

**ASSESSING NITROGEN FLOWS AND GREENHOUSE GAS EMISSIONS IN  
LOW INPUT CROPPING SYSTEMS OF LAKE VICTORIA BASIN**

**Ntinyari Winnie (Msc)**

**Registration Number A99/28433/2018**

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## DECLARATION

This thesis is my original work and has not been presented for any degree or award in any University

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

**Winnie Ntinyari**

Department of Agriculture Science and Technology

Registration Number: A99/28433/2018

### Supervisors

We confirm that the work reported in this thesis was carried out by the candidate under our supervision and has been submitted with our approval as university supervisors

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

**Prof. Joseph Onyango Gweyi**

Department of Agriculture Science and Technology

Kenyatta University, Nairobi -Kenya

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

**Dr. Cargele Masso**

International Institute of Tropical Agriculture (IITA)

Yaoundé-Cameroon

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

**Prof. Benson Mochoge**

Department of Agriculture Science and Technology

Kenyatta University, Nairobi -Kenya

## **DEDICATION**

To my beloved late Father Sebastian Mbaya Gitonga for his encouragement to pursue post-graduate education.

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## LIST OF ABBREVIATIONS AND ACRONYMS

ADS	-	Abuja Declaration Scenario
AEN	-	Agronomic Efficiency of Nitrogen
ANOVA	-	Analysis of Variance
APEN	-	Agro-physiological Nitrogen Efficiency
BAU	-	Business as Usual
BNF	-	Biological Nitrogen Fixation
CaCl <sub>2</sub>	-	Calcium chloride
CADDP	-	Comprehensive African Agriculture Development Programme
CCAFS	-	Climate Change Agriculture and Food Security
CH <sub>4</sub>	-	Methane
CHANS	-	Coupled Human and Natural Systems
CO <sub>2</sub>	-	Carbon dioxide
DAP	-	Days after Planting
EC	-	Electrical Conductivity
EUNEP	-	European Union Nitrogen Expert Panel
FAO	-	Food and Agriculture organization
FAOSTAT	-	Food and Agriculture Organizations statistics
GHGs	-	Greenhouse gases
GWP	-	Global warming potential
IFASTAT	-	International Fertilizer Association Statistics
IFDC	-	International Fertilizer Development Centre
IPCC	-	Intergovernmental Panel on Climate Change
N	-	Nitrogen
N <sub>2</sub> O	-	Nitrous Oxide
NB	-	Nitrogen Budget
NH <sub>4</sub> <sup>+</sup>	-	Ammonium
NH <sub>3</sub>	-	Ammonia
NIB	-	National Irrigation Board
NO <sub>3</sub> <sup>-</sup>	-	Nitrate

NUE	-	Nitrogen Use Efficiency
OECD	-	Organization for Economic Co-operation and Development
PNB	-	Partial Nitrogen Balance
RCBD	-	Randomized Complete Block Design
SSA	-	Sub-Saharan Africa

