QUANTIFICATION OF GREENHOUSE GAS FLUXES FROM SELECTED CROPPING SYSTEMS UNDER ON FARM CONDITIONS IN THARAKA-NITHI, KENYA

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DECLARATION

This thesis is my original work and has not been presented elsewhere for a degree or any other award.

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To my both parents', our sibling and to my lovely wife, Emily Keen and son, Paranta.

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To Almighty God, thanks for the gift of life, good health, and opportunities. I acknowledge my supervisor's support and unwavering assistance throughout the process. I also acknowledge the University of Embu for the Masters scholarship.

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LIST OF ACRONYMS AND ABBREVIATIONS

BNF	:	Biological Nitrogen Fixation
DNDC	:	Denitrification Decomposition
ECOSSE	:	Estimating Carbon in Organic Soils
EF	:	Emission Factors
EPIC	:	Erosion Productivity Impact Calculator
GHG	:	Greenhouse Gases
GHGI	:	Greenhouse Gases Intensities
GWP		Global Warming Potential
LR	:	Long Rains
NPP	:	Net Primary Production
PPM	:	Part Per Million
SOC	:	Soil Organic Carbon
SOM	:	Soil Organic Matter
SR	:	Short Rains
UNFCCC	:	United Nation Framework Convention on Climate Change
YSE	:	Yield Scale Emissions

ABSTRACT

The smallholder cropping systems have an adverse effect on greenhouse gas (GHG) emissions to the ecosystems due to varied contribution to the GHG budgets. Further, the uncertainty on the contribution of an individual anthropogenic trace gas (CH_4, CO_2, and N_2O) to the GHG emissions is rising due to disproportionate concentration contribution. The general objective was to quantify GHG emissions from selected cropping systems and asses N_2O dynamics. The specific objectives were to: i) quantify greenhouse gas fluxes (CH_4, CO_2 and N_2O) from selected cropping systems in Tharaka-Nithi County ii) evaluate N_2O emissions from smallholders' cropping systems, and ii) determine the environmental factors, climatic conditions, farm management practices, and soil properties that influence N_2O dynamics. The field experiment was undertaken under on-farm conditions, fully managed by farmers for one year (two cropping seasons). For the field experiment, five cropping systems were evaluated: i) sole maize, ii) maize intercropped with beans, iii) coffee, iv) banana, and iv) agroforestry. Gas was sampled using a static chamber arranged linearly in a randomized complete block design replicated thrice per cropping system. Gases were analyzed using gas chromatography (GC) fitted with a ^{63}Ni-electron capture detector (ECD) for N_2O and flame ionization detector (FID) for CH_4 and CO_2 using N as carrier gas. The cumulative soil GHG fluxes ranged from -1.34 kg CH_4-N ha^{-1} yr^{-1} under agroforestry to -0.77 kg CH_4-C ha^{-1} yr^{-1} under banana for CH_4, 0.30 kg N_2O-C ha^{-1} yr^{-1} to 1.23 kg N_2O-C ha^{-1} yr^{-1} for N_2O and 5949 kg CO_2-C ha^{-1} yr^{-1} to 12954 kg CO_2-C ha^{-1} yr^{-1} for CO_2. The maize yields ranged from 0 to 3.38 Mg ha^{-1}. The nitrous oxide yields scaled emissions ranged from 0.10 to 0.26 g kg^{-1} maize and 0.68 to 1.30 g kg^{-1} beans. The review indicated that coffee, tea, maize, and vegetables emit N_2O ranging from 1 to 1.9, 0.4 to 3.9, 0.1 to 4.26, and 48 to 113.4 kg N_2O-N ha^{-1} yr^{-1}, respectively. Precipitation was the key driver of both CO_2 and N_2O emissions in the study area. The yield-scaled and N_2O emissions factors ranged between 0.08 and 67 g N_2O-N kg^{-1} and 0.01 and 4.1% across cropping systems. Soil characteristics, farm management practices, and climatic and environmental conditions are significant drivers that influence N_2O emissions across SSA cropping systems. Smallholder farmers in Central Highland of Kenya also contribute to global GHG emissions through cropping systems. These results are within the previous GHG fluxes findings in SSA. Therefore, this forms the baseline for estimating GHG in the agro-ecosystems in Africa.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Over 2.5 billion people currently depend on agriculture worldwide (FAO, 2018). However, it is facing a great challenge in feeding the ever-growing population while improving adaptation to climate change (Okeyo et., 2014), especially in sub-Saharan Africa (Acosta-Alba et al., 2019; Groot et al., 2019; Naab et al., 2019). The world population is expected to exceed 9 billion by 2050, resulting in high food demand and causing an increase in agricultural production (Huang et al., 2018). This significantly impacts agricultural land, whereas, in Africa, most farming is cultivated in small fragmented parcels of land due to high population pressure on land (Kuivanen et al., 2016). Smallholder farmers in sub-Saharan Africa (SSA) face many challenges, including soil fertility and climatic variability, leading to environmental degradation (Tittonell et al., 2012). The growing threat of food anthropogenic emissions through converting natural forests into agricultural land (Pelster et al., 2017; Vermeulen et., 2012). Methane (CH_4), Carbon dioxide (CO_2), and Nitrous (N_2O) concentrations in the atmosphere have been increasing at rates of 0.8%, 0.5%, and 0.3% per year, respectively (Ciais et al., 2013; Grootboom et al., 2016). By the 2010s, Asia was the leading continent in agricultural emissions (43%), followed by the American continent (26%), Africa(15%), and Europe(12%), although Africa's emission was reported to have almost doubled, from 9% to 15% (Tubiello et al., 2018). Africa contributes 6-19% of N_2O to the global total, and agriculture contributes 38% of these gases (Hickman et al., 2014). Methane (CH_4) is a potent greenhouse gas with a global warming potential of 25 over 100 years timescales, and it occurs under anaerobic soil conditions in the agricultural sector (Fazli and Man, 2014). Methane is produced by methanogenic archaea, which converts simple substrates into methane through anaerobic degradation of organic matter (Pazinato et al., 2010; Serrano-Silva, et al., 2014). Methonotrophy occurs as results of anaerobic degradation of organic matter by methanogenic archaea while methanotrophy occurs when methanotrophs metabolize CH_4 as their source of carbon and energy (Kim et al., 2016). Microbial decomposition of organic matter and respiration of living plant roots are the primary determinants of carbon dioxide emissions (Konda et al., 2008).

Biogeochemical processes control the concentration of main GHGs in the soil (Paper et., 2016). The interaction of CO_2, N_2O, and CH_4 between the biosphere and the atmosphere depends on carbon (C), nitrogen availability, land management, and environmental conditions (Rosenstock et., 2016). For instance, natural and managed soils are the principal sources of nitrous oxide (Smith et., 2014). Inorganic fertilizer is the dominant anthropogenic source of N for crop growth and N_2O production (Yang et., 2019). Microbial processes such as nitrification and denitrification significantly contribute to N_2O in the soil. Temperature, moisture, and soil biological, chemical, and physical characteristics significantly impact nitrification and denitrification since they influence microbial activities (Tongwane et., 2016).

Soil fertility depends on the inherent soil properties, climatic conditions, adopted management practices, and types of fertilisation (Sánchez-Navarro et., 2019). In Africa, 40% of the soils have low nutrient capital reserves, 25% have aluminum toxicity, 18% have high leaching potential, and 9% have high P-fixation capacity (Bado and Bationo, 2018). Conventional agricultural practises such as intensive tillage, mono-cropping, and crop residue removal reduce soil fertility. Nutrient depletion in the soil mainly occurs through crop harvesting, erosion, and nutrient leaching (Oliveira et., 2019). In an attempt to improve soil fertility, farmers have continuously used inorganic fertiliser, which affects soil pH and soil structure and disrupts the habitat of microorganisms (La et., 2011). Mineral fertilizer helps to improve crop production and also affects soil quality characteristics by altering microbial processes hence causing soil acidification as induced by N fertilizer (Curtin et., 2019). Conservation agriculture has been reported to provide mitigation of GHG and increased soil carbon sequestration (Kakraliya et., 2018). Manure application can enhance soil organic carbon sequestration, improving soil fertility by increasing soil carbon, nutrient, and pH (Cai et., 2019). The balance between mineralization of organic N and immobilization of N by microbes depends on soil biological activities, the moisture and temperature, and the ratio of C/N in SOM (Andriamananjara et., 2019).

Countries are obligated to report their Nationally Determined Contributions (NDCs) and climate change mitigation options to the United Nations Framework Convention on Climate

Change (UNFCCC) (Gyanchndani et al., 2016; Elkahwagy et al., 2017). Further, as captured in the Paris Climate Agreement 2015, countries agreed to limit the global temperature increase below 1.5^{o} C by reducing GHG emissions (UNFCCC, 2015). To achieve this, most SSA countries consider agriculture a potential mitigation option to reduce GHG emissions (Richards et al., 2016). However, there are uncertainties in the national GHG inventories in SSA countries due to a huge data gap arising from countries in the region having only a few empirical studies carried out or none from agricultural production systems. It is imperative to note that only a few studies in SSA (less than 30 published studies) have attempted to quantify N_2O emissions based on different cropping systems. Consequently, most of the countries in SSA have continuously used the Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factors (EFs) and which tend to overestimate GHG emissions in SSA (Richard et al., 2016; Albanito et al., 2017; Macharia et al., 2020). To dentify mitigation measures and other climate-smart interventions, there is a need to establish baseline GHG emissions scenarios from different regional cropping systems.

1.2 Statement of the Problem

Cropping systems have varying GHG fluxes. Each cropping system's contribution toward national GHG inventories largely remains unknown, leaving a considerable data gap. At the same time, GHG emissions from smallholder mixed farms in Tharaka- Nithi remain mostly unknown since limited studies have attempted to address the challenge. Most studies conducted in Kenya on greenhouse gas emissions have reported GHG emissions from either on-station experiments or single isolated cropping systems with minimal attention to the nature of the smallholder farming systems, which generally adopt a mixed-farming approach, combining both crops and livestock production in the farming unit. Such studies have consistently ignored the simple fact that different cropping/farming systems produce varying amounts of GHG fluxes. Limited empirical studies have been conducted in sub-Saharan Africa (SSA) to quantify and understand the dynamics of soil N_2O fluxes from smallholder cropping systems. The literature on soil N_2O fluxes in SSA is fragmented, hence a pressing need to consolidate it to ease mitigation targeting and policy formulation initiatives. Hence, to identify specific smallholder farming systems' GHGs emissions hotspots and develop strategies for mitigations, there is a need to quantify GHGs emissions from specific cropping systems. There is also a need to evaluate N_2O emission status in SSA and determine environmental, climatic, and management practices that influence the rate of emission of N_2O in SSA.

1.3 Justification

The growing need for the quantification of GHG emissions for reporting of the NDCs to the UNFFCCC has surged. Calling for reporting of the NDCs. There is urgent call for refinement of the Tier 1 defaults values. Quantifying GHGs fluxes from selected cropping systems of smallholder farms will contribute toward national GHGs emission. Consolidating GHG emission data from each cropping system's specific N_2O emissions is essential to policymakers in their quest to develop GHG mitigation and/or adaptation strategies. The resultant calculated emission factors, yield-scaled N_2O emissions, will underwrite the current national default emission factors in the quest for the national GHG reporting initiative. This study will improve Kenyan’s reporting to UNFCCC on GHG budgets and contribute to developing mitigation measures for N_2O emission based on agro-ecological zone.

1.4 Objectives

To quantify GHG emissions from selected cropping systems and asses N_2O dynamics.

1.4.1 Specific Objectives

1. To quantify greenhouse gas fluxes (CH_4, CO_2 and N_2O) from selected cropping systems in Tharaka-Nithi County.
2. To evaluate N_2O emissions from smallholders’ cropping systems.
3. To determine the environmental factors, climatic conditions, farm management practices, and soil properties that influence soil N_2O dynamics.

1.5 Research Hypotheses

1. There is no significant difference in the quantities of greenhouse gas fluxes across the selected cropping systems in Tharaka-Nithi County.

2. There is no significant difference in quantities of N_2O emissions from smallholders' cropping systems.
3. Environmental factors, climatic conditions, farm management practices, and soil properties do not significantly influence N_2O dynamics.

1.6 Thesis structure

This thesis is presented in a paper format comprising four chapters. Chapter one entails an introductory section containing the general background information. It consists of a statement of the problem, justification, objective specific objective, and research hypothesis. Chapters two and three present the specific objective studies in paper format.

Chapter two covers objective one, i.e., the quantification of greenhouse gas fluxes (CH_4, CO_2 & N_2O) from selected cropping systems in Tharaka-Nithi County. The GHGs fluxes were sampled and analyzed in the laboratory to determine the change. It also presents the soil properties and biomass measurements.

Chapter three covers objectives two and three. Objective two is on the soil N_2O emissions from smallholders' cropping systems in SSA. The cropping systems of interest were maize, cereal-legume intercropping, coffee, tea, and vegetable. It also touches on soil N_2O emissions from organic and inorganic fertilizer use. Yields scale Emissions (YSE) and N_2O emissions factors (EF) are also covered. For objective three, the effect of environmental factors, climatic conditions, farm management practices, and soil properties such as soil temperature, soil type, and soil moisture on N_2O dynamics are covered. Mitigation options for N_2O emissions such as integrated soil fertility management, cereal-legume intercropping, fertilizer application management, and reduced/no-tillage options are also evaluated.

Chapter four ties up the whole thesis through a synthesis, conclusion, recommendation, and areas for further research.

CHAPTER TWO

GREENHOUSE GAS FLUXES FROM SELECTED SMALLHOLDER CROPPING SYSTEMS IN UPPER EASTERN KENYA

Abstract

The vast data gap on the contribution of smallholder cropping systems to GHG emissions and the need for most nations to meet Sustainable Development Goal 13 on climate action, i.e., on nationally determined contributions (NDC) and in compliance with the Paris Agreement calls for regular in-situ GHG measurements. The study objective was to quantify greenhouse gas fluxes (CH4, CO_2 & N_2O) from selected cropping systems in Tharaka-Nithi County. There were five cropping systems on two smallholder farms: sole maize, maize-bean intercrop, coffee, banana, and agroforestry. Greenhouse gases were sampled using three static chambers per cropping system. Gases were analyzed using gas chromatography (GC) fitted with a ^{63}Ni-electron capture detector (ECD) for N_2O and flame ionization detector (FID) for CH_4 and CO_2 using N as carrier gas. Cumulative annual fluxes of CH_4, N_2O, and CO_2) varied significantly on farms one and two across the cropping systems. The cumulative soil GHG fluxes ranged from -1.34 kg CH_4-N ha^{-1} yr^{-1} under agroforestry to -0.77 kg CH_4-C ha^{-1} yr^{-1} under banana for CH_4, 0.30 kg N_2O-C ha^{-1} yr^{-1} ^{to} 1.23 kg N_2O-C ha^{-1} yr^{-1} for N_2O and 5949 kg CO_2-C ha^{-1} yr^{-1} to 12954 kg CO_2-C ha^{-1} yr^{-1} for CO_2. The maize yields ranged from 0 to 3.38 Mg ha^{-1}. The nitrous oxide yields scaled emissions ranged from 0.10 to 0.26 g kg^{-1} maize and 0.68 to 1.30 g kg^{-1} beans. Smallholder farmers in Upper eastern Kenya contribute a limited amount of soil GHG emissions.

