EVALUATION OF GREENHOUSE GAS EMISSIONS AND WATER PRODUCTIVITY FROM RICE PRODUCTION AS AFFECTED BY WATER MANAGEMENT AND SOIL TYPE IN MWEA, CENTRAL KENYA

JANE WAITHIRA GITONGA

MASTER OF SCIENCE

(Civil Engineering)

JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

2020

Evaluation of Greenhouse Gas Emissions and Water Productivity from Rice Production as Affected by Water Management and Soil Type in Mwea, Central Kenya

Jane Waithira Gitonga

A Thesis submitted in partial fulfillment for the Degree of Master of Science in Civil Engineering (Water Option) in the Jomo Kenyatta University of Agriculture and Technology

2020

DECLARATION

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

Signature: ………………………………… Date: ……………………………

Jane Waithira Gitonga

This thesis has been submitted for examination with our approval as university supervisors.

Signature: ………………………………… Date: ……………………………

Prof. Patrick G. Home, PhD
JKUAT, Kenya.

Signature: ………………………………… Date: ……………………………

Dr. Hunja Murage, PhD
JKUAT, Kenya.

Signature: ………………………………… Date: ……………………………

Dr. John K. Mwangi, PhD
JKUAT, Kenya.

DEDICATION

This work is dedicated to my parents: John and Irine Gitonga and to my siblings: John, Grace, George and David and my nephew Jeremy Ryan. They are God's precious gift to me.

ACKNOWLEDGEMENTS

A special expression of gratitude goes to the Climate, Food and Farming (CLIFF) Network and Mazingira Centre, International Livestock Research Institute (ILRI). This work was undertaken as part of the CLIFF Network, an initiative of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). CCAFS is carried out with support from CGIAR Fund Donors and through bilateral funding agreements. Special thanks to: Dr. L. Merbold and Dr. D. Pelster for their beneficial advice, guidance, patience and encouragement throughout this research and for accommodating me during my stay as a Graduate fellow at Mazingira Centre and the entire Mazingira team for their support. I also thank P. Mutuo for helping me with chromatographic analysis, F. Mungethu for helping me in soil samples analysis and J. Owino, D. Korir and J. Macharia for assisting me during my data analysis. I am also sincere indebted to the entire KALRO (Prof. J. Kimani, Dr, D. Menge & Dr. E. Gichuhi) & JICA (Prof. Daigo Makihara, Dr. Mayumi Kikuta, Takahiro Kakehashi) management and staff for welcoming me with open arms and providing me with a research study site. Field work and data collection would have been a daunting task without their assistance. I am grateful to my supervisors, Prof. Patrick G. Home, Dr. Hunja Murage and Dr. John K. Mwangi for their assistance, guidance, patience, and encouragement throughout the study period. I thank my family: parents and siblings, for their prayers, love, and support during the course of the study, I remain indebted to them. Above all I thank Our Gracious Heavenly Father, from whom knowledge, wisdom, and strength flow. In Him, and through Him and for Him, did I accomplish this task.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS

ANOVA	Analysis of Variance
AWD	Alternate Wetting and Drying
CCAFS	Climate Change, Agriculture and Food Security
CF	Continuous Flooding
CH_4	Methane
CLIFF	Climate Food and Farming Network
CO_2	Carbon dioxide
CV	Coefficient of Variation
DAT	Days after Transplanting
EF	Emission Factors
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
GOK	Government of Kenya

GWP	Global Warming Potential
GWP_Y	Yield-scaled Global Warming Potential
ILRI	International Livestock Research Institute
IPCC	Inter-governmental Panel on Climate Change
JICA	Japan International Cooperation Agency
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KALRO	Kenya Agricultural & Livestock Research Organization
LSD	Least Significant Difference
MDG	Millennium Development Goal
MIS	Mwea Irrigation Scheme
N_2O	Nitrous Oxide
NH_4^+	Ammonium
NIB	National Irrigation Board
NO_3^-	Nitrate
NS	Nitisols

O_2	Molecular oxygen
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
WFPS	Water Filled Pore Space
VS	Vertisols

ABSTRACT

Food security for more than half the world population highly depends on the ability of the world to produce rice (*Oryza sativa*). Rice paddies are known to be one of the main anthropogenic sources of the greenhouse gas methane (CH_4), and use more water than all other staple food crops. Previous studies have examined the effectiveness of different water management regimes on mitigating GHG emissions and conserving water, however none of these were on smallholder rice farms in sub-Saharan Africa (SSA). In the SSA region, about 20% of the cultivated rice area is under flooded conditions also known as paddy rice fields. The area under rice cultivation in this region is forecast to rise to meet rice demand which has increased considerably than anywhere in the world. No previous research has investigated GHG emissions in rice production systems in Kenya and how soil type and water management regimes influences emissions. This study was therefore conducted during the rice growing season of 2017 (July – December) to address the paucity of data on GHG emissions from rice production in Kenya. Two rice water management systems (continuous flooding (CF) and alternate wetting and drying (AWD)) in two different soil types (Vertisols (VS) and Nitisols (NS)) were established in Mwea irrigation scheme (MIS) in central Kenya. The GHG fluxes were measured weekly (or more frequently depending on field management) using static GHG manual chambers. Alternate wetting and drying (AWD) water management regime greatly influenced GHG emissions ($P < 0.001$) during the rice growing season. AWD showed seasonal cumulative CH_4 emissions values of 2.19 and 0.90 kg CH_4-C ha^{-1}, 88% and 84% lower CH_4 emissions; while increasing N_2O emissions by 72% and 50% (0.31 and 1.29 Kg N_2O-N ha^{-1}), compared to CF in VS and NS respectively. With CH_4 and N_2O emissions expressed as CO_2 equivalents for a 100-yr horizon, AWD in the VS and NS soils lowered global warming potential (GWP) by 76% and 8%, respectively. Soil type had a significant ($P < 0.001$) effect on the GHG emissions with the VS soil having higher CH_4 and lower N_2O emissions compared to the NS soil. Interaction of water management regime and soil type greatly influenced ($P < 0.001$) the GHG emissions. Considering grain yield and GHG emissions together, AWD allowed for lower yield-scaled GWP. Higher water productivity was achieved under AWD in both soils. These findings suggest that AWD could be the best option for not only reducing GHG but also increasing irrigation water productivity.

CHAPTER ONE

INTRODUCTION

1.1. Background Information

Agriculture plays an important role in addressing two major global issues: mitigating climate change while feeding the growing human population (Linquist et al., 2015a). Current estimates suggests that food production will have to be doubled by the year 2050 in order to guarantee food and nutritional security (Linquist et al., 2015a), while simultaneously minimizing greenhouse gases (GHGs) emissions and other detrimental environmental effects associated with food production (Foley et al., 2011; Linquist et al., 2015a; LaHue, Chaney, Adviento-Borbe, & Linquist, 2016).

The agricultural sector, similar to other economic sectors, contributes to the increasing atmospheric concentration of greenhouse gases (Smith et al., 2014; Tubiello et al., 2015). About 10 – 12% of the total global anthropogenic GHGs emissions is from agriculture (Smith et al., 2014); primarily from livestock, biomass burning, rice production and management of agricultural soils (Eurostat, 2015).

Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) derived from agriculture and other anthropogenic sources, are fundamental greenhouse gases (GHG) contributing to global climate change and variability (Cai et al., 1997; Greenhouse Gas Working Group, 2010; Akinbile, Yusoff, Haque, & Maskir, 2012). Climate change results from increasing atmospheric concentration of CH_4, N_2O, and CO_2 gases, and is a threat to agricultural production due to the rising temperature and high frequency of extreme events such as droughts and floods (IPCC, 2014a).

Rice is critical to global food security as it is the most important cereal crop for more than half of the world’s population (McLean, Dawe, Hardy, & Hettel, 2002; Global Rice Science Partnership (GRiSP), 2010). In Africa, rice is an important staple crop (FAO, 2013), ranked third after maize and wheat in terms of consumption and production (Akinbile, El-Latif, Abdullah, & Yusoff, 2011). Rice is considered a food security crop in Kenya (Onyango, 2014), with consumption rate increasing by 12% annually, compared to annual increases in maize and wheat consumption of only one and four percent respectively (Muhunyu, 2012).

Rice cultivation is an important anthropogenic source of CH_4 as well as N_2O and CO_2 (Yan, Ohara, & Akimoto, 2003; Arunrat & Pumijumnong, 2017). Rice is a highly water intensive crop as it is heavily reliant on a continuous supply of water for a majority of its growing season (V&A Programme, 2009). According to Bouman & Tuong, (2001), water-use per growing season of rice typically ranges from 1000 – 2000 mm, which corresponds to 2 - 3 times more than other cereal crops. However, a large amount of this water is lost through surface runoffs, deep percolation, evapotranspiration and seepage (Guerra, Bhuiyan, Tuong & Barker, 1998).

Rice production needs to be intensified to meet the growing demand, but this will result in negative impacts on the environment if sustainable rice production systems are not developed (Minami & Neue, 1994). These negative environmental impacts are attributed mainly to the fact that the conventional method of growing rice on continuously flooded soils results in increased pressure on water resources and concentration of greenhouse gases (GHG) in the atmosphere (Jain et al., 2004; V&A Programme, 2009; Jain & Dubey, 2014).

1.2. Statement of the Problem

Agriculture at global level accounts for 70 – 80% fresh water abstraction and of this 85% is used in rice production systems (Jain & Dubey, 2014). Current intensive rice production techniques require large amounts of water and leads to an increase in the atmospheric greenhouse gas emissions (Jain, Pathak, Mitra, & Bhatia, 2004; Jain & Dubey, 2014).

Approximately 90% of the global rice production, is grown under paddy conditions (Lagomarsino et al., 2016). Consistent with this global trend, paddy rice production accounts for about 86% of Kenyan rice production, with much of this production occurring in the Mwea irrigation scheme (MIS) in central Kenya (Muhunyu, 2012). However, one of the major challenges to expansion of rice production in the MIS is shortage of water (Nyamai et al., 2012).

Flooded rice fields are also characterized by anaerobic conditions which are a significant source of methane (CH_4) emissions (Jain et al., 2004; Jain & Dubey, 2014; Linquist, Adviento-Borbe, Pittelkow, van Kessel, & van Groenigen, 2012) and account for 9 – 11% of the total global GHG emissions from agriculture (Smith et al., 2014). According to Linquist et al. (2012), rice emits approximately four times as much GHG per ton of product than wheat or maize. This is primarily attributed to anaerobic conditions in the rice fields which are conducive for methanogenic archaea due to the suitable conditions, high moisture and high organic matter content (Khalil, Rasmussen, Shearer, Yao, & Yang, 1998). One promising management strategy to reduce irrigation water use and at the same time to reduce CH_4 emissions in rice fields (Qin et al., 2010; Linquist et al., 2015) is the Alternate Wetting and Drying (AWD) method (Richards et al., 2014). AWD is based on repeated drainage and re-flooding of the field throughout the growing season.

Almost all studies on how conversion to AWD affects greenhouse gas (CH_4, N_2O and CO_2) emissions and water usage, were conducted in East and South-East Asia (Boateng et al., 2017). As the management effects tend to be site specific, it is therefore critical to measure GHG emissions and water productivity from rice production systems in order to identify whether Alternate Wetting and Drying method is a viable mitigation option that suit local conditions.

1.3. Justification of the Study

GHG mitigation options in rice production tend to be site specific depending on the differences in agricultural activities and environmental factors for different rice fields (Khalil et al., 2009). In addition, the quantity of GHG emissions from rice fields varies with factors such as irrigation water management, climatic conditions, rice cultivars, physical, chemical and biological properties of the soil among others. Majority of the reported studies have been carried out mainly in parts of East and South-East Asia with very little information on GHG emissions from rice paddy fields in Sub-Saharan Africa (SSA) which includes Kenya (Boateng, Obeng, & Mensah, 2017). It was mainly because of lack of data on GHG emissions from Kenyan rice production systems that the study was carried out.

In its efforts to promote sustainable agriculture (Sustainable Development Goal2), achieve food security, feed it's growing population, end hunger and improve nutrition, the Government of Kenya launched the ‘Big 4 Agenda’ whose primary goals are to reduce the cost of food to improve accessibility to all, enhance large scale food production, and to drive smallholder productivity. Through the National Rice Development Strategy (NRDS), the country is to see, among other strategies, rice yields per unit area increased through development of appropriate soil and water management techniques in irrigated rice (Irea, 2010). Alternate drying and wetting (AWD) could be one of the practices for achieving the goal of sustainable rice production while minimizing GHG emissions from rice fields.

1.4. Research Objectives

The main objective of this study was to quantify greenhouse gases (CH_4, N_2O and CO_2) emissions from rice production under alternate wetting & drying and continuous flooding in Vertisols and Nitisols soils commonly found in Mwea irrigation scheme, Kenya.

The specific objectives were:

i. To evaluate the effect of alternate wetting & drying and continuous flooding in Vertisols and Nitisols soil on greenhouse gas emissions from the rice fields;
ii. To evaluate the rice productivity under alternate wetting & drying and continuous flooding in Vertisols and Nitisols.

1.5. Research Questions

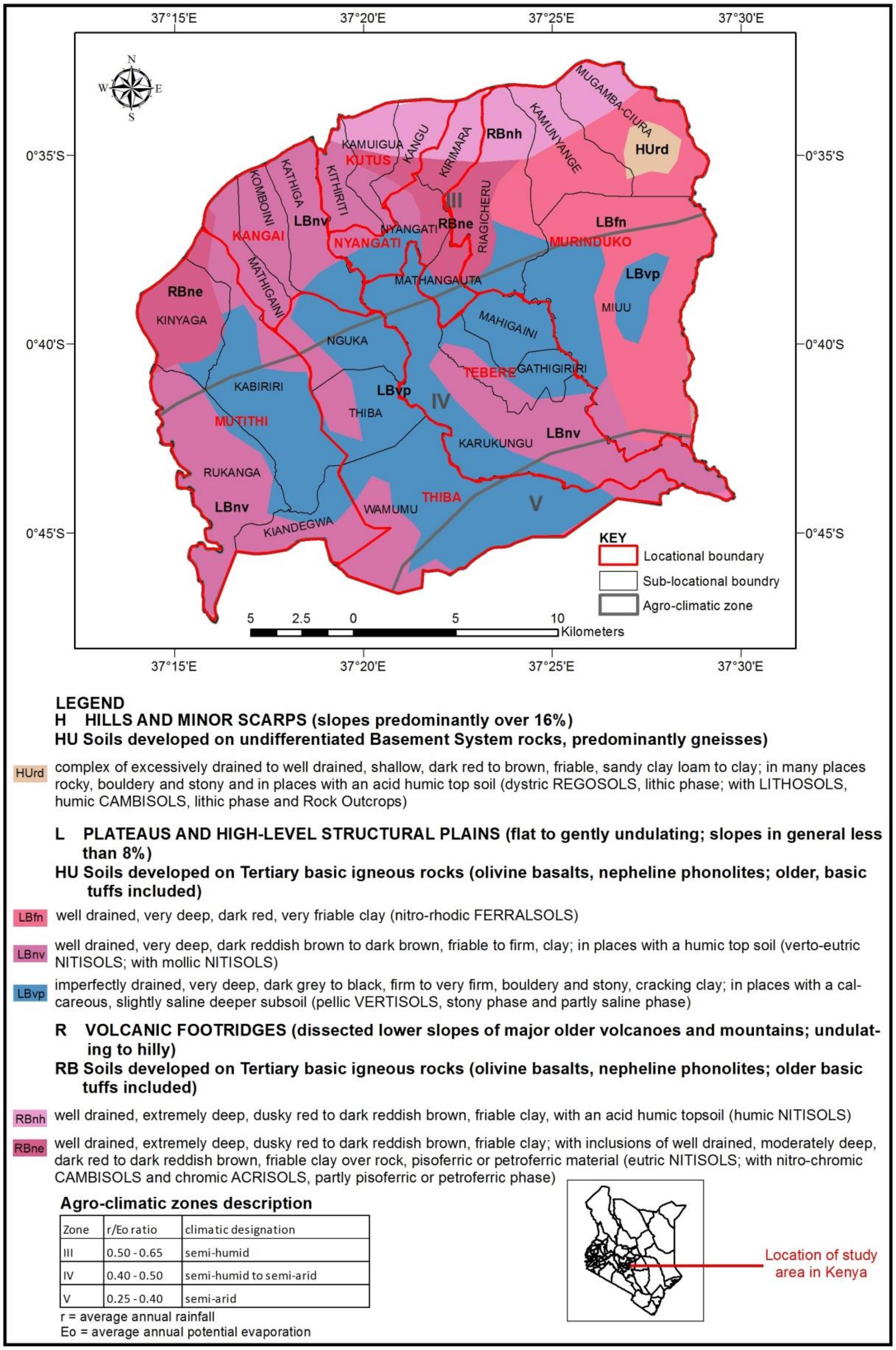
The study sought to answer the following questions:

i. How do water management regimes and soil type affect greenhouse gas emissions from rice production in Kenya?
ii. How is rice productivity affected by the interaction between water management regime and soil type?

1.6. Scope of study

1.6.1. Location and extent of Mwea Irrigation Scheme

The Mwea Irrigation Scheme is located in the lower slopes of Mt. Kenya, Kirinyaga County in the central part of Kenya. It lies between latitudes 37°13’E and 37°30’E and longitudes 0°32’S and 0°46’S (Figure 1.2). The scheme is divided into five sections: Tebere (the largest single section), Thiba, Mwea, Wamumu and Karaba (Muhunyu, 2012). The Kirogo-Mwea research farm (00°38S; 37°22E; elevation 1159m.a.s.l.), where the experiment was conducted, is part of this scheme within the Tebere section.



LEGEND

H HILLS AND MINOR SCARPS (slopes predominantly over 16%)

HU Soils developed on undifferentiated Basement System rocks, predominantly gneisses)

HUrd complex of excessively drained to well drained, shallow, dark red to brown, friable, sandy clay loam to clay; in many places rocky, bouldery and stony and in places with an acid humic top soil (dystric REGOSOLS, lithic phase; with LITHOSOLS, humic CAMBISOLS, lithic phase and Rock Outcrops)

L PLATEAUS AND HIGH-LEVEL STRUCTURAL PLAINS (flat to gently undulating; slopes in general less than 8%)

HU Soils developed on Tertiary basic igneous rocks (olivine basalts, nepheline phonolites; older, basic tuffs included)

LBfn well drained, very deep, dark red, very friable clay (nitro-rhodic FERRALSOLS)

LBnv well drained, very deep, dark reddish brown to dark brown, friable to firm, clay; in places with a humic top soil (verto-eutric NITISOLS; with mollic NITISOLS)

LBvp imperfectly drained, very deep, dark grey to black, firm to very firm, bouldery and stony, cracking clay; in places with a calcareous, slightly saline deeper subsoil (pellic VERTISOLS, stony phase and partly saline phase)

R VOLCANIC FOOTRIDGES (dissected lower slopes of major older volcanoes and mountains; undulating to hilly)

RB Soils developed on Tertiary basic igneous rocks (olivine basalts, nepheline phonolites; older basic tuffs included)

RBnh well drained, extremely deep, dusky red to dark reddish brown, friable clay, with an acid humic topsoil (humic NITISOLS)

RBne well drained, extremely deep, dusky red to dark reddish brown, friable clay; with inclusions of well drained, moderately deep, dark red to dark reddish brown, friable clay over rock, pisoferric or petroferric material (eutric NITISOLS; with nitro-chromic CAMBISOLS and chromic ACRISOLS, partly pisoferric or petroferric phase)

Agro-climatic zones description

Zone	r/Eo ratio	climatic designation
III	0.50 - 0.65	semi-humid
IV	0.40 - 0.50	semi-humid to semi-arid
V	0.25 - 0.40	semi-arid

r = average annual rainfall
Eo = average annual potential evaporation

Figure 1.1: Soils and agro-climatic zones of Mwea area

Source: Kenya Soil Survey, Complied by Matolo 2012

1.6.2. Soils

The dominant soils in the Tebere section, are pellic vertisols and verto-eutric nitisols (Frederick & Owido, 1981). The spatial distribution of soils of the entire Mwea area is illustrated in Figure 1.2.

1.6.3. Agro-climatology

Annual average precipitation for Mwea is 950 mm, with the long rains falling between March and May, while the short rainy period is between October and December. Moisture availability zones are based on the ratio of the measured average annual rainfall and the calculated average annual evaporation (Sombroek, Braun, & van der Pouw, 1982). The scheme traverses three agro-climatic zones (Figure 1.2) with maximum moisture availability ratio ranging from 0.50 to 0.65, 0.40 to 0.50, and 0.25 to 0.4 for zone III, zone IV, and zone V respectively. The area is generally hot, with average temperatures ranging between 23°C and 25°C, having about 10°C difference between the minimum temperatures in June/July and the maximum temperatures in October/March.

