whereas emissions of CH_4 and CO_2 positively correlate with the C/N ratio (Shi *et al.,* 2014). The decomposition processes which lead to emission of GHGs also depend on the stoichiometry of litter; C/N ratio. Adjustment of C/N/P ratios through activities like fertilizer application may affect the carbon sequestration (Allison *et al.,* 2010) and thus ultimately affects GHGs emissions.

2.8 Measurements of greenhouse gases

There are a number of approaches which can be used for measurement of land/atmosphere fluxes of GHGs: chambers, mass balance, Lagrangian stochastic (bLs) dispersion techniques, eddy covariance, eddy accumulation and flux gradient methods (Denmead, 2008). Chamber based (automated or manual) and micrometeorological approaches are the most widely used techniques for measuring GHG fluxes (Butterbach-Bahl *et al.,* 2016). Chamber systems can either be closed or open chambers and closed chambers are further subdivided into closed static and closed dynamic ones (Kutzbach *et al.,* 2007). Closed static chambers permits fluxes to be measured over longer times and replicates at several measurement points without the need for additional sensors (Yim *et al.,* 2002). On the other hand, in closed dynamic chambers systems, gases accumulating in the chamber are analysed either externally and pumped back into the chamber (Rochette *et al.,* 1997) or are being analysed inside the chamber with a compact NDIR sensor that continuously monitors the atmospheric CO_2 concentrations (Oertel *et al.,* 2015). Open dynamic chamber has two openings where gas concentrations are analysed at air inlet and outlet of the chamber and the differences of the concentrations at both ends gives the gas flux (Oertel *et al.,* 2016). Each of these methods has its niche and static chamber based method is suitable for small plots and very small gas fluxes (Denmead, 2008).

Static chamber-based method is commonly used due to relatively low costs, simple operation and portability (Butterbach-Bahl *et al.,* 2011). Additionally, gas samples collected using static chamber method can be stored for future analysis, it does not require power at the site and it allows for experiments with treatments (Rosenstock *et al.,* 2016). However, chamber based method is prone to disturbance and this amy influence the flux measured (Collier *et al.,* 2014). Furthermore, chamber based measurements are likely to miss peak events such as rainfall, since the experimentalists are not always at the site and they can only be closed for limited period of the day (Hensen *et al.,* 2013). The basic principle of static chamber method is that the emitted gases are trapped within within the chamber headspace and collected at regular intervals ; then analysed using gas chromatography, where the fluxes are calculated using the change in concentration over time (Collier *et al.,* 2014).

The major method used for analysing gas samples are gas chromatography (GC) and photoacoustic spectroscopy (PAS) method (Butterbach-Bahl *et al.,* 2016). The principle of PAS is that when a modulated light is projected with a constant cycle onto an absorbing medium, an acoustic signal with the same cycle is produced in the gas layer adhered to the material (McClelland *et al.,* 1996). That is PAS converts the absorption of light into acoustic signal which is then measured by a microphone (Leytem *et al.,* 2011). The GC method analyzes samples on qualitatively and quantitatively; where the samples are injected into a flow of a gas (carrier gas), then the components of the sampe are separated on molecular basis in the separation column and finally the components are detected by detectors (Kim, 1999). The most commonly used detectors in GC are Electron Capture Detector (ECD) for detecting N_2O, Flame Ionization Detector (FID) for detecting CH_4 and CO_2 and Thermal Conductivity Detector (TCD) for high concentrations of CO_2 (Wang *et al.,* 2010). This is because even though both detectors can reach low concentrations of the gas, FID is more sensitive than TCD (Budiman *et al.,* 2015). Electron Capture detector operates at 350° C with highest sensitivity to N_2O and lowest cross sensitivity to CO_2 (Wang *et al.,* 2010). Flame Ionization Detector operates at 250° C and to detect CO_2, it has to be fitted with a mechaizer which converts CO_2 to CH_4. The most common carrier gas used includes; helium, hydrogen and nitrogen andusually a purity of 99.9999% is recommended.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Study area

The study was carried in Anyiko irrigation rice scheme which is a smallholder system converted from Anyiko wetland located in North East Ugenya, Siaya County, Kenya (Figure 7). The irrigation scheme was established in 1977 by the Ministry of Agriculture and lies between longitudes 0°16’, 38°56’’E, 0°14’, 18°66’’E and latitudes 34°16’, 35°55’’N, 34°18’, 0°57’’N in Nzoia River Basin. Currently the scheme is managed by farmers. On inception, the scheme only used water diverted from the adjacent Anyiko wetland via a canal for irrigation however, over the years, the farmers have converted parts of the wetland to rice paddies and a number of canals dug out for irrigation. The area covered by the scheme currently is 48.56 hectares approximately 100 farmers, each owning a paddy rice field of approximately hectares. However, the area of the scheme expanded as a result of conversion of the wetland is unknown. Growing season of rice in the scheme runs from April to December annually in order to capture long rains seasons.

Rice growers in Anyiko rice paddy practises less intensive farming whereby only farmers who can afford fertilizers do apply it in their farms. For example, of the 27 farmers interviewed during preliminary visit, 59% apply fertilizer in their rice fields while 41% do not. In Anyiko scheme, most farmers practice first and second top-dressing without basal fertilization. However, the Ministry of Agriculture in Kenya recommend three splits of fertilizer applications; basal (with DAP or NPK), first and second topdressing with urea or ammonium sulphate (Oseko & Dienya, 2015). In this study, standard experimental fertilizer application entailed all the three splits: (basal, first and second top dressings), under fertilization (first and second top dressings only) and control (no fertilization. The standard fertilization rate was determined by first testing nitrogen and phosphorus content in the soil (Okalebo *et al.,* 2002).

3.2 Study design and sample collection

The study was carried out from September 2018 to January 2019, during rice growing season in Anyiko irrigation scheme. Six plots belonging to a farmer and running parallel to each other were selected then land preparation and weeding was done by the farmer. Planting and top dressing was done by the farmer the researcher and field assistance. The experiment was randomized complete block design (RCBD) with two replicates of three treatments as illustrated in Figure 8. The study settled on two replicates due to limit of funds to carry out study with three or more replicates. The three treatments included different fertilization scenarios: standard fertilization (basal, first and second top dressings), under fertilization (first and second top dressings only) and control (no fertilization) at 120 kg per hectare for each. Nitrogen Phosphorus Potassium (NPK) 23:23:0 was used for basal fertilization whereas calcium ammonium nitrate (CAN) was used for first and second top dressings. Basal application was done immediately after transplanting, first top dressing was done 21 days after transplanting (DAT) and second top dressing was done 45 DAT. The fertilizer was applied using broadcasting method since it is the most commonly used method by the farmers. The study involved six plots, each having three gas chambers (Figure 8).

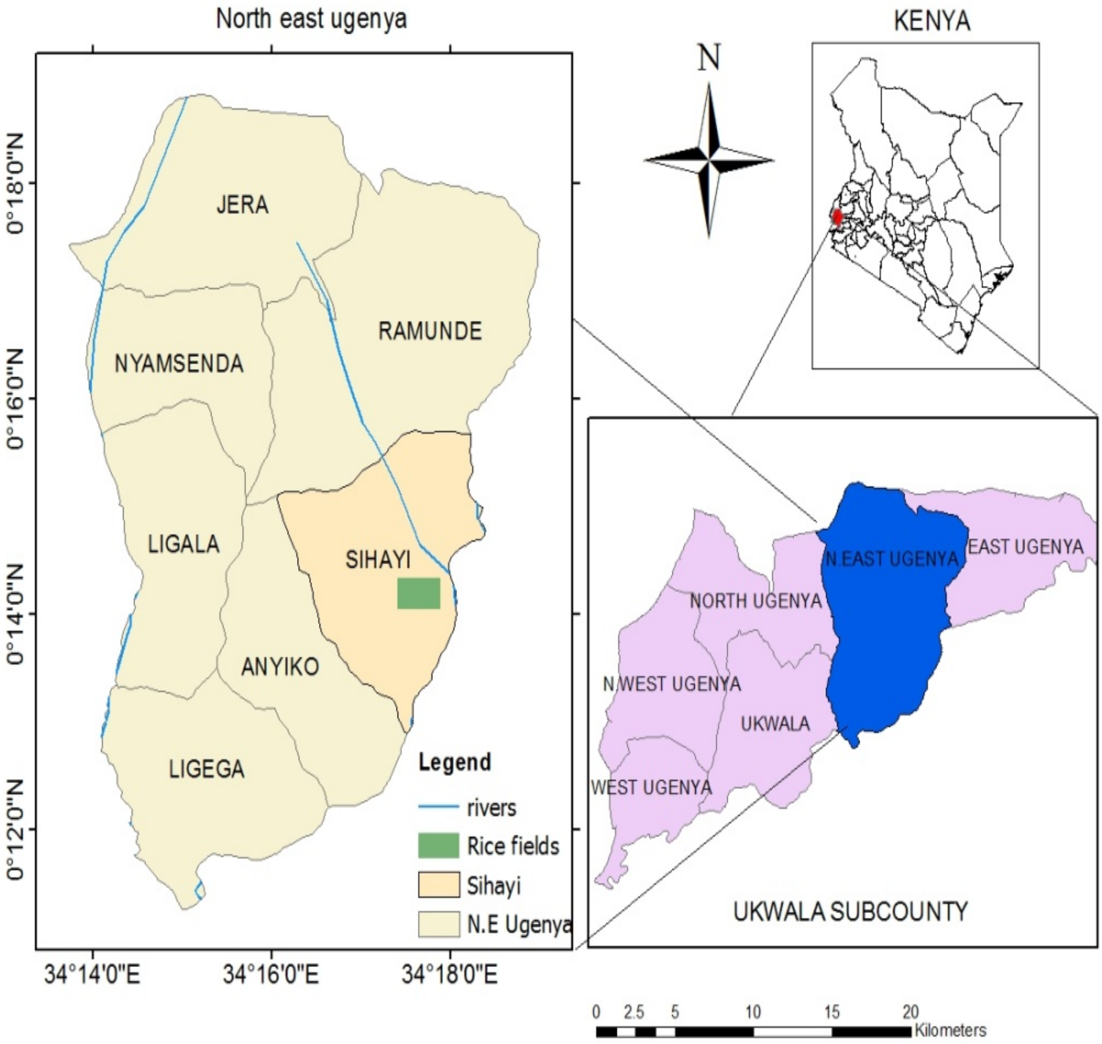

Figure 7: Map of Kenya showing Anyiko rice fields (Source: Modified from Topographical map of Kenya, scale 1:50,000)