Keywords: Carbon dioxide, methane, nitrous oxide, smallholder farms, cropping systems, yield scaled emissions

2.1 INTRODUCTION

Agriculture contributes 11 to 14 % of the total annual anthropogenic greenhouse gases (GHG) globally, besides 17% from land-use changes (Ciais et al., 2011; Paul et al., 2018; Musafiri et al., 2020a). Approximately 80% of farmland in sub-Saharan Africa (SSA) comprises smallholder farms, thus important in GHG inventories. Although the region contributes minimal GHG emissions globally, rising temperatures and changes in rainfall have been projected and may affect agricultural production due to low carbon development pathway alternatives (Fatumah et al., 2019). Climate variability can adversely affect SSA, given that the region has a high poverty level and low adaptive capacity to climate-change adaptation strategies due to resource limitations (Karienye & Macharia, 2020).

The main agriculture-related GHGs are carbon dioxide (CO_2), Methane (CH_4), and Nitrous oxide (N_2O). According to World Meteorological Organisation (WMO, 2020), the GHG atmospheric concentration are 413.2 ppm for CO_2, 1889ppb for CH_4, and 333.2 ppb for N_2O. Agricultural CO_2 results from burning organic matter, autotrophic and heterotrophic respiration. The CH_4 is primarily the net balance between methanogens and methanotrophs (Feliciano et al., 2017; Pazinato et al., 2010). Nitrous oxide (N_2O) is produced through co-denitrification, chemo-denitrification, nitrifier-denitrification, heterotrophic nitrification, and autotrophic nitrification (Butterbach-Bahl et al., 2013). The N_2O has a high global warming potential (GWP) of 265 and destroys the stratosphere (IPCC, 2014). Agricultural intensification and application of nitrogen-based fertilizers contribute to soil GHG emissions. The balance between mineralization of organic N and immobilization of N by microbes depends on soil biological activities, moisture and temperature, and the ratio of C: N in the soil. Methane (CH_4) is produced in oxygen-limited conditions by methanogens through the degradation of organic matter and can absorb infrared radiation 20 to 30 times more than CO_2 (Pazinato et al., 2010).

Upper Eastern Kenya is one of the key food baskets of Kenya. This region comprises smallholder farmers with diversified cropping systems under the same field. Cropping systems are rain-fed and non-mechanized (Ngetich et al., 2014). Smallholder farmers use inorganic and organic resources such as mineral fertilizers, animal manure, crop residue and tithonia diversifolia for enhanced crop yields (Kiboi et al., 2019; Macharia et al., 2020; Musafiri et al., 2020a-b; Githogo et al., 2022). However, crop residue utilization in the region is limited by crop-livestock competition (Macharia et al., 2020). Common crops grown in the region are maize (*Zea mays L.)* and beans (*Phaseolus vulgaris*) as staple crops, coffee (*Coffee arabica L.)*, and banana (*Musa sp)* as cash crops. Greenhouse Gas Emissions (GHGs) emissions from different cropping systems such as intercropping, mixed cropping, and cash crops have been getting more and more attention. Despite the challenges of decline in soil fertility promoted by insufficient use of inorganic and organic resources (Mucheru-Muna et al., 2014; Kiboi et al., 2019), climate variability has also become an ailing issue in the region. For instance, Kiboi et al. (2018) reported that farmers complained of poor harvest due to low precipitation. Therefore, smallholder farmers are faced with the triple challenge of improving soil fertility and responding to climate change through reduced GHG fluxes while enhancing food production. The soil GHG fluxes are mainly influenced by practices for improving crop yields, such as soil fertility management technologies (Lemarpe et al., 2021; Githogo et al., 2022). Additionally, soil C content, tillage practices, N fertilization, cover crops, aeration, and soil water content influence GHG fluxes (Pelster et al., 2017; Musafiri et al., 2021). Therefore, there is a need to assess soil GHG fluxes across different cropping practices under smallholder management practices.

The vast data gap on the contribution of smallholder cropping systems to GHG emissions and the need by the Kenyan government to report her Nationally Determined Contribution to the United Nations Framework Convention on Climate Change (UNFCCC) calls for regular in-situ GHG measurements. There is a likelihood of an increase in GHG emissions coupled with increasing GWP aided by agricultural lands due to low carbon development pathways. Additionally, the limitation of GHG measurements in smallholder farms further increases the uncertainty of GHG emissions. Therefore, this study quantified soil GHG fluxes from different cropping systems under on-farm from two smallholder farms in Upper Eastern Kenya.

2.2 Methods and Materials

2.2.1 Study Area

The study was carried out in Kangutu sub-location, Chuka /Igamba Ng'ombe sub-county, Tharaka-Nithi County, in Upper Eastern Kenya (Figure 2.1). The study location is in the Upper Midland three (UM3) agro-ecological zone, on the eastern slopes of Mt. Kenya, and lies at an altitude of 1500 m above sea level. The area receives annual rainfall between 1200 to 1400 mm and a yearly average temperature of 20°C (Jaetzold et al., 2007). It experiences two rainfall seasons, the Long rains (LR) from March through to June and short rains (SR) from October through to December (Jaetzold et al., 2007). The soil type is predominantly *Humic* Nitisols which are well-drained, very deep, dusky red to dark reddish-brown, friable clay with acidic topsoil, and moderate to high fertility.

2.2.2 Cropping Systems

The study area is predominantly smallholder, with small land parcels of 1.2 ha with highly diversified cropping systems. Cropping systems in Chuka are mostly for small-scale farming for subsistence purposes. A typical farmer grows maize (*Zea mays*) and beans (*Phaseolus vulgaris)* as staple crops and coffee (*Coffee arabica L*) at the periphery of of each farm. However, a majority of farmers have neglected it due to low coffee prices experienced in the recent past, and bananas (*Musa sp.*) mostly near the household as cash crops. Some farmers mix different crops in the same plot with fruit trees such as mangos (agroforestry). Farm boundaries are marked by planted exotic trees such as *Grevillea Robusta* together with woodlots such (*Eucalyptus sp*).

2.2.3 Study set-up

Two farms were purposely selected based on similarities in cropping systems, specifically the crop enterprises in different plots within the farm. The cropping systems of interest were five: maize monocrop, maize-beans intercrop, bananas, coffee, and agroforestry, which formed the treatments. On both farms, banana cropping systems were planted near the homestead. Hence, they could benefit directly from kitchen-related refuse/waste. During farm selection, the key parameters for consideration were near homogeneity in inputs applied and alignment to the cropping systems of interest. Planting in both seasons was done at the same time on both farms. However, during the middle of the LR 2019 season, the farmer cleared the coffee cropping system citing poor economic returns on farm one, but we continued determining the GHG fluxes. In each treatment, three static chambers were randomly installed (but closely for convenience during sampling) between the rows and within the rows.

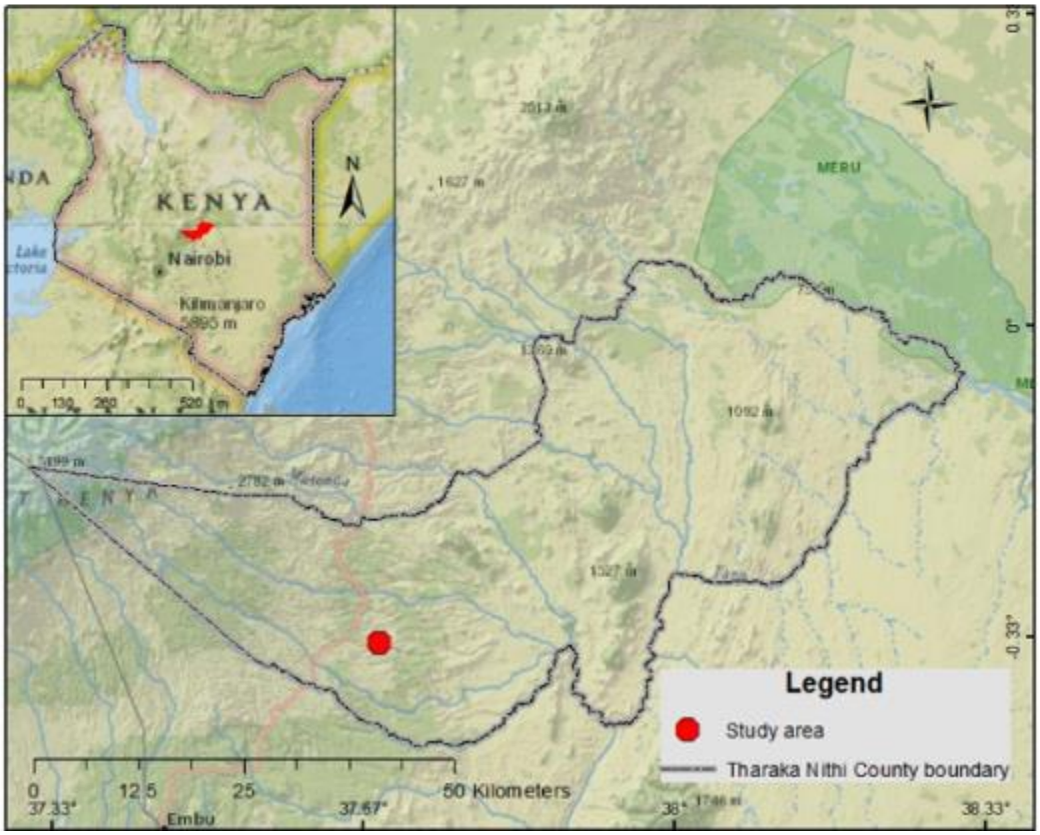

Figure 2. 1: Study area map

2.2.4 Greenhouse gases Concentration Measurement

The greenhouse gas fluxes were measured using the circular vented static chambers technique. Round chambers with a radius of 0.2 m and a height of 0.1 m consisting of two parts (base and lid) were used. The bases were installed one week (23rd April 2019) before the first measurement and left intact throughout the experimental period (30th April 2019- 29th April 2020). The lid was equipped with a gas sampling port used during gas sampling and a vent to stabilize air pressure during gas deployment. Rubber tapes were used to close the joints during gas sampling to ensure an air-tight seal between the base and the lid. Sampling was done following key farm operations like land preparation and fertilization whenever it rained and fortnightly for two seasons. During sampling, GHG was sampled per chamber using a 60 mL syringe fitted with Luer locks at intervals of 0, 10, 20, and 30 minutes and transferred into 20 mL pre-evacuated glass vials. Transferring a 60 mL sample to a 20 mL vial ensured over-pressurization to avoid contamination from the external air. The gas vials were packed and transported to the laboratory for analysis.

2.2.5 Flux Calculation and Data quality and Data assurance

The GHG gases were analyzed using gas chromatography (GC) fitted with a ^{63}Ni-electron capture detector (ECD) for N_2O and flame ionization detector (FID) for CO_2 and CH_4 using N as carrier gas. Calibration was done using CO_2, CH_4, and N_2O standards, and their peak area and concentrations were applied to determine the sampled CO_2, CH_4, and N_2O. The GHG concentrations were converted to mass per volume using the ideal gas law and measured chamber volume, internal chamber air temperature, and atmospheric pressure as shown by Equation 1. Fluxes were calculated using linear regression of gas concentrations versus chamber closure time

$$F = \frac{b \times Mw \times Vch \times 60 \times 10^6}{Ach \times Vm \times 10^9} \qquad (1)$$

Where, F= flux rate (ug m^{-2} n^{-1}), Mw = molecular weight of component (g mol^{-1}), Vch = chamber volume (m^3), Ach = chamber area (m^2), Vm = correlated standard gas molar volume ($m^3 mol^{-1}$) and $Vm = 22.4 \times 10^{-3}$ $m^3 mol^{-1}$.

Data quality was validated using CO_2 concentrations, whereby if the coefficient of determination (R^2) of CO_2 was more than 90%, it was considered normal. However, if $R^2 < 0.90$, then results were deemed contaminated and discarded.

2.2.6 Soil Properties and Meteorological data

The baseline and end-line soil samples were collected at the beginning of LR 2019 and the end of the SR 2019 season. The soil samples were analyzed for soil texture, total nitrogen, soil organic carbon, and pH at Mazingira Centre (ILRI-Nairobi, Kenya). The soil samples were oven-dried at 40°C for 72 hours, ground using a ball mill (Retsch ball mill, Haan, Germany), and sieved through a 2 mm aperture sieve. Grounded samples were used to determine C and N concentration using a C/N analyzer (Thermal Scientific, Flash 2000 Analyzer, Waltham, MA, USA). A glass probe pH meter determined soil pH at a 1: 2 soil: water solution ratio (Crison Instruments, Barcelona, Spain). For bulk density, core rings with a 100 cm^3 volume (Eijkelkamp Agrisearch equipment, Giesbeek, The Netherlands) were used to collect undisturbed samples, oven-dried for 24 hours at 105°C until constant weight was obtained and the bulk density calculated. Soil moisture was determined using the gravimetrical method and temperature using a thermometer during gas sampling. The gravimetric results were then converted to the volumetric units (water-filled pores space) following Githogo et al. (2022).

2.2.7 Biomass Measurement

During harvesting, a 2 m x 2 m sub-plot near each chamber was selected, and all the crops within the area were harvested. Both above and below-ground biomass was harvested for food crops. Fresh weight for the plant components (grains, leaves, stems, and roots) was determined using an electronic balance. A sub-sample for each plant component (leaves, stem, root, and grain) was weighed, air-dried for three weeks, re-weighed, and measured again for all components. The grain weight was reported at 12.5% moisture content, similar to Ngetich et al. (2014). During the LR 2019, the biomass subsamples (grain, leaves, stems and roots) were analysed for carbon and nitrogen content. In the laboratory, the sub-sample were oven dried at 60°C for 48 hours. To determine the C-N concentration, the sub-samples were ground using a hammer mill (IKA mills, MF 10.2, Willington, N.C., USA) and analyzed in a C/N analyzer.