1.6.4. Water resource availability for rice production

The Scheme itself is served by two rivers, the Nyamindi and the Thiba which are tributaries of Tana River. The Nyamindi River system serves Tebere section while Thiba River serves Thiba, Mwea, Wamumu and Karaba sections. The months of August to October are the most appropriate for rice cultivation since the temperatures are conducive for grain filling and with less risk of disease incidences (Mukiama & Mwangi, 1989). However, the scheme suffers from water shortages since this period coincides with the dry season, further putting a strain on water available for irrigation. This necessitates a staggered planting calendar implemented in the scheme (Ijumba, Mwangi, & Beier, 1990), as the available water is not enough to reach all farmers during the most opportune season.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Greenhouse gases (GHGs) refer to a group of compounds that are able to trap heat in the atmosphere keeping the earth's surface warm (Eurostat, 2015). However, increase in the concentration of these gases in the atmosphere, mainly as a result of human activities, is projected to lead to regional and global changes in climate (Grasty, 1999). Agricultural sector is one sector to consider in terms of climate change because it releases significant amounts of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) which are fundamental greenhouse gases (GHG) contributing to global climate change and variability (Cai et al., 1997; Akinbile et al., 2012; Tubiello et al., 2015). About 5.1 – 6.1 $GtCO_2$-eq/yr; which is 10-12% of the total global anthropogenic GHG emissions, is from agriculture (Linquist et al., 2012; Smith et al., 2014; Tubiello et al., 2015). With the rapidly increasing population growth and changing lifestyles, GHG emissions from agriculture are expected to escalate due to increase in food demand (Smith et al., 2007).

Not only is the agricultural sector one of the main drivers to climate change, the sector is also highly exposed to extreme climate events and impacts of climate change which affect farming activities (IPCC, 2014; European Commission, 2015). Climate change is expected to impact negatively future global food production (Grasty, 1999). This is mainly due to long-term water shortage, drought and desertification, pest and disease outbreak on crops as well as livestock, sea level rise and related salinization leading to loss of land, worsening soil conditions such as soil organic matter loss, leaching of soil nutrients and erosion (Grasty, 1999; Pradeep et al., 2003). These effects of climate change on agriculture differs both regionally and globally (Grasty, 1999). Food productivity, especially crop productivity, has been affected and is expected to be further altered due to these climatic changes (Grasty, 1999).

The food security for more than half the world population highly depends on the ability of the world to produce rice (Nguyen, 2002). However, due to global climate change causing changes to rainfall patterns and distribution, rise in temperatures and sea levels could lead to substantial modification in water resources and land available for rice production (Nguyen, 2002).

2.1.1. Agriculture GHG Emissions in Kenya

In Kenya, agricultural sector is the largest source of GHG emissions accounting for more than one-third of the national emissions (Stiebert, 2012). This is according to the national GHG emissions inventory carried out in 2010, which used the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines to develop an emissions baseline for the agricultural sector. However, the data required to calculate these emissions was lacking leading to considerable uncertainties in the calculation of agricultural sector emissions as well as the use of default emission factors that are not country specific to estimate these emissions (Stiebert, 2012).

2.2. Conceptual framework

This study was carried out through exploratory field experimentation. In such an experiment, a set of options to address a particular problem are available, but needs to be tested first to evaluate its potential to address the problem. In this case therefore, alternate wetting & drying was being tested against the continuous flooding in Vertisols and Nitisols soils in Mwea. We quantified greenhouse gas emissions and water productivity from rice production under both irrigation managements and on two different soil types that are commonly found in Mwea Irrigation Scheme. The experiment was conducted during the August-December crop growing season of year 2017 at the Kirogo-Mwea research farm managed by Kenya Agriculture and Livestock Research Organization.

2.3. Rice Production

2.3.1. Rice Production in a global perspective

Rice is critical to global food security (McLean et al., 2002) mainly because; for more than half of the world's population, it is the most important cereal crop (Fairhurst & Dobermann, 2002; Global Rice Science Partnership, 2013; FAO, 2013). To ensure food security, it is projected that in the next 30 years the annual global rice production will need to be increased to 760 million tonnes to meet the projected rice demand of the rapidly increasing world population (FAO, 2013).

According to WWF (2007), 114 countries were reported to be growing rice, of these, 38 were Sub-Saharan Africa (SSA) countries (McLean, Dawe, Hardy, & Hettel, 2002). Asia is the most important rice growing region in the world accounting for 91% of the world's rice production followed by Latin America and the Caribbean (LAC) (3.8%) and Africa in third place accounting for 2.9% of the world's rice production (McLean et al., 2002).

Throughout Africa, rice is an important staple crop (Global Rice Science Partnership, 2013; FAO, 2013) ranked third after maize and wheat in terms of consumption and production (Akinbile et al., 2011). Among African countries, rice is primarily grown in Nigeria, Kenya, Malawi, Ghana, Uganda and Tanzania (FAOSTAT, 2014).

2.3.2. Constraints to global Rice Production

Rice production in many countries has either stagnated or in some places reduced (Satyanarayana, Thiyagarajan, & Uphoff, 2007). This situation has been attributed to mainly to climate change which leads to water scarcity; causing farmers to abandon the conventional rice paddy cultivation to less water demanding crops (Satyanarayana et al., 2007).

Temperature increase, changes in rainfall pattern and its distribution due to global climate change, has led to substantial modification in water resources and land available for rice production (Nguyen, 2002). Other factors include: soil structure degradation, increasing production cost, weeds and pest infestations, biotic (i.e., weeds) and abiotic constraints, low efficiency of nitrogen fertilizers, and post-harvest losses (Papademetriou, Frank, & Edward, 2000).

2.3.3. Rice Production in Kenya

Kenya is no exception in the rapidly growing demands of rice. Rice (*Oryza sativa*) is the third stable food and most consumed cereal crop after maize and wheat in the country (Mati, Wanjogu, Odongo, & Home, 2011; Ndiiri, Mati, Home, & Odongo, 2013; Nyang'au, Mati, Kalamwa, Wanjogu, & Kiplagat, 2014) Local production is estimated at 100,000 to 120,000 metric tonnes per annum against a demand of 400,000 to 410,000 metric tonnes per annum (Mati et al., 2011).

According to Kimani et al. (2011), in Kenya, 95% of rice is grown under irrigation in paddy schemes which are managed by the National Irrigation Board (NIB) while 5% is rain fed. Production of rice under paddy rice systems is the most predominant method mainly in irrigation schemes established by the Government, which include Mwea, Bura, Hola, Perkera, West Kano, Bunyala and Ahero (Nyang'au et al., 2014).

2.3.4. Rice Production constraints in Kenya

Kenya is largely a dry country with 80% of the country being arid and semi-arid. It is classified as a water scarce country with per capita water availability of 650 cubic meters. Approximately, 17 percent of highly potential agricultural land sustains 75% of the country's population (Ngigi, 2002; Marshall, 2011). Cultivation of rice in paddy fields requires flooded fields with a continuous supply of water and also soils with high water-holding capacity. Few areas in the country have a combination of water and soils suitable for rice production hence placing a limitation on the possibility of meeting the national demand for rice. Shortage of water and suitable land for rice production means that an expansion of rice growing fields is not a likely option (Ndiiri et al., 2013).

Low production in the country is also attributed to a number of other factors namely; climate change, lack of newly improved and adapted varieties of rice, preference of farmers of a low yielding hybrid, aromatic variety (Basmati) which has a high market value, high input costs, susceptibility to pests and diseases; poor agronomic practices, lack of mechanization and deteriorating soil chemical and physical conditions due to continuous mono-cropping (Kimani, Tongoona, Derera, & Nyende, 2011).

Water shortage, however, is the main challenge facing production of rice in the country especially around the Mwea region resulting to a decline in production due to water stress (Kimani et al., 2011). Availability of high yielding cultivars is also another challenge for rice growers. Due to poor cultivars, a 20% yield loss as a result of deterioration in seedling vigor has been observed (Ndiiri et al., 2013).

2.4. Impacts of Rice Production on the Environment

2.4.1. Rice Fields as the main water consumer in Agriculture

Water is an important natural resource that is rapidly becoming scarce mainly as a result of climate change, the growing population and agriculture intensification (Rijsberman, 2006). The ability for the world to meet the increasing food demand is challenged by water scarcity (Hanjra & Qureshi, 2010). Around the world, pressure to reduce water used in irrigation is mounting (Thakur, Kassam, Stoop, & Uphoff, 2016). This is attributed to the fact that; at global level, agriculture accounts for approximately 70 – 80% freshwater abstraction and of this about 85% is used in rice (*Oryza sativa L*) production systems (Jain et al., 2014). For more than half of the world’s population, rice is an important staple crop (FAO, 2013). With high rice production to meet global demands; water use is enormous (V&A Programme, 2009).

Approximately 75% of the rice production comes from 79 million ha of irrigated lowlands (Tuong & Bouman, 2003a; Bouman, Lampayan, & Tuong, 2007). According to Bouman & Tuong, (2001), water-use per growing season of rice typically ranges from 1000 - 2000 mm, which corresponds to 2 - 3 times more than other cereal crops. However, a large amount of this water is lost through surface runoffs, deep percolation, evapotranspiration and seepage (Guerra et al., 1998).

2.4.2. Rice fields as major sources of GHG Emissions

Rice fields have been identified as an important anthropogenic sources of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions (Yan et al., 2003; Arunrat & Pumijumnong, 2017). According to Linquist et al. (2012), rice emits approximately four times as much greenhouse gas per tonne of product than wheat or maize; mainly due to CH_4 which is the dominant greenhouse gas emitted in flooded rice paddies (IPCC, 1992; Watson, Meira-Filho, Sanhueza, & Janetos, 1992).

Flooded rice paddy fields accounts for 9-11% of the total global GHG emissions from agriculture (Smith et al., 2014). According to FAO (2003), the area of rice grown globally is forecast to increase. This is expected to result to an increase in GHG emissions from rice fields, especially methane emissions, if the current rice production technologies are maintained (Watson et al., 1992).

2.5. Greenhouse Gas Emissions from Rice Fields

2.5.1. Methane (CH_4) Emissions

Irrigated rice production is the second largest source of anthropogenic methane after enteric fermentation from ruminants (Smith et al., 2007). Flooded rice paddy fields, create an anaerobic conditions in the saturated soils conducive for methanogenic archaea activities due to the temperate conditions, high moisture and organic substrate (Khalil et al., 1998). Methane production and oxidation in the soil is attributed to two microbial communities: methanogens and methanotrophs, respectively. The total methane emissions from flooded rice fields is the balance between methanogen and methanotroph activities (Fazli, Man, Shah, & Idris, 2013).

2.5.1.1. Production of Methane in Rice Fields

Methane production also referred to as methanogenesis is a microbial process that is strictly limited to anaerobic conditions since methanogenic archaea are more active in conditions which are highly reduced and anoxic (Ma, Qiu, & Lu, 2010).

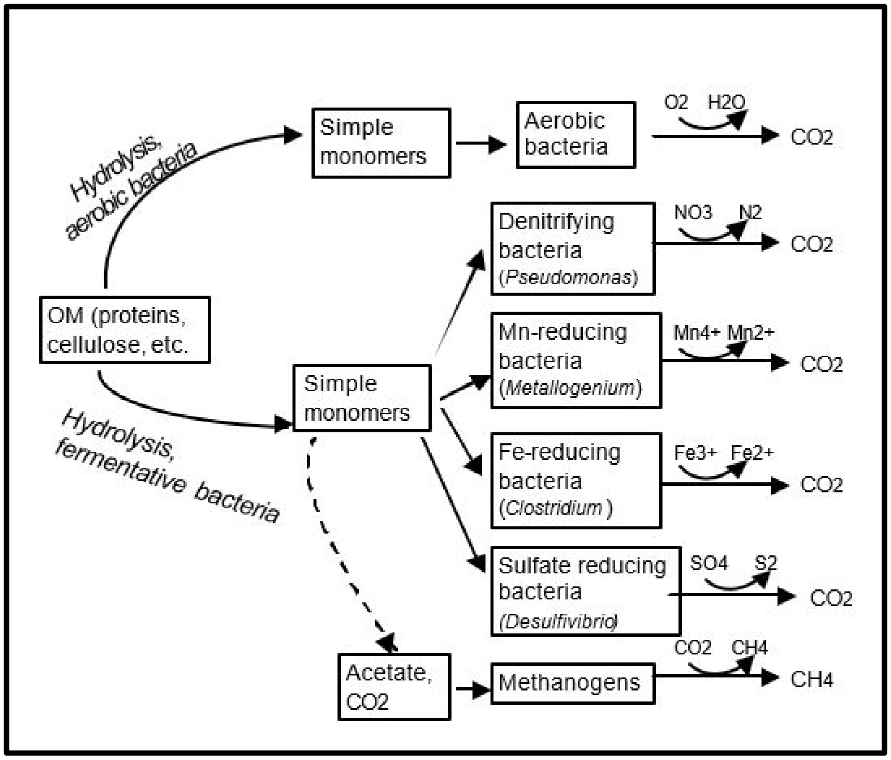


Figure 2.1: Depletion of electron acceptor usage in flooded rice fields leading to production of methane

Source: https://microbewiki.kenyon.edu/index.php/Central_Metabolism (Flooded soils)

Immediate flooding of rice fields does not result in methane production; this is as a result of the trapped molecular oxygen in soil pores and in the water and also the existence of the alternative oxidizing agents or electron acceptors that allow aerobic decomposition of the soil organic matter. However flooding the fields cuts off the oxygen supply from the atmosphere causing the paddy soil to be anoxic within hours of flooding (Chanton, Whiting, Blair, Lindau, & Bollich, 1997; Horwath, 2011).

Aerobic decomposition of soil organic matter (SOM) leads to the gradual depletion of oxygen present in most parts of the flooded soils by aerobic bacteria and chemical oxidation reactions creating anoxic conditions that lead to the usage of alternative electron acceptors (Horwath, 2011). The anaerobic conditions is as a result of depletion of electron acceptors or oxidizing agents such as nitrate (NO_3^-), manganese (IV) oxide (MnO_2), Iron (Fe) III, and sulfate ($SO^{2-}{}_4$) (Xu, Jaffé, & Mauzerall, 2007). Oxides of nitrogen are the first electron acceptors reduced by the soil microbes after oxygen depletion followed by manganese, iron and sulfate in that order (Figure 2.1). This results to an anaerobic environment in the flooded rice fields with methane produced as a by-product (Zou, Huang, Zheng, & Wang, 2007). After electron acceptor depletion, soil organic matter is then decomposed under anaerobic conditions by methanogenic archaea generating methane.

2.5.1.2. Oxidation of Methane in rice fields

Rice plant rhizosphere, due to deposits of organic root exudates, degrading root debris and sloughed-off cells, serves as the major carbon source and energy for CH_4 production in rice fields, especially at the later growth stages (Neue et al.1996; Ma et al., 2010).

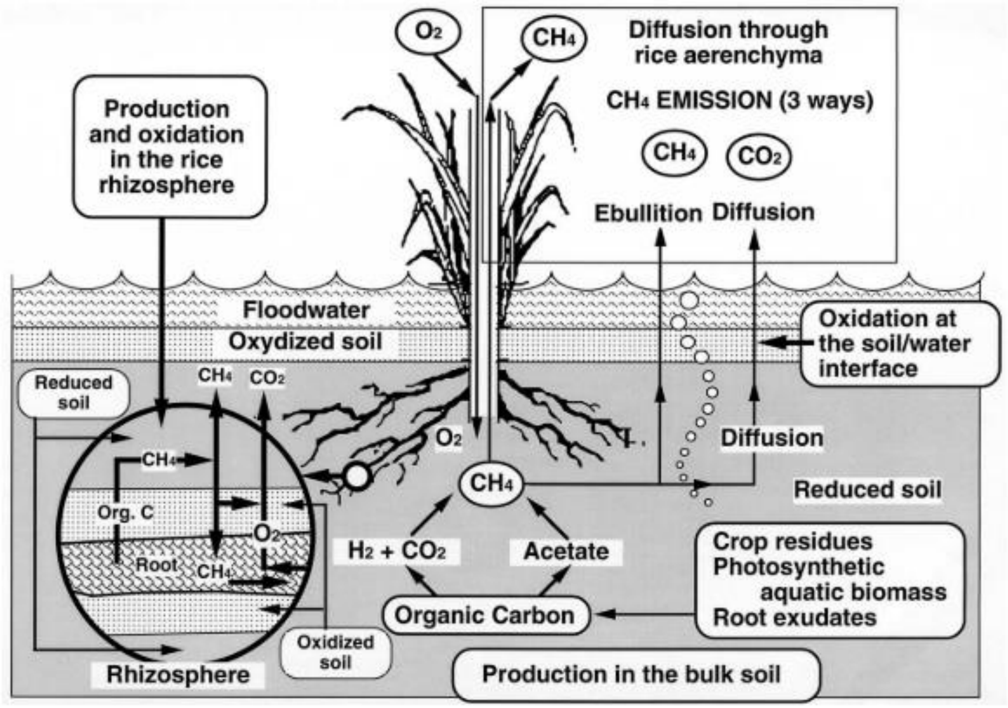


Figure 2.2: **CH_4 production, oxidation and emission via rice plants, ebullition and diffusion, from rice fields**

Source: (Le Mer & Roger, 2001)

However, rice plant rhizosphere and surface soil support high activity of methanotrophs which are more active in oxic soils and which oxidize a considerable portion of up to approximately 90% of total CH_4 produced in the soil depending on flood condition and time of growing season (Butterbach-Bahl, Papen, & Rennenberg, 1997). The rice plant roots are not only a source of carbon and energy for CH_4 production, but also act as an important site where CH_4 is oxidized by available oxygen from root secretion. A significant portion of methane produced in the soils is oxidized in the rhizosphere and at the soil-water interface either by aerobic methanotrophic archaea into CO_2 or anaerobically by the electron acceptors (Figure 2.2) (Zou et al., 2007 ; Xu et al., 2007).

The oxygen available in the rhizosphere from root secretion is used to activate growth and activity of the methanotrophs, and consequently increases the potential of CH_4 oxidation (Zhang et al., 2013) the remaining un-oxidized methane is released to the atmosphere by diffusion, ebullition, and through rice plants (Figure 2.2).

2.5.2. Nitrous oxide (N_2O) Emissions

Nitrous Oxide (N_2O) which is a significant long-lived greenhouse gas (GHG) is another important component of net GHG emissions from rice production (Watson, Meira, Sanhueza, & Janetos, 1992). Nitrous Oxide (N_2O) is naturally produced in the soils as part of the global nitrogen (N) cycle. However, N_2O emissions from agricultural soils are increased by the application of nitrogen (N) fertilizers that supply additional nitrogen to the global N cycle. Nitrous oxide emission intensity from the flooded rice fields is linked to nitrogen (N) fertilizer application rate (Figure 2.3) (Zou, Huang, Zheng, & Wang, 2007; Zheng et al., 2014)(Zheng, Huang, Yao, Liu, He, et al., 2014). Nitrous oxide production in the rice fields is as a result of nitrification and denitrification processes by microbial activities. Varying conditions of soil moisture causes a difference in soil temperature, soil oxygen status, and soil redox potential (Eh) which consequently bring about changes in N_2O emissions (Peng et al., 2011; Arunrat & Pumijumnong, 2017).

2.5.2.1. Production of Nitrous Oxide in rice fields

Drainage of rice fields increases the N_2O emissions (Fazli, Man, Shah, & Idris, 2013) due to nitrification processes (oxidized layer) which require presence of oxygen for the production of N_2O (Fazli et al., 2013). Ammonium (NH_4^+) is oxidized to nitrate (NO_3^-) in nitrification processes releasing part of the nitrogen produced as NO and N_2O to the atmosphere (Figure 2.3).

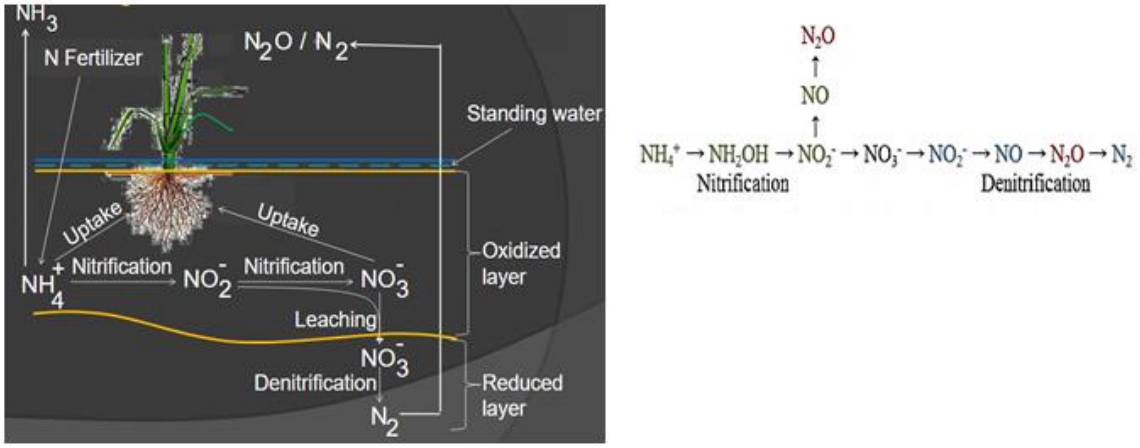


Figure 2.3: Conceptual schematic diagram of N_2O production via nitrification and denitrification processes in rice fields following fertilizer application

Source: (Norberg, 2017)

When fields are inundated during the growing season, denitrification processes; which occur in the reduced soil layer, are most important for the production of N_2O. Nitrate (NO_3) or nitrite (NO_2^-), in the denitrification processes is reduced to Nitric oxide, Nitrous oxide and Nitrogen gas (NO, N_2O or N_2), respectively (Figure 2.3). The denitrification processes also consume N_2O which serve as intermediary for the production of N_2. Under such conditions, N_2O is produced and also removed. The amount that is released in the atmosphere can be extremely variable and site specific for different rice fields. Both nitrification and denitrification processes by microbial activities can be combined if nitrate (NO_3^-) from nitrification diffuses in anaerobic parts of the field where denitrification takes place leading to high N_2O emissions.