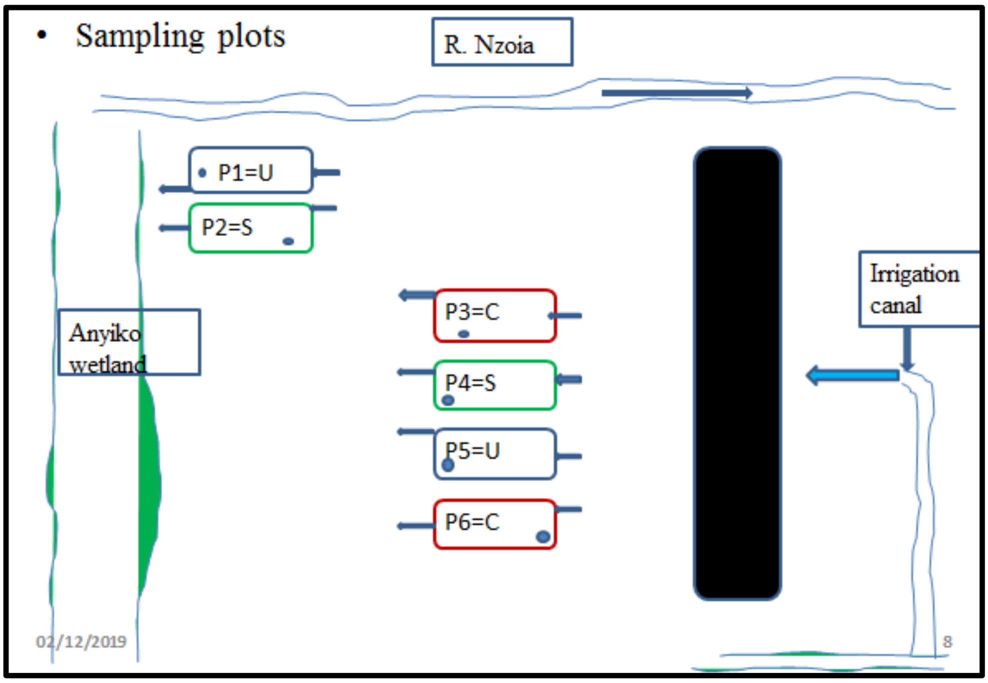

Figure 8: Diagram showing the randomized sampling plots. P1-P6 represent plots 1 to 6, U-under-fertilization, C-control, S-standard fertilization (Source: Author)

3.3 Chambers fabrication and installation

Static chamber method was used for greenhouse gas collection. The chambers were fabricated from locally available materials. The fabrication entailed covering the plastic buckets lid using duct tape, and three ports drilled for sampling, thermometer, and vent insertion as indicated in Plate 1A (Ajwang *et al.,* 2020). The chambers consisted of a base (anchor) obtained by cutting Polyvinyl chloride (PVC) buckets at around 15 cm from the top and then inserted 10 cm into the soil leaving about 5 cm of the bases protruding above the soil surface (Collier *et al.,* 2014) and a lid that was placed on top of the anchor during gas sampling (headspace). The chambers were fabricated from twenty-four 30-litre plastic buckets from which eighteen were used for bases and six as lids. The PVC buckets were used because they are inert to the gases being sampled (Collier *et al.,* 2014). The chamber bases were installed at least one week before gas sampling to prevent collection of GHGs emitted due to disturbances during installation. Three bases were installed in each plot of about a quarter of an acre and they remained in the field for the entire sampling period (Plate 1B) to avoid disturbance during subsequent samplings. Lids were put in place during sample collection only to help avoid heat build-up and collection of previously accumulated gases.

During sampling, the base and lid were clamped together using metallic clips to ensure they were airtight. Sampling started immediately after fixing the lids. The lids were covered with an insulating material (aluminium duct tape) to prevent heat build-up in the chambers during experiment which would otherwise interfere with the gas fluxes (Parkin & Venterea, 2010). The lids included a 50 cm long vent tube (2.5 mm diameter) to stabilize the pressure of the chambers during sampling, a thermometer to measure chamber internal temperature and a septum (sampling port) to allow sample collection (Plate 1A) (Rosenstock *et al.,* 2016). The chambers covered at least 4 rice plants in a transplanted system with spacing of 4 by 6 inches (Butterbach-Bahl *et al.,* 2016).

3.4 Gas sampling and analysis

Greenhouse gases, CO_2, CH_4 and N_2O fluxes were measured using vented static chamber method (Parkin & Venterea, 2010). In every sampling session, chambers were closed for 30 minutes and samples were taken after every 10 minutes where the first vial filled at time 0 was T_0 vial. This procedure was repeated after 10 minutes, 20 minutes and after 30 minutes to fill T_1, T_2 and T_3 vials respectively, giving a total of 4 samples per plot (Plate 1C). Gas pooling technique from the three chambers was applied to address spatial heterogeneity (Arias-Navarro *et al.,* 2013). Sampling was done between 10 am and 12 noon since studies have shown that this gives average daily emissions and accurate seasonal emission estimates (Butterbach-Bahl *et al.,* 2016).

Gas sample was collected using a 60 ml propylene syringe fitted with luer lock. Flushing technique was used, where the first 30 – 40 ml was used to flush the 10 ml vials, and the remaining 20 ml to fill the vial resulting to the vial being slightly over pressurized to minimize chances of leakage and contamination with ambient air (Arias-Navarro *et al.,* 2013). After the first sampling at time T_0, gas was mixed manually in the chamber by pumping several times with a syringe to ensure homogeneity of the sample before next sample collection. The samples were wrapped with parafilm over the crimp seal and transported to the International Livestock Research Institute (ILRI) laboratory, in Nairobi for analysis within 12 hours after collection. During each sampling session ambient air sample was collected using the same procedure as in the chambers in order to assess ambient GHGs concentration during sampling. In addition, air temperature was measured using digital thermometer to monitor environmental changes that could impact on GHG emission. Atmospheric pressure and chamber volume were also measured at the site for calculating gas fluxes.

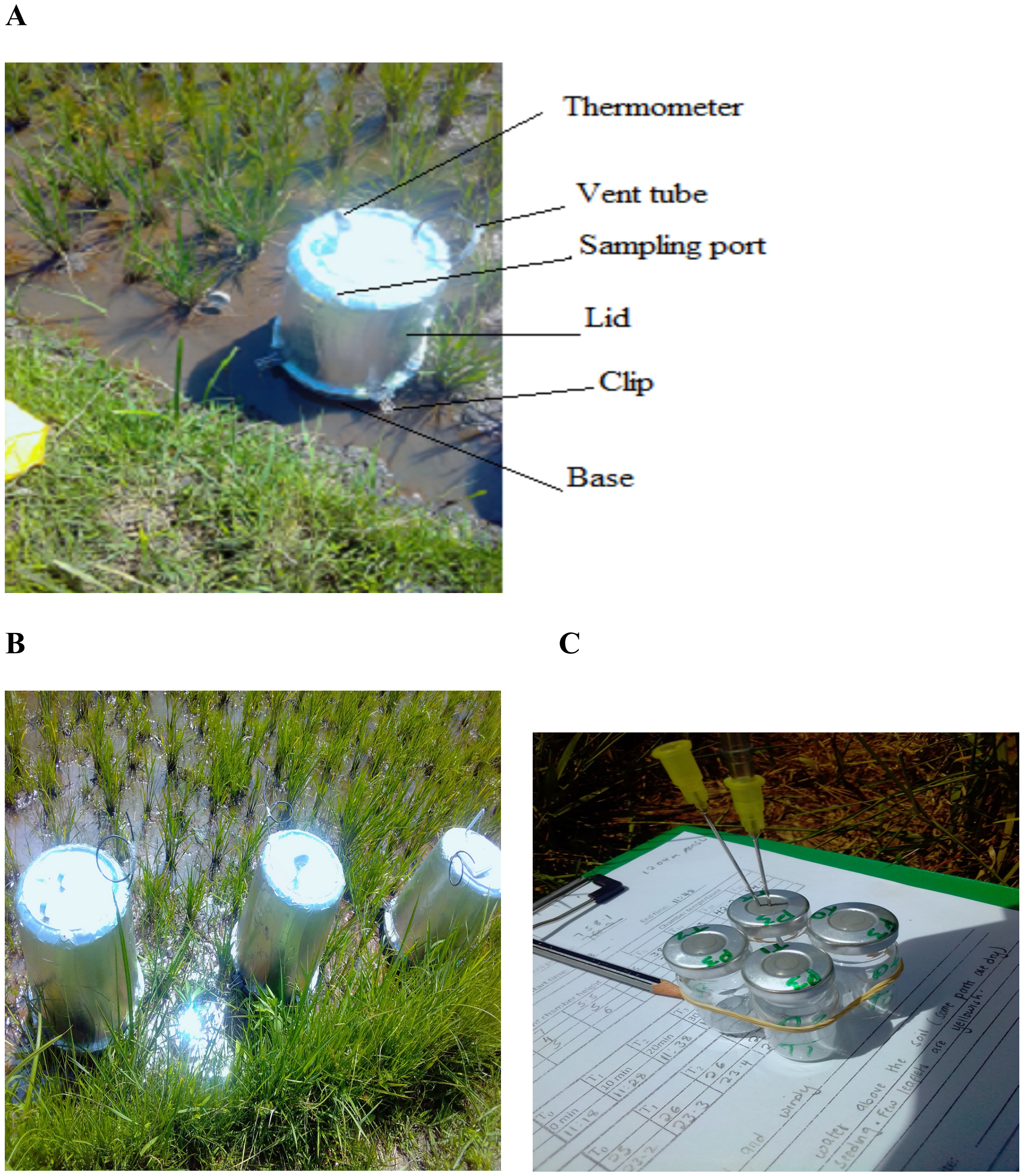

Plate 1: Few steps in closed chamber gas sampling method

(Source: Author).

(A) Pictorial representation of a fabricated gas chamber in the field, (B) The three chambers installed in a plot (C) Pre-labelled 10 ml glass vial with crimp seal fitted with two syringes, one for evacuation and one for refilling the vial.

Gas concentration was analysed using the SRI GHG gas chromatograph (model 8610C; SRI) with a methanizer in combination with a flame ionization detector (FID) for CH_4 and CO_2, and a 63Ni electron capture detector (ECD) for N_2O (Plate 2). The gas sample was injected through injection port and passed through liquid stationary phase. Here, the components were separated due to differences in their partitioning behaviour and then detected by a detector and recorded in a computer as peaks (Wang, 2010). The gas flux was then calculated using the equation below: (Butterbach-Bahl *et al.,* 2011).

$$\text{Flux}_{\text{GHG}(\text{mgm}^{-2}\text{h}^{-1})} = \text{Ct} \times \left(\frac{\text{M}}{\text{Vm}}\right) \times \left(\frac{\text{V}_{\text{ch}}}{\text{A}_{\text{ch}}}\right) \times \left(\frac{273.15}{273.15+\text{t}}\right) \times \text{P} \times 60 \qquad (3)$$

Where: Ct = slope derived from the linear regression (ppmmin^{-1}) for CH_4 and CO_2 and (ppmmin^{-1}) for N_2O-N, M = molar weight (gmol^{-1}) (C = 12 for CH_4 and CO_2, and N=28 for N_2O), Vm = molar gas volume (m^{1}mol^{-1}), (22.41), Vch = Volume of gas chamber, A_{ch} = Area of gas chamber, t = Chamber temperature (°C), P = Pressure at the time of sampling (atm), 60 = conversion factor of minutes to hour.