## ABSTRACT

Too little nitrogen (N) is a threat to cropping systems and soil fertility in sub-Saharan Africa (SSA). Nitrogen budgets (NB) and nitrogen use efficiency (NUE) are critical tools for assessing N dynamics in agriculture and have received little or no attention in the region. The study aimed to assess key N performance indicators at field and farm level based on N use scenarios and helps to inform policy on formulating relevant decision and practices to enhance N management for improved crop productivity and environmental sustainability. To achieve this, data were collected from farmers' fields and clustered into two categories, farmers applying and farmers not applying N fertilizers. Collected data on yield and N fertilizer were used to make projections on the changes of NUE based on scientific and policy recommendations for Sub-Saharan Africa for 2020 (base year), 2025, 2030, and 2050. Scenarios of N use were simulated under field conditions for maize crop in two catchments of the Lake Victoria basin. The scenarios included Business as Usual (BAU, 0 kg N ha<sup>-1</sup>), 25 % of the Abuja declaration (ADS 12.5 kg N ha<sup>-1</sup>), 50% of the Abuja declaration (ADS 25 kg N ha<sup>-1</sup>), and Abuja declaration-Abuja scenario (ADS, 50 kg N ha<sup>-1</sup>). A laboratory incubation experiment to assess the effects of two N use scenarios (12.5 and 50 kg N ha<sup>-1</sup>) and liming practices (CaCO<sub>3</sub>) on three acidic soils types from Lake Victoria basin on greenhouse gases was conducted. Data were analyzed using R programming language version 4.1.0. The results revealed negative N balances in different fields and farms. Similarly, at the farm gate, a deficit of -78.37 kg N ha<sup>-1</sup> was observed; an indicator of soil N mining. Significant differences in maize grain yield for both fertilized and unfertilized farms were realized with very low yields of 2.4 t ha<sup>-1</sup> (fertilized) and 1.4 t ha<sup>-1</sup> (unfertilized). The graphical representation of NUE of both maize and rice showed that most farmers were in the zone of soil N mining. Projected results showed that most maize farmers within Lake Victoria region will continue to experience NUE values >90%, low N inputs <50 kg N ha<sup>-1</sup>) and less than 5 t ha<sup>-1</sup> maize crop yield over the years. For rice farmers, Nyando and Nzoia catchments had surpassed the set target of both yield (6 t ha<sup>-1</sup>) and N input (50 kg N ha<sup>-1</sup>). The results revealed that increasing N input levels significantly influenced the growth and yield of maize crops. N deficits were observed in all the N use scenarios with a range of -66.6 to -125.7 kg N ha<sup>-1</sup> in Nyando and -62.5 to -105.4 kg N ha<sup>-1</sup> in Rangwe catchments with 50 % ADS scenario having the highest deficits. The partial N balance observed at Nyando (1.56 - 3.11) and Rangwe (1.10- 4.64) were higher than the optimal values, a sign of insufficient N inputs and possible risk of soil N depletion in all the scenarios. The values of  $\delta^{13}C$  of CO<sub>2</sub> showed that the source of CO<sub>2</sub> from soils was negligible and the largest contributor was from application of CaCO<sub>3</sub> followed by N fertilization in Ferralsol 1 and 2 while no visible differences observed in the Vertisol. N<sub>2</sub>O-N fluxes were highly influenced by N fertilization and CaCO<sub>3</sub> in Ferralsol 1 and 2 which was 13 (81.73 mg m<sup>-2</sup>) and 4 (38.80 mg m<sup>-2</sup>) times higher when compared to unfertilized and unlimed control. The study concludes that Lake Victoria basin faces an extreme depletion of available N resources, the recommended nutrient level; at 50 kg N ha<sup>-1</sup> is not sufficient to correct the negative balances, while managing acidity and soil fertility will lead to higher GHG fluxes but increase N availability.

## CHAPTER ONE: INTRODUCTION

### 1.1 Background to the study

Nitrogen (N) is a critical element for increased crop production and is a significant yield-determining nutrient in farming systems (Noor *et al.*, 2020; Quemada *et al.*, 2020). Nitrogen constitutes 90% of the applied fertilizer world-wide (Sutton *et al.*, 2013) and is sometimes accompanied with a little phosphorus (P) and potassium (K) during the application by small scale farmers but rarely with secondary or micronutrients and is the most important primary nutrient for crop production (Swarbreck *et al.*, 2019). As a major yield- determining nutrient in most farming systems, N is required in adequate but not in excess amounts for high yields and contributes to maintenance of soil organic matter (Cao *et al.*, 2017). In Sub- Saharan Africa (SSA), agricultural systems are characterized by sub-optimal application of N fertilizer, contributing to low crop productivity, malnutrition, and poor economy that is linked to vicious cycles of poverty. Approximately 80% of arable land is N deficit, with many countries having negative budgets, indicating higher crop removal and associated losses than the amount of N fertilizer applied (Masso *et al.*, 2017). The region represents the clearest example of a challenge created by too little N application leading to soil N depletion (Hickman *et al.*, 2020).

Managing N flows in arable land requires guidance on optimal achievable Nitrogen Use Efficiency (NUE) since higher values > 90% represent extreme depletion of available soil N while lower values <50% indicate increased losses, either through leaching ( $\text{NO}_3^-$ ), gaseous emissions ( $\text{N}_2\text{O}$ ,  $\text{NO}_x$ ) or by runoff (Zhang *et al.*, 2015; Ntinyari and Gweyi-

Onyango 2021). A standard NUE definition that fits the East Africa region is: the ratio of harvested N (edible crop portion) to the amount of N input applied (Zhang *et al.*, 2019). A more detailed and accurate range would be evident if all N sources, including atmospheric N deposition, biological N fixation, and livestock manure are put into consideration when making computation. Defining a target NUE for the specific countries will represent a significant step towards informing the right decisions for N management. Therefore, every policy or management practice should have a target NUE to be achieved within a given time frame.