2.5.3. Carbon dioxide (CO_2) Emissions

Anaerobic decomposition of organic matter in the soil, respiration by the rice root, and uptake or release of CO_2 by algae and aquatic weeds are factors considered to be related to the net carbon dioxide emissions from the rice paddy fields (Nishimura, Yonemura &

Minamikawa, 2015). The exchange of CO_2 in paddy fields is mainly from photosynthesis of rice plants and respiration of the plants as well as soil micro-organisms respiration. Carbon dioxide (CO_2) emissions from flooded rice fields are suppressed during flood irrigation, but some escapes into the atmosphere through bubble ebullition (Komiya et al., 2015). When the soil is drained creating oxidized environment in the soil, aerobic decomposition occurs resulting in consequent release of carbon dioxide (Jain et al., 2004).

2.5.4. Pathways of GHG from rice fields to the Atmosphere

Greenhouse gases (GHGs) produced in the paddy rice fields are emitted to the atmosphere via three pathways: rice plant-mediated transport, through soil/water/atmosphere interface by ebullition as gas bubbles and molecular diffusion (Butterbach-Bahl et al, 1997). Rice plant-mediated pathway is the major pathway for GHGs produced accounting for more than 90% of the total GHGs emitted from rice field soils to the atmosphere over the growing season (Butterbach-Bahl et al., 1997; Yu et al., 1997; Linquist etal., 2012). The rice plants acts as conduits for gas exchange between the flooded anoxic soils and the atmosphere (Butterbach-Bahl et al., 1997; Yu et al., 1997; Chanton et al., 1997; Linquist etal., 2012; Kraus et al., 2016). The aerenchyma enables the transport of gases both from the atmosphere to the root rhizosphere and from the soil to the atmosphere. Aerenchyma which are well developed intracellular air-spaces in the leaf blades and sheaths, culm, and roots, provide the plant roots with oxygen (O_2) in flooded anaerobic soil condition and also allows the transport of other gases, including CH_4, N_2O and CO_2 from the soil to the atmosphere providing an efficient gas exchange between the atmosphere and anaerobic soils (Neue et al., 1996). The internal structure of the aerenchyma, concentration gradients and diffusion coefficients of the rice plant roots, number of tillers, total biomass, rooting pattern, root mass and metabolic activity, influence the gas flux. Different rice varieties and at different growth and developmental progress, results in the variation in the total GHG emissions among the varieties (Zheng et al., 2014).

2.6. Factors affecting GHG emissions from Rice Production

Factors controlling GHG emissions from rice paddy fields include water management strategies, climatic conditions; Khalil et al., 1998), rice cultivars (Shalini-Singh et al., 1997; Khalil et al., 1998), physical, chemical and biological properties of the soil, organic matter amendments, plant physiology and quantity of organic residues.

2.6.1. Water Management

Climate change; which is an effect of the increasing greenhouse gas in the atmosphere, leads to immediate and long term impacts on water resources. Little to no rainfall affects crop production especially rice production as rice is a high water intensive crop. Proper agricultural practices such as water management will assist in transforming and ensuring food security (Aruna, 2014).

Water management in rice paddy fields not only saves on the water used for irrigation, but has been identified to be one of the most important factors in regulating CH_4 and N_2O emissions (Peng et al., 2011). Over the years, different water saving irrigation technologies such as: alternate wetting and drying, mid-season aeration, intermittent irrigation, have been studied mainly in East and South-East Asia (Cai et al., 1997).

During flooding, molecular oxygen (O_2) trapped in the soil is quickly consumed, microorganisms then use alternative electron acceptors during respiration leading further to soil reduction. The reduction of electron acceptors (e.g. NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}, and CO_2), in accordance with thermo-dynamic theory, creates anaerobic conditions in the soils. The redox potential in the soil drops suddenly leading to methanogenesis.

In flooded soils, succession of electron acceptor usage is as follows:

- Aerobic respiration: $\frac{1}{2} O_2 + 2e^- + 2H^+ \rightarrow H_2O$ (by facultative anaerobes and aerobes)
- Denitrification: $2NO_3^- + 12 H^+ + 10e^- \rightarrow N_2 + 6H_2O$ (by denitrifiers)

- Manganese reduction: $MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O$ (by manganese reducing bacteria)
- Iron reduction: $Fe(OH)_3 + 3\ H^+ + 2e^- \rightarrow Fe^{2+} + 2H_2O$ (by iron reducing bacteria)
- Sulfate reduction: $SO_4^{2-} + 10H^+ + 8e^- \rightarrow H_2S + 4H_2O$ (by sulfate reducing bacteria)
- Methane production: $CO_2 + 8\ H^+ + 8e^- \rightarrow CH_4 + 2\ H_2O$ (by methanogens)

Under anaerobic and reduced soil conditions, methanogens produce CH_4 through hydro-genotrophic (reduction of CO_2 by H_2 i.e., $CO_2 + H_2 \rightarrow CH_4 + H_2O$) and aceto-trophic (fermentation of acetate $CH_3COOH \rightarrow CH_4 + CO_2$) are the dominant reactions in methanogenesis (Jain et al., 2004). This process of soil reduction leads to the stabilization of the soil pH to near neutral. For example the process of electron acceptors reduction in the soils tends to stabilize the soil pH to neutral accelerating methane production rates since methanogens are more active at neutral pH (6.5 - 7.5) (Jain et al., 2004). CH_4 emissions occur at soil redox potential lower than approximately -100mV while N_2O emissions occur at soil redox potential lower than approximately +200mV. Water management practices that retain redox potential within the range of -100 to 200mV can minimize the emissions of these gases.

However, in dry soils after draining, the electron acceptors are regenerated lowering or completely cutting-off CH_4 production (Minamikawa & Sakai, 2005; Sakai, 2006). The methanotrophic archaea in the soil transform CH_4 to CO_2 by oxidation process. Appropriate water management in rice fields is the most effective mitigation options in reducing CH_4 emissions without affecting yield (Minamikawa et al., 2006).

2.6.2. Physical and Chemical Soil Characteristics

Soil properties: soil texture/percolation rate, soil pH, salinity, contents of soil organic carbon as well as electron acceptors control GHG emissions from the paddy rice fields (Minamikawa et al., 2006). The population of methanogens (CH_4 production) and methanotrophs (CH_4 oxidation) varies among soils (Sakai, 2006). Soil texture and pH play an important role in the production of GHGs in rice fields. For pH, methane producing archaea are neutrophilic hence soil conditions which are acidic or alkaline inhibit methane production (Mitra et al., 2002 ; Jain et al., 2004).

A study carried out in the Philippines by Gaunt et al., (1997), showed that production of methane in rice fields was influenced by the presence of organic substrate as well as reduction characteristics of each soil. In a study by Yagi & Minami, (1990), different soils under similar climatic conditions showed varying methane emission rates annually with high emissions being observed in the soils with lower percolation rates. With increased percolation rate, methane emissions decreased according to a study by Yagi et al. (1998). The nature of the clay also affects methane emissions since some clay types protect organic matter from mineralization delaying methanogenesis (Le Mer & Roger, 2001). High clay content tend to trap CH_4 hence reducing emissions in certain study (Roger & Joulian, 1997). Soils rich in lattice clay favor methanogenesis than sandy and loamy soils.

2.7. GHG and water-use mitigation options from Rice Production

Several studies over time have identified factors such water management, organic amendments, fertilizer management, changes in traditional practices, and improved rice cultivars as promising candidates and technologies for mitigation of GHG emissions from rice fields but each study has yielded varying outcomes among regions. For example, estimates of methane emissions from rice paddies vary greatly and have large uncertainties (Yan et al., 2003; Khalil et al., 2008; Zhuang et al., 2009) due to differences in agricultural activities and environmental factors that impact the production, oxidation and emissions of methane. It has been observed in various researches that methane emissions also show distinct diurnal as well as spatial variations (Neue et al., 1997; Xu, Jaffé, & Mauzerall, 2007). A wide range of daily CH_4 emissions ($< 0.01 - 1.44$ g CH_4 m^{-2} day^{-1}) have been reported in different studies (Roger & Joulian, 1997). Some of these options which hold positive as well as negative prospects in reducing GHG emissions as well as reducing water use from rice production are summarized in Table 2.1.

Table 2.1: Mitigation options which hold positive as well as negative prospects in reducing GHG emissions from rice fields

GHG	*Mitigation Options*	*Remarks*
CH_4	Water management	Appropriate water management in rice fields, increases or maintains crop yield (Minamikawa et al., 2006) as well as reducing CH_4 emissions. i.e., Alternate wetting and drying has been found to reduce CH_4 emissions 48%-93% (Qin et al., 2010; Linquist et al., 2015b; Xu et al., 2015) however a trade-off between CH_4 and N_2O has been observed (Yang et al., 2013)
	Improving organic matter management	Reducing the use of organic matter (i.e rice straw) or management of organic matter by promoting aerobic decomposition, composting (Yagi & Minami, 1990) or proper timing of application has shown a reduction in CH_4 emissions from rice fields
N_2O	Improving N fertilizer application	Application of only what the crop requires (Minamikawa et al., 2006) by providing an adequate amount of N to attain optimal yields (Linquist et al., 2012)
	Water management	Water-saving technologies must be accompanied by good nutrient management by reducing wastage of fertilizer reduces nitrous oxide emissions (IRRI, 2018)
	Introduction of advanced N fertilizers or inhibitors	Introduction of nitrification inhibitor i.e., Dicyandiamide (DCD) has shown low emissions of both CH_4 and N_2O (Linquist et al., 2012)
CO_2	Water management No or minimum tillage, Increasing C	Drying and re-wetting cycles, No or minimum tillage as well as increasing C input have been found to have a pronounced effect on soil CO_2 fluxes (Borken et al.,

GHG	*Mitigation Options*	*Remarks*
	input i.e., organic amendments	2009; Wu et al., 2010). Liu et al., (2013), Haque et al., (2014) and Y. Xu et al., (2015b), in their findings, observed that CO_2 emissions increase with reduction of irrigation water and reduce with increase in flood water in the rice fields.

2.7.1. Alternate wetting and drying (AWD) as a GHG mitigation option

Alternate drying and wetting (AWD) could be one of the practices for achieving the goal of sustainable rice production while minimizing GHG emissions from rice fields. Alternate wetting and drying is based on draining; by allowing water levels to decline modestly below the soil surface with time, and re-flooding the rice fields repeatedly throughout the growing season.

Flooded rice paddy fields create anaerobic conditions in the saturated soils conducive for methanogenic archaea activities due to the temperate conditions, high moisture and high organic matter content (Khalil et al., 1998). According to (Linquist et al., 2015), rice emits approximately four times as much greenhouse gas (GHG) per ton of product than wheat or maize; mainly due to CH_4 emissions. Flooded rice paddy fields accounts for 9 - 11% of total anthropogenic CH_4 emissions from agriculture (Smith et al., 2014).

AWD has been found to reduce CH_4 emissions (reductions ranging from 11% to 98%), while improving or maintaining rice yield when compared to the conventional rice production practice (Qin, Liu, Guo, Liu, & Zou, 2010; Richards et al., 2014; Xu et al., 2015b; Linquist, et al., 2015). The reduction of CH_4 is attributed to the draining cycle since the methanogenic archaea are affected due to altering of soil water content. AWD changes the population and composition activity of the methanogenic archaea since methanogens are more active in flooded soil conditions as compared to dry soil (Xu et al., 2007 ; Zhang et al., 2011). Draining of the paddy fields decreases CH_4 emissions not only due to the methanogens growth suppression but also due to the increase in the population of methanotrophic archaea (Fazli et al., 2013).

However, the AWD method is known for its drawback, which is based on the inverse relationship between methane (CH_4) and nitrous oxide (N_2O) emissions from rice fields. In brief, during a drying cycle the soils are temporarily aerated which reduces CH_4 emissions, but the aeration also results in nitrification and subsequent denitrification and thus increased N_2O emissions, which may negate or even exceed any mitigation potential from the reduced CH_4 emissions.

These increased N_2O fluxes are thought to be caused by nitrification of nitrate (NO_3^-) during the aeration stage, while the subsequent flooding provides ideal conditions for denitrification, of which N_2O is an intermediary product (Hou et al., 2000; Khalil et al., 2009; Linquist et al., 2012, Xu et al., 2015). These increased N_2O emissions may negate or even exceed any mitigation potential from the reduced CH_4 emissions (Zou et al., 2007; Wang et al., 2011; Lagomarsino et al., 2016).

2.7.2. Alternate wetting and drying (AWD) as water saving irrigation method

Water is an important natural resource that is rapidly becoming scarce mainly as a result of climate change, the growing population and agriculture intensification (Rijsberman, 2006). The ability for the world to meet the increasing food demand is challenged by water scarcity (Hanjra & Qureshi, 2010). Around the world, pressure to reduce water used in irrigation is mounting (Thakur et al., 2016). This is attributed to the fact that; at global level, agriculture accounts for approximately 70 - 80% freshwater abstraction and of this about 85% is used in rice (*Oryza sativa L*) production systems (Jain et al., 2014). For more than half of the world’s population, rice is an important staple crop (FAO, 2013). With high rice production to meet global demands; water use is enormous (Bruderle et al., 2009). According to Bouman & Tuong, (2001), water-use per growing season of rice typically ranges from 1000 - 2000 mm, which corresponds to 2 - 3 times more than other cereal crops. However, a large amount of this water is lost through surface runoffs, deep percolation, evapotranspiration and seepage (Guerra et al., 1998).

Water scarcity arising from factors such as higher competition for water from other non-agricultural sectors, climate change and natural rainfall variability increasingly challenge global rice production (Kraus et al., 2016). With limited fresh water resources, the conventional rice production practice, with its heavy reliance on a continuous supply of water for irrigation, is likely unsuitable.

One mitigation strategy, which over the years has been promoted to not only reduce irrigation water use in rice cultivation, but has also been found to reduce GHG emissions, while improving or maintaining rice yield is the alternate wetting and drying (AWD) irrigation method (Richards & Sander, 2014; Linquist et al., 2015a; LaHue, Chaney, Adviento-Borbe, & Linquist, 2016). Alternate wetting and drying (AWD) water saving irrigation method is one way that can be used to reduce the unproductive outflows from rice paddies and increase water productivity.

2.8. Research gap

To address the paucity of data on GHG fluxes from Kenyan rice production as well as the lack of studies investigating AWD and CF on different soil types, we quantified CH_4, N_2O and CO_2 emissions from rice production under both irrigation managements and on two different soil types that are commonly found in Mwea Irrigation Scheme. The aim of the study was mainly to quantify differences in GHG emissions from AWD and CF fields on two different soil types and to derive yield scaled GHG emissions for each of the four treatments. The study reports quantified greenhouse gas emissions, GWP and yield-scaled GWP from rice fields in Kenya and highlights the importance of water management strategies for the simultaneous benefits of increased/maintained yields, efficient water-use and contribution to global agriculture greenhouse gas mitigation. Also, little data is available on the correlation between soil physical, chemical and biological properties and

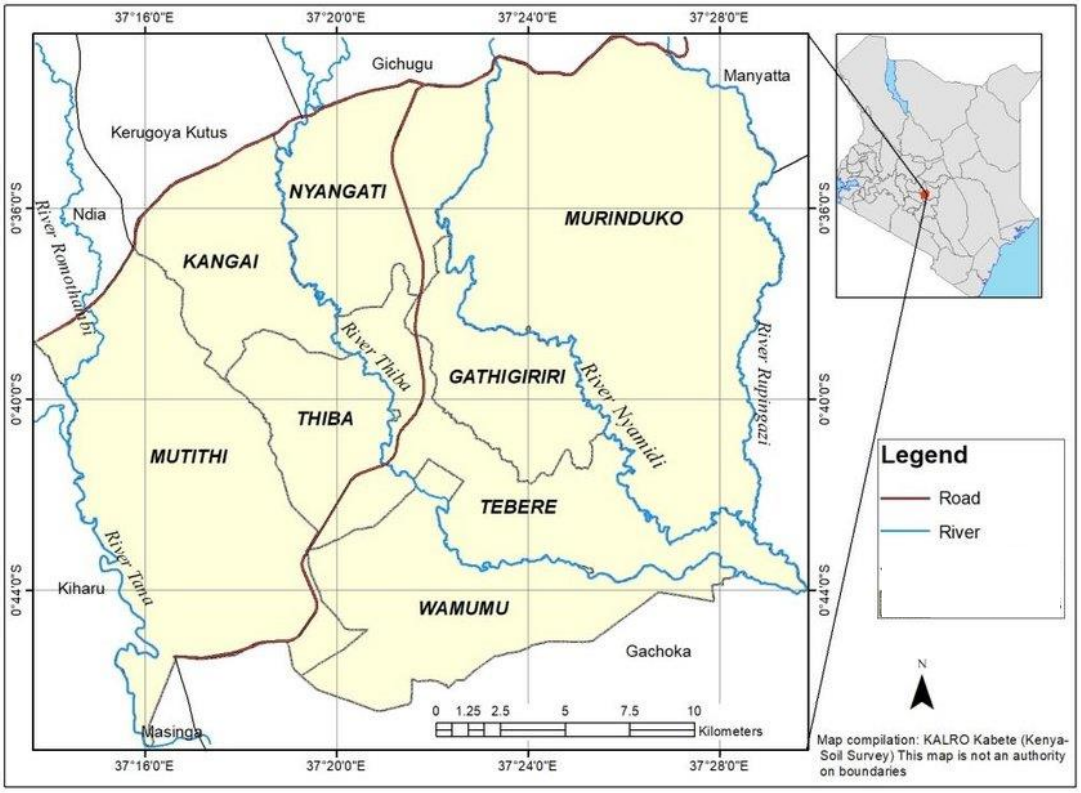
GHG emissions from rice fields in sub-Saharan Africa (SSA). As management effects on the GHG balance tend to be site specific, it is critical to measure GHG emissions from rice production systems in Kenya to determine whether changes in water management will result in increased, similar or decreased GHG emissions. In order to identify mitigation options that suit local conditions, it is important to quantify these GHG emissions from rice fields in the country.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Experimental Site Description

This study was carried out within the Mwea irrigation scheme (MIS) established by the Government of Kenya and managed by the National Irrigation Board. The scheme is located on the lower slopes of Mt. Kenya, Kirinyaga County in the central part of Kenya.



Map compilation: KALRO Kabete (Kenya-Soil Survey) This map is not an authority on boundaries

Figure 3.1: Base map of the Mwea rice scheme, Kenya

Source: (Nakhungu, Margaret, Deborah, & Peterson, 2019)

It lies between latitudes 37°13’E and 37°30’E and longitudes 0°32’S and 0°46’S (Figure 3.1). The MIS is divided into five sections: Tebere (the largest single section), Thiba, Mwea, Wamumu and Karaba (Muhunyu, 2012). The experiment was established within the Tebere section at the Kirogo-Mwea research farm managed by Kenya Agriculture and Livestock Research Organization (KALRO) (00°38S; 37°22E; elevation 1159m.a.s.l.).

The dominant soils in the Tebere section, are pellic vertisols (characterized by imperfectly drained, very deep, dark grey to black, firm to very firm, boulder and stony, cracking clay) and verto-eutric nitisols (which are characterized by well drained, very deep, dark reddish brown, friable to firm clay) (Frederick & Owido, 1981). Within the research farm, the dominant soil is the verto-eutric nitisols; however, the pellic vertisols were brought in the research farm in 2015 to be used for various rice researches within the farm.

3.2. Experimental Treatments and Design

The experiment was laid out as split plot with soil type as the main plot and water regime as the subplot. The two soil types were vertisols (VS) and nitisols (NS). The two water regimes were alternate wetting and drying (AWD) and continuous flooding (CF). The area of each subplot (Vertisols under continuous flooding -CFVS, Vertisols under alternate wetting and drying - AWDVS, Nitisols under continuous flooding - CFNS, nitisols under alternate wetting and drying - AWDNS) was 105.3m^2. The experiment layout within the research farm is a shown in Figure 3.2.

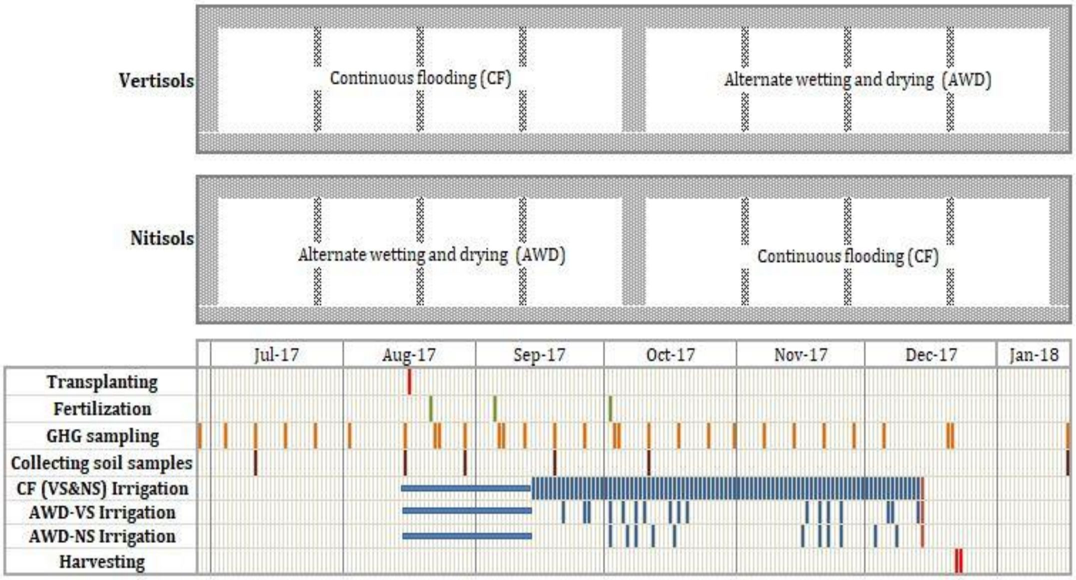


Figure 3.2: Schematic field layout and timeline in days / months when certain events were done for the duration of the experiment at the Kirogo Rice Research Farm within the Mwea Irrigation Scheme, Kenya

Source: Jane Gitonga, 2017

The water regimes in VS were separated by a masonry wall 0.3 m wide and 0.4 m above the soil surface and 1 m deep (Figure 3.3) which was also lined with a 250-gauge black polyethylene sheeting to minimize water flow between the water regimes. In the NS, water management regimes (AWD and CF) were 1m apart from each other. The water management regimes in the NS were lined with PVC corrugated sheets: 1.5 m deep and raised 0.4m above the soil surface (Figure 3.4), and also lined with a 250-gauge black polyethylene sheeting to minimize water flows between the regimes.