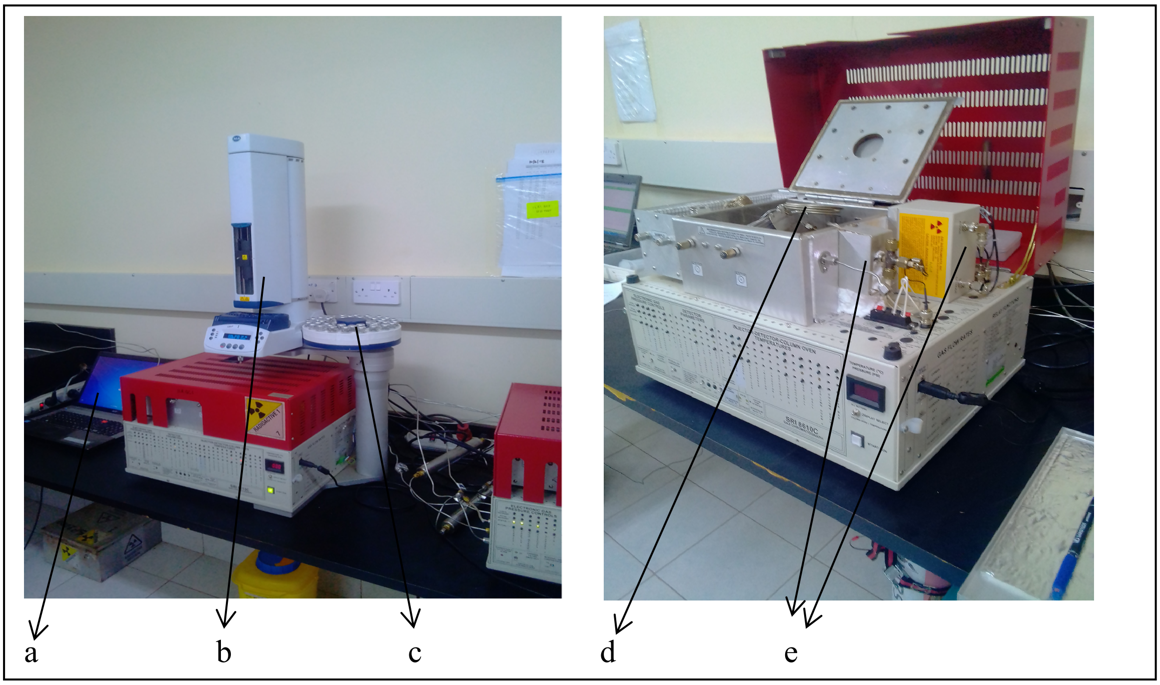

Plate 2: A pictorial representation of Gas Chromatograph at Mazingira center, ILRI (Source: Author)

(a) A computer for recording peaks, (b) automated injector, (c) gas sample tray, (d) separation columns, (e) the detection units (FID and ECD)

3.5 Soil sampling and analyses for ammonium, nitrate, total nitrogen and organic carbon

Soil samples were collected using random composite sampling technique at each sampling site using soil auger in a zigzag pattern to a depth of 15 cm. The samples were then transferred into polythene bags and placed in a cool box containing ice packs and transported to the Egerton

University Soil Science laboratory for analysis of NO_3-N, NH_4-N, OC and TN. Soil samples were collected on every sampling campaign for NO_3-N and NH_4-N analysis whereas for OC and TN analysis, sampling was carried out twice per month. At the same time, soil temperature was measured using digital thermometer at depths 11 to 20 cm to get a representative sample with minimal environmental impacts by factors like temperature and decomposition of organic matter in top soil. Soil moisture was determined by oven drying 250g of soil. Samples from each treatment plots were oven dried for 48 hours at 105°C to constant weight. The dried soil was reweighed and soil moisture calculated as described by Okalebo *et al.* (2002).

$$\text{Soil moisture content }\% = \left(\frac{\text{Weight of the moisture}}{\text{Weight of the dry soil}}\right) \times 100 \tag{4}$$

Standard procedures described by Okalebo *et al.* 2002 were followed to determine soil NO_3-N, NH_4-N, OC and TN. Nitrate-nitrogen and ammonium-nitrogen were determined using colorimetric method (Plate 3), where 10 g of fresh soil samples were extracted with 100 ml of 0.5 M K_2SO_4 (Okalebo *et al.,* 2002). The samples were filtered through Whatman 1.2 µm GFC filter paper and the supernatant analysed for NO_3-N and NH_4-N. The concentration of ammonium-nitrogen and nitrate nitrogen in the soil was calculated as follows (Okalebo *et al.,* 2002):

$$\mathrm{NH_4^+}\,(\mu\mathrm{g\,kg^{-1}})/\mathrm{NO_3^-}\,(\mu\mathrm{g\,kg^{-1}}) = \frac{(a-b) \times V \times MCF \times f \times 1000}{w} \tag{5}$$

Where a = concentration of N in the solution, b = concentration of N in the blank, v = volume of the extract; w = weight of the fresh soil; MCF = moisture correction factor; f = dilution factor.

Total nitrogen was determined by Kjeldahl digestion method (acid digestion, followed by steam distillation and then titration). A portion of the soil sample was oven dried (70°C) and from the dried sample, 0.3 g was digested using 2.5 ml of digestion mixture (hydrogen peroxide, sulphuric acid, selenium and salicylic acid) at 360°C for two hours. Thereafter, an aliquot of 10 ml was transferred into a reaction chamber. This was followed by addition of 10 ml of 1% sodium hydroxide and immediately steam distilled for two minutes into 5 ml of 1% boric acid. The distillate was titrated with 140 M HCl until endpoint (colour change from green to definite pink), plate 4A. Concentration of total nitrogen was calculated using the formula by Okalebo *et al.* (2002).

$$\%\text{ N in soil sample} = \frac{(b-a) \times 0.1 \times v \times 100}{1000 \times w \times al} \tag{6}$$

Where a = volume of the titre HCL for the blank, b = volume of titre HCL for the sample, v = final volume of the digestion, w = weight of the sample taken and al = aliquot of the solution taken for analysis.

Organic carbon was determined using Walkley-Black method (digestion by sulphuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) mixture) (Okalebo *et al.,* 2002). Soil samples was oven dried (70°C) to a constant weight. This was followed by complete oxidation of 0.3 g using 7.5 ml concentrated sulphuric acid and 5 ml aqueous potassium dichromate ($K_2Cr_2O_7$) mixture. The unused $K_2Cr_2O_7$ was titrated against ferrous ammonium sulphate to endpoint where colour changed from greenish to brown (Plate 4B). Difference between the added and residual $K_2Cr_2O_7$ gave the measure of OC content in soil and the concentration of OC was determined according to Okalebo *et al.* (2002)

$$\text{Organic Carbon (\%)} = \frac{(0.003 \times 0.2\ (\text{Vb}-\text{Vs}) \times 100)}{\text{w}} \qquad (7)$$

Where Vb = volume in ml of 0.2 M ferrous ammonium sulphate used to titrate reagent blank solution, Vs = volume in ml of 0.2 M ferrous ammonium sulphate used to titrate sample solution and 12/4000 is the mili-equivalent weight of C in grams.

Plate 3: A photo of spectrometer used for reading absorbance which help to determine concentrations

(Source: Author).

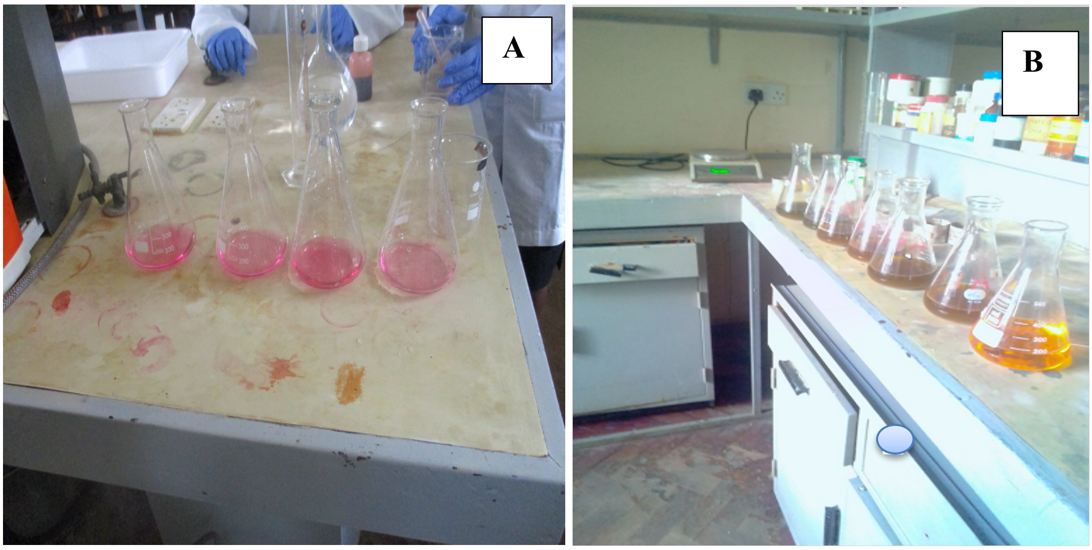

Plate 4: (A) Final colour change to pink after titration during TN analysis, (B) final colour change to brown after OC analysis

(Source: Author)

3.6 Data analysis

Data collected were statistically analyzed using IBM SPSS statistics version 20 (USA). All tests were carried out at $p < 0.05$ significance level and data subjected to normality (Shapiro-Wilk) and homogeneity of variance (Levene's) tests. The data for soil carbon and total nitrogen was checked for normality distribution prior to subjecting to ANOVA. The data for NH_4-N, NO_3−N and fluxes of CH_4, CO_2, and N_2O were not normally distributed and therefore analyzed using the non-parametric Kruskal–Wallis test. Under different fertilizer application scenarios, only N_2O emission varied significantly and hence, Tukey's post hoc test was used to determine whether there were indeed differences between the means. All the mean values were presented with their respective standard errors. Spearman's rank correlation was conducted to determine the relationship between soil properties (C/N ratio, soil moisture content, organic carbon, total nitrogen) and GHGs. The relationship between nutrient stocks and GHGs was analysed using Spearman correlation.

CHAPTER FOUR

RESULTS

4.1 Study site characteristics with respect to selected drivers of GHG emissions from soil

The mean air temperature and soil temperature for the site were 27.06 ± 3.32◦C and 23.46 ± 1.45◦C, respectively (Table 1). The soil moisture content differed significantly within the plots [one-way ANOVA, F(2, 57) = 7.74 P = 0.001] with control plots recording lower moisture content (53.93 ± 3.35%) compared to standard fertilized plots (69.14 ± 4.06%) and under-fertilized plots (74.72 ± 4.15%) (Tukey's post-hoc test $P < 0.05$) as indicated in Table 1. The soil bulk density showed no significant variations among the sites [one-way ANOVA F (2, 57) = 1.697, P = 0.192].