Quantifying N inputs and outputs of a defined operation boundary helps advance knowledge towards maintaining a nutrient balance, which is the first step towards N management. The overall goal of N management has close linkage to Sustainable Development Goals, specifically those focusing on food supply and pollution (Morseletto, 2019). Farmers remain the crucial determinants of total N flows into cropping systems, implying that their activities have direct or indirect effects on improving N management (Quemada *et al.*, 2020; Ntinyari *et al.*, 2022 a,b). Nitrogen budgets/balances (NB) are critical N performance indicators used by farmers with advanced knowledge to make fertilizer use and management (Quemada *et al.*, 2020; Zhang *et al.*, 2020). Policymakers also use nitrogen balances to assess and monitor the environmental impacts of agricultural practices at national and regional scales. In Africa, farmers lack knowledge and extension services in N budgeting hence making nutrient use management difficult. In addition, the national nitrogen budget essential to informing the policies to monitor and report performance of sustainable agriculture and N management do not exist. Moreover, poor collection on N data makes it difficult to

define effective policies towards improving African agriculture (Elrys *et al.*, 2019). Besides, good policy development in agricultural systems require high spatial resolution data input (Kros *et al.*, 2018).

Nitrogen use efficiency (NUE) is an agro-environmental indicator that makes it possible to determine if a system is utilizing the applied N optimally or not, as depicted in either low or high NUE values presented by Quemada *et al.* (2020). NUE is presented as a percentage between N outputs over N inputs for specific agricultural systems. The values for NUE depends on the system management; with high NUE % observed when N output in crop removal increases while N input decreases. The concept of NUE is critical in evaluating crop production and is impacted by the management of fertilizers. It also indicates potential of N loss to environment from agricultural systems as farmers strive to achieve increasing demand for food security (Fixen *et al.*, 2015; Ntinyari *et al.*, 2022c).

Farming activities are strongly affected by climate change and are major contributors to changes in climatic patterns with about a quarter of total global greenhouse gas (GHG) emissions emanating from land-use activities (Laborde *et al.*, 2021). N fertilizers is one of the leading sources of GHG emission in agricultural systems. According to Intergovernmental Panel on Climate Change (IPCC), (2014), agriculture contributes to approximately 24% of the GHG fluxes worldwide. In developing countries GHG contribution from agriculture is estimated to be up to 66% (Pelster *et al.*, 2017). The current GHG emissions are estimated to escalate in future due to changing diets and increase in population, particularly in developing nations (Smith *et al.*, 2007). The three major GHG produced from agriculture with a more significant impact on global

warming are carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) (Nayak *et al.*, 2015). Carbon dioxide is largely released from microbial decay or from soil organic matter, while N<sub>2</sub>O is generated from microbial transformation of soil nitrogen and CH<sub>4</sub> is released through decomposition of organic materials in oxygen-deprived environments (Smith *et al.*, 2008). Notably, the global warming potential of N<sub>2</sub>O and CH<sub>4</sub> in 100-year time horizon is estimated to be 298 and 34 times higher that of CO<sub>2</sub> (IPCC, 2014).

## **1.2 Problem Statement**

East Africa region is linked to low application of mineral N inputs into their cropping systems. Extreme levels of soil degradation and low yields are associated with poor understanding of key N fluxes into the cropping systems either for specific crop or at farm level. The complexity of N cycle in agriculture requires critical analysis and understanding to be able to manage each single source of input and output. Having no existing nitrogen budget estimated at field and farm spatial scale explains the challenge for identifying the N fluxes and limits choice of management practices, moreso in East Africa region where majority of farmers are smallholders.

Insufficient application of N inputs in SSA has been linked to NUEs beyond 100% (Edmonds *et al.*, 2009) as compared to 70% in regions with sufficient use of N in cropping systems (Masso *et al.*, 2020; Sutton *et al.* 2013). Several studies (Quemada *et al.*, 2020; Mosier *et al.*, 2013; Powell *et al.*, 2010; de Klein *et al.*, 2017), define NUE as a critical indicator for agricultural systems but there are no robust and uniform protocols for monitoring N at international levels. The lack of consensus on how NUE should be

calculated at different boundaries in agricultural systems complicates the processes of communicating NUE results to scientific, policy and extension stakeholders. Therefore, there is need to develop sound understanding of NUE using global comparison methods for easier formulating of governing policies towards N management.