Figure 3.3: Masonry wall separating AWD and CF water regimes in the VS soil. Basmati 370 rice variety 5 days after transplant during basal fertilizer application

Source: Jane Gitonga, 2017

Figure 3.4: PVC corrugated sheets in the Nitisols. The AWD and CF plots were 1m apart from each other

Source: Jane Gitonga, 2017

3.3. Field Management

Land preparation for both soil types was standard wet tillage and harrowing. This involved submerging the fields for 7 days, then conducting manual breaking up of the soil. This was followed by wet harrowing and puddling. The fields were then leveled using a wooden leveling bar. The rice seedlings were prepared by first soaking the seeds for three days. The pre-geminated seeds were then sown in the nursery which was not flooded but kept moist. Basmati 370 rice seedlings were manually transplanted (two plants per hill) into puddled soils at a spacing of 0.30 m x 0.15 m on 16 August 2017. Basal fertilizer was applied five days after transplanting in all subplots by broadcasting N:P:K 17:17:17 (N in the form of ammonium) at a rate equivalent to 25 kg N ha^{-1}. Ammonium sulphate was applied as a top dressing at a rate equivalent to 25 kg N ha^{-1} 20 and 48 days after transplant (DAT) on 05 September and 02 October, 2017, respectively.

All subplots were flooded to 0.03 m until 30 DAT. In the CF treatment, the water level was then increased to about 0.10 m height. For the AWD, the water level was allowed to subside via percolation and evapotranspiration, and the plots were irrigated only when the water table dropped to about 0.20 m below the soil surface. The AWD subplots were then re-flooded to a water level of about 0.05 m above soil surface. To monitor and measure water table depth in the AWD subplots, three field water tubes (0.1 m diameter plastic pipe cut into 0.3 m lengths and perforated with holes from 0.1 m to the 0.2 m mark on the lower circular surface) were embedded in each subplot for the entire crop growing season.

The water table depth in the AWD subplots was monitored and measured from the installed field water tubes on sampling days using a measuring ruler. The average of the three field water tubes gave the approximate depth of the water table of the entire subplot. The water level above the soil surface in the CF subplots was also determined using a measuring ruler. The plots were irrigated using a pipeline system from an existing borehole on the research farm or from pumping water from the unlined open water channels within the research farm. The two water sources were equipped with a water flow meter to measure water input in each treatment plot from transplanting to drainage. The exact dates when various activities in the experimental farm were undertaken are indicated in Table 3.1.

Table 3.1: Calendar of events for the duration of the experiment

Event	CF	AWD
Soaking of seeds	Soaking of Basmati 370 seeds was done on 23.07.17	Soaking of Basmati 370 seeds was done on 23.07.17
Seed sowing	The seeds were sown in the nursery on 26.07.17	The seeds were sown in the nursery on 26.07.17
Land preparation	Fields submerged for 7 days, then conducting manual rotavation, followed by wet harrowing and puddling and leveling from 02.08.17 to 14.08.17	Fields submerged for 7 days, then conducting manual rotavation, followed by wet harrowing and puddling and leveling from 02.08.17 to 14.08.17
Transplanting	Pre-germinated seedlings were manually transplanted at a spacing of 30 cm x 15 cm on 16.08.17	Pre-germinated seedlings were manually transplanted at a spacing of 30 cm x 15 cm on 16.08.17
Fertilizer application	Basal application on 21.08.17 1st and 2nd top dressing were applied on 05.09.17 and 02.10.17 respectively	Basal application on 21.08.17 1st and 2nd top dressing were applied on 05.09.17 and 02.10.17 respectively
Water management	Flooded to about 3cm until 30DAT to allow crop establishment.	Flooded to about 3cm until 30DAT to allow crop establishment.

Event	CF	AWD
	Continuously flooded with 10cm water from 15.09.17. Irrigation stopped a week before harvest on 14.12.17.	AWD started on 15.09.17. Irrigation stopped a week before harvest on 14.12.17.
Harvesting	Harvest was done on 22-23.12.17	Harvest was done on 22-23.12.17

DAT – Days after Transplant

The soil temperature (°C) and volumetric water content (m^3 m^{-3}) at 0.05 m depth of soil adjacent to sampling chambers were measured using a hand-held digital sensor (ProCheck, Decagon Devices Inc., Pullman WA, USA). Irrigation in both treatments was discontinued a week before harvesting, to allow for maximum transfer of nutrients to the grains according to Wanjogu et al. (1995). Rainfall and air temperature data were collected from a weather station located in the research farm. Harvesting occurred on 22nd and 23rd December 2017.

3.4. Greenhouse Gas Sampling and Analysis

Greenhouse gas (GHG) fluxes were measured using static GHG chambers (Butterbach-Bahl et al., 2011). The chambers consisted of two components: circular base units and chamber lids (Figure 3.5). First, circular base units (0.30 m in diameter) were placed 0.05 m into the soil with approximately 0.15 m of the collar remaining above the soil surface. These bases were left in the soil throughout the entire sampling period, only being removed during land preparation. A hole was drilled in the upper side of the bases and equipped with sealable tubes which remained open to allow water movement into the bases unit during irrigation.

The second component was the chamber lid, which consisted of a white, 30-L PVC bucket equipped with a rubber seal, a sampling port, a vent tube, a battery driven fan, and a thermometer port. The rubber seal was used to ensure a gas tight seal during chamber deployment, while the vent tube was used to equalize pressure between the inside and outside of the chamber. The fan ensured air mixture to avoid potential gas gradients in the chamber during sampling (Butterbach-Bahl, Kiese, & Liu, 2011) and the sealed thermometer port allowed the monitoring of the chamber headspace air temperature during deployment. Boardwalks were installed in the plots to avoid disturbing the soils during sampling (Figure 3.5).

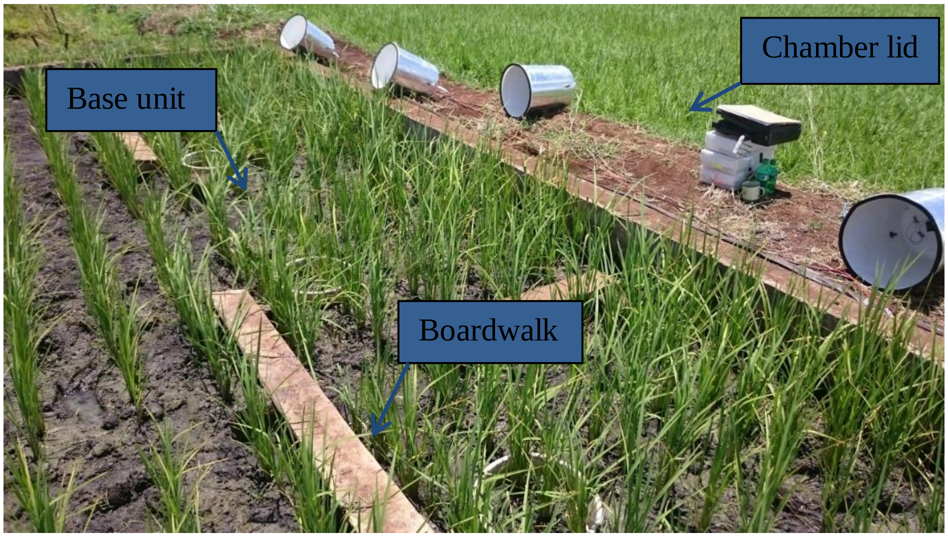


Figure 3.5: Base units installed in the AWD-VS subplot, chamber lids and boardwalks in preparation for sampling

Source: Jane Gitonga, 2017

Sampling of the chamber headspace commenced immediately after deploying the chamber lid on top of the respective base unit (Figure 3.6a) and sealing with binder clips (Figure 3.6b). Sampling started at about 0900h and ended at about 1400h each sampling day. Gas samples were collected from each chamber by inserting a needle connected to a 60 ml plastic syringe with a luer-lock (Figure 3.6c) immediately upon deployment (T0) of the chamber lids onto the base units, and after 10, 20 and 30 minutes (T10, T20 and T30 respectively). A total of 4 samples were collected from each chamber. Each sample was immediately transferred into a 20 ml pre-evacuated glass vial (Figure 3.6d). The vials were sealed with butyl rubber septa to avoid gas losses prior to gas analysis and were over-pressurized to reduce the potential for contamination with ambient air.

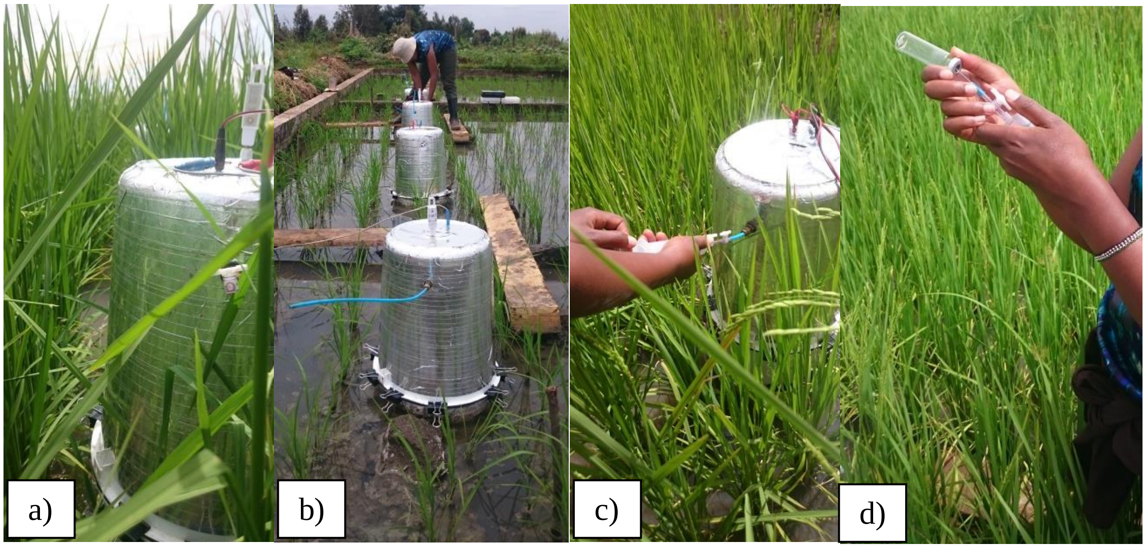


Figure 3.6: Sampling procedure; a) placing the chamber lids, b) sealing with binder clips, c) inserting a needle connected to a 60 ml plastic syringe, d) transferring gas samples in 20 ml pre-evacuated glass vials

Source: Jane Gitonga, 2017

Each chamber base accommodated three rice hills with two rice plants per hill. Sampling started a month before seedling transplantation in the fallow season and continued every once a week from transplant to harvest. However during fertilization and drainage, sampling was done twice per week. A final sampling was carried out after harvest on 17th January 2018.

All gas samples were analyzed within a week from the day of sampling at the Mazingira Centre within the International Livestock Research Institute (ILRI) in Nairobi, Kenya.

Alongside the headspace sampling, the water height and base unit height were also measured from four points within the base unit using a tape measure to obtain the headspace volume for each chamber at each sampling date. Furthermore, chamber headspace air temperatures were measured at the beginning, middle and end of sampling.

Figure 3.7: Gas chromatograph - SRI 8610C at Mazingira centre lab, ILRI

Source: Jane Gitonga, 2017

The GHG concentrations (CH_4, N_2O and CO_2) were determined using a gas chromatograph (GC) - SRI 8610C 2.74m Hayesep-D column (Figure 3.7). The GC was fitted with a flame ionization detector (FID) for CH_4 and CO_2 (CO_2 passed through a methanizer) and also Ni-electron capture detector (ECD) for N_2O with 20 mL/min flow rate for the Nitrogen (N_2) carrier gas (Pelster et al., 2017). The electron capture detector was set at 340°C, and the flame ionization detector was set at 350°C. The GHG fluxes from the rice fields were calculated from the rate of concentration change in the chamber headspace over time.

The fluxes were corrected for mean chamber temperature and air pressure, as shown in (Equation 1).

$$F = \left(\frac{\Delta c}{\Delta t}\right) \times \left(\frac{V}{A}\right) \times \left(\frac{M}{Vm}\right) \qquad (Equation\ 1)$$

where F is the CH_4 (mg CH_4-C m^{-2} h^{-1}), CO_2 (mg CO_2-C m^{-2} h^{-1}) and N_2O (μg N_2O-N m^{-2} h^{-1}) flux, (Δc/Δt) is the rate of increase of each gas concentration over time, V is the volume of the chamber headspace (m^3), A is the surface area of chamber (m^2), M is the molar mass of the element (N for N_2O, C for CH_4 and CO_2) and Vm is standard gaseous molar volume (m^3 mol^{-1}) corrected for temperature and atmospheric pressure considering the ideal gas law.

The minimum detection limit computed according to Parkin et al., (2012) was on average 0.013 CH_4-C mg m^{-2} h^{-1}, 1.995 N_2O-N μg m^{-2} h^{-1} and 1.702 CO_2-C mg m^{-2} h^{-1}. The cumulative GHG emissions from each sub-plot were calculated using linear interpolation between the individual sampling days. During the crop growing season, the presence of rice plants in the chambers during sampling meant that measured CO_2 included both plant respiration CO_2 and soil respiration as well. The CO_2 equivalent (CO_2-eq) for CH_4 and N_2O emissions was calculated using (Equation 2):

$$CO_2eq = (CH_4\ x\ 34 + N_2O\ x\ 298) \qquad (Equation\ 2)$$

Where; CO_2-eq is the CO_2 equivalent (Kg CO_2-eq ha^{-1}), CH_4 is the total amount of methane emission (kg ha^{-1}), N_2O is the total amount of nitrous oxide emission (kg ha^{-1}), 34 and 298 are the radiative forcing potentials for CH_4 and N_2O, respectively (Myhre, Shindell, Bréon, Collins, Fuglestvedt, et al., 2013), to CO_2 over a 100-yr time horizon.

3.5. Soil Sampling and Analysis

Soil samples for determination of inorganic N concentration (NH_4^+-N and NO_3^--N) were collected from each sampling plot at two points near the chamber frames using a soil auger

(0-20 cm). The soils were manually homogenized before transferring in labeled zip-lock bags. All samples were immediately placed in a cool box with ice and transported to the lab where they were stored in a refrigerator (about 4°C) for fewer than three days before analysis. Soil samples for inorganic N concentration were collected twice before transplant and once in August, October, December and in January 2018 after harvest. For extraction, approximately 20 g of each soil sample were mixed with 100 ml of 2M KCL for one hour on a mechanical shaker.

The NO_3^--N analysis was done by diazotizing with sulphanilic acid and naphthalene sulphonic acid to form a highly coloured dye that was measured colorimetrically using Helios Delta Spectrophotometer (9423 UVG, Thermo Electron Corporation, England), while NH_4^+-N concentrations were measured using the green indophenol method (655nm) using the same spectrophotometer. Approximately 30 g of the remaining soil samples were oven dried at 105°C until a constant soil weight was achieved to determine soil water content. After harvest, soil samples to determine soil pH, total C and N content, soil texture analysis and bulk density were collected at each sampling plot at two points near the chamber frames. Soil samples for soil pH, C and N measurements were taken at 0-20cm while for the soil texture, soil samples were collected using a soil auger at various depths (0-10cm, 10-20cm, 20-30cm, 30-50cm). Standard test methods of analyzing these soil properties were used. Soil texture was determined by the hydrometer method (Gee & Bauder, 1979) (Figure 3.8).

Figure 3.8: Soil texture analysis using the hydrometer method at Mazingira centre lab, ILRI for soils collected at Kirogo Rice Research farm

Source: Jane Gitonga, 2017

Soil pH was measured using a pH meter (Jenway model 3540, Bibby Scientific Ltd, UK) in soil to water ratio of 1:2.5 after shaking the suspension for ten minutes. Soil samples to determine the bulk density taken from each sampling plot at two points near the chamber frames using 100 cm^3 soil core samplers were oven dried at 105°C until constant weight was achieved. Total C and N concentrations were analyzed from ground soil samples using the elemental analyzer (Elementar, vario MAX cube, Germany).

3.6. Statistical analysis

An analysis of variance (ANOVA) was done using R studio (R studio version 3.4.3) to analyze the effects of water regimes, soil type and their interaction on GHG fluxes. Water regimes (AWD and CF) and soil type (Vertisols [VS] and Nitisols [NS]) were treated as fixed factors while the chambers were treated as random factor. Tukey HSD range test was done as a post-hoc multiple comparison test when the analysis of variance was significant at $P < 0.05$ probability level.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Climatic Conditions

The cumulative rainfall received in the fallow season (June 27th 2017 - August 5th 2017 & 24th December 2017 - 17th January 2018) and in the crop growing season (16th August 2017 - 23rd December 2017) was 28.6 mm and 406.5 mm respectively. Rainfall, temperature and relative humidity at the Kirogo Rice Research farm from start (Jun 27th 2017) of gas sampling to the end (17th January 2018) of the sampling period are as shown in Table 4.1 and Appendix 1.

Table 4.1: Climatic conditions from June 2017 to January 2018 at the Kirogo Rice Research farm, within the Mwea Irrigation Scheme, Kenya

Year	Month	Rainfall (mm)	Temperature (°C)	Relative humidity (%)
2017	June*	0.4	21.3	63.3
	July	12.5	20.6	64.2
	August	18.1	21.7	59.2
	September	23.6	22.3	55.6
	October	149.6	23.6	59.0
	November	230.8	21.5	74.6
	December	0.1	21.6	65.9
2018	January**	0.00	21.8	62.1

*Weather data from (start of sampling) 27th June – 30th June 2017

**Weather data from 1st January – 17th January 2018 (last day of sampling)

Rice growing season in Mwea Irrigation Scheme (MIS) is usually from July – December each year, which coincides with the short rains experienced in Kenya in the months of October to November. Average daily air temperature during the sampling period (from fallow season to end of crop growing season) ranged from 19°C to 26°C (Appendix 1).

4.2. Soil Properties

In this study, soil texture analysis showed that vertisols soil had 69.44% clay content while the sand and silt content were 13.88% and 16.68% respectively. For nitisols the clay, sand and silt contents were 47.59%, 25.08% and 27.33% respectively (Table 4.2). Vertisols had a higher clay content compared to the nitisols, while the nitisols had higher sand and silt content compared to the vertisols. Soils with high clay content have more fine particles and thus can retain more water and nutrients needed by the rice plants (Obasi et al., 2015; Dou et al., 2016). The nitisols had higher sand and silt particles as compared to the vertisols, hence well drained compared to the vertisols. The vertisols are characterized as dark grey to black, poorly drained and cracking clay while the nitisols are characterized as dark reddish brown, well drained and fragile to firm clay (Sombroek, Braun, & van der Pouw, 1982).

Rice is known to prefer slightly acidic soils, but can grow in soils with a pH range of 5-8 (Dhanyac, 2011; Matsuo, Ae, Vorachit, & Thadavon, 2015). The pH of the two soil types was within this range with the nitisols being acidic (pH = 5.7) and the vertisols being neutral pH = 7.2 (Table 4.2). The bulk density of the vertisols (0.91 g cm^{-3}) was lower than the nitisols (1.14 g cm^{-3}). Generally soils with finer texture have lower bulk density (Obasi et al., 2015; Dou et al., 2016). Thus, the low bulk density for the vertisols compared to the nitisols can be attributed mainly to the fact that they have finer texture.

Table 4.2: Soils physical and chemical characteristics for the study site Kirogo Rice Research Farm

Properties	**Vertisols**	**Nitisols**
Sand (%)*	13.88 ±1.39	25.08 ± 5.65
Silt (%)*	16.68 ± 2.11	27.33 ± 3.49
Clay (%)*	69.44 ± 1.71	47.59 ± 8.41
pH	7.2	5.7
Bulk density (g cm^{-3})	0.91 ± 0.08	1.14 ± 0.04
Total Carbon (%)	1.54 ± 0.08	1.87 ± 0.33
Total Nitrogen (%)	0.08 ± 0.004	0.12 ± 0.03
C:N Ratio	20.47	15.74
NO_3^- - N**	0.25 ± 0.05	0.22 ± 0.10
NH_4^+ - N**	2.30 ± 0.55	3.63 ± 0.16

[1] Numbers in the table represent means ± standard deviation (n=4)

[2] *Soil samples for soil texture analysis were taken from 0-50cm depth

[3] **Soil samples for NO_3^- - N and NH_4^+ - N were taken from 0-20cm depth

The total carbon (C) content in both soils was higher than the total nitrogen (N) content. However, the vertisols had a higher C:N ratio compared to the nitisols. The vertisols had slightly higher NO_3^- - N compared to the nitisols, but lower NH_4^+ - N compared to the nitisols (Table 4.2).