Table 1: Ancillary variables affecting GHG emissions measured at the study site during the experiment. (Values are presented as mean ± standard deviation, n = 10)

Treatment	Density (g/ml)	Moisture content (%)	Soil temperature (°C)
Control	0.95 ± 0.15^{a}	53.93 ± 14.97^{a}	23.99 ± 1.27^{a}
Under	1.01 ± 0.18^{a}	74.72 ± 18.55^{b}	22.95 ± 1.33^{a}
Standard	1.04 ± 0.17^{a}	69.14 ± 18.17^{bc}	23.43 ± 1.60^{a}

Similar letters indicate no significant difference whereas different letters indicate significant differences along the column. (One-way ANOVA)

4.2 Comparison of greenhouse gases' fluxes among the fertilization scenarios

The mean CH_4 flux was slightly lower in the under-fertilized plots (7.80 ± 2.12 mg $m^{-2}\,h^{-1}$) compared to that of standard fertilized (10.68 ± 3.79 mg $m^{-2}\,h^{-1}$) and control (10.82 ± 3.74 mg $m^{-2}\,h^{-1}$) plots. No significant difference in the CH_4 fluxes was observed among the fertilization scenarios (Kruskal–Wallis test, P = 0.964) as shown in Figure 11a. No significant differences in mean CO_2 flux observed among the three fertilization scenarios (Kruskal–Wallis test, P = 0.573; Figure 11b). The mean carbon dioxide (CO_2) flux was slightly higher in the standard fertilized plots (248.29 ± 41.22 mg $m^{-2}\,h^{-1}$) compared to that of the under fertilized plots (208.81 ± 36.20 mg $m^{-2}\,h^{-1}$) and control plots (174.80 ± 26.81 mg $m^{-2}\,h^{-1}$). The mean N_2O flux was significantly higher in standard fertilized plots (4.37 ± 3.18 µg $m^{-2}\,h^{-1}$) than in the control plots (−3.59 ± 2.56 µg $m^{-2}\,h^{-1}$), (Tukey's post-hoc test, P = 0.009). However, there was no statistical difference in the mean N_2O fluxes between standard fertilized plots and under-fertilized plots with a mean of −0.59 ± 0.45 μg m^{-2} h^{-1}, (Tukey's post-hoc test, $P = 0.140$; Figure 11c). The mean N_2O fluxes in control and under-fertilized plots also had no statistical difference (Tukey's post-hoc test, $P = 0.260$; Figure 11c). The mean GHG fluxes indicated that under-fertilized rice plots were a sink for N_2O (−0.59 ± 0.45 μg m^{-2} h^{-1}) and a source for CH_4 (6.93 ± 2.42 mg m^{-2} h^{-1}) and CO_2 (208.81 ± 36.20 mg m^{-2} h^{-1}). Standard-fertilized rice plots were source for N_2O (4.37 ± 3.18 μg m^{-2} h^{-1}), CO_2 (248.29 ± 41.22 mg m^{-2} h^{-1}) and CH_4 (4.00 ± 6.34 mg m^{-2} h^{-1}). The control rice plots acted as sink for N_2O (−3.59 ± 2.56 μg m^{-2} h^{-1}) and a source for CH_4 (8.30 ± 4.79 mg m^{-2} h^{-1}) and CO_2 (174.80 ± 26.81 mg m^{-2} h^{-1}).

Global warming potential of CH_4 and N_2O were estimated by multiplying their fluxes by the IPCC global warming potentials factors which are 25 and 298, respectively, Solomon *et al.* (2007), and thus converting into CO_2 equivalents. The combined effect of the three treatments (got by summing up the total gas emitted by each treatment) on greenhouse gases emission summed up in the mg CO_2 equivalents (CO_2 E) did not show any statistical difference (Table 3). The total effect for the three treatments after applying the CO_2 equivalents was not significantly different (Kruskal–Wallis test, $P > 0.05$).

Table 3: Total effect of the greenhouse gases summed up in mg CO_2 Eq. (Values are presented as mean ± standard error).

The GWP of CH_4 and N_2O calculated using the IPCC GWP factors.

Treatment	N_2O_E (mg m^2 h^{-1})	CH_4_E (mg m^2 h^{-1})	CO_2 (mg m^2 h^{-1})	Total (mg CO_2 E)
Control	-1.07 ± 0.76	207.54 ± 119.81	174.80 ± 124.72	381.27 ± 124.72
Under	-0.18 ± 0.13	173.19 ± 60.41	208.81 ± 36.20	381.83 ± 69.86
Standard	1.30 ± 0.94	100.09 ± 158.50	248.29 ± 41.22	349.69 ± 170.77

The total values for milligram of CO_2 equivalent (last column) is the total sum of the values in each row.

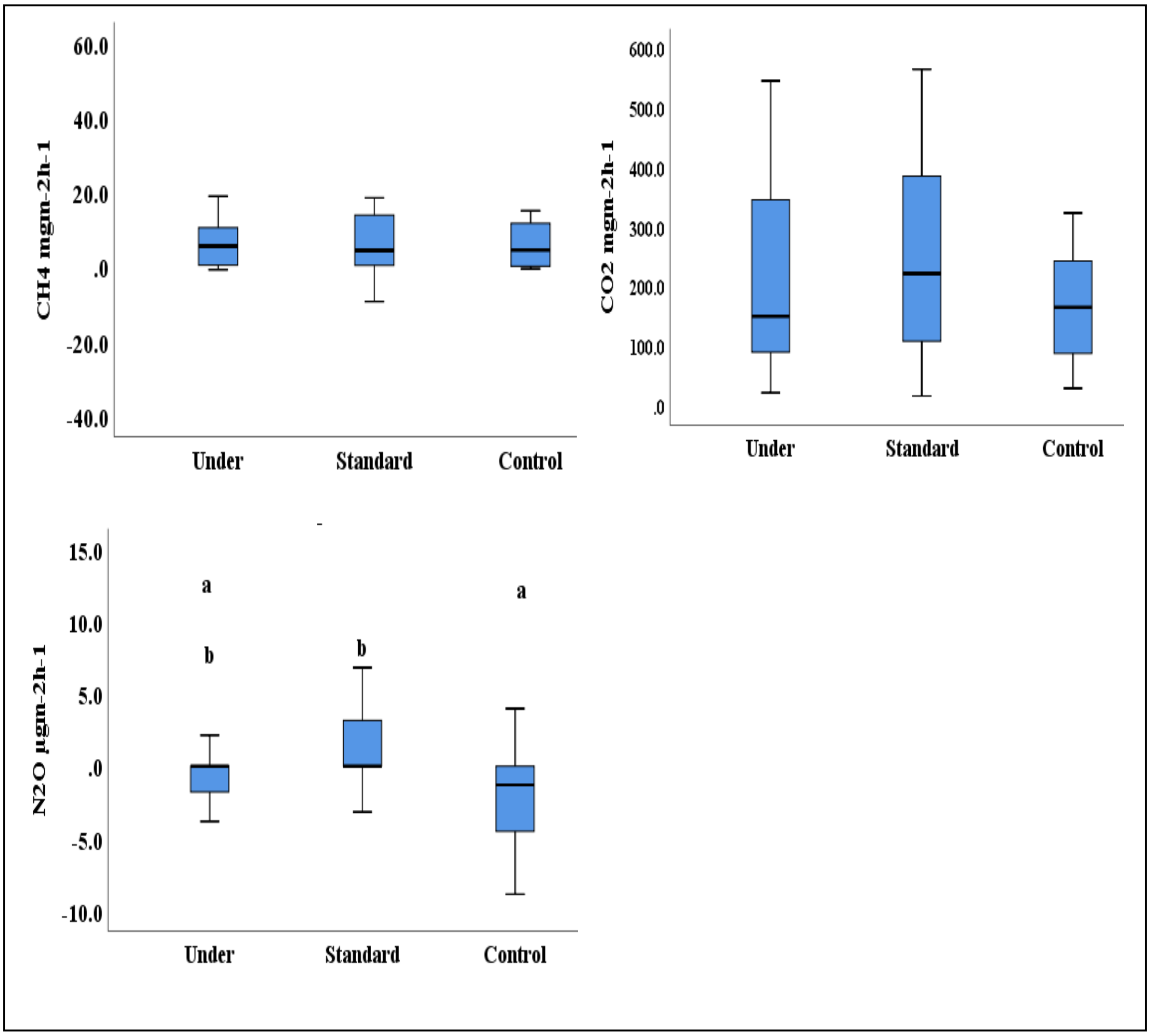

Figure 11: Comparison of GHG fluxes among the different treatments
(CH_4 mgm^{-2}h^{-1}, CO_2 mgm^{-2}h^{-1}, and N_2O µgm^{-2}h^{-1}) among the three fertilization scenarios

Different letters denote significant difference, while similar letters indicate no significant differences (Kruskal-Wallis test, $P > 0.05$). Pairwise comparison indicated that the significant difference was between control and standard fertilization. Box plots indicate mean variation of GHGs under different treatments whereas the whiskers depict their standard error of mean. The negative values indicate that the plot was a sink or the amount of gas present was too little to be detected by the machine.

4.3 Comparison between soil organic carbon and nitrogen content among fertilization scenarios

Mean TN for the control plots was 0.70 ± 0.38%, 0.78 ± 0.43% for under-fertilized and 0.71 ± 0.35% for standard fertilized plots. The mean soil organic carbon fluxes did not differ significantly among the three treatments (one-way ANOVA, F(2,33) = 0.219, P = 0.804; Figure 9). The mean organic carbon for the control plots was 2.21 ± 0.70%, for the under-fertilized was 2.26 ± 0.68% and for the standard fertilized plots 2.08 ± 0.64%. Mean TN also did not differ significantly among the three treatments (one-way ANOVA, F(2, 33) = 0.134, P = 0.875; Figure 9). Mean soil NH_4-N for control plots was 44.96 ± 9.60 µg/Kg, 63.57 ± 10.28 µg/Kg for standard fertilized plots and 68.02 ± 12.49 µg/Kg for under-fertilized plots (Figure 10). Mean soil NH_4-N however did not differ significantly among the three treatments (Kruskal–Wallis test, P = 220). Similarly, mean NO_3-N was also insignificant among the three treatments (Kruskal–Wallis test, P = 0.602). Control plots had a mean of 49.37 ± 18.82 µg/Kg, 63.64 ± 26.20 µg/Kg for under-fertilized plots and 71.66 ± 29.44 µg/Kg for standard fertilized plots (Figure 10). The C/N ratio did not differ significantly among the three treatments [one-way ANOVA, F(2, 33) = 0.399, P = 0.674]. The C/N ratio for the control plots ranged from 1.2:1 to 8.0:1, under-fertilized plots ranged from 1.3:1 to 8.0:1 while, that for standard fertilized plots ranged from 1.2:1 to 5.7:1.

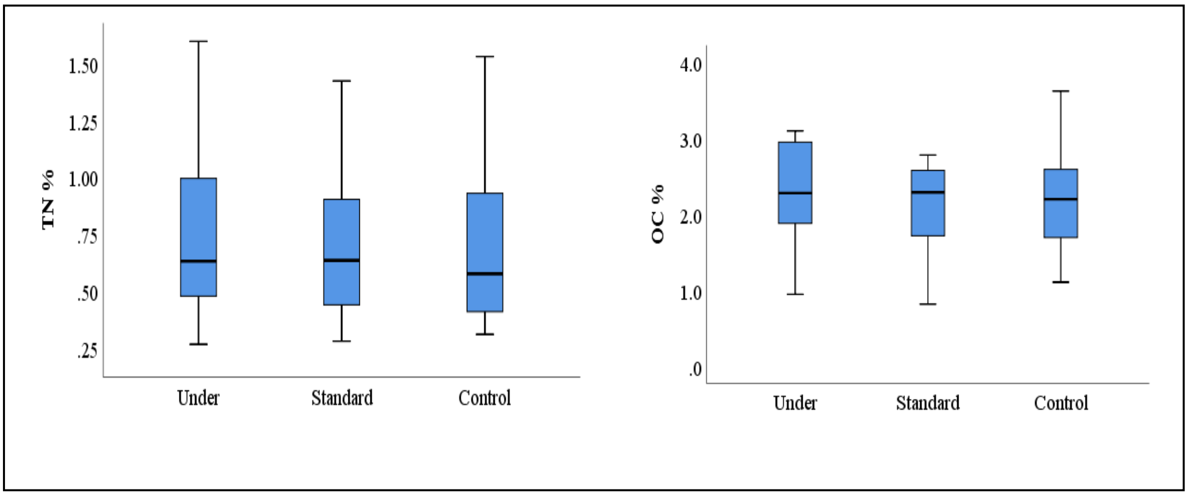

Figure 9: Comparisons between total nitrogen and carbon stocks in the soil under different fertilizer treatments (One-way ANOVA, P>0.05).