2.2.8 Greenhouse gas yield-scaled emissions

The greenhouse yield scaled emissions (YSE) was calculated by dividing cumulative annual N_2O fluxes with grain yields following Musafiri et al. (2020a) and Githogo et al. (2022) as described in equation 2.

$$N_2O\ YSE = \frac{Soil\ N_2O\ fluxes}{Grain\ yield} \qquad (2)$$

Where $N_2O\ YSE$ is soil nitrous oxide yield-scaled emissions (g N_2O-N kg^{-1} grain yield), $Soil\ N_2O\ fluxes$ is cumulative annual soil nitrous oxide fluxes (g N_2O ha^{-1} yr^{-1}), and grain yields are annual grain yields (kg ha^{-1} yr^{-1}).

2.2.9 Statistical Analysis

The data were tested for normality in distribution using the Shapiro–Wilk test. The soil N_2O fluxes were not normally distributed. The data were log-transformed following Musafiri et al. (2020). Linear mixed model was implemented in SAS 9.4 software to determine the influence of fixed factors treatments and random factors block and seasons on measured parameters. Soil GHG fluxes (CO_2, CH_4, and N_2O). Means separation was done using Tukey's Honest Significant test at $p<0.05$. The study utilized Pearson's correlation to test the association between soil GHG fluxes (CO_2, CH_4, and N_2O) and soil temperature, moisture, carbon, nitrogen, C: N ratio, and bulk density.

2.3 Results

2.3.1 Meteorological and soil characteristics

The cumulative annual precipitation was 2027 mm (Figure 2.2-4c). The distribution of the precipitation was 460mm during the LR 2019 season and 1567 for the SR 2019 season. The rainfall distribution during the LR season was similar to the long term of 420 to 750 (Jaetzold et al., 2007). However, the SR season was higher than the long-term rainfall amounts of 250 to 450 mm (Jaetzold et al., 2007). The mean soil moisture across the cropping systems was maize (0.24 m^3 m^{-3}), maize beans (0.26 m^3 m^{-3}), agroforestry (0.25 m^3 m^{-3}), and banana (0.27 m^3 m^{-3}), and coffee (0.26 m^3 m^{-3}) on farm 1. On farm 2, the soil moisture content was maize (0.25 m^3 m^{-3}), maize-beans (0.25 m^3 m^{-3}), agroforestry (0.24 m^3 m^{-3}), banana (0.26 m^3 m^{-3}) and coffee (0.27 m^3 m^{-3}) Figure 2.2-4c).

At the start of the experiment on farm one, bulk density ranged from 1.00 to 1.05 g/cm^{-3}, soil pH from 5.38 to 6.75, total nitrogen from 0.18 to 0.26%, total soil organic carbon (SOC) from 2.02 to 2.75%, and C/N ratio from 10.58 to 11.67 across the cropping systems (Table 2.1). On farm two, bulk density ranged from 0.87 to 0.97 g cm^{-3}, soil pH ranged from 5.26 to 6.14, total nitrogen from 0.15 to 0.18%, total SOC from 1.73 to 2.07%, and C/N ratio from 10.59 to 11.53 across the cropping systems (Table 2.1). While at the end of the experiment, farm one had a bulk density ranging from 1.04 to 1.15 g cm^{-3}, soil pH from 5.56 to 6.63, total nitrogen from 0.2 to 0.28 %, total SOC from 2.2 to 3.06%, and C/N ratio from 10.93 to 11.44. On farm two, bulk density ranged from 0.89 to 1.09 g/cm^{-3}, soil pH from 5.75 to 6.2, total nitrogen from 0.17 to 0.22 %, total SOC from 1.81 to 2.43 %, and a C/N ratio from 10.50 to 11.39 across the cropping systems.

Table 2. 1: Soil properties for 0 to 20 cm depth sampled during the beginning and end line for both season

	Farm 1					Farm 2				
Cropping Systems	**Bulk density g/cm^{-3}**	**pH**	**N (%)**	**SOC (%)**	**C/N ratio**	**Bulk density g/cm^{-3}**	**pH**	**N (%)**	**SOC (%)**	**C/N ratio**
Baseline										
Maize	1.01	5.88	0.18	2.1	11.67	0.93	5.8	0.16	1.82	11.38
Maize-Bean	1.02	5.69	0.22	2.46	11.18	0.97	5.45	0.17	1.8	10.59
Agroforestry	1.05	5.38	0.2	2.28	11.40	0.94	5.26	0.17	1.93	11.35
Banana	1.01	6.75	0.26	2.75	10.58	0.87	5.78	0.18	2.07	11.50
Coffee	1.00	6.60	0.18	2.02	11.22	0.93	6.14	0.15	1.73	11.53
End of Experiment										
Maize	1.15	5.77	0.21	2.37	11.29	1.06	5.75	0.22	2.43	11.05
Maize-Bean	1.07	5.56	0.25	2.86	11.44	1.09	6.01	0.17	1.81	10.65
Agroforestry	1.09	5.29	0.2	2.24	11.20	1.00	6.2	0.19	2.11	11.11
Banana	1.08	6.63	0.28	3.06	10.93	0.95	6.05	0.18	1.89	10.50
Coffee	1.04	5.6	0.2	2.2	11.00	0.89	5.84	0.18	2.05	11.39

2.3.2 The GHG Fluxes

Throughout the study period, soil in all the cropping systems predominantly acted as a CH_4 sink (Figure 2.2a, b). On farm 1, The CH_4 fluxes on farm one differed significantly (*p=**0.0002***) during LR 2019 and ranged between -0.72 and -0.32 kg CH_4-C ha^{-1}. During the SR, the CH_4 varied greatly (*p=0.*0008), ranging between -0.65 and -0.42 kg CH_4-C ha^{-1} (Table 2.2). We observed a significant ($p<0.0011$) difference in annual CH_4 fluxes where the variation was between -1.34 and -0.81 kg CH_4-C $ha^{-1}yr^{-1}$. Additionally, the seasonal interaction was significant ($p<0.0015$). On farm 2, the methane uptake significantly ($p<0.05$) varied across the cropping systems. During the LR 2019, the methane uptake ranged from -0.51 and -0.35 kg CH_4-C ha^{-1}. Methane uptake ranged from -0.60 and -0.35 kg CH_4-C ha^{-1} during the SR 2019. The cumulative annual methane uptake ranged from -1.09 and -0.77 kg CH_4-C ha^{-1} yr^{-1}. The seasonal p-value of the CH_4 uptake was significant at $p=0.0015$ and $p<0.0001$ on farms one and two.

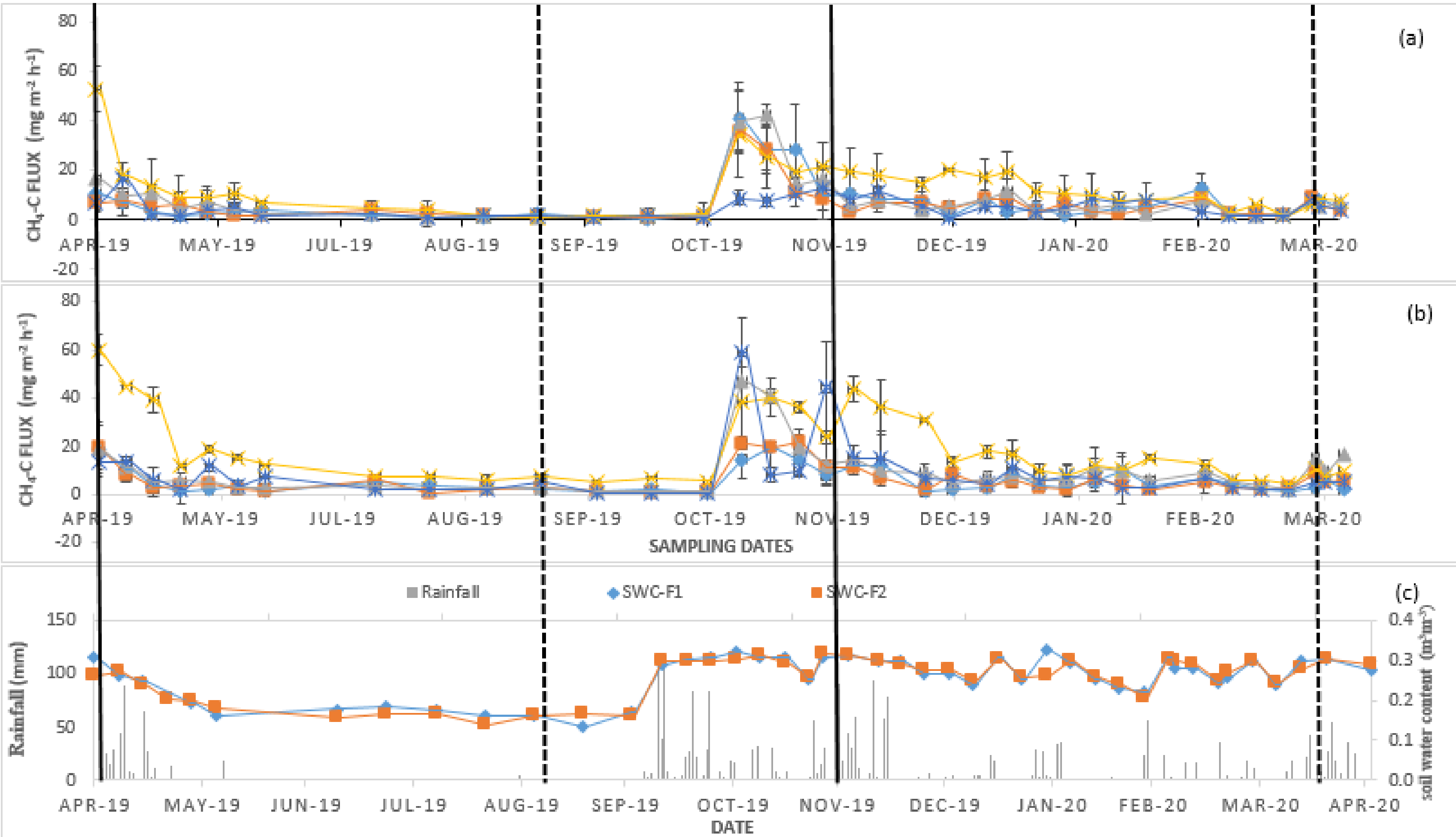

Figure 2. 2: Soil Methane Farm 1 (a), Farm 2 (b) and precipitation and soil water content (c) from different land utilization types in Upper Eastern Kenya

Table 2. 2: Seasonal and annual cumulative greenhouse gas (GHG) fluxes for two cropping seasons between April 2019 and April 2020 for different cropping systems in Upper Eastern Kenya

Season[1]	Treatment	Farm 1			Farm 2		
		CH_4 (kg CH_4-C ha^{-1})	**N_2O (kg N_2O-N ha^{-1})**	**CO_2 (kg CO_2-C ha^{-1})**	**CH_4 (kg CH_4-C ha^{-1})**	**N_2O (kg N_2O-N ha^{-1})**	**CO_2 (kg CO_2-C ha^{-1})**
LR 19	Maize	-0.39a[2]±0.04	0.04c±0.01	1844b±83	-0.51b±0.02	0.11b±0.01	1764bc±64
	Maize-Bean	-0.69b±0.04	0.08b±0.01	2394ab±82	-0.47b±0.04	0.11b±0.01	3510a±316
	Agroforestry	-0.72b±0.02	0.04c±0.01	1992ab±120	-0.44ab±0.03	0.08b±0.01	1668c±67
	Banana	-0.43a±0.01	0.13a±0.01	2503a±191	-0.35a±0.02	0.48a±0.02	3748a±426
	Coffee	-0.32a±0.03	0.05c±0.01	1900ab±36	-0.49b±0.01	0.08b±0.01	2818ab±97
	P *value*	***0.0002***	**<.0001**	***0.04***	***0.0044***	**<0.0001**	**0.0011**
SR 19	Maize	-0.42a±0.01	0.28b±0.01	6659ab±190	-0.52bc±0.03	0.43b±0.01	5438cd±133
	Maize-Bean	-0.65b±0.02	0.32a±0.02	7220a±150	-0.57bc±0.03	0.23c±0.01	7522b±451
	Agroforestry	-0.62b±0.03	0.26b±0.01	6298ab±325	-0.35a±0.05	0.40b±0.02	4281d±402
	Banana	-0.43a±0.03	0.32a±0.03	6825b±599	-0.42ab±0.01	0.75a±0.03	9210a±191
	Coffee	-0.6b9±0.05	0.27b±0.01	5536b±171	-0.60c±0.04	0.39b±0.02	5782c±173
	P *value*	***0.0008***	***0.03***	***0.02***	***0.0108***	**<0.0001**	**<0.0001**
Annual	Maize	-0.81a±0.05	0.33bc±0.01	8504ab±251	-1.03b±0.05	0.54b±0.01	7202cd±194
	Maize-Bean	-1.34b±0.05	0.40ab±0.01	9614a±221	-1.04b±0.07	0.34c±0.01	11032b±767
	Agroforestry	-1.34b±0.03	0.30c±0.02	8290ab±441	-0.79a±0.06	0.48b±0.03	5949d±400
	Banana	-0.87a±0.04	0.45a±0.03	9328a±692	-0.77a±0.03	1.23a±0.01	12958a±439
	Coffee	-1.01a±0.08	0.32bc±0.01	7436b±199	-1.09b±0.03	0.48b±0.03	8599b±269
	P Value	***0.0011***	***0.005***	***0.04***	***0.0035***	<0.0001	<0.0001
	Seasonal p value[3]	0.0015	<.0001	<.0001	0.003	<.0001	<.008
	Interaction[4]	<.0001	0.1083	<.0001	<.0001	0.09	<0.0001

[1] Season LR 2019 indicates the long rains 2019 season, SR 2019 indicates the short rain 2019 season.
[2] Soil GHG emissions with the same letter are not significantly different at p=0.05.
4 Seasonal p-value. 5 Interaction between season and different cropping systems.

The N_2O fluxes ranged between 0.22 µg N m^2 h^{-1} (23rd July 2019) and 60.12 µg N m^2 h^{-1} (30th April 2019) during the study period (Figure 2.3a, b). We observed low N_2O from May to September 2019. However, the daily N_2O fluxes peaked from October 2019 following the onset of rainfall on 10th October, reaching a maximum of 59.20 µg N m^2 h^{-1}. Cumulative seasonal N_2O differed significantly ($p<0.0001$) across cropping systems during LR19 on farm one. The N_2O fluxes ranged from 0.04 to 0.13 kg N_2O-N ha^{-1} and 0.08 to 0.48 kg N_2O-N ha^{-1} on farms one and two, respectively. We observed a significant ($P=0.03$, $P=0.01$) difference during SR 2019 in N_2O fluxes with a range of 0.26 to 0.32 kg N_2O-N $ha^{-1}yr^{-1}$ in farm one and 0.23 and 0.75 kg N_2O-N ha^{-1} on farm two. The annual N_2O fluxes differed significantly ($p=0.005$, $p<0.0001$) on farms one and two. The range was between 0.30 and 0.45 kg N_2O-N $ha^{-1}yr^{-1}$ on farms and 0.34 and 1.23 kg N_2O-N $ha^{-1}yr^{-1}$ on farms one and two, respectively. The seasonal value was significant at $p<0.0001$ in the two farms.