The mean soil temperature (°C), mean volumetric soil water content (m^3m^{-3}) and water table ranges (cm) over the crop growing season from transplant to harvest are shown in Table 4.3. Soil water content in all subplots increased drastically when irrigation started at the beginning of the rice growing season (Figure 4.1a). However after seedling transplanting, the soil water content remained relatively constant throughout the crop growing season. Soil temperature in all plots showed undulant fluctuation in both the fallow and rice growing season (Figure 4.1b). There was no significant difference in soil temperatures from all the subplots over the sampling period (Table 4.3).

Table 4.3: Mean volumetric soil water content, mean soil temperature and water table ranges for each treatment during the rice growing season at the Kirogo Rice Research farm

Treatment	Mean volumetric soil water content[1]	Mean soil temperature[2]	Water table range[3]
	$m^3\ m^{-3}$	^{o}C	cm
CF-VS	$0.64^{a} \pm 0.005$	$29.4\ ^{ns} \pm 1.00$	3.0 – 10.0
AWD-VS	$0.63^{a} \pm 0.009$	$30.1\ ^{ns} \pm 1.02$	-20.0 – 5.0
CF-NS	$0.53^{b} \pm 0.010$	$30.1\ ^{ns} \pm 0.64$	3.0 – 10.0
AWD-NS	$0.49^{b} \pm 0.018$	$31.2\ ^{ns} \pm 0.83$	-20.0 – 5.0

CF-VS – Vertisols under continuous flooding, AWD-VS – Vertisols under alternate wetting and drying, CF-NS – Nitisols under continuous flooding, AWD-NS – Nitisols under alternate wetting and drying

[1&2] Means ± SE followed by the same letter are not significantly different at $P < 0.05$

[3] Numbers are ranges of the water table level in each treatment over the crop growing season

^{ns} no significance at $P < 0.05$

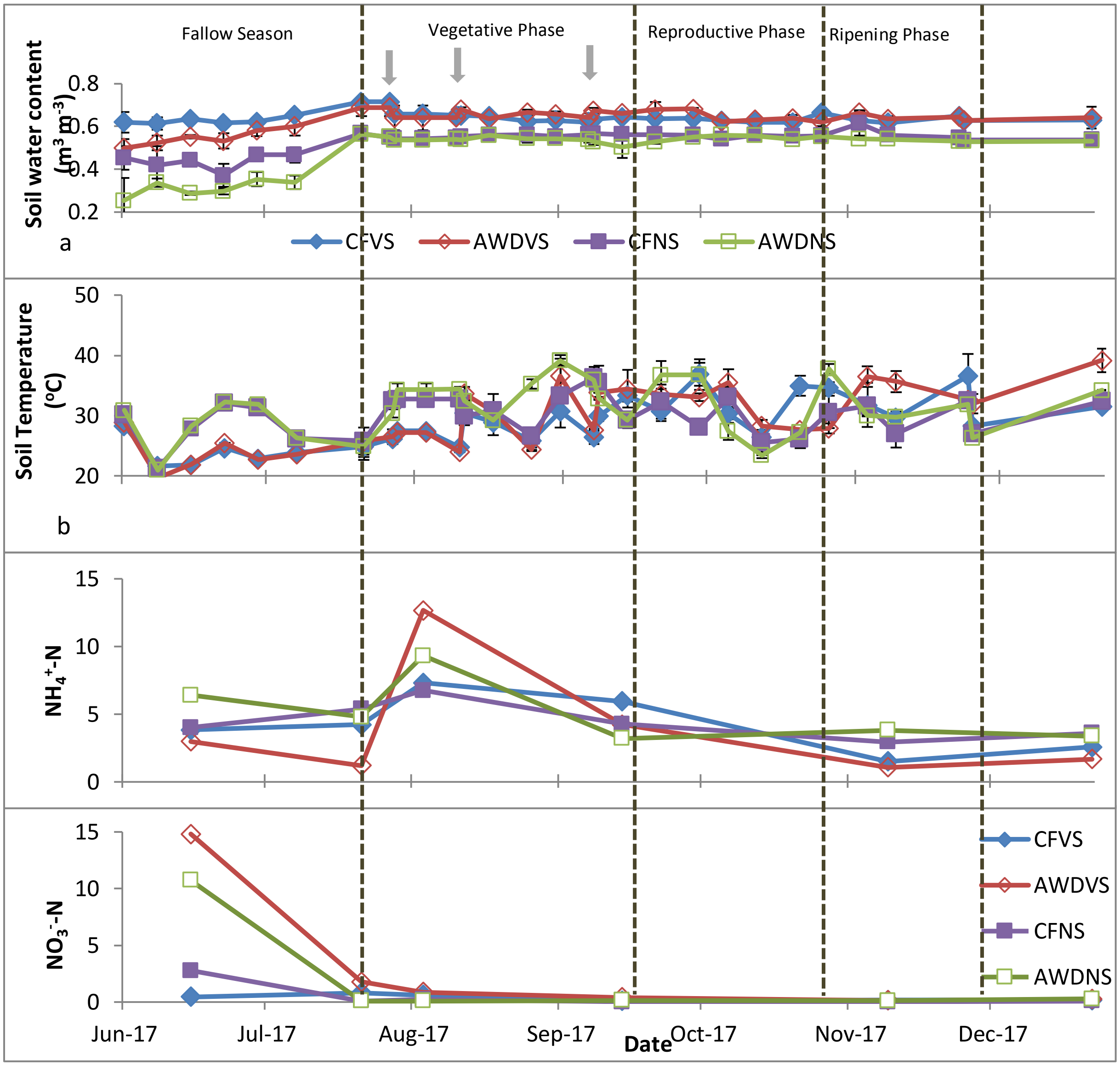


Figure 4.1: Mean volumetric soil water content (m^3m^{-3}), mean soil temperature (ºC), Ammonium (NH_4^+) and Nitrate (NO_3^-) during the rice growing season at the Kirogo Rice Research farm

[1] Every data point is an average (n = 4) measured at 5cm depth in soil adjacent to sampling chambers;
[2] Soil samples for NO_3^- - N and NH_4^+ - N were taken from 0-20cm depth;
[3] CF – Continuous flooding, AWD – Alternate wetting and drying, VS – Vertisols, NS – Nitisols;
[4] Vertical dashed lines corresponds to the period of sampling during the fallow and the growing season;
[5] Bars indicate standard deviation of four points
[6] Arrows (left – right) denotes basal application, 1st top dressing and 2nd top dressing respectively.

4.3. Greenhouse Gas Emissions

4.3.1. Methane Emissions

The methane (CH_4) fluxes shown in Figure 4.2 are averages of emissions from the four chambers in each subplot throughout the fallow and rice growing season. During the sampling period, CH_4 fluxes from all the subplots ranged from -0.15 – 2.6 mg CH_4-C m^{-2} h^{-1}. CH_4 emissions in the continuously flooded (CF) subplots were significantly higher ($P < 0.001$) than in the alternate wetting & drying (AWD) subplots (Table 4.7). However, the continuously flooded vertisols (CF-VS) had higher CH_4 emissions than ($P < 0.001$) continuously flooded nitisols (CF-NS).

Initially, the CH_4 emissions in the CF-VS remained low from transplant to mid-September when water levels were low to allow rice crop establishment and then gradually increased with peaks of 1.17, 2.39, 2.56 mg CH_4-C m^{-2} h^{-1} after the 2nd top dressed fertilizer application, mid-reproductive stage and then mid-ripening stage respectively (Fig. 4.2a). In the CF-NS, emissions gradually increased after transplant with peaks of 0.71, 0.67 and 0.58 mg CH_4-C m^{-2} h^{-1} after the 1st top dressed fertilizer application, 2nd top dressed fertilizer application and mid-ripening stage respectively (Fig. 4.2c). At the end of the reproductive stage, CH_4 emissions decreased in both CF subplots. However, during the ripening stage, CH_4 emissions increased briefly before decreasing when the subplots were drained a week before harvest.

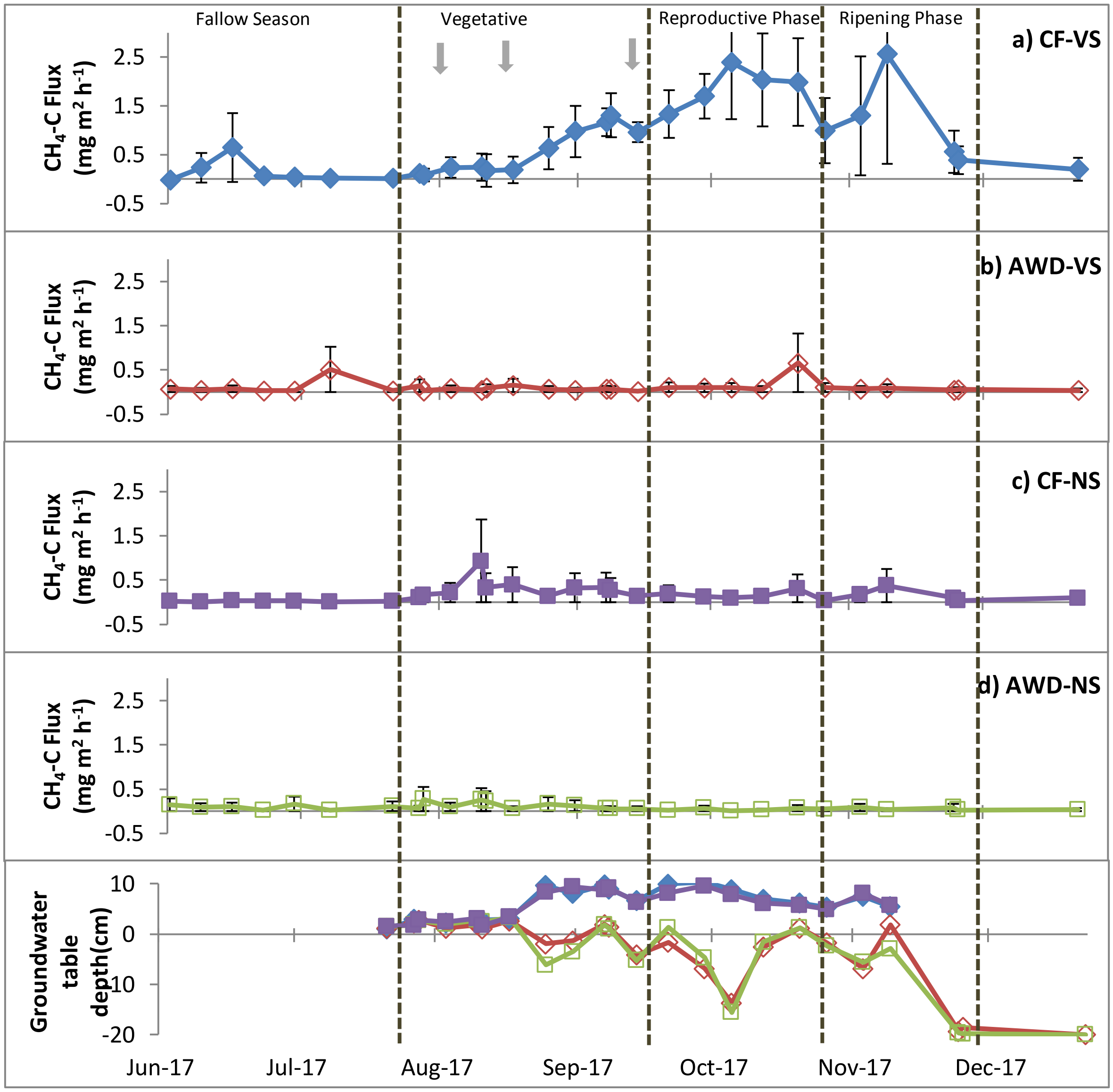


Figure 4.2: Variation in CH_4 (mg CH_4-C m^{-2} h^{-1}) emissions over the sampling period in each treatment with corresponding water table depth (cm)

[1] Vertical dashed lines corresponds to the period of sampling during the fallow season and the growing season subdivided into developmental stages of rice growth (vegetative stage: from transplant to panicle initiation), reproductive stage (from panicle initiation to flowering) and ripening stage (flowering to mature/harvest stage). Bars indicate standard deviation of four replicates

[2] Arrows (left – right) denotes basal application, 1st top dressing and 2nd top dressing respectively.

Table 4.4: Seasonal cumulative CH_4 (Kg CH_4-C ha^{-1}) emissions as affected by CF and AWD water regimes in the two soil types

Treatment	**Soil**	
	VS	**NS**
	(Kg CH_4-C ha^{-1})	
CF	$18.55^a \pm 0.85$	$5.77^b \pm 0.20$
AWD	$2.19^c \pm 0.07$	$0.90^c \pm 0.04$
Analysis of Variance		
Treat.	$P < 0.001$	
Soil	$P < 0.001$	
Treat. x soil	$P < 0.001$	

[1] CF – Continuous flooding, AWD – Alternate wetting and drying, VS – Vertisols, NS – Nitisols

[2] Numbers in the table represent means ± SE; SE refers to the standard error of measurement for four replicates

[3] Means followed by the same letter are not significantly different at $P < 0.05$

Methane fluxes in the AWD-VS averaged 0.13 and 0.06 mg CH_4-C m^{-2} h^{-1} during the crop growing season and fallow season respectively (Fig. 4.2b), while emissions in the AWD-NS plot averaged 0.07 mg CH_4-C m^{-2} h^{-1} in the crop growing season and -0.03 mg CH_4-C m^{-2} h^{-1} in the fallow season (Fig. 4.2d). The alternate wetting & drying (AWD) water regime significantly reduced ($P < 0.001$) CH_4 emissions (Table 4.7); with consistently low fluxes throughout the rice growing seasons. However, CH_4 emissions in the AWD-VS, were higher ($P < 0.001$) than in the AWD-NS (Table 4.7). AWD-VS reduced CH_4 emissions by 88% compared to CF-VS while AWD-NS reduced CH_4 emissions by 84% compared to CF-NS.

The introduction of aerobic soil conditions with alternate wetting & drying (AWD) significantly ($P < 0.001$) reduced seasonal cumulative CH_4 emissions in both soil types compared to continuously flooded (CF). This showed that water management regimes had a significant effect on CH_4 emissions from the rice field. Various studies have reported significant reduction of growing season CH_4 emission; ranging from 11% to 98% reduction, (Linquist et al., 2015a; LaHue et., 2016; Lagomarsino et al., 2016) with the introduction of AWD. According Yan et al. (2005), single and multiple rice field drainages reduced average CH_4 fluxes by 60% and 52% respectively, compared to CF.

The reduction of CH_4 emissions in this study may be attributed to a number of factors: i) methanogenic archaea bacteria; responsible for CH_4 production, were inhibited by the aerobic soil conditions when water levels were allowed to subside via percolation and evapotranspiration in the AWD treatments. These conditions changed their population, composition, and activity (Xu et al., 2007; Zhang et al., 2011; Fazli et al., 2013); ii) in both soils types under AWD, lowering the surface standing water depth decreased CH_4 emissions not only via suppression of the methanogens but also because oxygen penetration into the soil could have increased the population of methanotrophic bacteria (Fazli et al., 2013), which oxidize existing methane to CH_3OH (Zou et al., 2007; Xu et al., 2007). The remaining un-oxidized methane was then released to the atmosphere through the aerenchyma cells of the rice plants (Neue & Sass, 1994); iii) according to Hou et al. (2000) and Ramu et al. (2012) available organic carbon i.e., root exudates, sloughed-off cells, decay of roots, soil organic matter and plant litter, control methane production and is high in flooded soils with high organic carbon content. Because of increased CH_4 transportation through the rice aerenchyma cells (Pittelkow, Adviento-Borbe, Hill, Six, van Kessel, et al., 2013), CH_4 emissions from rice production tend to be low during the early vegetative stages and increase during the reproductive stages as was observed in this study (Figure 4.2)

The type of soil had a significant effect ($P < 0.001$) on CH_4 emissions. In the VS soil, CH_4 emissions were higher than in the NS soil indicating that soil type had an influence on the CH_4 emissions irrespective of the water management regime. Various studies (Wang et al., 1992; Mitra et al., 2002; Jain et al., 2004; Bao et al., 2014) have shown that differences in soil characteristics such as pH, organic carbon and nitrogen pools, water holding capacity, texture, among other factors are important factors that regulate the CH_4 emissions from rice fields. Also, according to Minamikawa et al., (2006), Bao et al., (2014), the population of methanogens (CH_4 production) and methanotrophs (CH_4 oxidation) varies among soil types.

The high CH_4 emission observed from the VS soil; compared to the NS soil, were attributed to: i) near neutrality of the VS (pH = 7.2) compared to the nitisols (pH = 5.7). Methane producing archaea are neutrophilic hence soil conditions with a pH range of between 6.5 – 7.5 have been observed to have the highest CH_4 production (Wang et al., 1992; Mitra et al., 2002 ; Bao et al., 2014); ii) high clay content and water holding capacity of the VS soil could have resulted in completely reduced soil conditions conducive for the methanogens (Sander et al., 2014). This study also provided evidence that CH_4 emissions were significantly influenced by the interactions of water regimes and soil type. ANOVA indicated that water regime, soil type as well as their interaction, all strongly affected cumulative seasonal CH_4 fluxes ($P < 0.001$) (Table 4.7). The effect of the water regime on the CH_4 emissions depended on whether the soils were VS or NS. Also, the effect of the soil type on CH_4 depended on whether the soil was under CF or AWD. VS soils emitted higher CH_4 emissions both under CF and AWD compared to the NS, however, the CH_4 emissions were higher in the VS under CF than under AWD. This was mainly attributed to the VS soil physical and chemical characteristics that favor methane production as well as the flooded soil condition.

4.3.2. Nitrous Oxide Emissions

During the sampling period, N_2O fluxes from all the subplots ranged from -7.66 – 1237.58 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$. Low levels of N_2O emissions were observed in the fallow season in all sub-plots (Figure 4.3). During the rice growing season, N_2O emissions were consistently low with sudden peaks observed following fertilizer application. Major peaks were observed in the nitisols (854.05 and 1237.58 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ in the CF-NS (Fig 4.3c) and AWD-NS (Fig 4.2d) respectively) following basal fertilizer application as compared to the vertisols where minor peaks of 140.85 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ and 48.78 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ were observed in the CF-VS (Fig 4.3a) and AWD-VS (Fig 4.3b) respectively.

However, the amplitudes of the peaks dropped and remained low over the duration of the crop growing season with minor peaks of 208.49 µg N_2O-N m^{-2} h^{-1} and 107.98 µg N_2O-N m^{-2} h^{-1} observed later in the AWD-VS (Fig 4.3b) and AWD-NS (Fig 4.2d) respectively, following 2nd top dressed fertilizer application. Similar to the CH_4 emissions, N_2O emissions were affected by the water regime and type of soil and their interaction. Continuously flooded subplots significantly inhibited the N_2O emissions while introduction of AWD increased N_2O emissions.