(box plots indicate the percentage concentration and whiskers indicate standard errors)

Carbon nitrogen ratio (C/N), TN, organic carbon and soil moisture were determined as some of the drivers of GHG emissions using Spearman correlation. Carbon/nitrogen ratio affects GHGs emissions by influencing mineralization and immobilization processes of the soil. Nitrous oxide showed positive correlation with TN but negative correlation with organic carbon (OC) and C/N ratio; however, both the positive and negative correlations were statistically not significant (Table 2). Methane showed an insignificant positive correlation with OC, C/N ration and TN (Table 2). Carbon dioxide showed an insignificant positive correlation with OC and C/N ration whereas it had a negative correlation with TN which was equally not significant. Total nitrogen and C/N ratio showed a significant negative correlation (rs = −0.808) whereas OC and C/N ratio had a significant positive correlation (rs =0.370), as illustrated in Table 2. However, there was no significant correlation between the soil moisture and the GHGs as shown in Table 2.

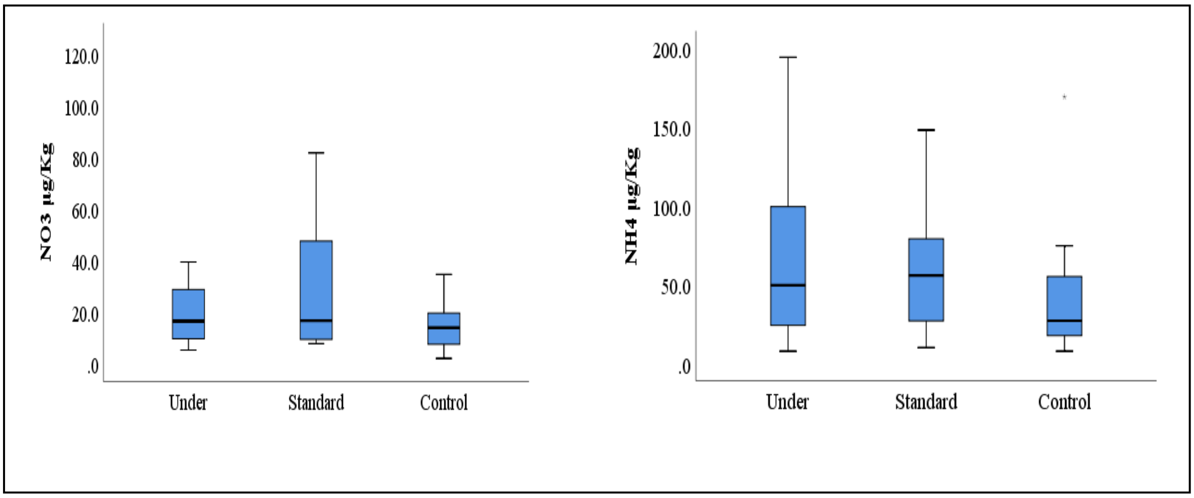

Figure 10: Distribution of nitrogen species (nitrate and ammonium) under different fertilization scenarios in the soil (Kruskal-Wallis test, P>0.05).

(Box plots indicate mean variation of nutrients levels under different treatments whereas the whiskers depict their standard error of mean).

Table 2: Spearman Correlation between greenhouse gases, organic Carbon, total nitrogen and carbon-nitrogen ratio (C/N)

Parameters	N_2O	CH_4	CO_2	OC	TN	C/N
N_2O	1.000					
CH_4	**-0.395****	1.000				
CO_2	0.004	0.050	1.000			
OC	-0.153	0.159	0.054	1.000		
TN	0.046	0.016	-0.005	0.192	1.000	
C/N	-0.149	0.123	0.030	**0.370***	**-0.808****	1.000

* Correlation is significant at 0.05, ** Correlation is significant at 0.01

4.4 Temporal variation of the greenhouse gases' fluxes during sampling

Methane fluxes significantly varied from the first sampling to the last sampling campaign (Kruskal-Wallis, df 9 P = 0.018). Methane emission during the first sampling was very low but increased significantly during the second sampling. The variation majorly occurred in the first, second and third weeks of sampling (Figure 12). Similarly, CO_2 showed significant variation during sampling (Kruskal-Wallis, df 9 P = 0.000) and it increased linearly during the subsequent weeks of sampling (Figure 12). Nitrous oxide was high in the first sampling compared to the rest of the sampling weeks. However, there was no significant variation in N_2O fluxes during sampling period (Kruskal-Wallis, df 9 P = 0.336) as shown in Figure 12.

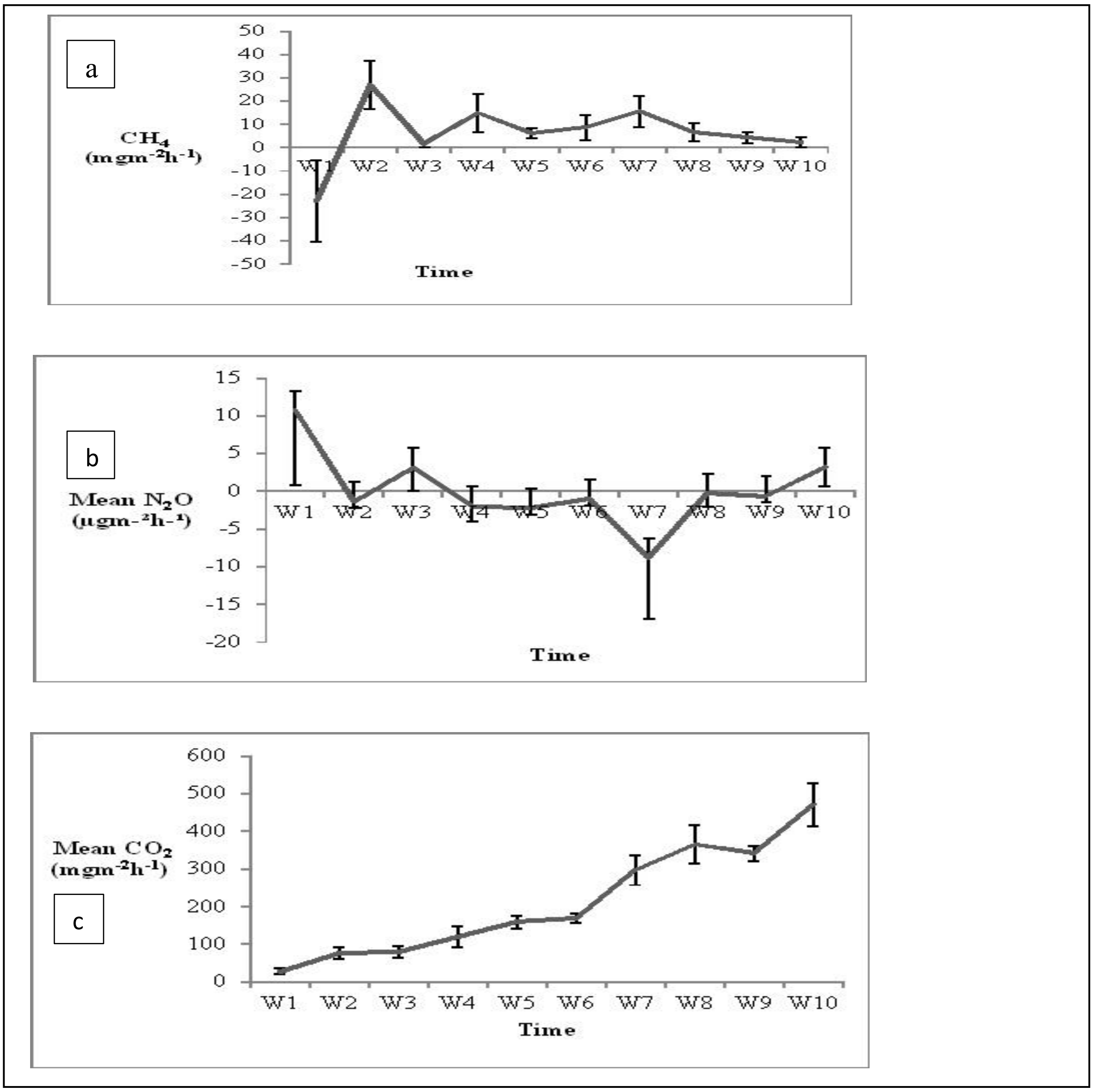

Figure 12: Temporal variation of the GHG fluxes in the study site (n = 10)

W1 to W10 represent the sampling dates in a chronological order (W1 = first week of sampling on 26/9/2018 and W10 = tenth week of sampling on 1/1/2019). a = CO_2, b = CH_4 and c = N_2O

CHAPTER FIVE

DISCUSSION

5.1 Carbon and nitrogen stocks in rice paddies

Wetland based rice production is an important source of greenhouse gases emissions (Wang *et al.,* 2017). Increased conversion of wetlands to rice paddies reduces their ability of carbon sequestration, thus increasing amount of GHGs (Mitchell, 2013). The low levels of carbon obtained in this study could be due to drainage of wetland and land preparation for rice plantation which exposed the accumulated carbon to oxygen, accelerating oxidation of organic matter to CO_2 and thus reducing carbon stocks. Kumar *et al.* (2014) and Ma *et al.* (2016) reported loss of organic carbon through cultivation and wetland drainage, which could be an explanation for the observed low levels of carbon in this study. Mitsch & Hernandez, (2013) also noted that drainage of saturated wetland soils in addition to its natural dryness result in increased oxygen diffusion, translating to higher rates of decomposition of OC, consequently an increase in CO_2 emissions. The observed low soil organic carbon can also be attributed to the high CO_2 emission in all the three fertilization scenarios. According to VandenBygaart *et al.* (2003), when soils in a natural state are converted to agricultural land, there is an important loss of soil organic carbon (SOC) mainly in form of CO_2. Furthermore, rice paddies are characterized with anoxic conditions which result to methanogenesis process, leading to loss of carbon as CH_4 and hence reduce carbon stocks (Jain *et al.,* 2004).

The loss of soil carbon in Anyiko rice paddies can also be explained by the alternate drying (experienced when there is no rain) and wetting conditions (experienced during rainfall) which favours growth of microorganisms resulting to high carbon mineralization (Ma *et al.,* 2017). Other studies have also observed an increase in soil microbial activity and carbon mineralization under alternate drying and wetting conditions by incubation experiment (Fierer & Schimel, 2002; Zhao *et al.,* 2011). The alternate drying and wetting season experienced during the experiment supplied more oxygen into the soil and hence increased oxidation of soil organic carbon which results to obtained high emission of CO_2 into the atmosphere.