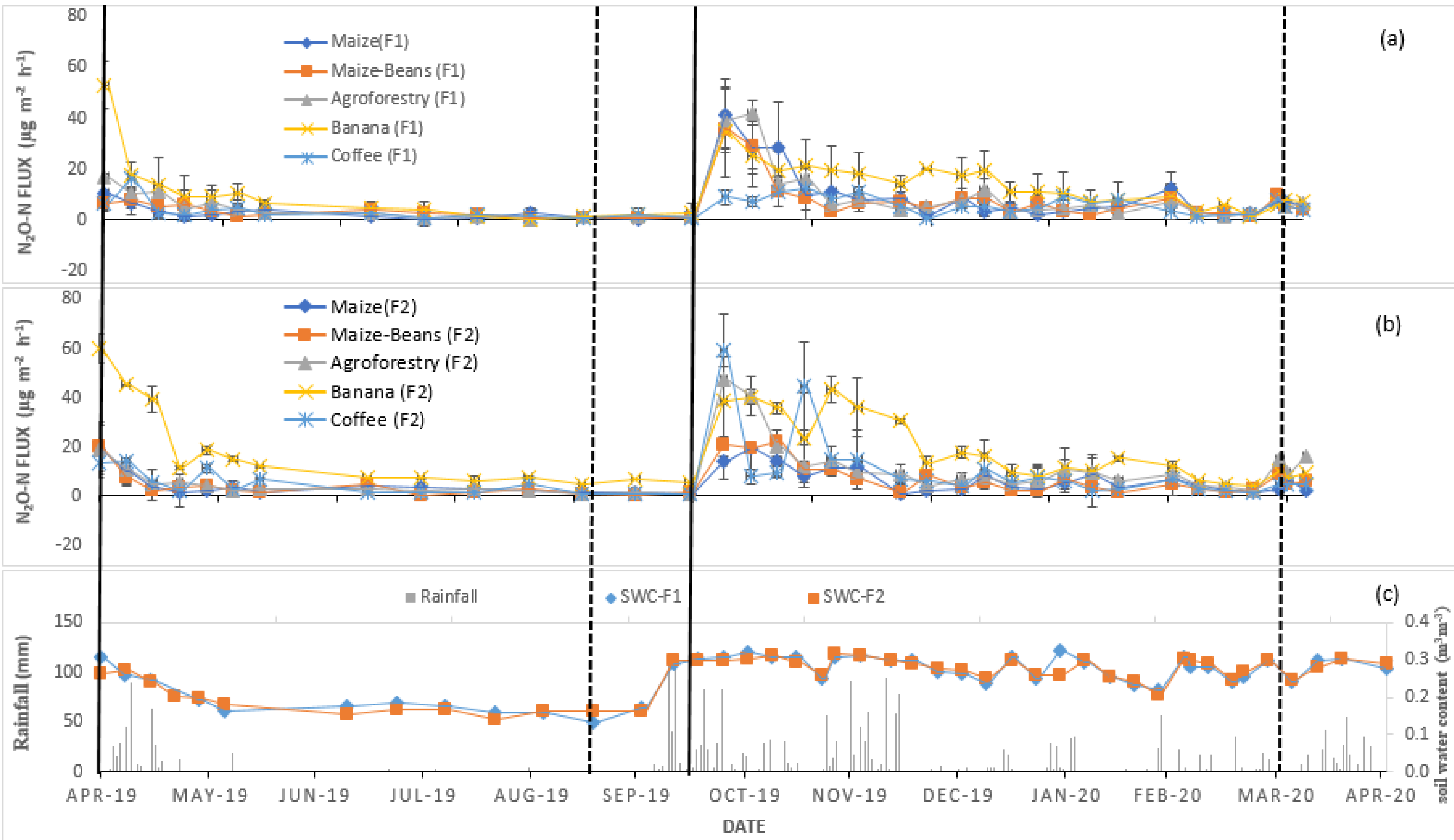

Figure 2. 3*:* Soil nitrous oxide Farm 1 (a), Farm 2 (b) and precipitation and soil water content (c) from different land utilization types in Upper Eastern Kenya

Soil CO_2 emission varied across cropping systems during the study period (Figure 2.4a,b). The daily CO_2 fluxes ranged from 10.10 to 680.24 mg C m^{-2} h^{-1} across cropping systems and farms. We observed peak CO_2 fluxes at the onset of rainfall (30th April 2019 and 7rd May 2019) across all the cropping systems, ranging from108 to 256 and 135 to 274 mg C m^{-2} h^{-1} on farms one and two, respectively. Additionally, from 10th October 2019, CO_2 fluxes in all cropping systems peaked in the first four weeks. Conversely, we observed lower emissions (<163 mg C m^2 $h^{-1)}$ during the dry period from June to the first week of October (Figure 2.4a, b). However, during this period, mean CO_2 fluxes in banana cropping systems and agroforestry were higher than in other cropping systems.

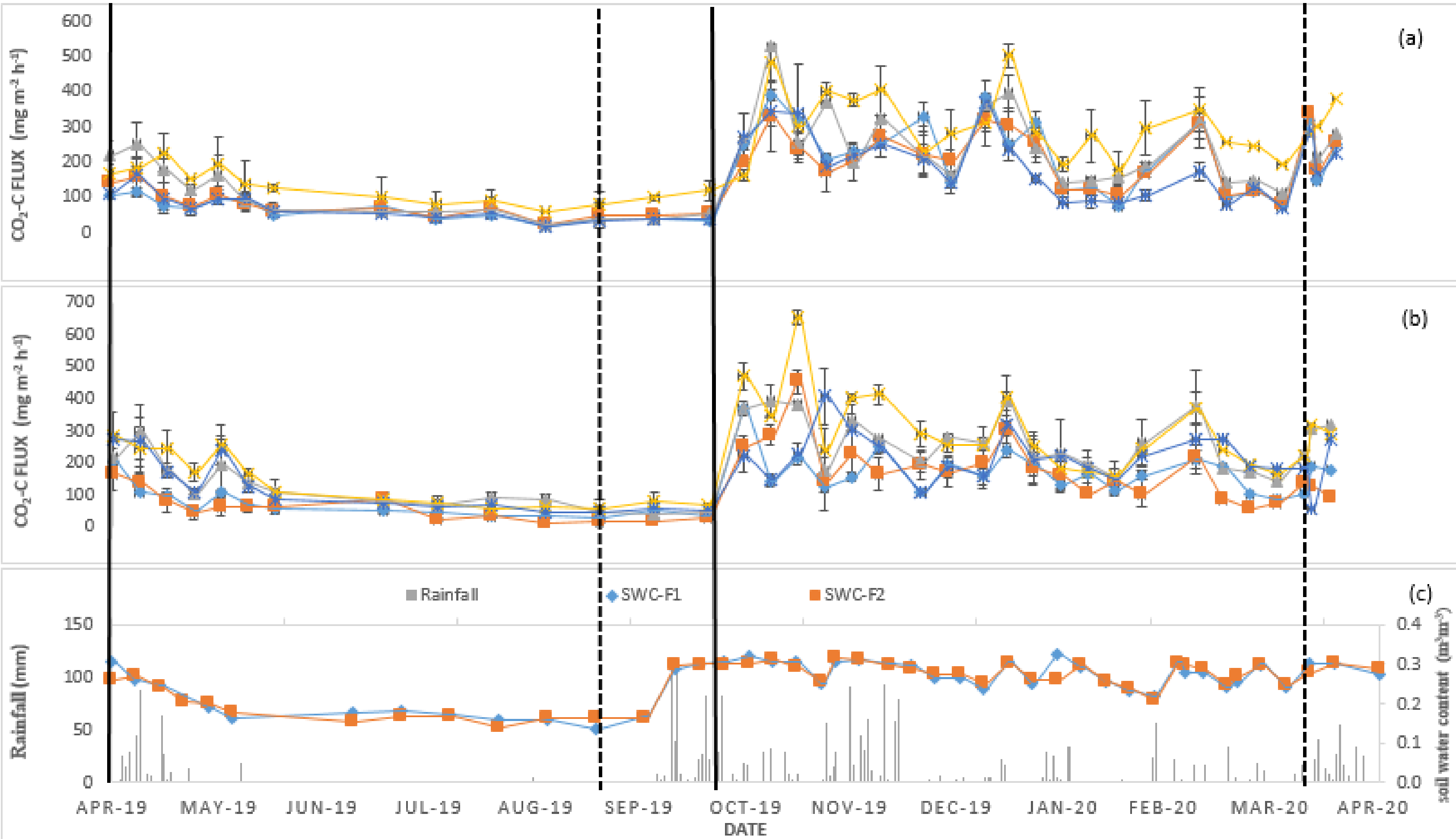

Figure 2. 4:. Soil carbon dioxide Farm 1 (a), Farm 2 (b) and precipitation and soil water content (c) from different land utilization types in Upper Eastern Kenya

We observed a significant ($P<0.0001$) difference in cumulative CO_2 fluxes during LR 2019 on farms one and two. The variation in the CO_2 emissions across the cropping systems ranged from 1844 kg CO_2-C ha^{-1} under maize monocrop to 2503 kg CO_2-C ha^{-1} under banana and 1668 kg CO_2-C ha^{-1} under agroforestry to 3748 C ha^{-1} under banana on farm one and two respectively. During SR, the CO_2 emissions varied significantly across the cropping seasons ($p=0.02$, $p<0001$) on farms one and two, respectively. The range of variation was 5536 kg CO_2-C ha^{-1} under coffee to 7220 CO_2-C ha^{-1} under maize beans in farm one. The CO_2 emissions in farm two ranged from 4281 kg CO_2-C ha^{-1} under agroforestry to 9210 kg CO_2-C ha^{-1} in the banana cropping system. The annual CO_2 fluxes differed significantly ($p=0.04$, $p<0.0001$) on farms one and two, respectively. The range of CO_2 fluxes on farm one was 8504 to 9614kg CO_2-C $ha^{-1}yr^{-1}$ while the range on farm two was from 5949 to 12958 kg CO_2-C $ha^{-1}yr^{-1}$.

2.3.3 Crop Production

On farm one, during the LR 2019 we experienced crop failure (Table 2.3) because of limited rainfall amounts. The grains of beans crop and maize on maize monocrop cropping system totally failed (Table 2.3). During the LR 2019, the crop yields ranged from 0.04 Mg ha^{-1} under agroforestry and 0.06 t ha^{-1}under maize beans. During the SR 2019, the maize grain yields ranged from 2.65 Mg ha^{-1} under maize beans to 3.38 Mg ha^{-1} maize monocrop. During the SR 2019, the bean grain yields were harvested in the two-cropping systems maize-beans (0.31 Mg ha^{-1}) and agroforestry (0.37 Mg ha^{-1}).

On farm two, maize grain yields were 0.05 Mg ha^{-1} under maize monocrop, and the crop failed in the maize beans and agroforestry during the LR 2019 (Table 2.3). We experienced total crop failure for beans during the LR 2019. In the SR 2019, maize grain yields ranged from 0.16 Mg ha^{-1} under maize beans to 0.31 Mg ha^{-1} under agroforestry. The beans' grain yields ranged from 0.44 Mg ha^{-1} to 0.76 Mg ha^{-1} during the SR 2019.

Table 2. 3: Crop production during the two cropping seasons in the Upper Eastern Kenya

Cropping System	Farm 1					Farm 2				
	Grain (Mg ha^{-1})	Stem (Mg ha^{-1})	Root (Mg ha^{-1})	Leave (Mg ha^{-1})	Total	Grain (Mg ha^{-1})	Stem (Mg ha^{-1})	Root (Mg ha^{-1})	**Leave (Mg ha^{-1})**	Total
LR 2019[b]										
Maize	0	0.02	0.03	0.01	0.06	0.05	0.02	0.02	0.03	0.12
Maize-Beans	0.06	0.01	0.03	0.03	0.13	0	0.01	0.01	0.02	0.04
Agroforestry	0.04	0.01	0.03	0.02	0.08	0	0.01	0.01	0.03	0.05
Banana	-[f]	-	-	-	-	-	-	-	-	-
Coffee	-	-	-	-	-	-	-	-	-	-
Maize	3.38	0.29	0.03	0.25	3.95	2.37	0.18	0.02	0.2	2.77
SR 2019[b]										
Maize-Beans	2.65	0.22	0.03	0.25	3.15	3.02	0.16	0.01	0.29	3.48
Agroforestry	2.88	0.06	0.03	0.26	3.23	1.84	0.31	0.09	0.24	2.48
Banana[c]	-	-	-	-	-	-	-	-	-	--
Coffee[d]		-	-	-		-	-	-	-	-
SR 2019[e]										
Maize	-	-	-	-	-	-	-	-	-	-
Maize-Beans	0.31	0.21	0.03	0.02	0.57	0.44	0.12	0.02	0.11	0.69
Agroforestry	0.37	0.31	0.02	0.14	0.7	0.76	0.18	0.01	0.16	1.11
Banana	-	-	-	-	-	-	-	-	-	-
Coffee	-	-	-	-	-	-	-	-	-	-

[a] Season LR 2019 is the long rains 2019 season, SR 2019 is the short rain 2019 season
[b] Maize harvest during the season except for the coffee
[c] Banana yields not harvested
[d] Reported is the coffee berry yields
[e] Reported are the beans yields (during the long rains 2019 season, we experienced total crop failure for the beans).
[f] The sign indicates that the crop was not harvested

2.3.4 Yield scaled emissions

The maize yield scaled emissions ranged from 0.10 g kg^{-1} Maize to 0.15 g kg^{-1} maize on farm type one. The beans yield scaled emissions ranged from 0.82 g kg^{-1} beans to 1.30 g kg^{-1} beans. On the farm, the maize grain yields ranged from 0.11 g kg^{-1} Maize to o.26 g kg^{-1} maize, and the beans N_2O yield scaled emissions ranged from 0.68 g kg^{-1} beans to 0.78 g kg^{-1} beans (Table 2.4).