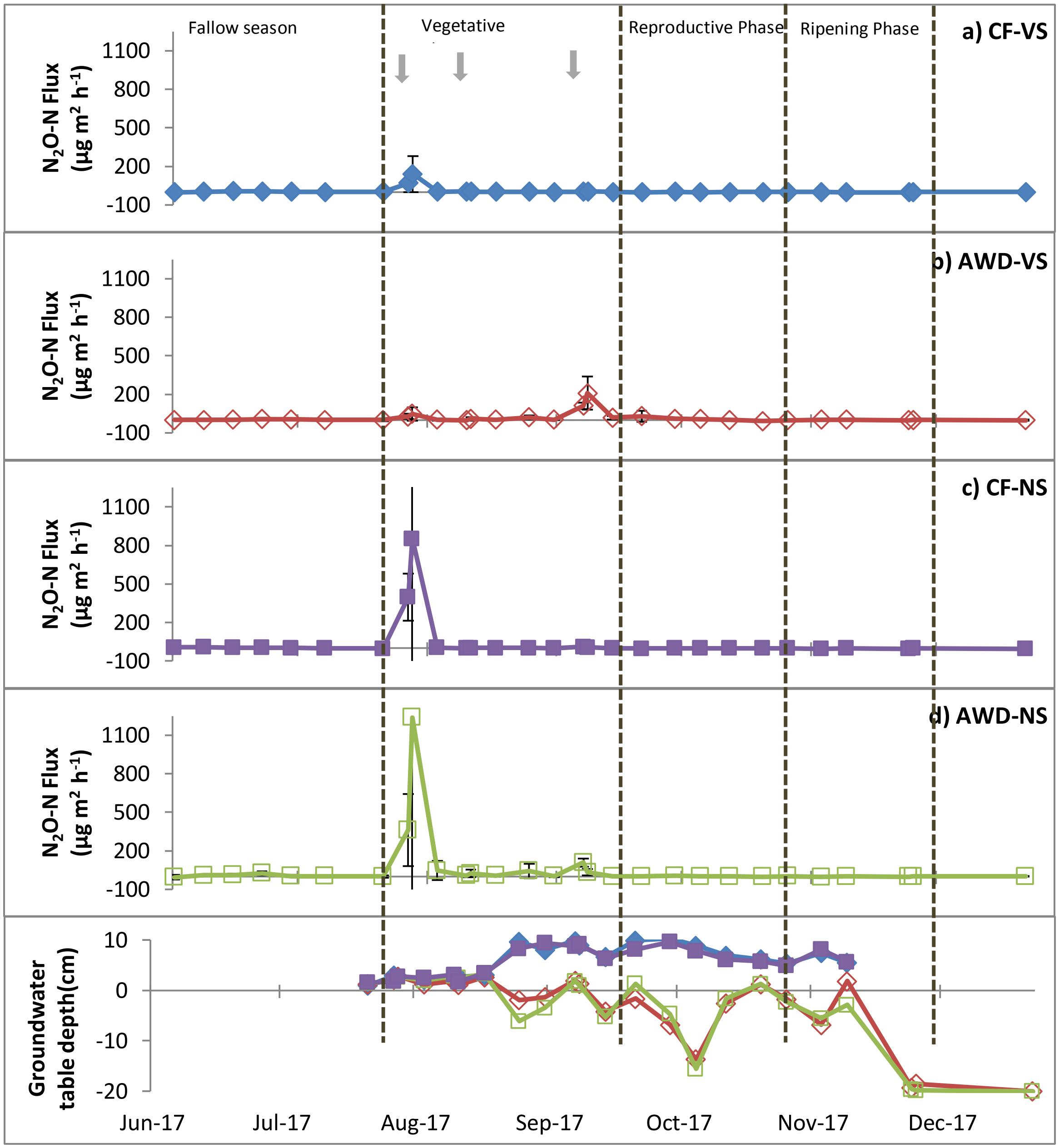


Figure 4.3: Variation in N_2O (µg N_2O-N m^{-2} h^{-1}) emissions over the sampling period in each treatment with corresponding water table depth (cm)

[1] Vertical dashed lines corresponds to the period of sampling during the fallow season and the growing season subdivided into developmental stages of rice growth (vegetative stage: from transplant to panicle initiation), reproductive stage (from panicle initiation to flowering) and ripening stage (flowering to mature/harvest stage). Bars indicate standard deviation of four replicates

[2] Arrows (left – right) denotes basal application, 1st top dressing and 2nd top dressing respectively.

AWD in the VS soil increased N_2O emissions by 72% compared to the CF-VS while AWD in the NS soil increased N_2O by 50% compared to the CF-NS. N_2O emissions were significantly higher in the nitisols than in the vertisols with 79% higher emissions in the CF-NS than CF-VS and 76% higher emissions in the AWD-NS than AWD-VS (Table 4.8). ANOVA ($P < 0.001$) indicated that interaction of water regime and soil type had a significant effect on the emissions of N_2O with water regimes in the NS having slightly higher emissions than water regimes in the VS.

Table 4.5: Seasonal cumulative N_2O (Kg N_2O-N ha^{-1}) emissions as affected by CF and AWD water regimes in the two soil types

Treatment	Soil	
	VS	**NS**
	(Kg N_2O-N ha^{-1})	
CF	$0.18^a \pm 0.01$	$0.86^b \pm 0.03$
AWD	$0.31^c \pm 0.01$	$1.29^d \pm 0.05$
Analysis of Variance		
Treat.	$P < 0.001$	
Soil	$P < 0.001$	
Treat. x soil	$P < 0.001$	

[1]CF – Continuous flooding, AWD – Alternate wetting and drying, VS – Vertisols, NS – Nitisols

[2]Numbers in the table represent means ± SE; SE refers to the standard error of measurement for four replicates

[3]Means followed by the same letter are not significantly different at $P < 0.05$

While the introduction of AWD in rice fields generally causes a decrease CH_4 emissions in the crop growing season, N_2O emissions will usually increase (Akiyama, Yagi, & Yan, 2005; Lagomarsino, Agnelli, Linquist, Adviento-Borbe, Agnelli, et al., 2016). Varying the soil moisture through drainage causes changes to soil temperature, soil oxygen status, and soil redox potential (Eh), which may change N_2O emission rates (Lagomarsino et al., 2016). The greater N_2O emissions from the AWD subplots were attributed mainly to the introduction of aerobic soil conditions in the rice fields which resulted in high soil redox potential that stimulated the N_2O producers hence increasing N_2O emissions in the AWD subplots compared to the CF subplots. Also, flooded soil conditions (i.e. water depth ranged from 3 – 10cm) acted as a barrier, inhibiting or slowing the movement of N_2O produced via denitrification in the reduced soil layer to the atmosphere during which time the N_2O could be reduced further to N_2 (Zou et al., 2005; Peng et al., 2011; Y. Xu et al., 2015b).

The type of soil also had a significant ($P < 0.001$) effect on N_2O emissions. Lower N_2O emissions from the VS under AWD compared to NS under AWD were observed in this study. This could mainly be attributed to the pH of the vertisols which was higher (7.2) than the nitisols (5.7). According to Webster & Hopkins, (1996), the increase in the pH increases the N_2O reductase enzyme activity. High pH may have increased the N_2O reductase enzyme activity resulting in lower emissions from the VS soil.

There was also a significant ($P < 0.001$) water regime-by-soil type interaction effect on N_2O emissions from the rice fields. Alternate wetting & drying (AWD) in well aerated NS soils, resulted in the highest N_2O emissions from the AWD-NS subplot as compared to AWD in VS. Also the CF-VS subplot had the lowest N_2O emissions compared to the other subplots indicating that the interaction of the continuous flooding (CF) in soils with high water holding capacity and clay content inhibited the production of N_2O.

4.3.3. Carbon dioxide Emissions

Patterns of CO_2 emissions were similar between the two soil types (Figure 4.4). In the fallow season, CO_2 emissions remained low mainly because emissions were only from the soil respiration. However after transplanting, CO_2 emissions gradually increased in all subplots. In the reproductive stage, CO_2 emissions decreased in the nitisols while a peak was observed in the vertisols. Emissions gradually decreased in all subplots in the ripening stage to close to zero after harvest. Soil and treatment interaction showed significant effect on CO_2 emissions ($P < 0.001$) (Table 4.9).

Water management regimes had a significant effect ($P < 0.01$) on CO_2 emissions. Drying and re-wetting cycles as well as soil water content have been found to have a pronounced effect on soil CO_2 fluxes (Borken et al., 2009; Wu et al., 2010). Liu et al. (2013), Haque et al. (2014) and Y. Xu et al., (2015b), in their findings, observed that CO_2 emissions increase with reduction of irrigation water and reduce with increase in flood water in the rice fields.

This CO_2 emissions reduction in the flooded soil conditions is mainly attributed to the reduction in diffusivity and substantial reduction in the biological activity in the soil (Haque, Kim, Ali, & Kim, 2014; Y. Xu, Ge, Tian, Li, Nguy-Robertson, et al., 2015). Flooding cuts off oxygen exchange from the atmosphere and as a consequence biological activities are reduced under the anoxic soil conditions inhibiting CO_2 production. Averaged over both soil types, AWD increased CO_2 emissions by 10% compared to CF.

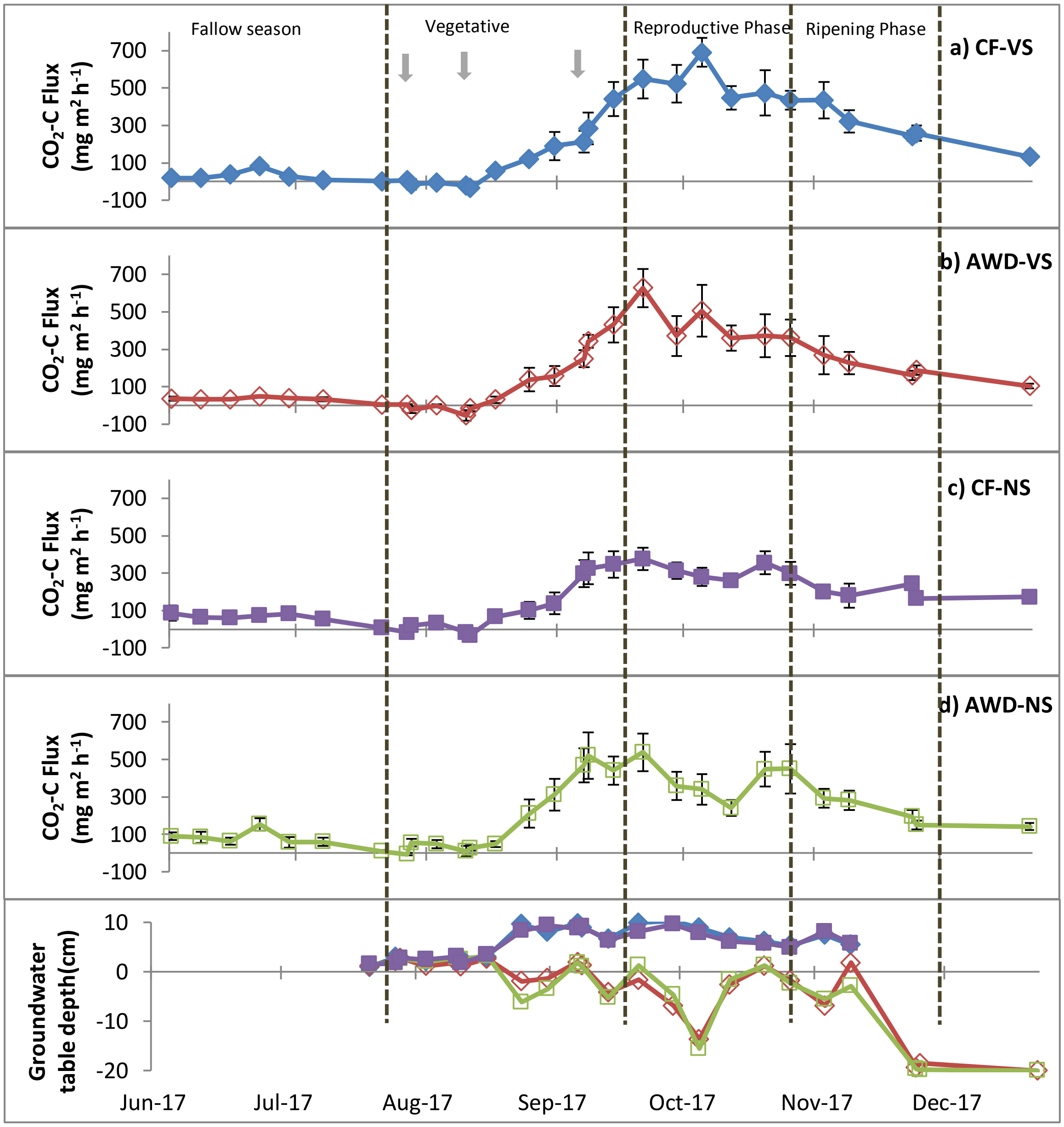


Figure 4.4: **Variation in CO_2 (mg CO_2-C m^{-2} h^{-1}) emissions over the sampling period in each treatment with corresponding water table depth (cm)**

[1] Vertical dashed lines corresponds to the period of sampling during the fallow season and the growing season subdivided into developmental stages of rice growth (vegetative stage: from transplant to panicle initiation), reproductive stage (from panicle initiation to flowering) and ripening stage (flowering to mature/harvest stage). Bars indicate standard deviation of four replicates

[2] Arrows (left – right) denotes basal application, 1st top dressing and 2nd top dressing respectively.

Table 4.6: Seasonal cumulative CO_2 (Mg CO_2-C ha^{-1}) emissions as affected by CF and AWD water regimes in the two soil types

Treatment	Soil	
	VS	**NS**
	(Mg CO_2-C ha^{-1})	
CF	$3.78^a \pm 0.14$	$3.04^b \pm 0.09$
AWD	$3.32^b \pm 0.12$	$4.16^a \pm 0.13$
	Analysis of Variance	
Treat.	$P = 0.006$	
Soil	$P = 0.693$	
Treat. x soil	$P < 0.001$	

[1] CF – Continuous flooding, AWD – Alternate wetting and drying, VS – Vertisols, NS – Nitisols

[2] Numbers in the table represent means ± SE; SE refers to the standard error of measurement for four replicates

[3] Means followed by the same letter are not significantly different at $P < 0.05$

The type of soil did not have a significant effect on CO_2 emissions ($P = 0.693$), however a reduction in CO_2 emissions in the VS subjected to AWD acting contrary to CO_2 emissions when NS subjected to AWD was observed. This could be attributed mainly to high soil pH in the VS soils as CO_2 production is lower in soils with high pH (Wang et al., 2010). The interaction between water regime and soil type also had a significant ($P < 0.001$) effect on the CO_2 emissions where the well aerated. NS soils under AWD had the highest CO_2 emissions compared to similar soil under CF.

4.3.4.Carbon dioxide Equivalent (CO_2-eq) Emission

To compare the impact of each GHG, the global warming potential (GWP) of each gas is computed over a 100 year period as shown in Table 4.10. This is based on each GHG warming power and atmospheric lifetime. As a basis of comparison, carbon dioxide (CO_2) is assigned a GWP of one and CH_4 and N_2O GWP are computed in relationship to carbon dioxide. For example, relative to CO_2, atmospheric CH_4 is considered as the second most abundant GHG after CO_2 (Watson et al., 1992; Neue et al., 1996; Grasty, 1999; Yan et al., 2003; Minamikawa et al., 2006; Zhang et al., 2011) with a global warming potential (GWP) 34 times more than CO_2 and has a lifetime of about 10 years (Myhre, Shindell, Bréon, Collins, Fuglestvedt, et al., 2013). N_2O on the other hand is more potent per gram than methane (CH_4) (The Guardian, 2011) and is approximately 298 times more potent than CO_2 on a 100-year time-scale (Myhre, Shindell, Bréon, Collins, Fuglestvedt, et al., 2013).

Table 4.7: Global warming potential (GWP, Kg CO_2-equivalent ha^{-1}) and Yield scaled GWP (GWP_Y, kg CO_2-eq kg grain $yield^{-1}$)

Treatment	CH_4 GWP	N_2O GWP	GWP reduction	GWP_Y	GWP_Y reduction
	(kg CO_2-eq ha^{-1})		(%)	(kg CO_2-eq kg grain $yield^{-1}$)	(%)
CF-VS	630.70	53.64		0.13	
AWD-VS	74.46	92.38	76	0.03	74
CF-NS	196.18	256.28		0.10	
AWD-NS	30.60	384.42	8	0.09	4

[1] Continuous flooding (CF) & alternate wetting and drying (AWD) in the two soil types: vertisols (NS) and nitisols (NS)

[2] Basmati 370 rice grain yield data showed no significant difference in the yields from all treatments

The CO_2 equivalent (CO_2-eq) for CH_4 and N_2O emissions was calculated using the Equation 3:

$$CO_2eq = (CH_4 \, x \, 34 + N_2O \, x \, 298) \qquad Equation \; 3$$

Where; CO_2-eq is the CO_2 equivalent (Kg CO_2-eq ha^{-1}), CH_4 is the total amount of methane emission (kg ha^{-1}), N_2O is the total amount of nitrous oxide emission (kg ha^{-1}), 34 and 298 are the radiative forcing potentials for CH_4 and N_2O, respectively (Myhre, Shindell, Bréon, Collins, Fuglestvedt, et al., 2013), to CO_2 over a 100-yr time horizon.

With CH_4 and N_2O emissions expressed as CO_2 equivalents for a 100-yr horizon, AWD in the VS and NS soils lowered GWP by 76% and 8%, respectively (Table 4.8) due to the large reduction of CH_4 in both soil types under AWD water regime. The average CO_2-eq was higher in the VS soil than in the NS soil mainly due to the higher CH_4 emissions in the CF-VS subplot. Yield-scaled GWP calculated as the ratio of growing season GWP (Kg CO_2-eq ha^{-1}) and grain yield (Kg ha^{-1}) (Table 4.10) was reduced by 74% and 4% in the AWD-VS and AWD-NS respectively.

4.4. Water productivity

4.4.1. Rice Yield

The Basmati 370 grain yield showed no significant differences in the grain yield between the water management regimes (CF and AWD) irrespective of the soil type (Table 4.11). Therefore, drying and re-wetting cycles in the AWD subplots in this study did not significantly affect the grain yield (kg ha^{-1}) relative to the continuously flooded subplots. There was also no significant difference in the grain yield from the two soil types (VS and NS soil) irrespective of the water management regimes. However, the VS soil (averaged over both water management regimes) had a slightly higher grain yield (14%) compared to the NS soils. Water management regime-by-soil type interaction was also observed to have no significant effect on the grain yield (Table 4.11).

Table 4.8: Yield and yield components data for each treatment during the rice growing season at the Kirogo Rice Research farm

Treatment	Number of panicles (No. m^{-2})	Spikelet per panicle	Spikelet number (spikelet m^{-2})	1000 grains weight (g)	Filled grains ratio (%)	Grain yield (g m^{-2})	Above ground DMW (g m^{-2})	Harvest index
CF-NS	247$_a$	77.5$_a$	21296$_a$	23.9$_b$	90.8$_a$	461.31$_a$	941.0$_{ab}$	0.49$_a$
AWD-NS	260$_a$	68.6$_a$	19977$_a$	24.9$_{ab}$	88.6$_a$	441.81$_a$	860.5$_b$	0.51$_a$
CF-VS	264$_a$	74.3$_a$	22066$_a$	26.5$_a$	92.2$_a$	540.00$_a$	1142.4$_a$	0.47$_a$
AWD-VS	290$_a$	65.4$_a$	21117$_a$	26.3$_a$	90.8$_a$	505.88$_a$	954.4$_{ab}$	0.53$_a$
Analysis of Variance								
Soil	ns	ns	ns	**	ns	ns	*	ns
Treat.	ns	*	ns	ns	ns	ns	*	*
Soil x Treat.	ns	ns	ns	ns	ns	ns	ns	ns

[1] **P ≤ 0.01, *P ≤ 0.05, ns = not significant

[2] Means followed by the same letter are not significantly different at $P < 0.05$

[3] CF – Continuous flooding, AWD – Alternate wetting and drying, VS – Vertisols, NS – Nitisols

The introduction of AWD irrespective of the soil type did not have a significant effect on the grain yield. This can be attributed mainly to the fact that there was no significant difference in the amount of water applied in the vegetative stage in all subplots. According to Myers et al. (2002), rice plants do not require huge amounts of water for growth but can thrive under flooded conditions during part of its growth cycle. Also, according to Minamikawa & Sakai (2005), rice plants require flooded soil conditions mainly during the rooting stage, but in the other stages during growth, the plant does not always need to be flooded.

Reported effects of AWD on rice grain yield are highly varied with some studies reporting yield penalties (Y. Xu et al., 2015b; Linquist et al., 2015a; Lagomarsino et al., 2016) while others showing no decline or change in yield (Yao et al., 2012; LaHue et al., 2016). This variability is attributed mainly to the wide range of water-saving rice production systems classified as AWD (LaHue, Chaney, Adviento-Borbe, & Linquist, 2016). To minimize yield loss, adopting this systems to site specific management such as: flooding duration, drainage frequency, soil type, rice varieties among other factors (Lagomarsino et al., 2016) is crucial.

4.4.2.Water Use in the Vertisols and Nitisols

The irrigation water applied (m^3) in the VS under alternate wetting and drying (AWD) and under continuous flooding (CF) was 188.3 m^3 and 269.1 m^3 per 105.3 m^2 subplot area (equivalent to 17882m^3 ha^{-1} and 25556m^3 ha^{-1}), respectively. With the introduction of AWD in the vertisols, total water saving was 26% (equivalent to 7674 m^3 ha^{-1}). In the nitisols (NS) under AWD and under CF, the irrigation water applied was 158.0 m^3 and 321.2 m^3 per 105.3 m^2 subplot area (equivalent to 15006m^3 ha^{-1} and 30503m^3 ha^{-1}), respectively. With the introduction of AWD in the nitisols, total water use (rainfall + irrigation water) was reduced by 45% (equivalent to 15498 m^3 ha^{-1}) (Table 4.12).

Following a *meta*-analysis from 56 studies with 528 side-by-side comparison of AWD to CF, Carrijo et al. (2017) reported that, introduction of AWD; mainly during the wet season, reduced water use by 25.7% which translated to great water savings. Other than less irrigation, reduced water use can also be attributed, in part, to reduced seepage and percolation losses in AWD rice fields. These losses are significantly reduced in the absence of flood water and are highly dependent on the hydrological properties of different soils (Carrijo, Lundy & Linquist, 2017). According to (Sharma, Lav, Bhushan, Ladha, Naresh et al., 2002), 51% of water applied in sandy loam soil in India was being lost via percolation while in clayey soil in California, (Linquist et al., 2015b) reported that about 15% of water applied was being lost via both seepage and percolation.

From the study, to maintain the water levels at about 10 cm above the soil surface; the continuously flooded subplots were irrigated more frequently over the growing season. However, the continuously flooded nitisols were irrigated more frequently (Table 4.12) compared to the continuously flooded vertisols; with the nitisols under CF using 14.2% (equivalent to 4947 m^3 ha^{-1}) more water. This could be mainly attributed to the fact that vertisols; unlike the nitisols, have higher water holding capacity due their high clay content while the nitisols are well-drained compared to the vertisols since they have higher sand and silt content.