The two major microbial processes responsible for nitrogen transformations in soil are mineralization and assimilation by plants and microorganisms (Booth *et al.,* 2005). In this study, the amount of total nitrogen increased from the initial value recorded in pre-test of 0.18 ± 0.06% to 0.73 ± 0.38% after the experiment. Application of nitrogen fertilizer in the soil during the experiment led to increased nitrogen stocks in under-fertilized and standard fertilized plots. Even though the amount of total nitrogen increased, the effect of the different treatments on the nitrogen substrate of the plots was not significant. According to Fuhrmanna *et al.* (2018), accumulation of nitrogen in the soil could be due to immobilization and retention of N fertilizer in the soil. The applied nitrogen fertilizer increased the available nitrogen stock but did not affect the amount of NH_4-N and NO_3-N among the fertilizer application scenarios. However, the standard fertilized and under-fertilized plots had high amount of NH_4-N and NO_3-N compared to control plots. This could be associated with fact that application of N fertilizer supplied more nitrogen substrate resulting to enhancement of mineralization and ammonification process (Chirinda *et al.,* 2018). Consequently, there was more ammonium in the fertilized plots than in the control plots, though the impact was not substantial. Furthermore, lowland rice is usually grown in waterlogged soils and this condition leads to reductive deamination (conversion of amino acid-N to ammonia via saturated acids), a process called ammonification (Sahrawat, 2010). Additionally, due to varying weather conditions at the study site, the field experienced episodic dry and wet periods. During dry periods, soils become relatively aerated and ammonium formed during mineralization is converted to nitrate via nitrite under oxic conditions (nitrification) (White & Reddy, 2001). This can explain the observed high amount of NO_3-N in the paddy soil during this study. Sahrawat (2010) noted that nitrification can be supported at the rice plant's root-soil interface in wetland soils due to oxygen transported through the air spaces or aerenchyma tissues of the stem and roots of the plant.

The ratio of carbon to nitrogen (C/N) in arable soils usually ranges between 8:1 and 15:1, with the median being 10:1 and 12:1 (Brady & Weil, 2008). The C/N ration in this study ranged between 1:1.2 and 8:1 which is quite low compared to the normal range of 8:1 and 15:1. Carbon nitrogen ratio in the soil is very important because it affects mineralization and immobilization processes of soil. The available carbon and nitrogen stocks in soil, either due to deposition from the atmosphere, addition of manure and application of inorganic fertilizer influences the GHGs emissions (Oertel *et al.,* 2016). During this study, it was noted that N_2O emissions increased with decreased C/N ratio but CH_4 and CO_2 had a positive correlation with C/N ratio, though not significant. This is in agreement with the study by Oertel *et al.* (2016) who reported a negative correlation of N_2O emission with the C/N ratio, with the lowest emission being recorded at $C/N \geq 30$ and highest at C/N values of 11 in addition to a positive correlation of CO_2 and CH_4 emission with the C/N ratio. Toma and Hatano (2007) noted that, N_2O and CO_2 emissions increased as the C/N ratio decreased, but not significantly. It is worth noting that in

Toma and Hatano (2007) result for CO_2 contradicts the results of the study by Oertel *et al.* (2016) and the results of this study. Moreover, intensive management of the peat lands has been found to alter the soil C/N balance, leading to higher variability of GHG emission (Veber *et al.*, 2017).

Other environmental and agronomic factors like temperature, moisture content (soil humidity), water regimes, pH, C:N ratio, fertilizer application among others affect the mineralization processes in waterlogged rice soils and thus influence GHGs emissions (White & Reddy, 2001; Li *et al.,* 2003). The observed high NO_3^-content compared to NH_4^+ could be because of varying environmental factors during the experiment, like water regime. Soil humidity affects microbial activities where for example, denitrifying bacteria strictly requires anoxic conditions and therefore N_2O emissions have been found to be optimal at 60 % water filled pore space (WFPS) compared to 30 % WFPS (Gao *et al.,* 2014). Similarly, Gao *et al.* (2014) and Smith *et al.* (2003) noted that CH_4 production has a positive correlation with soil humidity. Sahrawat (2008) explained that mineralization of organic nitrogen in aerobic soils resulting to formation of NO_3^- through nitrification which is more sensitive to high temperature than ammonification. Increase in temperature results to increased microbial metabolism. An exponential increase of CO_2 and NO emission with temperature was recorded (Ludwig *et al.,* 2001; Tang *et al.,* 2003). However, more studies need to be done to investigate the impact of environmental and agronomic factors (water regimes, fertilizer application, tillage) on nitrification and ammonification processes.

5.2 Greenhouse gas fluxes under different fertilizer application scenarios

Greenhouse gas fluxes for CH_4 and CO_2 were not affected by fertilizer application regime however, N_2O fluxes varied significantly among the three treatments. It seems therefore that the rice paddy soil had adequate carbon stocks for the production of GHGs, particularly CH_4 and CO_2 and fertilizer application did not affect the emission of these two gases. Furthermore, applying NPK 23:23:0 and CAN at a rate of 50 kg per acre at planting and for top dressing respectively promotes release of N_2O as opposed to when fertilizer is applied only at planting or no fertilizer used at all.

Methane emissions in flooded paddy rice fields or any waterlogged soils occur due to anoxic conditions (Ma *et al.,* 2009). The emissions of CH_4 to the atmosphere from paddy rice fields constitute a predominant source of anthropogenic CH_4 (Agnihotris *et al.,* 1998). The three fertilization scenarios did not have an effect on the amount of CH_4 emission. This compares with a study done by Linquist *et al.* (2012), which reported that there was no effect of fertilizer N application rate on CH_4 emissions. Even though CH_4 emission was not affected by the varying fertilization scenarios, the general CH_4 emissions from all the treatment plots were high. The consistent high moisture content created by the hydrologic modification to suit rice production provided favourable conditions for methanogens, which proliferate methanogenesis (Veber *et al.,* 2017). Fertilized larger plants provide more carbon substrate (roots and exudates) for methanogens thus enhancing CH_4 production (Lu *et al.*, 2000). Therefore, plants in plots with fertilizer grew large in size compared to un fertilized plots, thus leading to enhanced GHGs emission. It is also important to note that fertilization leads to enlarged aerenchyma in rice plants thus enhancing the pathway for gas movement from the soil substrate and consequently facilitates CH_4 emission (Tang *et al.,* 2018). Nitrogen fertilizer applications however have been reported to have varying effects on CH_4 emissions. Shang *et al.* (2011) reported stimulation of CH_4 emission with N fertilizer application. According to Venterea *et al.* (2005) methane emission is inhibited with N fertilizer application and in certain situations there are no significant effects of different N fertilizer application regimes on methane emission (Mosier *et al.*, 2006).

Fertilizer application regime did not affect the CO_2 emissions. Since fertilizer application had no direct effect on carbon stocks, however under similar humidity conditions, one would not expect to see a difference in organic carbon based GHG emission. Carbon dioxide emissions to the atmosphere occur under oxic conditions which favours microbial decomposition of organic matter (Whiting & Chanton, 2001). The dry incidents experienced during sampling could have led to oxygen supply into the soil, enhancing the aeration and thus increased CO_2 emissions. In rice paddies, apart from drainage, oxic conditions (oxygen supply) also occur at the soil-water interface and in the roots hence increasing CO_2 emissions to the atmosphere (Boateng *et al.,* 2017). A study done by Cheng-Fang *et al.* (2012) showed no significant effect of N fertilizer application on cumulative CO_2 emissions. These results are consistent with the findings of this study where CO_2 emissions within the plots treated with different fertilization scenarios did not differ significantly. However, variable results have been reported from different studies where Iqbal *et al.* (2009) and Xiao *et al.* (2005) reported increased CO_2 emissions with use of N fertilizer from rice paddy farms whereas Burton *et al.* (2004) recorded a decrease in CO_2 emissions with use of N fertilizer. Long term studies are necessary to improve the understanding of the effect of fertilizer application on carbon stocks and CO_2 emissions in rice paddies.

Nitrogen fertilizer application affected the nitrogen stocks and therefore a notable difference in N_2O emission from the three treatments. Emission of N_2O is influenced by the availability of nitrogen species (NH_4^+ and NO_3^-) in the soil since they are required by microbes for nitrification and denitrification processes (Cowan *et al.,* 2015). Bin-feng *et al.* (2016) reported that N_2O emissions became progressively greater as the quantities of N fertilizer applied increased. He noted that N inputs in the range of 52.5–300 kg N ha^{-1} per season caused a significant increase (average 145%) in N_2O emissions. When fertilizer is applied into the soil, there is increased supply of nitrogen substrate for decomposers resulting to enhanced emission of N_2O (Chirinda *et al.,* 2018). Linquist *et al.* (2012) meta-analysis study also reported that N_2O emissions increased significantly with increasing N fertilizer application rates, which is in agreement with findings of this study.

Despite the observed differences in the emission levels of the three treatments, their net N_2O emissions were still very low compared to those reported in literature. The low N_2O emissions could be attributed to other environmental factors like immobilization and retention of N fertilizer in soil (Fuhrmanna *et al.,* 2018). Another possible reason for the low N_2O fluxes could be due to some of the nitrogen being lost through leaching thus reducing amount of nitrogen substrate available for N_2O emissions. Bronson *et al.* (1997) in their study also observed negligible N_2O emissions during rice growing season when the soils were flooded. This is probably because anoxic conditions in the flooded paddies are suitable for denitrification and the major product of this process is nitrogen gas (N_2).

The greenhouse gases have varying residence time in the atmosphere and different radiative force and thus different global warming potential GWP. The global warming potential of each gas is measured over a certain period of time using CO_2 as the reference gas. Over a span of 100 years, the GWP for CO_2, CH_4 and N_2O have been found to be 1, 25, and 298 respectively (Solomon *et al.,* 2007). To evaluate the overall effect of GHG production in this study, the GWPs was applied to the fluxes measured and the carbon dioxide equivalent (CO_2 Eq) summed up. However, the effect of the three treatments on the overall GWP was not significant. This could be probably because of the short duration of the study and similar weather conditions experienced in all the treatment plots. Fertilizer application had no effect on the net GWP. This is in contrast with the study by Bin-feng *et al.* (2016) which noted that response of GWP to N addition was 3-10 folds greater for fertilization of 250–300 kg N ha^{-1} (266%) than for 50–250 kg N ha^{-1} (26 to 80%). Methane and nitrous oxide emissions from rice fields are however of great concern due to their radiative effects as well as GWP (Intergovernmental Panel on Climate Change, 1995).

5.3 Temporal variability in rice field Greenhouse gas emission

Greenhouse gases emission from paddy rice fields mainly depend on soil microbial processes (methanogenesis, oxidation, nitrification and denitrification) and on pathways of gas transport like aerenchyma, molecular diffusion and ebullition (Wang *et al.,* 2017; Zhang *et al.,* 2006). The microbial processes are affected by various environmental factors like water regime, soil temperature, pH, redox potential and availability of electron acceptors and donors which could possibly explain the observed temporal variation in emission of gases (Wang *et al.,* 2017), although all the parameters were not monitored during this study. The significant temporal variation of CO_2 and CH_4 emissions reported could be associated with varying water regimes experienced during study period. Tang *et al.* (2018) observed higher CO_2 emissions with intermittent flooded fields (32.39%) compared to continuously flooded fields (24.84%). The stages of plant growth also affect the GHG emission and therefore one would expect temporal variation of CO_2 and CH_4 during rice plant growing season. Wang *et al.* (2017) reported that emission rate of CH_4 was relatively low (0.04–0.55mgm^{-2}h^{-1}) during the initial stage, increased as the crop matured (7.99mgm^{-2}h^{-1}) and then decreased following drainage and ripening of the rice crop (0.28–0.75mgm^{-2}h^{-1}). Nitrous oxide emission did not exhibit temporal variability during the cropping period in this study. According to Bronson *et al.* (1997), N_2O emissions are in most cases negligible (2 mg N m ^{2}d ^{1}) during rice growth which could explain the observed insignificant effect of time on N_2O emission.