Table 2. 4: Yield scaled emissions under different cropping systems in Upper Eastern Kenya

Cropping System	Farm 1				Farm 2			
	Total grain yields (kg ha^{-1} yr^{-1})		YSE[1] (g kg^{-1} grain)		Total grain yields (kg ha^{-1} yr^{-1})		YSE (g kg^{-1} grain)	
	Maize	beans	Maize	Beans	Maize	beans	Maize	Beans
Maize	3380		0.10	-	2420	-	0.22	
Maize-Beans	2710	310	0.15	1.30	3020	440	0.11	0.78
Agroforestry	2920	370	0.10	0.82	1840	760	0.26	0.63
Banana	-	-	-	-	-	-	-	-
Coffee	-	-	-	-	-	-	-	-

[1]N_2O Yield scaled emissions

2.3.5 Correlation of greenhouse gas fluxes and soil properties

Soil methane uptake was negatively correlated with soil's bulk density (Table 2.5). Soil nitrous oxide fluxes were positively correlated with soil moisture and negatively correlated with soil bulk density and nitrogen content. Soil carbon dioxide emissions were positively correlated with soil moisture and soil organic carbon content.

Table 2. 5: Correlation between soil greenhouse gas fluxes and soil properties

Parameter	Methane	Nitrous oxide	Carbon dioxide
Soil moisture	-0.58**	0.61***	0.54**
Soil pH	0.19	-0.05	0.01
Soil bulk density	-0.58**	-0.73***	-0.26
SOC	-0.13	-0.08	0.67***
Nitrogen	-0.12	-0.51**	0.17

Rho values, ***$p<0.01$ and **$p<0.05$

2.4. Discussion

2.4.1 Soil greenhouse gas fluxes under different cropping systems

Smallholder farms emit a limited amount of soil GHG fluxes (Pelster et al., 2017; Ortiz-Gonzalo et al., 2018; Rosenstock et al., 2018). We observed uptake for CH_4 emissions consistent with other studies conducted in SSA, which also reported that upland soils predominantly uptake CH_4 (Pelster et al., 2017; Musafiri et al., 2020). The CH_4 fluxes were < -1.39 kg CH_4-C $ha^{-1}yr^{-1}$ across all cropping systems. We observed a slight increase in CH_4 fluxes at the onset of the first rain in all cropping systems. This might have resulted from an increase in water content in soil pores, limiting oxygen availability and favoring anaerobic conditions, thus lowering the CH_4 uptake (Pelster et al., 2017).

The low uptake of CH_4 can be attributed to gas diffusivity. Conversely, the CH_4 uptake is high during the dry period, possibly due to high gas diffusivity, which favors aerobic conditions. The most increased cumulative CH_4 uptake in maize-bean and agroforestry could have been attributed to different levels of N concentration in soils that ultimately inhibit methanotrophic activities in soil compartments (Wanyama et al., 2019). The significant difference between a banana and maize-beans intercrop cropping systems could be attributed to rooting systems. In banana cropping, deep rooting allows water absorption, creating a wet microsite that encourages CH_4 production compared to maize cropping, which only becomes activated during rainy systems. Through the continuous accumulation of leaf litter, agroforestry cropping systems might have also contributed to significant changes in CH_4 uptake. As observed on farm two, the low uptake in banana cropping systems could have been due to increased methanogenic archaea, reducing the CH_4 uptake. Further, dropping plant litter in bananas may serve as mulching on the ground hence limiting evaporation thus creating a moist environment for CH_4 emission (Peng et al., 2002). The seasonal interaction between the cropping systems reflects the influence of precipitation on the CH_4 fluxes (Wanyama et al., 2019). In addition, the variability in soil bulk density and variation in soil pH (Table 2.1) could have contributed to the seasonal difference in CH_4 fluxes.

The peak cumulative soil N_2O fluxes following precipitation were consistent with previous studies in Kenya (Macharia et al., 2020; Musafiri et al., 2020; Githongo et al., 2022). The peak N_2O fluxes could be attributed to the birch effect (Musafiri et al., 2020). The cumulative soil N_2O fluxes were in line with previous studies in SSA (Pelster et al., 2017; Musafiri et al., 2020b; Githongo et al., 2022). There were high N_2O fluxes in the banana cropping systems across the seasons. This can be explained by the inclusion of manure around the base of crops which increases the N levels in soils, thus favoring a heterogeneous phylogenetic group of microbes that increases denitrification (Butterbach et al., 2013). Banana roots boost the soil's root respiration, and optimal moisture content in soils favors denitrification. The addition of nitrogen to grounds increases soil respiration and net ecosystem exchange, provided carbon is not limiting. Therefore, there was a general increase in N_2O fluxes after fertilization, coinciding with rainfall events. Musaifiri et al. (2020b) reported the same observation where there was an increase in N_2O upon the addition of fertilizers and rainfall events. There was a mixed observation in N_2O fluxes across the cropping systems in different seasons. Maize and coffee had the lowest emissions compared to all cropping systems. This could have been attributed to low nutrient availability, continuous cropping coupled with low residue availability due to completion by humans and animals for fibre (Macharia et al., 2020). Emissions of N_2O only occur when microbial N immobilization and plant N requirement are balancing (Peng et al., 2011).

The cumulative soil CO_2 emissions were in the range of those observed in previous studies in Kenya (Pelster et al., 2017; Musafiri et al., 2020b; Githongo et al., 2022). We observed high soil CO_2 emissions from different cropping systems that could be attributed to the high soil organic carbon in the study (Table 1). The soil CO_2 emissions reported in the current study resulted from root respiration and decomposition. The study underscored the need to study the total CO_2 budget from respiration and photosynthesis.

2.4.2 Maize yields

The crop failure observed in the current study was consistent with previous studies in Upper Eastern Kenya (Githongo et al., 2022) and could be attributed to low precipitation. The mean maize grain yields were lower than those reported in previous studies in the study area

(Ngetich et al., 2014; Musafiri et al., 2020b; Githongo et al., 2022). The maize crop was also mixed with the beans, and the yields were low. The low crop yield could be attributed to low soil fertility and precipitation.

2.4.3 Yield scaled emissions

The yield scaled emissions were consistent with those of the previous studies in Upper Eastern Kenya (Macharia et al., 2020; Musafiri et al., 2020b; Githongo et al., 2022). The low N_2O yield scaled emissions in the study area could be attributed to the reduced N_2O emissions.

2.5 Conclusion

The study investigated the influence of selected cropping systems on greenhouse gases emission. As per the hypothesis, soil GHG fluxes (CH_4, N_2O and CO_2) differed across the cropping systems. The soil acted as the CH_4 sink in all cropping systems. Greenhouse gases emission was also found to be affected by rainfall availability which increases soil water content. Banana cropping systems emitted the highest soil CO_2 compared to other cropping systems. Crop production was significantly affected by the availability of rainfall, where LR 19 registered a lower yield than SR 2019 due to precipitation differences. Fertilizer application to the cropping systems determines GHGs emissions. However, smallholder farmers in SSA apply limited amounts of inorganic fertilizer to their farms. Only a few treatments received inorganic fertilizer, especially in the first season, while in the second season, almost all treatments received less than 25 kg N $ha^{-1}yr^{-1}$. This may have attributed to lower GHGs emissions, given that soil in the study area has low soil fertility. Applying recommended nutrients to soil helps increase yield production while reducing GHG emissions. Using recommended soil nutrients in consideration of crop requirements should be a major issue for farmers.

CHAPTER THREE

3.0 NITROUS OXIDE EMISSIONS FROM SMALLHOLDERS' CROPPING SYSTEMS IN SUB-SAHARAN AFRICA.

Abstract

Increased concentration of atmospheric nitrous oxide (N_2O), a potent greenhouse gas (GHG), is of great concern due to its impact on ozone layer depletion leading to climate change. Ozone layer depletion allows penetration of ultraviolet radiations, which are hazardous to human health. Climate change culminates in reduced food productivity. Limited empirical studies have been conducted in Sub-Saharan Africa (SSA) to quantify and understand the dynamics of soil N_2O fluxes from smallholder cropping systems. The literature on soil N_2O fluxes in SSA is limited; hence, pressing need to consolidate it to ease mitigation targeting and policy formulation initiatives. The study objectives were to i) evaluate N_2O emissions from smallholders' cropping systems, and ii) determine the environmental factors, climatic conditions, farm management practices, and soil properties that influence N_2O dynamics. The review covered the state of N_2O emissions from selected cropping systems, drivers that significantly influence N_2O emissions, and probable soil N_2O emissions mitigation options from 30 studies in SSA cropping systems. Review outcome indicates that coffee, tea, maize, and vegetables emit N_2O ranging from 1 to 1.9, 0.4 to 3.9, 0.1 to 4.26, and 48 to 113.4 kg N_2O-N ha-1 yr^{-1}, respectively. Yield-scaled and N_2O emissions factors ranged between 0.08 and 67g N_2O-N kg^{-1} and 0.01 and 4.1% across cropping systems. Soil characteristics, farm management practices, and climatic and environmental conditions influenced N_2O emissions across SSA cropping systems. Site-specific soil N_2O emissions mitigation measures are required due to high variations in N_2O drivers across SSA. In conclusion, appropriate fertilizer and organic input management combined with improved soil management practices are potential approaches to N_2O emissions mitigation in SSA. The following recommendations were arrived at: recommend that (i) while formulating soil N_2O emissions mitigation approaches, in SSA, policymakers should consider site-specific targeting approaches, and (ii) more empirical studies need to be conducted in diverse agroecological zones of SSA to qualify various mitigation options on N_2O emissions, yield scaled N_2O emissions, and N_2O emission factors which are essential in improving national and regional GHG inventories.

Keywords: nitrous oxide, yield scaled N_2O emissions, emission factors, mitigation options

3.1 INTRODUCTION

Nitrous oxide (N_2O), a potent greenhouse gas (GHG) with a global warming potential (GWP) of 265 relative to carbon dioxide, has attracted a lot of attention globally (IPCC, 2014). Its global concentration in the atmosphere has been on the rise (estimated at ~331.1 ppb in 2018 (WMO, 2018)) and contributing to ~6% of the GHG-caused global warming effect (Thakur & Medhi, 2019). The increased N_2O concentration has increased the average atmospheric temperature causing global warming, which is associated with unreliable precipitation and prolonged droughts (Omoyo et al., 2015). The prolonged droughts result in crop failures, while unpredictable rainfall inconveniences the planting schedule for rainfed smallholder farming prompting food insecurity (Kabirigi et al., 2015). Besides its negative effects on climate variability, N_2O is also associated with stratospheric ozone layer depletion (Ravishankara et al., 2009; Rochette et al., 2018) and acidic rain formation (Ciais et al., 2013).

Agriculture is a major source of anthropogenic N_2O emissions contributing about 60% of global N_2O emissions predominantly from the application of N fertilisers, animal manure, and crop residues left in the fields (Vermeulen et al., 2012; Jalota et al., 2018). In SSA, agriculture covers ~12.6% of total cultivated land, which is dominated by smallholder farmers who produce crops depending on resource availability (Tittonell et al., 2005). It is worth noting that over 95% of the agricultural land in SSA is rainfed, non-mechanized, and under small-scale farming with inherent low fertility due to continuous farming with limited use of external soil inputs (Altieri & Koohafkan, 2008) and which could have a direct effect in the amounts of soil N_2O emitted (Pelster et al., 2017). These agricultural soils in SSA contribute between 6 and 19% of total global anthropogenic N_2O emissions (Hickman et al., 2011; Kim et al., 2016).

Different cropping systems are grown across different regions in SSA. The common crops grown in West Africa, Southern Africa, and part of Central Africa, are cassava, yams, and cereals such as maize and sorghum (Tongwane & Moeletsi, 2018). Maize cropping systems together with perennial cropping systems are common in Eastern and part of Southern Africa (Ortiz-Gonzalo et al., 2017). Different dynamics across cropping systems contribute differently to N_2O emissions in SSA (Tongwane & Moeletsi, 2018). For instance, cereal-legume intercropping contributes to N_2O emission by adding more NH_4^+, NO_3^- into the soils through the mineralization of organic matter (Frimpong et al., 2012; Snapp et al., 2019). Additionally, farmers in SSA integrate both livestock and crops leading to a trade-off between manure and crop residues, a dynamic that influences N cycling (including N_2O) in the soils (Rufino et al., 2014; Thornton & Herrero, 2015). However, it's worth noting that majority of smallholder farmers in SSA rarely retain crop residues on the fields as a source of nutrient but instead use it as animal feeds and as fuel for cooking (Macharia et al., 2020).

Nitrogen is a very important element and undergoes various transformation processes on the earth surface (Figure 3.1). Biological fixation of nitrogen is carried out by leguminous plants in association with rhizobia bacteria and nitrogenase enzyme to convert atmospheric nitrogen gas to ammonia (Barnard et al., 2005). Human-induced activities such as the production of fertiliser, sewage, farm produce, and manure application also account for N addition into the soil, which is later released as N_2O emissions (Figure 3.1). High accumulation of N in the soil is associated with environmental problems such as ammonia volatilization and leaching, which are also indirect losses of N from the soils. Net N_2O emissions are because of complex biogeochemical processes that take place in the soils (Eugster and Merbold, 2015). Nitrification occurs during aerobic conditions and oxidizes ammonium (NH_4^+) to nitrate (NO_3^-) and nitrite (NO_2) (Baggs et al., 2006). Denitrification occurs in oxygen-limited conditions and reduces NO_3^- and NO_2^- to N_2O and nitrogen gas (N_2) (Baggs, 2011). These processes are aided by the availability of three major microorganisms: ammonia-oxidizing bacteria (AOA), ammonia-oxidizing archaea (AOA), and nitrite-oxidizing bacteria (NOB) (Beeckman et al., 2018). Nitrous oxide emissions can also occur through dissimilatory nitrate reduction to ammonium and co-denitrification (Butterbach-Bahl et al., 2013). Other non-biological processes involved in N_2O emissions are chemo-denitrification and decomposition of hydroxylamine, although they release negligible N_2O emissions (Hénault et al., 2012). These processes are influenced by soil moisture, temperature, C/N ratio, oxygen concentration, organic carbon, and nitrogen availability (Pelster et al., 2017).