Table 4.9: Number of irrigation and water used (irrigation + rainfall) for each subplot over the growing season at the Kirogo rice research farm

Subplot	No. of irrigation	Irrigation m^3	Irrigation m^3 ha^{-1}	Irrigation + rainfall m^3 ha^{-1}	Water saving %
CFVS	53	269.1^{a}	25556	29778	
AWDVS	32	188.3^{c}	17882	22104	26
CFNS	68	321.2^{b}	30503	34725	
AWDNS	26	158.0^{c}	15006	19228	45
		ANOVA			
Water regime		$P < 0.001$			
Soil type		$P = 0.369$			
Water x Soil		$P < 0.001$			

However, the nitisols under AWD water regime used 15% (equivalent to 2876 m^3 ha^{-1}) less water compared to the vertisols under AWD. This could be attributed mainly to the fact that the vertisols in the scheme fall under the class of montmorillonitic clays that crack when dry (Sombroek, Braun, & van der Pouw, 1982). Upon re-flooding of the vertisols under AWD, a considerable amount of the water applied was lost to deep seepage when cracks were first filled up.

This also indicated that there was an interaction effect (water regime x soil type) as the water used in each soil type depended on whether the soil was under AWD or CF. From the analysis, the water regimes (CF & AWD) had a significant effect on the amount of water applied ($P < 0.001$), while the type of soil (VS & NS) did not have a significant effect ($P = 0.369$) on the amount of water applied. However, there was a significant water regime x soil type interaction effect ($P < 0.001$) on the amount of water applied in each subplot (Table 4.12).

4.4.3.Water Productivity in the Vertisols and Nitisols

Water productivity is defined as the amount of grain yield obtained per unit total water input (irrigation and rainfall). Water productivity (kg m^{-3}) in the vertisols under continuous flooding (CF-VS) and alternate wetting and drying (AWD-VS) was 0.18 kg m^{-3} and 0.23 kg m^{-3}, respectively while in the nitisols under continuous flooding (CF-NS) and alternate wetting and drying (AWD-NS) was 0.13 kg $m^{-3}$and 0.23 kg m^{-3} respectively.

Table 4.10: Grain yield, total water used and water productivity for each subplot over the growing season at the Kirogo rice research farm

Subplot	[1] **Grain yield** kg ha^{-1}	**Total water used** m^3 ha^{-1}	**Water productivity** kg m^{-3}	**Water productivity** %
CF-VS	5400.0^a	29778	0.18	
AWD-VS	5058.8^a	22104	0.23	28
CF-NS	4613.1^a	34725	0.13	
AWD-NS	4418.1^a	19227	0.23	77

Basmati 370 rice grain yield data

Productivity was 28% and 77% higher in the VS and NS respectively under AWD compared to the CF. Although AWD did not significantly increase the yield (kg ha^{-1}), productivity was observed to be higher with the introduction of AWD in both soil types (Table 4.13). Productivity in the nitisols was much higher than in the vertisols mainly due to the fact that CF in the well-drained nitisols resulted to more frequent irrigation in the reproductive and ripening stages to maintain water levels lost through not only evapotranspiration but also seepage and percolation losses. With the introduction of AWD in this soil type, the seepage and percolation losses were minimized and less irrigation was done throughout the growing season without affecting the grain yield.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The study showed that:

- Seasonal cumulative CH_4 emissions from AWD were 88% and 84% lower than from CF; in VS and NS respectively. Compared to rice fields under alternate wetting and drying irrigation system, the continuously flooded rice fields resulted in high methane (CH_4) emissions;
- Seasonal cumulative N_2O emissions increased by 72% and 50%, in VS and NS respectively. Introducing periodic aerobic soil conditions during the rice growing season resulted in increased nitrous oxide (N_2O) emissions in both soils compared to the continuously flooded rice fields;
- The cumulative CH_4 emissions from the VS soil were 69% higher while the cumulative N_2O emissions were 79% lower than the NS soil. The GHG emissions were greatly dependent on the soil physical and chemical properties with vertisols having the highest CH_4 emissions and nitisols having the highest N_2O emissions under AWD.
- Interaction between the water management regimes and soil type significantly affected the GHG (CH_4, N_2O and CO_2) emissions from the rice fields;
- Compared to CF, water productivity under AWD was 28% and 77% higher in the VS and NS soils respectively. AWD in both nitisols and vertisols reduced water use while maintaining rice grain yield;
- Alternate wetting and drying (AWD) irrigation system has the potential to minimize known environments impacts of rice production while maintaining yield.

5.2. Recommendations and limitation of the study

5.2.1. Recommendations

This study recommends the following:

- Alternate wetting and drying may compromise rice grain yield mainly in dry seasons. It is therefore important to fine tuning this irrigation strategy to site specific conditions and manage the drying and wetting cycle (i.e begin irrigation before water levels go below the rooting zone) as rice plant are extremely sensitivity water stress.
- A trade-off between CH_4 and N_2O was observed in this study. However, since the GWP was largely dominated by CH_4 emissions (mainly in the vertisols); the increase in N_2O emissions under AWD did not affect the decrease in GWP. It is therefore important to manage the duration of aerobic soil conditions (how long rice fields are left to dry) as well as properly balance the number of wetting and drying events so as counterbalance the reduction of CH_4 with the simultaneous N_2O increase in AWD.
- The peaks following fertilizer application significantly contributed to the high seasonal N_2O emissions. It is therefore important to provide an adequate amount of N (only what the crop requires) accompanied by proper water management.

5.2.2. Area of further research and limitation of the study

- Further research: To develop a comprehensive and accurate GHG inventory from rice production in the country, it is important to quantify GHG emissions from different rice growing (agro-ecological) regions in the country with different weather conditions, soil types and agricultural activities.
- Limitation: This study was conducted in only one cropping season and there were no spatial replications due to physical (land availability and size of plot where the experiment was set-up) and financial constraints and hence insufficient to claim validity at national level. However, it presents the best available data for rice

production emissions in Kenya and can be seen as a step to country-specific emission factor for Kenya.

REFERENCES

Agribusiness Information Portal. (2013). *Rice Value Chain*. (May).

Akinbile, C. ., El-Latif, A., Abdullah, R., & Yusoff, M. (2011). Rice Production and Water use Efficiency for Self-Sufficiency in Malaysia: A Review. *Trends in Applied Sciences Research*, Vol. 6, pp. 1127–1140.

Akinbile, C. O., Yusoff, M. S., Haque, A. A. M., & Maskir, N. S. (2012). An appraisal of methane emission of rice fields from Kerian Agricultural Scheme in Malaysia. *Research Journal of Environmental Sciences, 6*(3), 107–117. https://doi.org/10.3923/rjes.2012.107.117

Akiyama, H., Yagi, K., & Yan, X. (2005). Direct N2O emissions from rice paddy fields: Summary of available data. *Global Biogeochemical Cycles*, *19*(1), 1–10. https://doi.org/10.1029/2004GB002378

Aruna, M. J. (2014). Effect of withholding irrigation water after complete heading on rice yield and seed quality in Mwea, Kirinyaga County, Kenya. *Katalog BPS*, *XXXIII*(2), 81–87. https://doi.org/10.1007/s13398-014-0173-7.2

Arunrat, N., & Pumijumnong, N. (2017). Practices for Reducing Greenhouse Gas Emissions from Rice Production in Northeast Thailand. *Agriculture*, *7*(1), 4. https://doi.org/10.3390/agriculture7010004

Bao, Q. L., Xiao, K. Q., Chen, Z., Yao, H. Y., & Zhu, Y. G. (2014). Methane production and methanogenic archaeal communities in two types of paddy soil amended with different amounts of rice straw. *FEMS Microbiology Ecology*, *88*(2), 372–385. https://doi.org/10.1111/1574-6941.12305

Boateng, K., Obeng, G., & Mensah, E. (2017). Rice Cultivation and Greenhouse Gas

Emissions: A Review and Conceptual Framework with Reference to Ghana. *Agriculture*, *7*(1), 7. https://doi.org/10.3390/agriculture7010007

Borken, W., & Matzner, E. (2009). Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Global Change Biology*, *15*(4), 808–824. https://doi.org/10.1111/j.1365-2486.2008.01681.x

Bouman, B. A. ., & Tuong, T. . (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, *49*(1), 11–30. https://doi.org/10.1016/S0378-3774(00)00128-1

Bouman, B. A. M., Lampayan, R. M., & Tuong, T. P. (2007). *Water management in irrigated rice : coping with water scarcity*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=QR2007000088

Butterbach-Bahl, K, Papen, H., & Rennenberg, H. (1997). Impact of gas transport through rice cultivars on methane emission from rice paddy fields. *Plant, Cell and Environment*, *20*, 1175–1183. https://doi.org/10.1046/j.1365-3040.1997.d01-142.x

Butterbach-Bahl, Klaus, Kiese, R., & Liu, C. (2011). Measurements of biosphere atmosphere exchange of CH4 in terrestrial ecosystems. In *Methods in Enzymology* (1st ed., Vol. 495). https://doi.org/10.1016/B978-0-12-386905-0.00018-8

Cai, Z., Xing, G., Yan, X., Xu, H., Tsuruta, H., Yagi, K., & Minami, K. (1997). Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant and Soil*. https://doi.org/10.1023/a:1004263405020

Carrijo, D. R., Lundy, M. E., & Linquist, B. A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. *Field Crops Research*. https://doi.org/10.1016/j.fcr.2016.12.002

Chanton, J. P., Whiting, G. J., Blair, N. E., Lindau, C. W., & Bollich, P. K. (1997). *Stable isotopes , diurnal variations , and C02 exchange from of belowground was correlated to the quantity of live aboveground biomass and the rate of CO were methane was observed in the floodwater overlying the*. *11*(1), 15–27.

Dhanyac. (2011). All About Agriculture: Climate and Soil for Rice Cultivation. Retrieved March 12, 2019, from http://agricultureandupdates.blogspot.com/2011/10/climate-and-soil-for-rice-cultivation.html

Dou, F., Soriano, J., Tabien, R. E., & Chen, K. (2016). *Soil Texture and Cultivar Effects on Rice (Oryza sativa, L.) Grain Yield, Yield Components and Water Productivity in Three Water Regimes*. https://doi.org/10.1371/journal.pone.0150549

European Commission. (2015). EU Agriculture and Climate Change. *Factsheet*.

Eurostat. (2015). *Greenhouse gas emission statistics. URLhttp://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics. Accessed on 14 December, 2016*. *2012*(July 2015), 1–7. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics

Fairhurst, T. H., & Dobermann, a. (2002). Rice in the Global Food Supply. *Better Crops International*, *16*(May), 8–11.

FAO. (2013). Part 3: Feeding the world. *FAO Statistical Yearbook 2013*, 123–158.

FAOSTAT. (2014). *Asia and Pacific Commission on Agricultural Statistics*. (October), 8–12. Retrieved from http://www.mdpi.com/2071-1050/10/3/671

Fazli, P., Man, H. C., Shah, U. K., & Idris, A. (2013). *Characteristics of Methanogens* *and Methanotrophs in Rice Fields : A Review.*

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, *478*(7369), 337–342. https://doi.org/10.1038/nature10452

Frederick, S., & Owido, O. (1981). *A study of the drainage problems in some parts of the Mwea Irrigation Scheme, Kenya*.

Gee, G. W., & Bauder, J. W. (1979). Particle Size Analysis by Hydrometer: A Simplified Method for Routine Textural Analysis and a Sensitivity Test of Measurement Parameters1. *Soil Science Society of America Journal*, *43*(5), 1004. https://doi.org/10.2136/sssaj1979.03615995004300050038x

Global Rice Science Partnership, (GRiSP). (2010). *Global Rice Science Partnership (GRiSP) CGIAR Thematic Area 3: Sustainable crop productivity increase for global food security A CGIAR Research Program on Rice-Based Production Systems*. Retrieved from http://ricecrp.org/wp-content/uploads/2017/03/RICE-phase-I-2011-2015.pdf

Global Rice Science Partnership (GRiSP). (2013). Rice almanac, 4th edition. Los Baños (Philippines): International Rice Research Institute. 283 p. In *Annals of Botany* (Vol. 92). https://doi.org/10.1093/aob/mcg189

Grasty, S. (1999). Agriculture and Climate Change. *Most*, *14*(2), 12–16.

Greenhouse Gas Working Group. (2010). Agriculture's role in greenhouse gas emissions & capture. *Greenhouse Gas Working Group Rep. ASA, CSSA, and SSSA, Madison, WI*, (August), 16pp.

Guerra, L. C.; Bhuiyan, S. I.; Tuong, T. P.; Barker, R. (1998). Producing more rice with less water from irrigated systems. Retrieved November 22, 2018, from https://cgspace.cgiar.org/handle/10568/36526

Hanjra, M. A., & Qureshi, M. E. (2010). Global water crisis and future food security in an era of climate change. *Food Policy*, *35*(5), 365–377. https://doi.org/10.1016/J.FOODPOL.2010.05.006

Haque, M. M., Kim, S. Y., Ali, M. A., & Kim, P. J. (2014). Contribution of greenhouse gas emissions during cropping and fallow seasons on total global warming potential in mono-rice paddy soils. *Plant and Soil*, *387*(1–2), 251–264. https://doi.org/10.1007/s11104-014-2287-2

Horwath, W. R. (2011). Greenhouse gas emissions from rice cropping systems. *Understanding Greenhouse Gas Emissions From Agricultural Management*, (3), 67–89. https://doi.org/10.1021/bk-2011-1072.ch005

Hou A.X. , G.X. Chen, Z.P. Wang, O. Van Cleemput, and W.H. Patrick, J. (2000). Methane and Nitrous Oxide Emissions from a Rice Field in Relation to Soil Redox and Microbiological Processes. *Soil Science Society of America Journal*, *64(6), 2180-2186.*, (41101172). https://doi.org/10.2136/sssaj2000.6462180x

IJUMBA, J. N., MWANGI, R. W., & BEIER, J. C. (1990). Malaria transmission potential of Anopheles mosquitoes in the Mwea- Tebere irrigation scheme, Kenya. *Medical and Veterinary Entomology*, *4*(4), 425–432. https://doi.org/10.1111/j.1365-2915.1990.tb00461.x

IPCC. (2014a). Climate Change 2014: Mitigation of Climate Change. Summary for Policymakers and Technical Summary. In *Climate Change 2014: Mitigation of Climate Change. Part of the Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* https://doi.org/10.1017/CBO9781107415416.005

IPCC (2014b). Summary for Policymakers. In *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/CBO9781107415324

Irea, S. (2010). *Coalition for African Rice Development FINAL REPORT Mapping of Poverty Reduction Strategy Papers, Sector Strategies and Policies related to Rice Development in Kenya*.

IRRI (2018). Rice and climate change. Retrieved September 6, 2018, from International Rice Research Institute - IRRI website: http://irri.org/news/hot-topics/rice-and-climate-change

Jain, N., Pathak, H., Mitra, S., & Bhatia, A. (2004). Emission of methane from rice fields - A review. *Journal of Scientific and Industrial Research*, *63*(2), 101–115.

Jain, Niveta, & Dubey, R. (2014). *Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic Plains*. 355–363. https://doi.org/10.1007/s10333-013-0390-2

Khalil, M. A. ., Shearer, M. ., Butenhoff, C. ., Xiong, Z. ., Rasmussen, R. ., Xu, L., & Xing, G. (2009). *Emissions Of Greenhouse Gases From Rice Agriculture*.

Khalil, M. A. K., & Butenhoff, C. L. (2008). Spatial variability of methane emissions from rice fields and implications for experimental design. *Journal of Geophysical Research: Biogeosciences*, *113*(3), 1–11. https://doi.org/10.1029/2007JG000517

Khalil, M. A. K., Rasmussen, R. A., Shearer, M. J., Yao, H., & Yang, J. (1998). *trace gases from rice fields in China*. *103*.

Kimani, J. M., Tongoona, P., Derera, J., & Nyende, A. B. (2011). Upland rice varieties development through participatory breeding. *Journal of Agricultural and Biological Science*, *6*(9), 39–49

Komiya, S., Noborio, K., Katano, K., Pakoktom, T., Siangliw, M., & Toojinda, T. (2015). Contribution of Ebullition to Methane and Carbon Dioxide Emission from Water between Plant Rows in a Tropical Rice Paddy Field. *International Scholarly Research Notices*, *2015*, 1–8. https://doi.org/10.1155/2015/623901

Kraus, D., Weller, S., Klatt, S., Santabàrbara, I., Haas, E., Wassmann, R., Butterbach-Bahl, K. (2016). How well can we assess impacts of agricultural land management changes on the total greenhouse gas balance (CO2, CH4 and N2O) of tropical rice-cropping systems with a biogeochemical model? *Agriculture, Ecosystems and Environment*, *224*, 104–115. https://doi.org/10.1016/j.agee.2016.03.037

Lagomarsino, A., Agnelli, A. E., Linquist, B., Adviento-Borbe, M. A., Agnelli, A., Gavina, G., … Ferrara, R. M. (2016). Alternate Wetting and Drying of Rice Reduced CH4 Emissions but Triggered N2O Peaks in a Clayey Soil of Central Italy. *Pedosphere*, *26*(4), 533–548. https://doi.org/10.1016/S1002-0160(15)60063-7

LaHue, G. T., Chaney, R. L., Adviento-Borbe, M. A., & Linquist, B. A. (2016). Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. *Agriculture, Ecosystems and Environment*, *229*(July), 30–39. https://doi.org/10.1016/j.agee.2016.05.020

Le Mer, J., & Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: A review. *European Journal of Soil Biology*, *37*(1), 25–50. https://doi.org/10.1016/S1164-5563(01)01067-6

Linquist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., & van Groenigen, K. J. (2012). Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops*

Research, *135*, 10–21. https://doi.org/10.1016/j.fcr.2012.06.007

Linquist, B. A., Anders, M. M., Adviento-Borbe, M. A. A., Chaney, R. L., Nalley, L. L., da Rosa, E. F. F., & van Kessel, C. (2015). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. *Global Change Biology*, *21*(1), 407–417. https://doi.org/10.1111/gcb.12701

Linquist, B., Snyder, R., Anderson, F., Espino, L., Inglese, G., Marras, S., Hill, J. (2015). Water balances and evapotranspiration in water- and dry-seeded rice systems. *Irrigation Science*, *33*(5), 375–385. https://doi.org/10.1007/s00271-015-0474-4

Linquist, B., Van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, *18*(1), 194–209. https://doi.org/10.1111/j.1365-2486.2011.02502.x

Ma, K. E., Qiu, Q., & Lu, Y. (2010). Microbial mechanism for rice variety control on methane emission from rice field soil. *Global Change Biology*, *16*(11), 3085–3095. https://doi.org/10.1111/j.1365-2486.2009.02145.x

Marshall, S. (2011). The Water Crisis in Kenya : Causes , Effects and Solutions. *Global Majority E-Journal*, *2*(1), 31–45.

Mati, B. M., Wanjogu, R., Odongo, B., & Home, P. G. (2011). Introduction of the System of Rice Intensification in Kenya: Experiences from Mwea Irrigation Scheme. *Paddy and Water Environment*, *9*(1), 145–154. https://doi.org/10.1007/s10333-010-0241-3

Matsuo, K., Ae, N., Vorachit, S., & Thadavon, S. (2015). Present Soil Chemical Status and Constraints for Rice-Based Cropping Systems in Vientiane Plain and Neighboring Areas, Lao PDR. *Plant Production Science*. https://doi.org/10.1626/pps.18.314

McLean, J., Dawe, D., Hardy, B., & Hettel, G. (2002). Rice Almanac: Source book for the most important economic activity on earth. *IRRI, Los Baños, Philippines*, 298. https://doi.org/books.irri.org/9789712203008_content.pdf

Minami, K., & Neue, H.-U. (1994). Rice paddies as a methane source. *Climatic Change*, *27*(1), 13–26. https://doi.org/10.1007/BF01098470

Minamikawa, K., & Sakai, N. (2005). The effect of water management based on soil redox potential on methane emission from two kinds of paddy soils in Japan. *Agriculture, Ecosystems and Environment*, *107*(4), 397–407. https://doi.org/10.1016/j.agee.2004.08.006

Mitra, S., Wassmann, R., Jain, M. C., & Pathak, H. (2002). Properties of rice soils affecting methane production potentials: 2. Differences in topsoil and subsoil. *Nutrient Cycling in Agroecosystems*, *64*(1–2), 183–191. https://doi.org/10.1023/A:1021175404418

Muhunyu, J. G. (2012). Is doubling Rice Production in Kenya by 2018 Achievable? *Journal of Developments in Sustainable Agriculture*, *7*, 46–54.

Mukiama, T. K., & Mwangi, R. W. (1989). Field studies of larval Anopheles arabiensis Patton of Mwea Irrigation Scheme, Kenya. *International Journal of Tropical Insect Science*, *10*(01), 55–62. https://doi.org/10.1017/s1742758400003349

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 659–740. https://doi.org/10.1017/ CBO9781107415324.018

N. Obasi, S., Onweremadu, E. U., T., E. C., & Iwuanyanwu, U. P. (2015). Characterization and Classification of Selected Rice Soils of Tropical Rainforest Region, Southeastern Nigeria. *Agriculture, Forestry and Fisheries*, *4*(3), 46. https://doi.org/10.11648/j.aff.s.2015040301.18

Ndiiri, J. A., Mati, B. M., Home, P. G., & Odongo, B. (2013). Water productivity under the system of rice intensification from experimental plots and farmer surveys in mwea, kenya. *Taiwan Water Conservancy*, *61*(4), 63–75.