5.4 Greenhouse gases mitigation measures

Increase of GHGs concentration in the atmosphere is alarming and therefore, the synergistic effects of climate change mitigation, adaptation and food security needs to be addressed. Application of the concept of wise use of wetlands (use of wetland products and services on a sustainable basis) is crucial to ensuring that wetlands continue to fully deliver their vital role in supporting maintenance of ecological character, biological diversity and human well-being. Wise use of wetlands is key to conservation of global ecosystem and climate change mitigation (Yoon, 2009). Another method is the adoption of the blue carbon movement where efforts are being put on the use of wetlands to absorb and sequester significant amounts of carbon in the oceans to alleviate the global increase of CO_2 levels (Ventura, 2014).

Generally, mitigation of GHG emissions form agriculture is difficult due to lack of end product substitution (Garthorne-Hardy, 2013). Rice paddies have been reported to be a major producer of methane yet rice production is an essentail measure of food secuirty. However, measures are being put in place to mitigate GHGs emissions from rice fields through application of Systemof Rice intensification (SRI) which requires less agricultural inputs (land, seeds. fertilizer input, pesticides use) and less water compared to conventional rice cultivation (Geethalakshmi *et al.,* 2011; Thakur *et al.,* 2010). Jain *et al.* (2013) noted that despite being major contributor of CH_4, rice fields that adopt SRI could reduce CH_4 production by about 30 - 60 %. However, the ability of SRI as a water saving technology, increasing yield and reducing GHGs is still a controversial subject (Geethalakshmi *et al.,* 2016). In addition, CO_2 emission from rice paddies can be reduced by avoiding burning of rice straws after rice harvesting.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study assessed soil organic carbon, soil nutrients stocks and greenhouse gas emissions under different treatments including: control (no fertilizer applied), under-fertilization (involved first and second topdressings fertilizer application only), and standard fertilization (involved basal, first and second fertilizer application). The following are the conclusions of the study as per the objectives;

I. The various fertilization regimes did not significantly affect the soil nitrogen species (ammonium and nitrate), total nitrogen and soil organic carbon stocks and therefore the study failed to reject the first hypothesis.

II. Even though the fertilizer application regime did not affect the amount of available ammonium and nitrate, there was a significantly higher N_2O emission under standard fertilization compared to no fertilizer application (control). This was contrary to the first hypothesis of the study and therefore for this case the hypothesis was rejected. Fertilizer application regime however, had no effect on CH_4 and CO_2 emissions in the short time of the study and for this case the null hypothesis was accepted. From this study, even though the effect of the three fertilizer application scenarios on CO_2 was not significant, we can conclude that cultivation and land preparation for planting rice increased the loss of organic carbon in the form of CO_2 and therefore the ability of the Anyiko wetland to store carbon was reduced. Our findings suggest that the cumulative effects of such changes in the wetland land use may have negative implications on the ecosystem climate change regulating services.

6.2 Recommendations

At least a year round study should be done to get a comprehensive and more informative seasonal and temporal variation of soil nutrients in rice paddies that is, measurement should be done before planting, during rice growth and after harvesting.

Comprehensive study with different treatment levels (fertilizer type and different fertilizer application rates) should be done to find out their effect on GHGs emissions. This will help policy makers to figure out the amount of fertilizer to be used to strike a balance between yield and emission levels.

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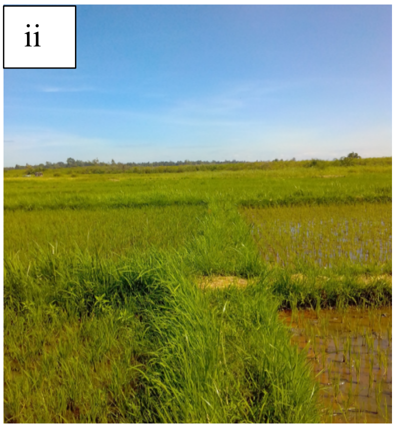
APPENDICES

Appendix A: Photos showing rice paddy, experimental set up and analysis

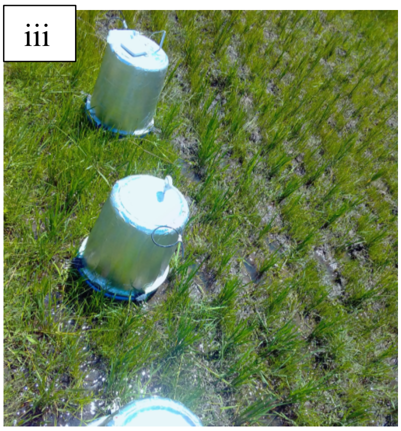
i) Rice plants immediately after transplanting, ii) few sampling plots, iii) Closed chambers ready for sampling, iv) Samples shaking in a shaker incubator, v) nitrate and ammonium samples ready for reading with vi) spectrophotometer with samples, vii) OC samples after titration, viii) TN samples during distillation.

i

ii



iii



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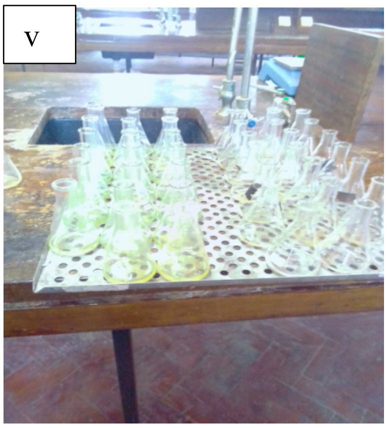
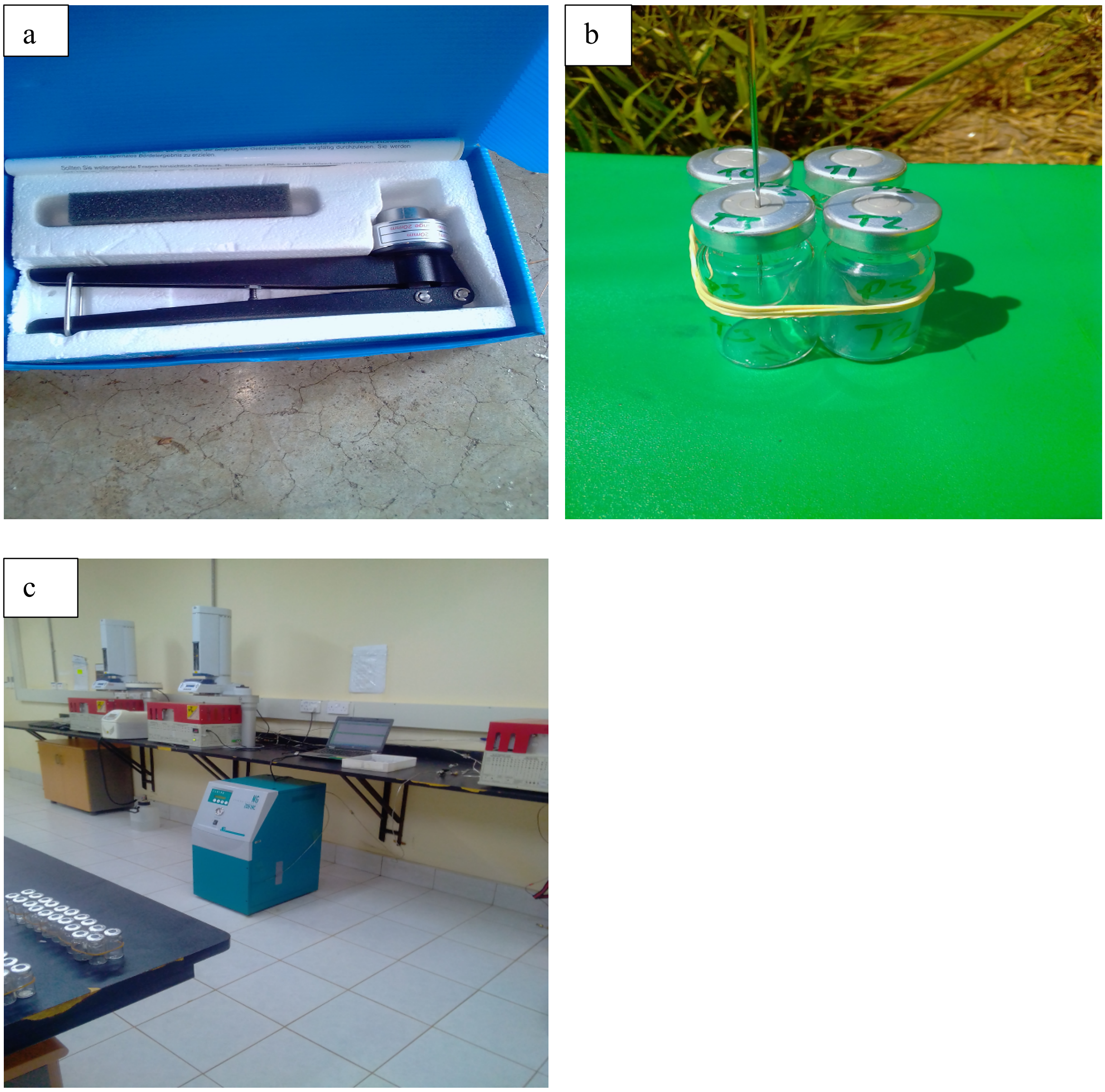


vi

vii

viii

Appendix B: Photos showing a) a crimper, b) vials fitted with a syringe, c) computerized gas chromatograph and a carrier gas.



Appendix C: Pairwise comparison (Kruskal Wallis, P=0.05), two-sided test for the treatments for Nitrous oxide

Sample 1 -sample 2	Test statistic	Std. error	Std. test statistic	Sig.	Adj. Sig.
Control - under	5.825	5.166	1.127	.260	.779
Control - standard	13.450	5.166	2.603	**.009**	**.028**
Under - Standard	-7.625	5.166	-1.476	.140	.420

Appendix D: Pairwise comparison (Kruskal Wallis, P= 0.05, two tailed), of temporal variation for CO_2 and CH_4.

CO_2 Sig.

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
W1	--									
W2	.428	--								
W3	.390	.947	--							
W4	.116	.437	.477	--						
W5	**.026**	.150	.170	.508	--					
W6	**.020**	.124	.141	.447	.921	--				
W7	**.000**	**.002**	**.003**	**.024**	.109	.133	--			
W8	**.000**	**.001**	**.001**	**.008**	**.047**	.060	.704	--		
W9	**.000**	**.001**	**.001**	**.008**	**.045**	.057	.692	.987	--	
W10	**.000**	**.000**	**.000**	**.002**	**.013**	**.017**	.372	.608	.620	**--**

CH4 Sig

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
W1	--									
W2	**.003**	--								
W3	.803	**.001**	--							
W4	.064	.247	**.039**	--						
W5	.192	.089	.128	.585	--					
W6	.209	.086	.141	552	.960	--				
W7	**.019**	.508	**.010**	.620	.298	.275	--			
W8	.155	.133	.102	.667	.908	.869	.355	--		
W9	.498	**.020**	.372	.241	.530	.563	.095	.457	--	
W10	.934	**.003**	.766	.077	.221	.241	**.024**	.181	.552	--

Appendix E: Field sampling sheet for recording air temperature, soil temperature, air pressure and chamber heights for calculating area and volume.