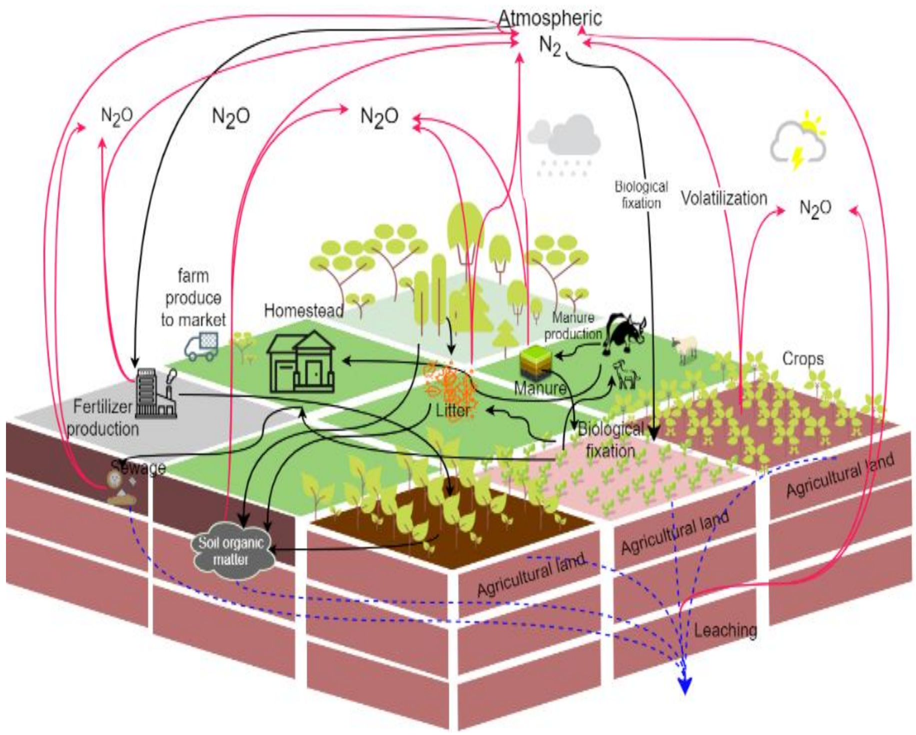

Figure 3. 1: Nitrogen transformation processes in the soil. The arrows show; red = N_2O emissions, black = N_2O sources, and blue = N loss through leaching.

Countries are obligated to report their Nationally Determined Contributions (NDCs) and climate change mitigation options to the United Nations Framework Convention on Climate Change (UNFCCC) (Gyanchndani et al., 2016; Elkahwagy et al., 2017). Further, as captured in the Paris Climate Agreement 2015, countries agreed to limit the global temperature increase below 1.5°C by reducing GHG emissions (UNFCCC, 2015). To achieve this, most SSA countries consider agriculture a potential mitigation option to reduce GHG emissions (Richards et al., 2016). However, there are uncertainties in the national GHG inventories in SSA countries due to a huge data gap arising from countries in the region having only a few empirical studies carried out or none from agricultural production systems. It is imperative to note that only a few studies in SSA (less than 30 published studies) have attempted to quantify N_2O emissions based on different cropping systems (figure 3.2).

Figure 3. 2: Map showing the location of the reviewed N_2O related studies in sub-Saharan countries. Basemap sources: National Geographic, Esri, Garmin, HERE, UNEP, WCMC, USGS, NASA, ESA, MERI, NRCAN, GEBCO, NOAA, and increment P Corp.

Consequently, most of the countries in SSA have continuously used the Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factors (EFs) and which tend to overestimate GHG emissions in SSA (Richard et al., 2016; Albanito et al., 2017; Macharia et al., 2020). Therefore, in this paper, we reviewed; i) the state of N_2O emissions from selected cropping systems in SSA, ii) drivers that significantly influence N_2O emissions, and iii) possible mitigation options for SSA. We hypothesised that; i) there are significant variations in N_2O emissions across different cropping systems in SSA, ii) environmental factors, climatic conditions, farm management practices, and soil properties directly influence N_2O dynamics, and iii) combination of inorganic fertiliser and organic manure application serves as the best mitigation options for N_2O emissions in SSA compared to sole application of either inorganic fertiliser and animal manure.

3.2. Methodology

The literature review surveyed peer-reviewed papers on N_2O fluxes from Sub-Saharan Africa cropping systems published until December 2020. To include as many published studies as possible, we used search terms such as "nitrous oxide," "Sub-Saharan Africa," "cropping systems," "greenhouse gas emission," "nitrous oxide yield-scaled emissions," "nitrous oxide emission factors," and "mitigation measures" in Web of Science and Google Scholar. Thirty (30) peer-reviewed papers were selected according to the following exclusion-inclusion criteria:

1) Study measured nitrous oxide fluxes in situ in Sub-Saharan Africa.
2) The static chamber method was used in nitrous oxide measurements.
3) Nitrous oxide measurements were conducted from a specified period.
4) The study reported nitrous oxide fluxes and either yield, N_2O emission factors, yield-scaled emission, or mitigation potential.
5) Soil properties, cropping system, soil fertility management, and experimental durations were clearly described.

A qualitative analysis was implemented to assess nitrous oxide fluxes, N_2O emission factors; yield scaled N_2O emission factors, and mitigation potential. This included reporting the data observed from different cropping systems in Sub-Saharan Africa.

3.3 Soil N_2O emissions from cropping systems in sub-Saharan Africa

3.3.1. Maize cropping system

Most of the soil N_2O quantification experiments carried out in SSA are under maize cropping systems (Table 3.1). This is due to the fact that maize is considered an important food and source of cash for most rural families in sub-Saharan Africa (Midega et al., 2018). Millar et al. (2004) reported N_2O emissions ranging between 0.1 and 4.1 kg N_2O-N ha^{-1} from maize cropping systems in Kenya under improved-fallow agroforesty systems (Table 3.1). While investigating the effects of organic and mineral fertilisers in Zimbabwe, Mapanda et al. (2011)

reported N_2O emissions ranging between 0.1 and 0.5 kg N_2O-ha^{-1}. Further, while investigating the effects of clearing savanna woodland for maize cropping in Zimbabwe, Mapanda et al. (2012) reported N_2O emissions ranging from 0.8 to 2.5 kg N_2O-N ha^{-1} (Table 3.1). Hickman et al. (2015), while investigating the relationship between N inputs and N_2O emissions from maize cropping systems in Kenya, reported fluxes ranging between 0.1 to 0.3 kg N_2O-N ha^{-1} yr^{-1} (Table 7). Further, with no application of either fertiliser or manure, Rosenstock et al. (2016) reported N_2O emissions from maize cropping systems as 0.9 kg N_2O-N ha^{-1} yr^{-1} in Kolero-Tanzania (Table 3.1).

Pelster et al. (2017) reported that maize cropping systems with low fertiliser inputs (<25 kg N ha^{-1}) were responsible for N_2O fluxes ranging between -0.1 to 1.8 kg N_2O-N $ha^{-1}yr^{-1}$ in Kisumu, Kenya and attributed to dry soil which limits anaerobic condition for denitrification (Table 3.1). While investigating N_2O emissions from different rates of inorganic fertiliser and their combination with organic in Zimbabwe under maize cropping systems, Nyamadzawo et al. (2017) reported N_2O emissions ranging from 0.3 to 0.5 kg N_2O-N ha^{-1} yr^{-1}. Additionally, while investigating the contribution of different soil fertility technologies towards national GHG budget in the central highlands of Kenya, Macharia et al. (2020), reported N_2O emissions ranging from 0.13 to 1.22 kg N_2O-N $ha^{-1}yr^{-1}$ across treatments. Maize cropping systems under different soil fertility technologies also accounted for N_2O emissions ranging from 0.21 to 0.38 kg N_2O-N $ha^{-1}yr^{-1}$ (Musafiri et al., 2020). Maize cropping systems in SSA were noted to emit less N_2O emissions compared to the global average probably due to soil degradation and N mining alongside the inadequate nutrient replenishment from external inputs (Zhou et al., 2014).

3.3.2 Cereal-legume intercropping system

Legume intercropping is a farming practice that acts as an N source through atmospheric N fixation to the soils (Mugwe et al., 2019). However, adding N to the soils may come at a cost of increased N2O emissions if supply exceeds plant demand (Hickman et al., 2015). Maize-bean intercropping systems in Kenya, recorded N_2O emissions of 4.1 kg N_2O-N ha^{-1} following the incorporation of *Sesbania macroptilium* (Millar et al., 2004). These fluxes were the highest recorded in SSA, which could be attributed to the application of residue with 60%

more N content above the normal threshold (1.7–1.8%) (Melillo et al., 1982). Baggs et al. (2006), in a short-term experiment in Western Kenya working on the effects of tillage and residue quality on GHG emissions under improved-fallow agroforestry system, showed that maize (*Zea mays*) intercropped with beans (*Phaseolus vulgaris*) emitted N_2O emissions ranging from 0.2 to 0.6 kg N_2O ha^{-1}. Rotation of millet and beans in Mali accounted for N_2O emissions that ranged from 0.9 to 1.5 kg ha^{-1} yr^{-1} (Dick et al., 2008). Ortiz-Gonzalo et al. (2018) showed that maize (*Zea mays*) intercropped with beans (*Phaseolus vulgaris*) in central highlands of Kenya emitted N_2O in the range of 0.18 to 0.27 kg N_2O-N ha^{-1}. In Ethiopia, inorganic fertilized maize crops intercropped with lablab *(L. purpureus)* and Crotalaria *(C. juncea)* emitted N_2O emissions which ranged between 0.17 and 0.33 kg N_2O-N ha^{-1} (Raji & Dörsch, 2020). Intercropping cereals with legumes or in rotation provides synergies in managing soil nutrients in the field and may result in relatively lower N_2O emissions.

3.3.3 Coffee cropping system

Coffee is among the annual crops grown in SSA as a cash crop. In Kenya, Ortiz-Gonzalo et al. (2018), reported N_2O emissions that ranged between 1 and 1.9 kg N_2O-N $ha^{-1}yr^{-1}$ from coffee cropping system following fertilizer application of 85 kg N ha^{-1} (Table 1). In Tanzania, Gütlein et al. (2018) found that coffee cropping systems accounted for 0.35 kg N_2O-N ha^{-1} yr^{-1}. Soil N_2O emissions from coffee cropping systems in SSA are at a lower range, probably due to a decline in soil fertility in SSA's soil and little nutrient supply from both organics and inorganics (Hickman et al., 2014).

3.3.4 Tea cropping system

Tea cropping systems are highly valuable and mostly found in agro-ecological zones that receive high rainfall amounts. Rosenstock et al. (2016) showed that tea cropping systems in western Kenya emitted N_2O fluxes that ranged between 0.4 and 0.7 kg N_2O-N ha^{-1}. Tea cropping systems in Kenya emitted N_2O fluxes that ranged from 1.2 to 1.4 kg N_2O-N ha^{-1} yr^{-1} (Wanyama et al., 2018). Emissions of N_2O for tea cropping systems were also at a lower range attributed to low inherent soil fertility status with little or no replenishment with soil amendments.

3.3.5 Vegetable cropping system

Urban and peri-urban vegetable farming in SSA utilises a lot of nutrients with an objective of achieving food demands (Drechsel et al., 2015). As a result of increased organic or inorganic fertilisation, vegetable cropping systems produce highest N_2O emissions across the different cropping systems in SSA. For instance, vegetable cropping systems in Niger produced N_2O emissions ranging between 48 and 92 kg N_2O-N ha^{-1} yr^{-1} (Predotova et al., 2010). Peri-urban vegetable gardens in Burkina Faso emitted N_2O emissions that ranged from 80.5 to 113.4 kg N_2O-N ha^{-1} yr^{-1} (Lompo et al., 2012). Cumulative annual vegetable fluxes in Kaptumo, Kenya were found to be 0.9 kg N_2O-N ha^{-1} yr^{-1} (Rosenstock et al., 2016). Similarly, in Kenya, Africa indigenous vegetables produced N_2O emissions ranging from 0.4 to 3.0 kg N_2O-N ha^{-1} (Kurgat et al., 2018). While comparing GHG emissions in two ecoregions of SSA, Benin (rain forest) and Nigeria (dry savanna) in a short experiment performed under controlled conditions under local amaranth (*Amaranthus cruentus*), Olaleye et al. (2020) reported N_2O emissions ranging from 0.01 to 0.02 and 0.06 to 0.3 kg N_2O-N kg of $soil^{-1}$ day^{-1}, respectively. There was high variation of N_2O emissions (0.01 to 113 kg N_2O-N ha^{-1} $yr^{-1)}$ for vegetable cropping systems with high range reported attributed to high N input (750 kg N ha^{-1}) in the vegetable gardens.

3.3.6 N_2O emissions from organic and inorganic fertiliser use

Organic resources in SSA not only improve soil fertility and overall soil health but also increases crop yields (Vanlauwe et al., 2014). However, addition of organic resources may contribute to increased soil N_2O emissions (Millar et al., 2004). Some of the organic inputs used in SSA include animal manure, *tithonia diversifolia*, numerous leguminous plants, crop residues, and some herb trees such *Lantana Camara* (Macharia et al., 2014; Snapp et al., 2019; Nganga et al., 2020). A couple of studies have quantified the effects of organic resources on N_2O emisions in SSA across cropping systems. For instance, use of crop residues for maize cropping systems in Kenya under mixed fallow systems emitted N_2O fluxes amounting to 4.1 kg N_2O-N $ha^{-1}season^{-1}$ (Millar et al., 2004). Addition of *tithonia diversifolia* increased N_2O emissions especially during the first weeks of application as shown by Kimetu et al. (2006) implying that organic matter decomposes rapidly in the soil. The green manure quickly releases nutrient to the soil immediately after addition since they contain easily decomposable organic matter for microrganism consumption as substrates (Kiboi et al., 2018). Use of cattle manure as treatment in production of tomato planted in wetland of Zimbabwe accounted for N_2O emissions ranging from 0.01 to 0.06 kg N_2O-N ha^{-1} (Masaka et al., 2016). Higher N_2O fluxes of 43 μg N_2O-N m^{-2} h^{-1} were observed in the central highlands of Kenya under manure treatment compared with (3 μg N_2O-Nm^{-2} h^{-1}) under no external inputs. While investigating GHGs emissions from maize cropping systems under different soil fertility management, Macharia et al. (2020) showed that plots treated with animal manure accounted for annual cumulative N_2O emissions of 1.22 kg N_2O-N ha^{-1} yr^{-1}.

Inorganic fertiliser application significantly determines the amount of soil N_2O emissions mainly due to addition of N. Hickman et al. (2014) showed that plot treated with 200 kg N ha^{-1} registered 24% more N_2O emissions than plots that received no fertiliser. Use of inorganic fertilisers for maize plots in Zimbabwe emitted N_2O emissions that ranged between 0.35 to 0.52 kg N_2O-N ha^{-1} (Nyamadzawo et al., 2017). Ortiz-Gonzalo et. (2018) reported 95% of the total N_2O emissions in fertilized plots compared to unfertilized plots under cereal-legume and coffee cropping systems in Kenya. For instance, higher fertiliser rate of more than 100 kg N ha^{-1} yr^{-1} documented N_2O emissions ranging between 3.49 to 4.29 kg N_2O-N ha^{-1} while fertiliser rates below 100 kg N ha^{-1} yr^{-1} recorded N_2O emissions ranging between 1.22 and 1.79 kg N_2O-N ha^{-1} in Ghana under maize cropping systems (Atakora et al., 2019). Sole inorganic fertiliser plots planted with maize crops under two sites in Tanzania, emitted N_2O emissions ranging from 0.14 to 0.44 kg N_2O-N ha^{-1} in Iringa site and 0.18 to 0.72 kg N_2O-N ha^{-1} in Mbeya site (Zheng et al., 2019). Inorganic fertilised plots under maize cropping systems in central highland of Kenya emitted 10% more N_2O emissions than control plots as reported by Macharia et al. (2020). The above studies show that an increase in N application results in higher N_2O emissions regardless of fertiliser type and cropping system. Soil N_2O emissions only occur when the N demand by plant and immobilization by micro-organisms is balanced.