Neue, H.-U., & Sass, R. L. (1994). Trace Gas Emissions from Rice Fields. In *Global Atmospheric-Biospheric Chemistry* (pp. 119–147). https://doi.org/10.1007/978-1-4615-2524-0_8

Neue, H. U., Wassmann, R., Kludze, H. K., Bujun, W., & Lantin, R. S. (1997). Factors and processes controlling methane emissions from rice fields. *Nutrient Cycling in Agroecosystems*, *49*(1), 111–117. https://doi.org/10.1023/a:1009714526204

Neue, H. U., Wassmann, R., Lantin, R. S., Alberto, M. C. R., Aduna, J. B., & Javellana, a. M. (1996). Factors affecting methane emission from rice fields. *Atmospheric Environment*, *30*(10–11), 1751–1754. https://doi.org/10.1016/1352-2310(95)00375-4

Ngigi, S. N. (2002). Review of Irrigation Development in Kenya. *The Changing Face of Irrigation in Kenya: Opportunities for Anticipating Change in Eastern and Southern Africa.*, *2025*, 35–54.

Nguyen, N. V. (2002). Global climate changes and rice food security. *International Rice Commission, FAO, Rome, Italy*, (Table 1), 24–30. Retrieved from http://www.hechoenperu.org.pe/fao/docs/Agriculture/3-Nguyen.pdf

Norberg, L. (2017). *Greenhouse Gas Emissions from Cultivated Organic Soils*.

Nyamai, M., Mati, B. M., Home, P. G., Odongo, B., Wanjogu, R., & Thuranira, E. G. (2012). Improving land and water productivity in basin rice cultivation in Kenya through system of rice intensification (SRI). *Agricultural Engineering International: CIGR Journal*, *14*(2), 1–9.

Nyang'Au, W. O., Mati, B. M., Kalamwa, K., Wanjogu, R. K., & Kiplagat, L. K. (2014). Estimating rice yield under changing weather conditions in kenya using ceres rice model. *International Journal of Agronomy*, *2014*. https://doi.org/10.1155/2014/849496

Onyango, A. O. (2014). Exploring Options for Improving Rice Production to Reduce Hunger and Poverty in Kenya. *World Environment*, *4*(4), 172–179. https://doi.org/10.5923/j.env.20140404.03

Oo, A. Z., Sudo, S., Inubushi, K., Mano, M., Yamamoto, A., Ono, K., … Ravi, V. (2018). Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India. *Agriculture, Ecosystems and Environment*, *252*(November 2017), 148–158. https://doi.org/10.1016/j.agee.2017.10.014

Papademetriou M.K., Frank J. Dent Edward, E. M. H. (2000). Bridging the rice yield gap in the Asia-Pacific Region. *Fao*, 215. Retrieved from http://coin.fao.org/coin-static/cms/media/9/13171760277090/2000_16_high.pdf

Parkin, T. B., Venterea, R. T., & Hargreaves, S. K. (2012). Calculating the Detection Limits of Chamber-based Soil Greenhouse Gas Flux Measurements. *Journal of Environment Quality*, *41*(3), 705. https://doi.org/10.2134/jeq2011.0394

Pelster, D., Rufino, M., Rosenstock, T., Mango, J., Saiz, G., Diaz-Pines, E., … Butterbach-Bahl, K. (2017). Smallholder farms in eastern African tropical highlands have low soil greenhouse gas fluxes. *Biogeosciences*, *14*(1), 187–202. https://doi.org/10.5194/bg-14-187-2017

Peng, S., Hou, H., Xu, J., Mao, Z., Abudu, S., & Luo, Y. (2011). Nitrous oxide emissions from paddy fields under different water managements in southeast China. *Paddy and Water Environment*, *9*(4), 403–411. https://doi.org/10.1007/s10333-011-0275-1

Pittelkow, C. M., Adviento-Borbe, M. A., Hill, J. E., Six, J., van Kessel, C., & Linquist, B. A. (2013). Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agriculture, Ecosystems and Environment*, *177*, 10–20. https://doi.org/10.1016/j.agee.2013.05.011

Pradeep Kurukulasuriya, S. R. (2003). *Climate Change and Agriculture and Agriculture*. (October 1996). https://doi.org/10.1017/CBO9781107415324.004

Qin, Y., Liu, S., Guo, Y., Liu, Q., & Zou, J. (2010). Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. *Biology and Fertility of Soils*, *46*(8), 825–834. https://doi.org/10.1007/s00374-010-0493-5

Ramu, K., Watanabe, T., Uchino, H., Sahrawat, K. L., Wani, S. P., & Ito, O. (2012). Fertilizer induced nitrous oxide emissions from Vertisols and Alfisols during sweet sorghum cultivation in the Indian semi-arid tropics. *Science of the Total Environment*, *438*, 9–14.

Richards, M., Sander, B. O. (2014). Alternate wetting and drying in irrigated rice. Implementation guidance for policymakers and investors. *Journal of AHIMA / American Health Information Management Association*, *67*(9), suppl 2p; quiz 49–50.

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management*, *80*(1–3), 5–22. https://doi.org/10.1016/J.AGWAT.2005.07.001

Roger, P. A., & Joulian, C. (1997). Environmental impacts of wetland rice cultivation.

Rice Quality: A Pluridisciplinary Approach, 23.

S. Nishimura, S. Yonemura, K. Minamikawa, K. Y. (2015). Seasonal and diurnal variations in net CO2 flux throughout the year from soil in paddy field. *Journal of Geophysical Research: Biogeosciences RESEARCH*, 661–675. https://doi.org/10.1002/2014JG002746.Received

Sakai, Y. M. (2006). Methane Emission from Paddy Fields and its Mitigation Options on a Field Scale. *Microbes and Environments*, *21*(3), 135–147. https://doi.org/10.1264/jsme2.21.135

Sander, B. O., Samson, M., & Buresh, R. J. (2014). Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma*, *235–236*, 355–362. https://doi.org/10.1016/j.geoderma.2014.07.020

Satyanarayana, A., Thiyagarajan, T. M., & Uphoff, N. (2007). Opportunities for water saving with higher yield from the system of rice intensification. *Irrigation Science*, *25*(2), 99–115. https://doi.org/10.1007/s00271-006-0038-8

Shalini-Singh, Kumar, S., & Jain, M. C. (1997). Methane emission from two indian soils planted with different rice cultivars. *Biology and Fertility of Soils*, *25*(3), 285–289. https://doi.org/10.1007/s003740050316

Sharma, P.K., Lav, Bhushan, Ladha, J.K., Naresh, R.K., Gupta, R.K., Balasubramanian, B.V., Bouman, B. A. . (2002). *Crop-water relations in rice-wheat cropping under different tillage systems and water-management practices in a marginally sodic, medium-textured soil. In: Water-wise Rice Production, Volume 1*

Shearer, M. J., Ren, L., Khalil, M. A., & Shearer, M. J. (1998). *Factors affecting methane emissions from rice fields*. *103*. https://doi.org/10.1029/98JD01115.This

Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. T. (2014). Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. *Annals of Botany*, *1*(1), 7340–7349. https://doi.org/10.1104/pp.900074

Smith, P., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., … Sirotenko, O. (2007). Agriculture In Climate Change 2007: Mitigation. *Cambridge University Press*, (4), 1–44. https://doi.org/10.2753/JES1097-203X330403

Sombroek, W. G., Braun, H. M. H., & van der Pouw, B. J. a. (1982). *Exploratory soil map and agro-climatic zone map of Kenya, 1980* (p. 60). p. 60.

Stiebert, S. (2012). *Kenya's Climate Change Action Plan: Mitigation Chapter 2: Preliminary Greenhouse Gas Inventory*. (August).

Thakur, A. K., Kassam, A., Stoop, W. A., & Uphoff, N. (2016). *Modifying rice crop management to ease water constraints with increased productivity, environmental benefits, and climate-resilience*. https://doi.org/10.1016/j.agee.2016.10.011

The Guardian. (2011). What are the main man-made greenhouse gases? | Environment | The Guardian. Retrieved August 30, 2018, from https://www.theguardian.com/environment/2011/feb/04/man-made-greenhouse-gases

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Smith, P. (2015). The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012. *Global Change Biology*, *21*(7), 2655–2660. https://doi.org/10.1111/gcb.12865

Tuong, T. P., & Bouman, B. A. M. (2003). Rice production in water-scarce environments. *IWMI Books, Reports*. Retrieved from https://ideas.repec.org/p/iwt/bosers/h032635.html

US-EPA. (2013). Global Mitigation of Non-CO_2 Greenhouse Gases. *Environmental Protection*, (June), 2010–2030. https://doi.org/EPA-430-R-13-011

V&A, P. (2009). *Vulnerability and Adaptation experiences from Rajasthan and Andhra Pradesh: The System of Rice Intensification SDC V&A Programme, India*.

W.O. Nyang'au, B.M. Mati, K. Kulecho, R. K. W. and L. K. (2014). Assessment of the Adaptability of Management Practices to System for Rice Intensification in Kenya , USING v. *Journal of Civil Engineering (IEB), 5*(3), 292–300. https://doi.org/10.2166/wcc.2014.114

Wang, J. Y., Jia, J. X., Xiong, Z. Q., Khalil, M. A. K., & Xing, G. X. (2011). Water regime-nitrogen fertilizer-straw incorporation interaction: Field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. *Agriculture, Ecosystems and Environment*, *141*(3–4), 437–446. https://doi.org/10.1016/j.agee.2011.04.009

Wang, L., Han, Z., & Zhang, X. (2010). *Effects of Soil pH on CO_2 Emission from Long-Term Fertilized Black Soils in Northeastern China*. Retrieved from http://file.scirp.org/pdf/5-1.1.13.pdf

Watson, R. T., Meira Filho, L. G., Sanhueza, E., & Janetos, a. (1992). Greenhouse gases: sources and sinks. *Climate Change*, *92*, 25–46. Retrieved from http://www.ipcc.ch/ipccreports/1992 IPCC

Webster, F., & Hopkins, D. (1996). Contributions from different microbial processes to N 2 O emission from soil under different moisture regimes. *Biology and Fertility of*

Soils, *22*(4), 331–335. https://doi.org/10.1007/BF00334578

Wu, X., Yao, Z., Brüggemann, N., Shen, Z. Y., Wolf, B., Dannenmann, M., … Butterbach-Bahl, K. (2010). Effects of soil moisture and temperature on CO2and CH4soil-atmosphere exchange of various land use/cover types in a semi-arid grassland in Inner Mongolia, China. *Soil Biology and Biochemistry*, *42*(5), 773–787. https://doi.org/10.1016/j.soilbio.2010.01.013

WWF. (2007). *More Rice with Less Water: SRI - System of Rice Intensification*. 49.

Xu, S., Jaffé, P. R., & Mauzerall, D. L. (2007). A process-based model for methane emission from flooded rice paddy systems. *Ecological Modelling*, *205*(3–4), 475–491. https://doi.org/10.1016/j.ecolmodel.2007.03.014

Xu, Y., Ge, J., Tian, S., Li, S., Nguy-Robertson, A. L., Zhan, M., & Cao, C. (2015). Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Science of the Total Environment*, *505*, 1043–1052. https://doi.org/10.1016/j.scitotenv.2014.10.073

Yagi, K., & Minami, K. (1990). Effect of organic matter application on methane emission from some japanese paddy fields. *Soil Science and Plant Nutrition*, *36*(4), 599–610. https://doi.org/10.1080/00380768.1990.10416797

Yan, X., Ohara, T., & Akimoto, H. (2003). Development of region-specific emission factors and estimation of methane emission from rice fields in the East, Southeast and South Asian countries. *Global Change Biology*, *9*(2), 237–254. https://doi.org/10.1046/j.1365-2486.2003.00564.x

Yan, X., Yagi, K., Akiyama, H., & Akimoto, H. (2005). Statistical analysis of the major variables controlling methane emission from rice fields. *Global Change Biology*, *11*(7), 1131–1141. https://doi.org/10.1111/j.1365-2486.2005.00976.x

Yang, S., Peng, S., Xu, J., He, Y., & Wang, Y. (2013). Effects of water saving irrigation and controlled release nitrogen fertilizer managements on nitrogen losses from paddy fields. *Paddy and Water Environment*, *13*(1), 71–80. https://doi.org/10.1007/s10333-013-0408-9

Yao, F., Huang, J., Cui, K., Nie, L., Xiang, J., Liu, X., Peng, S. (2012). Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. *Field Crops Research*, *126*, 16–22. https://doi.org/10.1016/j.fcr.2011.09.018

Yu, K. W., Wang, Z. P., & Chen, G. X. (1997). Nitrous oxide and methane transport through rice plants. *Biology and Fertility of Soils*, *24*(3), 341–343. https://doi.org/10.1007/s003740050254

Zhang, G. B., Ji, Y., Ma, J., Liu, G., Xu, H., & Yagi, K. (2013). Pathway of CH_4 production, fraction of CH4 oxidized, and 13C isotope fractionation in a straw-incorporated rice field. *Biogeosciences*, *10*(5), 3375–3389. https://doi.org/10.5194/bg-10-3375-2013

Zhang, W., Yu, Y., Huang, Y., Li, T., & Wang, P. (2011). Modeling methane emissions from irrigated rice cultivation in China from 1960 to 2050. *Global Change Biology*, *17*(12), 3511–3523. https://doi.org/10.1111/j.1365-2486.2011.02495.x

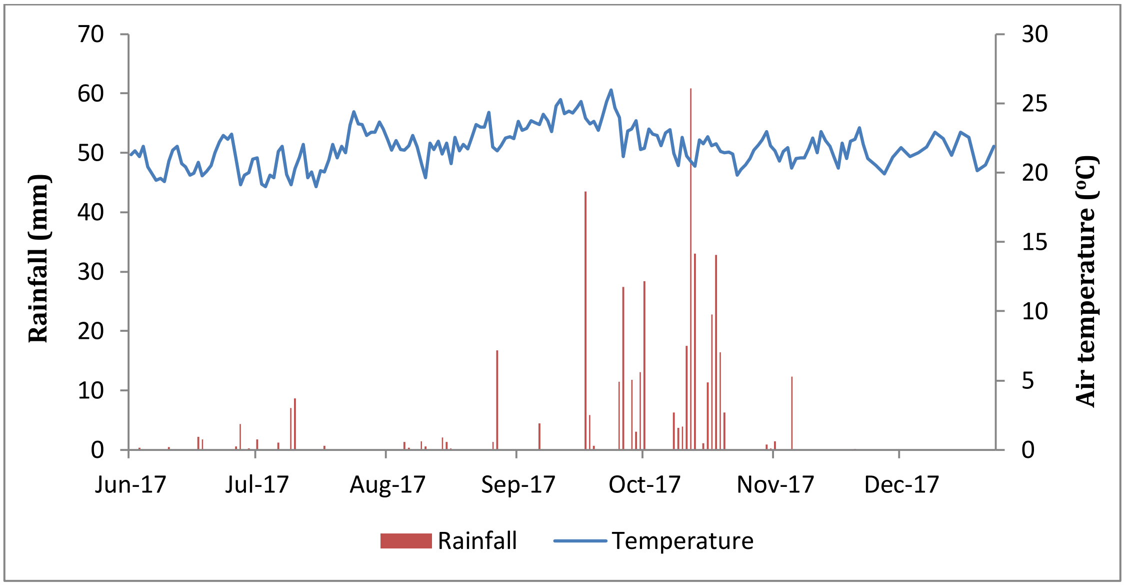
Zheng, H., Huang, H., Yao, L., Liu, J., He, H., & Tang, J. (2014). Impacts of rice varieties and management on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. *Biogeosciences*, *11*(December 2013), 3685–3693. https://doi.org/10.5194/bg-11-3685-2014

Zhuang, Q., Melack, J. M., Zimov, S., Walter, K. M., Butenhoff, C. L., & Aslam K Khalil, M. (2009). Global methane emissions from wetlands, rice paddies, and lakes. *Eos*, *90*(5), 37–38. https://doi.org/10.1029/2009EO050001

Zou, J., Huang, Y., Zheng, X., & Wang, Y. (2007). Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: Dependence on water regime. *Atmospheric Environment*, *41*(37), 8030–8042. https://doi.org/10.1016/j.atmosenv.2007.06.049

APPENDICES

Appendix I: Seasonal variation in the precipitation and temperature measured at the Kirogo Rice Research Farm during the entire sampling period



Appendix II: Analysis of variance (ANOVA) for the effect of water regime, soil type and their interaction on CH_4 emissions during the entire sampling period

```
                               Df Sum Sq Mean Sq F value Pr(>F)    
Mwea_Cum$Water                  1  86851   86851   583.8 <2e-16 ***
Mwea_Cum$Soil                   1  38139   38139   256.4 <2e-16 ***
Mwea_Cum$Water:Mwea_Cum$Soil    1  25381   25381   170.6 <2e-16 ***
Residuals                    3076 457636     149                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix III: Analysis of variance (ANOVA) for the effect of water regime, soil type and their interaction on N_2O emissions during the entire sampling period

```
                                Df Sum Sq Mean Sq F value Pr(>F)
Mwea_Cum$Water                   1   87    86.8    7.495   0.00622 **
Mwea_Cum$Soil                    1   2     1.8     0.156   0.69252
Mwea_Cum$Water:Mwea_Cum$Soil     1   478   478.5   41.307  1.5e-10 ***
Residuals                     3076  35630    11.6
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix IV: Analysis of variance (ANOVA) for the effect of water regime, soil type and their interaction on CO_2 emissions during the entire sampling period

```
                                Df Sum Sq Mean Sq F value   Pr(>F)    
Mwea_Cum$Water                   1   60.8    60.8   98.82   < 2e-16 ***
Mwea_Cum$Soil                    1   522.0   522.0  848.40  < 2e-16 ***
Mwea_Cum$Water:Mwea_Cum$Soil     1   17.7    17.7   28.84  8.43e-08 ***
Residuals                      3076 1892.7     0.6                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix V: Post-hoc multiple comparison test for the effect of water regime, soil type and their interaction on CH_4 emissions during the entire sampling period

```
Tukey multiple comparisons of means
95% family-wise confidence level
factor levels have been ordered
Fit: aov(formula = Mwea_Cum$CH4 ~ Mwea_Cum$Water * Mwea_Cum$Soil)
$`Mwea_Cum$Water`
           diff      lwr      upr p adj
CF-AWD 10.62043 9.758558 11.48229     0
$`Mwea_Cum$Soil`
          diff     lwr      upr p adj
VS-NS 7.037857 6.17599 7.899725     0
$`Mwea_Cum$Water:Mwea_Cum$Soil`
                   diff        lwr       upr     p adj
AWD:VS-AWD:NS  1.296564 -0.3013138  2.894441 0.1579469
CF:NS-AWD:NS   4.879132  3.2812545  6.477009 0.0000000
CF:VS-AWD:NS  17.658283 16.0604054 19.256160 0.0000000
CF:NS-AWD:VS   3.582568  1.9846910  5.180446 0.0000001
CF:VS-AWD:VS  16.361719 14.7638419 17.959596 0.0000000
CF:VS-CF:NS   12.779151 11.1812737 14.377028 0.0000000
```

Appendix VI: Post-hoc multiple comparison test for the effect of water regime, soil type and their interaction on N_2O emissions during the entire sampling period

```
Tukey multiple comparisons of means

95% family-wise confidence level

factor levels have been ordered


Fit: aov(formula = Mwea_Cum$CO2 ~ Mwea_Cum$Water * Mwea_Cum$Soil)

$`Mwea_Cum$Water`

            diff       lwr       upr     p adj

AWD-CF 0.3357864 0.0953028 0.5762701 0.0062214

$`Mwea_Cum$Soil`

            diff        lwr       upr     p adj

NS-VS 0.04850429 -0.1919793 0.2889879 0.6925234

$`Mwea_Cum$Water:Mwea_Cum$Soil`

                   diff          lwr       upr     p adj

AWD:VS-CF:NS  0.2872821 -0.158567461 0.7331318 0.3472915

CF:VS-CF:NS   0.7397687  0.293919082 1.1856183 0.0001211

AWD:NS-CF:NS  1.1240594  0.678209808 1.5699090 0.0000000

CF:VS-AWD:VS  0.4524865  0.006636934 0.8983362 0.0451414

AWD:NS-AWD:VS 0.8367773  0.390927660 1.2826269 0.0000088

AWD:NS-CF:VS  0.3842907 -0.061558883 0.8301403 0.1192078
```

Appendix VII: Post-hoc multiple comparison test for the effect of water regime, soil type and their interaction on CO_2 emissions during the entire sampling period

```
Tukey multiple comparisons of means

95% family-wise confidence level

factor levels have been ordered


Fit: aov(formula = Mwea_Cum$N2O ~ Mwea_Cum$Water * Mwea_Cum$Soil)

$`Mwea_Cum$Water`

            diff       lwr       upr p adj

AWD-CF 0.2810144 0.2255872 0.3364415     0

$`Mwea_Cum$Soil`

          diff       lwr       upr p adj

NS-VS 0.823389 0.7679619 0.8788162     0

$`Mwea_Cum$Water:Mwea_Cum$Soil`

                   diff        lwr       upr     p adj

AWD:VS-CF:VS  0.1291953 0.02643506 0.2319556 0.0068157

CF:NS-CF:VS   0.6715700 0.56880974 0.7743303 0.0000000

AWD:NS-CF:VS  1.1044034 1.00164313 1.2071637 0.0000000

CF:NS-AWD:VS  0.5423747 0.43961442 0.6451350 0.0000000

AWD:NS-AWD:VS 0.9752081 0.87244780 1.0779683 0.0000000

AWD:NS-CF:NS  0.4328334 0.33007311 0.5355937 0.0000000
```