Site: ____________ Ambient pressure: ____________

Date: ____________ Start time: ____________ End time: ____________

Quadrat	4 point chamber height				Chamber temperature			
					T_0	T_{10}	T_{20}	T_{30}
Chamber 1								
Chamber 2								
Chamber 3								
Average								

Observation/notes

Weather: ____

____

State of vegetation: ____

____

____

____

Incidents/changes/current activities in the site: ____

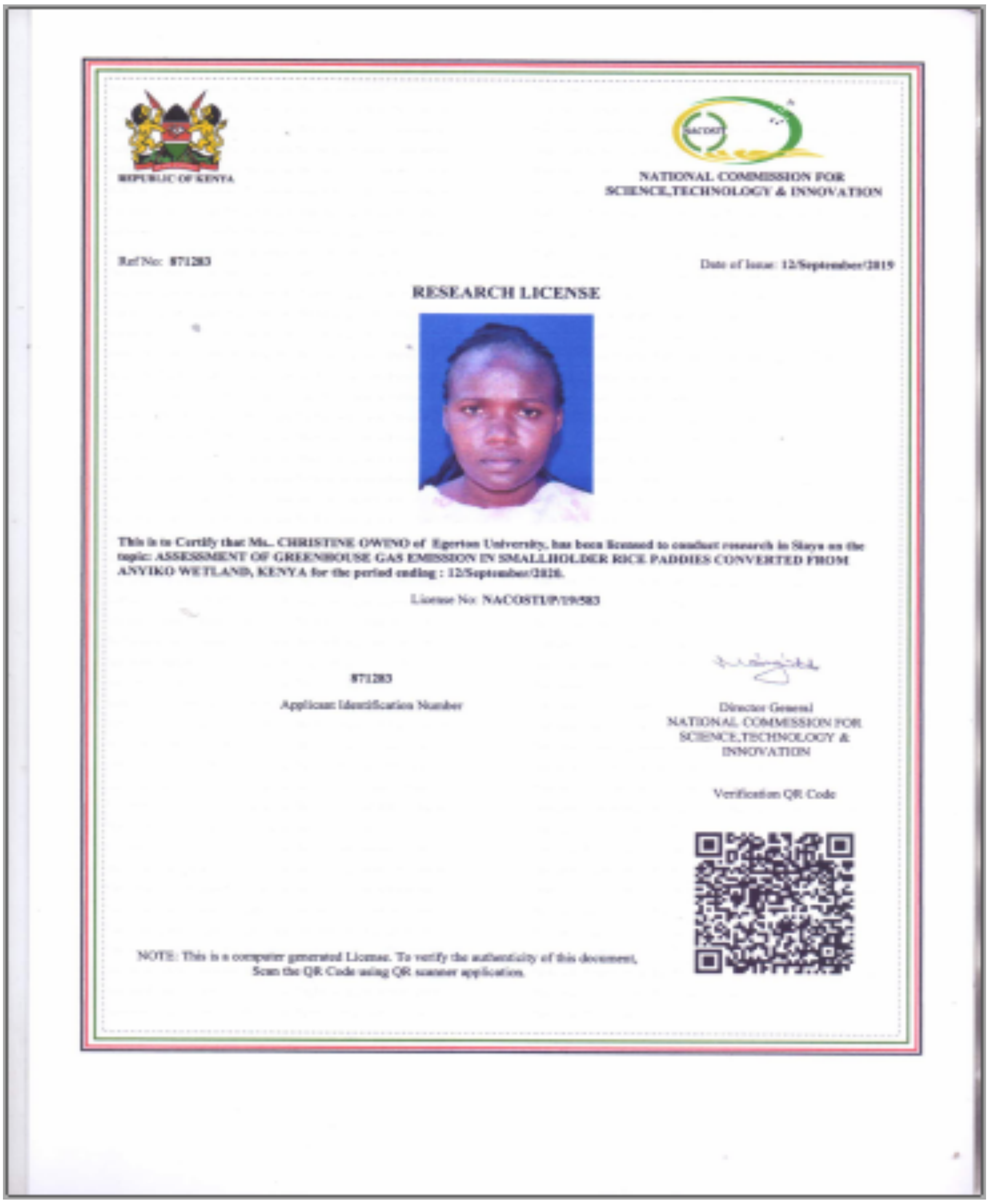
____

____

____

____

Appendix F: Research permit



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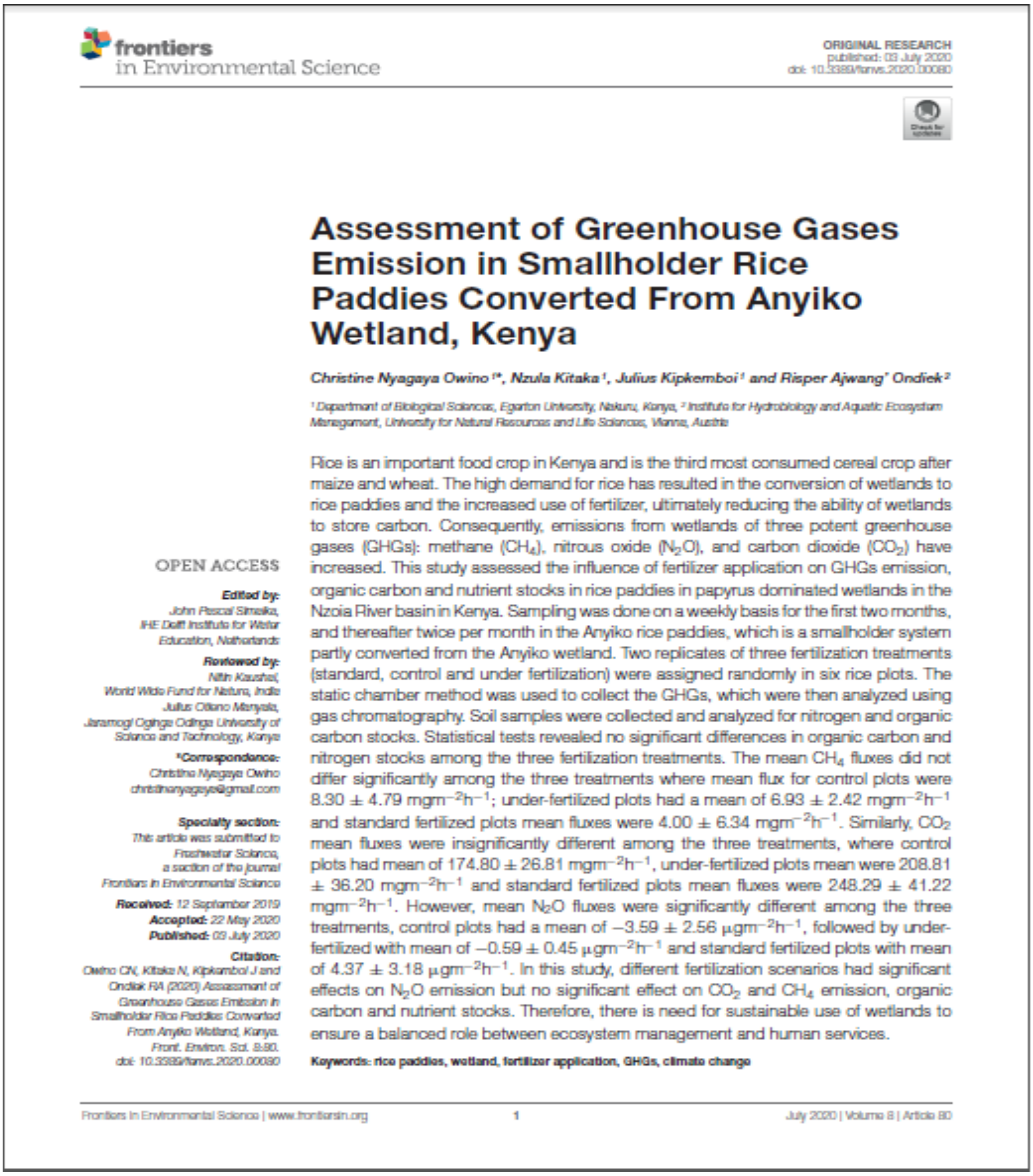
Appendix G: Manuscript Abstract



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Assessment of Greenhouse Gases Emission in Smallholder Rice Paddies Converted From Anyiko Wetland, Kenya

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Rice is an important food crop in Kenya and is the third most consumed cereal crop after maize and wheat. The high demand for rice has resulted in the conversion of wetlands to rice paddies and the increased use of fertilizer, ultimately reducing the ability of wetlands to store carbon. Consequently, emissions from wetlands of three potent greenhouse gases (GHGs): methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) have increased. This study assessed the influence of fertilizer application on GHGs emission, organic carbon and nutrient stocks in rice paddies in papyrus dominated wetlands in the Nzoia River basin in Kenya. Sampling was done on a weekly basis for the first two months, and thereafter twice per month in the Anyiko rice paddies, which is a smallholder system partly converted from the Anyiko wetland. Two replicates of three fertilization treatments (standard, control and under fertilization) were assigned randomly in six rice plots. The static chamber method was used to collect the GHGs, which were then analyzed using gas chromatography. Soil samples were collected and analyzed for nitrogen and organic carbon stocks. Statistical tests revealed no significant differences in organic carbon and nitrogen stocks among the three fertilization treatments. The mean CH_4 fluxes did not differ significantly among the three treatments where mean flux for control plots were 8.30 ± 4.79 $mgm^{-2}h^{-1}$; under-fertilized plots had a mean of 6.93 ± 2.42 $mgm^{-2}h^{-1}$ and standard fertilized plots mean fluxes were 4.00 ± 6.34 $mgm^{-2}h^{-1}$. Similarly, CO_2 mean fluxes were insignificantly different among the three treatments, where control plots had mean of 174.80 ± 26.81 $mgm^{-2}h^{-1}$, under-fertilized plots mean were 208.81 ± 36.20 $mgm^{-2}h^{-1}$ and standard fertilized plots mean fluxes were 248.29 ± 41.22 $mgm^{-2}h^{-1}$. However, mean N_2O fluxes were significantly different among the three treatments, control plots had a mean of -3.59 ± 2.56 $\mu gm^{-2}h^{-1}$, followed by under-fertilized with mean of -0.59 ± 0.45 $\mu gm^{-2}h^{-1}$ and standard fertilized plots with mean of 4.37 ± 3.18 $\mu gm^{-2}h^{-1}$. In this study, different fertilization scenarios had significant effects on N_2O emission but no significant effect on CO_2 and CH_4 emission, organic carbon and nutrient stocks. Therefore, there is need for sustainable use of wetlands to ensure a balanced role between ecosystem management and human services.

Keywords: rice paddies, wetland, fertilizer application, GHGs, climate change

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