However, contrasting results have been reported concerning the use of organic and inorganic fertiliser application regarding N_2O emissions in SSA. Dick et al. (2008) reported less N_2O emissions in plots treated with both organic and inorganic fertiliser (0.9 kg N_2O-N ha $^{-1}$) than plots treated with sole manure (1.5 kg N_2O-N ha^{-1}) in semi-arid areas of Mali. Similarly, increasing N input through combination of inorganic fetiliser (60 kg N ha^{-1}) and manure (97.5 kg N ha^{-1}) increases N_2O emissions by 22 times higher than control plots under rape fruits in Zimbabwe (Nyamadzawo et al., 2014). Positive N balance was reported in the combination of organic and inorganic fertiliser during maize growth in western Kenya compared with sole inorganic fertiliser application (Sommer et al., 2015). However, Nyamadzawo et al. (2017) found that sole manure application reduces N_2O emissions by 16% compared to sole inorganic and integrated application, which increases N_2O emissions by 28 and 9%, respectively, in reference to control in Zimbabwe. Combination of inorganic and organic fertiliser as reported by Ortiz-Gonzalo et al. (2018) in two farms were 5 and 3 folds higher than unfertilised coffe and maize cropping systems respectively in Thara farm while in Kahau farm, fertilised plot registered 6 and 2 folds higher N_2O emissions than unfertilised plots for maize and coffee plots respectively. The combination of inorganic fertiliser and maize stover treatments (150 kg N ha^{-1} each) had a significantly higher N_2O emissions (0.55 to 2.2 kg N ha^{-1}) compared to sole fertiliser application at the same rate (0.34 to 0.72 kg N ha^{-1}) in Tanzania (Zheng et al., 2019). Combination of organic and inorganic manure increases N_2O emissions by 5 folds in comparison with control under maize cropping systems in central highland Kenya (Macharia et al., 2020). From the above studies, we concluded that combination of organic and inorganic fertiliser has mixed results concerning N_2O emissions. It is worth noting that combination of organic and inorganic fertilisers can only lower N_2O emissions when organic manure with low C/N ratio and inorganic fertiliser with high C/N ratio are combined.

3.3.7 Yield- scaled N_2O emissions and nitrous oxide emissions factors

Farm management activities for cropping systems should be geared towards improving soil fertility, agronomic productivity and environmental sustainability. Yield-scaled emissions (YSE) relates N_2O emissions and crop yields and expressed as emissions per unit yield can be used to assess management impact (van Groenigen et al., 2010). The amount of N_2O emitted determines the amount of YSE, therefore it provides an entry point to assess the ability of management to mitigate N_2O emissions without compromising productivity (Venterea et al., 2010). Few studies have attempted to give YSE on different cropping systems based on inorganic and organic fertiliser application in SSA, ranging from 0.02 to 67.7 gN_2O-N kg^{-1}. For instance, Mapanda et al. (2011) under maize cropping systems, reported YSE emissions ranging from 0.02 - 3.93 g N_2O-N kg^{-1}. Nyamadzawo et al. (2017) reported YSE of 0.26 gN_2O-N kg^{-1} yield from integrated fertiliser management for maize cropping systems in Zimbabwe. Maize cropping systems in Eastern Africa accounted between 1.1 to 67 g N_2O-N kg^{-1} aboveground N uptake (Pelster et al., 2017). Maize cropping systems in Ghana shows that N fertilisalition above 100 kg N ha^{-1} yr^{-1} were responsible to upto 1.24 g N_2O kg^{-1} grain while N below 100 kg ha^{-1} yr^{-1} accounted for less than 0.6 g N_2O kg^{-1} grain (Atakora et al., 2019). Maize cropping systems treated with combination of manure and inorganic fertiliser accounted for approximately 3 folds higher YSE than control in central highland of Kenya (Macharia et al., 2020).

Although limited studies have been conducted in SSA, most of the derived emissions factors were below 1% and ranged between 0.1 to 0.9% across cropping systems in SSA (Chikowo et al., 2004; Baggs et al., 2006; Masaka et al., 2014; Hickman et al., 2015; Zheng et al., 2019; Macharia et al., 2020). However, there are instances where the EFs exceeds 1% from maize, vegetable cropping systems and soil laboratory incubation studies (Dick et al., 2008; Lompo et al., 2012). In Mali, for instance, Dick et al. (2008) reported highest EFs for maize cropping of 4.1%, attributed to field management interferences where higher fluxes of N_2O were noted even before application of fertiliser. For maize cropping systems in Kenya, N_2O EFs ranged from 0.01 to 0.9% (Baggs et al., 2006; Hickman et al., 2015; Macharia et al., 2020) while in Zimbabwe it was below 0.2% (Chikowo et al., 2004). Similarly, in Tanzania, EFs ranged between 0.13 and 0.42% (Zheng et al., 2019). Rosenstock et al. (2016) showed that tea cropping EFs were below 1% in Kenya. Vegetables cropping systems EFs in Zimbabwe ranged from 0.3 to 4% attributed to high fertiliser application (Lompo et al., 2012; Masaka et al., 2014). Yield-scaled emissions reported in most of the SSA farming systems may highly be associated with existing climate variability and soil fertility decline which could have lowered crop yield which determines YSE other than higher N_2O emissions. Also, EFs reported in the above studies are mainly below the default IPCC Tier I EFs suggesting that the use of default EFs on SSA's GHG emissions estimations may overestimate it resulting to incorrect targeting of adaptation and mitigation measures.

Table 3. 1:In situ empirical studies on N_2O emissions from different cropping systems in sub-Saharan Africa

Cropping systems	Country	Sampling frequency	Sampling duration	Soil type	N_2O Fluxes	N_2O Efs (%)	N_2O YSE (g N_2O kg^{-1} grain)	References
Annual emissions								
Sorghum, peanut and groundnut	Burkina Faso	1-3 per week	Jun–Sep 2006	Sandy	0.19 -0.67 kg ha^{-1} yr^{-1}	*	*	Brummer et al. (2008)
Millet–legume intercrop	Mali	Monthly	Jan 2004 - Feb 2005	Alfisol	0.9 -1.5 kg ha^{-1} yr^{-1}	4.1	*	Dick et al. (2008)
Vegetable	Niger	Twice a day for 6 days	Apr 2006–Feb 2007	Sandy	48 – 92 kg ha^{-1} yr^{-1}	*	*	Predotova et al. (2010)
Vegetable	Zimbabwe	Twice a day	Mar 2008–Mar 2009	Clay	80.5 – 113.4 kg ha^{-1} yr^{-1}	3 -4		Lompo et al. (2012)
Maize	Zimbabwe	During raining season	Jun 2006 - May 2009	Clay/loam	0.8 – 2.5 kg ha^{-1} yr^{-1}			Mapanda et al. (2012)
Fruit	Zimbabwe	2days – 2 weeks	2011 -2013	Sandy loam	2.5 – 112 kg ha^{-1}	*	2.1 – 14	Nyamadzawo et al. (2014)
Maize	Kenya	Daily to Weekly	99 days	Clay	0.16- 0.81 kg $ha^{-1}yr^{-1}$	*	*	Hickman et al. (2014)
Maize	Kenya	Daily to Weekly	March 2011 - July 2011	Sandy-clay	0.1 – 0.3 kg ha^{-1} yr^{-1}	0.11	0.27 -0.8	Hickman et al. (2015)
Tea, Vegetable and Maize	Kenya	Weekly	Jan – Dec 2013	Sand-clay	0.4 – 3.9 kg ha^{-1} yr^{-1}	0.4-0.8	*	Rosenstock et al. (2016)
Maize, beans and sorghum	Kenya	Weekly	Aug 2013–Aug 2014	Nitisols	-0.1 – 1.8 kg ha^{-1} yr^{-1}	*	1.1 – 67	Pelster et al. (2017)
Maize,Bean and Coffee	Kenya	1-2 times a week	Feb 2015 – Feb 2016	Nitisol	1 – 1.9 kg ha^{-1} yr^{-}	<1	0.08 – 0.15	Ortiz-Gonzalo et al. (2018)
Tea	Kenya	1-2 times per week	Aug 2015 - July 2016	Humic Nitisol	0.6 – 2.34 kg ha^{-1} yr^{-1}	*	*	Wanyama et al. (2018)
Maize	Ghana	Daily during fertilization then weekly	Augt 2013 - Aug 2014	Ferric Luvisol	1.22 – 4.29 kg ha^{-1} yr^{-1}	0.1 – 0.55	0.39 -1.24	Atakora et al. (2019)
Maize	Tanzania	Weekly to Monthly	Dec 2015 - Nov 2017.	Alfisol/Andisol	0.26 – 2.24 kg ha^{-1} yr^{-1}	0.1-1.3	0.18	Zheng et al. (2019)
Maize-legumes (Lablab/ Crotalaria	Ethiopia	Weekly	107 -123 days	Clay–loam	0.17 – 0.33 kg $ha^{-1}yr^{-1}$	0.2 - 0.25		Raji and Dörsch (2020)

Maize	Kenya	Weekly	Feb 2017-Feb 2018	Sandy loam	0.13-1.22 kg $ha^{-1}yr^{-1}$	0.2-0.9	0.5 - 2.2	Macharia et al. (2020)
Maize	Kenya	Weekly	March 2018-March 2019	Nitisol	0.21- 0.38 kg $ha^{-1}yr^{-1}$	0.05 - 0.14	0.02-0.03	Musafiri et al. (2020)
				Seasonal fluxes				
Maize	Zimbabwe	Weekly	Dec 2000-Feb 2001	Sandy loam	0.1 – 0.3 kg ha^{-1}	0.2	*	Chikowo et al. (2004)
Maize	Kenyaraji	1 -2 times per week	84 days	Sandy-clay	0.1 – 4.1 kg ha^{-1}	*	*	Millar et al. (2004)
Maize	Kenya	Weekly	Feb –June 2002	Silt-clay-loam	0.2- 0.6 kg ha^{-1}	*	*	Baggs et al. (2006)
Soybeans and Maize	Madagascar	Weekly	Nov 2006–Apr 2007	Ferrasol	0.3 kg ha^{-1}	0.46 - 0.47	*	Chapuis-Lardy et al. (2009)
Maize	Zimbabwe	Once every two months	Jan 2006 - May 2009	Clay and andy loam	0.1 – 0.5 kg ha^{-1}	*	0.02 -3.93	Mapanda et al. (2011)
Maize	Zimbabwe		2008/2009 growing season	Sandy loam	0.26 – 0.52 kg ha^{-1}	*	0.22 – 0.68	Nyamadzawo et al. (2017)
Vegetable	Kenya	1-3 days per week	Sept 2015 - July 2016	Humic Nitisol	0.4 – 3.0 kg ha^{-1}	0.0 – 2.6	*	Kurgat et al. (2018)
Coffee,Maize - Beans	Kenya	1-3 days per weeks	Feb 2015 - Feb 2016	Nitisol	0.18 -1.9 kg ha^{-1}			Ortiz-Gonzalo et al. (2018)
				Short duration				
Maize-Beans	Nigeria	1-3 days to 2 weeks	21 days	Ferric lixisol	0.1 – 0.3 kg N ha^{-1}/day	1		Roing et al. (2004)
Maize	Kenya	3 times per month	4 weeks	Humic Nitisol	1.3 – 12 μg m^{-2} h^{-1}	*	*	Kimetu et al. (2007)
Vegetables	Zimbabwe	Bi-weekly	Sept 2007 – Nov 2008	Loamy sandy	2.5 – 18.8 **g** N_2O-N h^{-1}	0.3 - 1.0	*	Masaka et al. (2014)
Banana-Coffee	Uganda	4-5 times per month	May 2018 - June 2018	Sandy clay loam:	3.7 -6.7 μg m^{-2} h^{-1}		*	Fatumah et al. (2019)
Amaranth	Benin/Nigeria	Daily during planting there after 2 weeks	21 days	Haplic Lixisols/ Plethnic Plinthosols	24.8 – 279.5 mgN/kgsoil			Olaleye et al. (2020)

N/B. *All mesurements were carried out using static chambers.*

**Indicate where there was no value rep*

3.4 Drivers of soil N_2O emissions in SSA

Studies across SSA have documented varied soil N_2O emissions under different environmental, climatic and soil conditions as well as farm management practices (Frimpong & Baggs., 2010; Nyamadzawo et al., 2017; Pelster et al., 2017; Atokora et al., 2019; Macharia et al., 2020). Environmental factors (land use land cover changes), soil properties (bulk density, temperature, moisture, pH, type, organic carbon, and nitrogen), and climatic factors (temperature and precipitation) may significantly influence soil N_2O fluxes. Farm management practices, including fertiliser application (rates, time, type, and method), tillage, crop type, and residue management, may also influence N_2O emissions. It is noteworthy that these factors don't occur singly but their interdependency determines whether the soil is a net sink or source of N_2O emissions (Rosenstock et al., 2016).

3.4.1 Effects of soil temperature and elevation on N_2O emissions in SSA

Soil temperature significantly influence soil N_2O fluxes by increasing microbial activities that are responsible for N_2O emissions in the soil (Butterbach-Bahl et al., 2013). Nitrous oxide emissions increase with increase in soil temperature as result of increased rates of decomposition of organic matter (Fatumah et al., 2019). The increase in N_2O emissions with rising temperature can be associated with increased nitrogen mineralization, hence higher availability of nitrogen lost as N_2O fluxes (Barnard et al., 2005). However, denitrifying bacteria are very sensitive to soil temperature and operate best at optimum temperature of 30^{o}C, beyond which the activities go down thus lowering N_2O emissions (Oertel et al., 2016). Various studies in SSA, such as Mapanda et al. (2011) in Zimbabwe, Lompo et al. (2012) in Burkina-Faso, Rosenstock et al. (2016) in Kenya, and Atakora et al. (2019) in Ghana, have reported significant positive correlation between soil temperature and nitrous oxide emissions.

Atmospheric temperature also influences N_2O emissions, and which vary alongside altitude. For instance, Fatumah et al. (2019) in Uganda documented higher N_2O emissions in higher altitude (1200-1300 m) characterized with low temperature as compared to low altitudes (1100 to 1200 m and 900 to 1100 m) with higher temperature in Uganda. Further, in Kenya higher soil N_2O emissions were documented in Kaptumo with an elevation of 2000 m compared to Kolero with an elevation of 1250 m (Rosenstock et al., 2016). It is noteworth that higher elevations recorded greater soil C and N which could have resulted to the high N_2O fluxes. However, atmospheric temperature decreases with increasing elevation therefore may influence soil microbial activities responsible for N_2O emissions.

3.4.2 Effects of soil moisture content on N_2O emissions in SSA

Soil moisture is a crucial driver of N_2O fluxes as it determines oxygen, and organic substrates availability (Baggs et al., 2006). Several studies have shown that increased soil moisture content especially at the onset of a season results in increased microbial activities resulting enhanced soil N_2O emissions (Dick et al., 2006; Ortiz Gonzalo et al., 2018; Wanyama et al., 2018; Fatumah et al., 2019; Macharia et al., 2020). Increased N_2O emissions following onset of precipitation can be attributed to increased soil C and N mineralization and decomposition due to birch effect (Birch, 1958) and provision of sufficient anaerobic microsites for denitrification process that increases N_2O emissions (Butterbach-Bahl et al., 2013). It also increases the bacterial growth and other activities thereby increasing respiration rates and soil aeration. Further, soil moisture increases nutrients' transport to soil microbes responsible for denitrification process. For instance, increase in soil moisture from 40% to 90% increased N_2O fluxes by 46% in Madagascar (Rabenarivo et al., 2014). In Kenya, a difference of 32% in rainfall amounts between two seasons (LR 2017 and SR 2017) resulted to a difference of four to six times more N_2O emissions in SR 2017 than in LR 2017, across treatments (Macharia et al., 2020). Soil moisture influences N_2O emissions by activating microbial activities such as denitrification and nitrification.

3.4.3 Effects of soil type and properties on N_2O emissions in SSA

Soil type plays a key role in N_2O dynamics by controlling the availability of soil carbon and nitrogen (Chantigny et al., 2010). Soil texture influences the water holding capacity and gas diffusivity rate and therefore regulates oxygen availability, enhancing microbial activities (Butterbach-Bahl et al., 2013). Course soil texture emits less N_2O emissions compared to fine texture due to high oxygen accumulation that limits denitrification rates, which is the ideal process for N_2O emissions production (Zhu et al., 2020). On the other hand, clayey soil microsites pores contribute toward N_2O emissions production by enhancing anaerobic conditions favorable for denitrification to take place. Studies have documented that the addition of inorganic fertilisers on fine-textured soil and organic fertiliser on coarse-textured soil significantly increase N_2O oxide emissions (Mapanda et al., 2011; Nyamadzawo et al., 2017; Macharia et al., 2020). Regarding soil type, coarse textured soils are generally C deficient while fine-textured soils are generally N deficient (Pelster et al., 2012). The application of organic fertiliser on coarse-textured soil supplies mineralisable C, stimulating N2O emissions in the C limited soils while addition of inorganic fertiliser in fine soil supply N providing substrate for microbial community, hence increasing N_2O emission.

Soil bulk density influences N_2O fluxes through the regulation of diffusion of oxygen into the soils which is essential for nitrification processes (Butterbach-Bahl et al., 2013). It limits soil aeration which enhances the production of N_2 into the atmosphere through diffusion. Wanyama et al. (2018) found negative correlation between bulk density and soil N_2O fluxes, implying that increase in bulk density results to higher soil compaction and lower N_2O emissions.

Soil pH has significant effects on N_2O emissions as it controls bacterial activities, nutrient availability and soil structure. Nitrification–denitrification microbes are pH-sensitive; hence its alteration determines N_2O emissions. Low soil pH may alter the functions of N_2O reductase enzymes, which are responsible for reducing N_2O/N_2 ratio and may lead to higher N_2O emissions (Bakken et al., 2012). Under acidic soils, an increase in soil pH leads to less N_2O emissions, though N_2O emissions increase with a decrease in pH in alkaline soil (Chapuis-Lardy et al., 2007). Manure application may also contribute to increased soil pH, resulting in lower N_2O emissions (Ortiz-Gonzalo et al., 2018). However, Macharia et al. (2020) found higher N_2O emissions in manure-treated plots despite having the highest pH. Consequently, caution should be taken during the continuous application of fertiliser since it may promote soil acidification and encourage N_2O emissions.

Soil N_2O emissions can significantly be influenced by soil C, N, and C/N ratio (Fatumah et al., 2019). The C/N ratio can predict whether mineralisation or immobilasation takes place. Use of crop residues with high C/N ratio results in prolonged decomposition of organic matter. Consequently, combination of low-quality crop residue with high quality manure may offset N loss by balancing C/N therefore reducing immobilization. Low soil organic carbon limits denitrification and microbial activity resulting in lower N_2O emissions (Rosenstock et al., 2016). Studies have reported positive correlation between inorganic nitrogen (NO_3-N and NH_4^+-N) and N_2O fluxes (Millar et al., 2004; Pelster et al., 2017; Wanyama et al., 2018; Macharia et al., 2020). Both soil C and N influence N_2O fluxes; therefore, the soil C/N ratio is an important predictor of the emissions. For instance, Wanyama et al. (2018) documented a negative correlation between soil C/N ratio and N_2O fluxes. This was attributed to the potential decrease in N mineralization with an increase in C/N ratio. Macharia et al. (2020) also reported positive correlations between N_2O emissions and inorganic nitrogen (IN), suggesting that N's availability in the soil significantly determines N_2O emissions.

3.5 Soil N_2O mitigation options in emissions in SSA

Given the diversity in drivers that influence soil N_2O fluxes in SSA, there is no single mitigation option applicable across all agro-ecological conditions. Therefore, targeted approach and which is specific per agro-ecological zone is necessary in recommending different interventions in SSA. For instance, soil type–soil fertility management targeting is an appropriate mechanism in evaluating N_2O emissions mitigation. Organic manure may provide an essential entry point in mitigating N_2O emissions under sandy (coarse textured) soils, which are generraly C deficient. Manure enriches the coarse textured soils with mineralisable C thus improving soil fertility and general soil health and crop yields but may come at a cost of more N_2O emissions (Macharia et al., 2020). However, with most of the land mass in SSA being Arid and Semi-arid (ASALs) (45-55%), there is a need to achieve a nexus between crop production and N_2O emissions (Barro, 2004). Therefore, to assess the suitability of effective mitigation options, N_2O yield-scaled emissions, which compares N_2O emissions and crop yields can be used.

3.5.1 Intergrated soil fertility management

Integrated soil fertility management is an agricultural practice centered towards combination of locally available organic resources and mineral fertilisers with an aim of improving nutrients and water efficiency with a goal of increasing crop production (Vanlauwe et al., 2014). Combining manure and inorganic fertilisers has been reported to increase agricultural productivity while mitigating N_2O emissions in sandy loam (moderate texture) soils in Zimbabwe by increasing minerasable C (Nyamadzawo et al., 2017). Sommer et al. (2015) also found that integrated soil fertility management practices have the potential to improve N balance and contribute to environmental sustainability better than either sole inorganic fertiliser or organic fertilisers application. Crop residues retention has the potential of increasing agricultural productivity with lower N_2O emissions compared with synthetic fertilisers (Tongwane et al., 2016). Integrated soil fertility management contributes to mitigation of N_2O emissions by improving soil health and crop productivity which increases yield hence reducing YSEs.

3.5.2 Cereal-Legume intercropping

Cereal-legume intercropping enhances soil and crop productivity through nitrogen fixation and soil conservation. Leguminous crops have low C/N ratio than cereal crops (Fosu et al., 2007). This implies that combining both cereals and legumes in the field may reduce immobilisaton of N in the soil, increase the availability of N and better synchronization by the plant. Therefore, cereal-legume intercrop/rotation targeting might be an essential entry point in mitigation soil N_2O fluxes among smallholder farming systems in SSA. For instance, cereal-legume intercropping or rotation might enhance soil N_2O mitigation. Dick et al. (2008) found significantly low soil N_2O fluxes under cereal-legume rotation cropping in Mali. According to Frimpong et al. (2011) cowpea-maize intercrop emitted lower N_2O emissions compared with cowpea alone. Using legume-cereal rotation improves nitrogen fixation, thus reducing the need for inorganic fertiliser (Lupwayi et al., 2011), which, if applied, could lead to extra N_2O fluxes. The grain-legumes in SSA has the capacity to fix approximately 15 to 210 kg N ha^{-1} (Bekunda et al., 2010), thus improving soil fertility. This implies that use of legumes, intercropped or rotation, may reduce N mining of maize crops currently ranging between 14- 110 kg N ha^{-1} yr^{-1} in SSA (Sommer et al., 2013). In addition to reduced N_2O emissions, improving soil fertility, farmers practicing cereal-legume intercropping spread the risk of failure of one crop incase of climate variability hence increasing their economic plausibility and nutritional security (Kamanga et al., 2010).

3.5.3 Fertiliser application management

Fertiliser application management is very crucial for plant growth and N cycle in the soil. Effective N fertiliser management in the farm needs to consider the amount of N required by the plants and the N being supplied. This is because N application to the soils might significantly influence N_2O emission in SSA (Hickman et al., 2015). For instance, even though Hickman et al. (2014) observed no significant difference in N_2O fluxes between fertiliser application rates in Western Kenya, the emissions increased with increase in fertiliser application rate. This implies that application of the right amount of N to the soil could significantly mitigate N_2O emissions as opposed to use of countries'-specific blanket fertiliser application recommendations. Further, determination of the site-specific fertiliser type can be essential in mitigation N_2O emissions. Use of nitrogen inhibitors and split application can also be essential mechanism of reducing N_2O fluxes from smallholder cropping systems in SSA. Finaly, Nafi et al. (2020) documented that micro-dosing (application of fertiliser at the root) lowered N losses. Therefore, establishment of site-specific 4Rs of fertiliser application (right time, right rate, right place, and right type) is requisite in mitigating N_2O fluxes in SSA.

3.5.4 Reduce/No tillage option

Soil disturbance through tillage could significantly increase N_2O emissions as it alters soil physical properties such as bulk density. Tillage method targeting can offer bases for N_2O fluxes mitigation among smallholder cropping systems in SSA. For instance, Chikowo et al. (2004) and Baggs et al. (2006) documented lower N_2O emissions under no tillage compared to tilled farms. Since conservation tillage (no tillage or minimum tillage) increases agricultural productivity and lowers N_2O emissions, their adoption among smallholder farmers in SSA could mitigate the effects N_2O emissions.

3.6 Conclusion

A better understanding of soil N_2O emissions, YSE, and EFs from different cropping systems in SSA is essential in promoting agricultural sustainability and climate change mitigation.

Finding from the SSA studies agrees with the hypothesis that N_2O emissions significantly differ across cropping systems. However, N_2O emissions remained relatively low compared to global averages, except for vegetable cropping systems mainly due to inherently low soil fertility due to continuous farming with limited replenishment with external inputs. We found out that better nutrient management through the combination of organic and inorganic fertilizers could provide a viable option in mitigating N_2O emissions in SSA. The review also reveals that SSA's EFs are lower than IPCC Tier 1 default EFs meaning that the use of default EFs may overestimate soil N_2O emissions and lead to inaccurate targeting of climate change adaptation and mitigation measures in SSA. However, a few exceptional cases, mainly from vegetable production and applied more fertilizers comparatively, documented more than 1% in SSA. The review paper identified environmental, climatic, and soil properties as critical drivers that significantly influence N_2O fluxes dynamics in SSA. This study revealed that "umbrella" (universal) recommendations for climate change mitigation measures might not be effective across SSA cropping systems based on their diversity. Therefore, devising site-specific mitigation interventions could be a plausible entry point to mitigate N_2O emissions. We singled out options for targeting N_2O emissions mitigation in SSA: integrated soil fertility management; cereal-legume intercropping; reduced/ no-tillage; and improved fertilizer application management. We recommend establishing more empirical studies in area with varying agro-ecological zones and soil types in SSA to qualify various mitigation options on N_2O emissions, yield scaled N_2O emissions, and N_2O emission factors, which are essential in improving national and regional GHG inventories.

CHAPTER FOUR

4 SYNTHESIS, CONCLUSION, AND RECOMMENDATION

4.1 Synthesis

The focus of this study was to quantify GHGs emissions from selected cropping systems under on-farm conditions in Tharaka-Nithi, Kenya. This was address by quantifying GHGs fluxes from selected cropping systems under on farm condition. Nitrous Oxide, a potent GHGs has attracted a lot attention globally due to adverse effect on increase global temperatures and destruction impact on the stratosphere to the ozone layer (Chapter 2), evaluating N_2O emissions from smallholders' cropping systems (Chapter 3) and determine the environmental factors, climatic conditions, farm management practices, and soil properties directly influencing N_2O dynamics (Chapter 3).

Smallholder cropping systems has direct link to greenhouse gas (GHG) (CH_4, N_2O and CO_2) emissions as result of organic and inorganic fertilizers. Of the three GHGs, N_2O has attracted high attention globally due to its high global warming potential and ozone layer destruction nature (Chapter 3). A better understanding of soil N_2O emissions, YSE and EFs from different cropping systems in SSA is essential in promoting agricultural sustainability and climate change mitigation (Chapter 3). To achieve appropriate mitigation measure for N_2O emissions, site specific characteristics and key drivers of GHGs such as climatic condition, farm management practices and soil properties are required (Chapter 3).

Soil temperature, precipitation, soil fertility management are the key drivers of GHGs emissions. Appropriate mitigation for N_2O emissions, such as integrated soil fertility management; cereal-legume intercropping; reduced/ no-tillage; and improved fertilizer application management, provide best opportunity for to increase food production in SSA (Chapter 3).

4.2 Conclusion

Based on study's finding the following are the conclusions

1. Smallholders' farmers in the Tharaka-Nithi, Kenya contribute limited amount of soil GHG emissions.
2. Nitrous Oxide emissions from SSA's cropping systems are relatively lower than the global average.
3. Soil temperature, soil moisture, soil type and soil fertility management practices are key drivers of N_2O emissions.

4.3 Recommendations

Based on the findings I recommend that

1. Applying recommended nutrients to soil helps increase yield production while reducing GHG emissions.
2. Establishment of more empirical studies in area with varying agro-ecological zones and soil types in SSA to qualify various mitigation options on N_2O emissions, yield-scaled N_2O emissions and emission factors, which are essential in improving national and regional GHG inventories.
3. Use of integrated soil fertility management, cereal-legume intercropping, reduced/no tillage, and improved fertiliser application are main targeting approaches that could provide best options in mitigating GHGs fluxes.

4.3 Areas of further study

The following areas need further research

1. Further research is required to study the effect of different soil type across varying agro-ecological on GHGs emissions
2. There is a need to identify specific mitigation option best fit each agro-ecological zone for GHGs emissions.

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