Crop yields are low in SSA due to low fertilizer input due to low purchasing power of many small-scale farmers within the region (Beesigamukama *et al.*, 2020; Gweyi, 2006). Existing evidence show average cereal yield is as low as 1.4 t ha<sup>-1</sup> against potential of 4 -13 t ha<sup>-1</sup> in SSA when proper nutrition and improved varieties are considered (Mueller *et al.*, 2012; Tamene; *et al.*; 2016). Small-scale agriculture is the most dominant form of agricultural production contributing to majority of national level food supply with major farm size being less than 2 ha (Leitner *et al.*, 2020). According to African Union, (2006) agricultural ministers pointed out that increasing N fertilizer application rates to 50 kg N ha<sup>-1</sup> in SSA is the only solution to lift the low productivity levels (Ntinyari *et al.*, 2022b). Although recommendations by the Abuja declaration have been made to increase fertilizer inputs, their influence on NUE has not been evaluated at plot level. Besides, most of the studies have relied on model projections in estimating the change in yield over time (Leitner *et al.*, 2020: Mueller *et al.*, 2012). Furthermore, they have neglected key indicators for NUE for major crops within the region.

There is also a limitation of data on quantity of gaseous emission released from region as influenced by N fertilizer use and soil quality management. One major greenhouse gas, nitrous oxide (N<sub>2</sub>O), is a threat to the environment and its direct quantification from

the soils remains critical (Leitner *et al.*, 2020). Therefore, being a component of NB, N<sub>2</sub>O direct measurement to get actual amount emitted from fertilizer applications in cropping system will be necessary. Other than N<sub>2</sub>O, CO<sub>2</sub> is also another greenhouse that results from increased microbial decomposition when N fertilization is added.

Soil acidity is another issue of concern in soil quality and overall crop productivity. Approximately 40% of the world's agricultural soils are acidic which is a serious threat affecting agricultural gross income (Kunhikrishnan *et al.*, 2016). Fageria & Nascente, (2014) reported soil acidity to influence many chemical and biological reactions that control plant nutrients availability and toxicity of some elements. To optimize soil chemical characterizing and create a favorable condition for plants thrive, liming is applied to raise the pH. In most of the agricultural systems, optimal soil pH is maintained by ground application of limestone, dolomite or other calcareous materials to neutralize the acidity levels (Žurovec *et al.*, 2021). Data is lacking on the influence of managing acidity and N fertilization to NUE and GHG emissions particularly for the East Africa with little and anticipated increase in N use.

### **1.3 General objective**

To identify and assess nitrogen performance indicators, soil management practices and scenarios of selected crops and farms in Lake Victoria basin for increased yield performance and N use optimization.

#### **1.3.1 Specific objectives**

- i. To model nitrogen budgets at two spatial scales in selected crops and farms within Lake Victoria basin.

- ii. To determine nitrogen use efficiency, deficit and surplus in selected crops and farms and future trends within Lake Victoria basin.
- iii. To analyze simulated nitrogen use scenarios on their effects on nitrogen balance indicators and yield in maize within Lake Victoria basin.
- iv. To quantify emission fluxes of GHG and nitrogen availability in lowland and upland soils as influenced by N fertilizer scenarios and liming practice in Lake Victoria basin.

#### **1.4 Hypotheses**

- i) Nitrogen budgets in fields and farms levels have a variation on N cycling and management reflecting smallholder farmers' scenarios in Lake Victoria basin
- ii) NUE and N surplus/ deficit vary in different selected crops and farms in Lake Victoria basin
- iii) Simulated N use scenarios significantly affect crop yield and nitrogen balance indicators in maize cropping systems
- iv) GHG fluxes and nitrogen availability are significantly affected by the fertilizer application and liming practices

#### **1.5 Research Questions**

- i) What is the nitrogen budgets of selected crops and farms at two spatial scales in Lake Victoria basin and insights on N cycling and management reflecting smallholders' farmers' scenarios in Lake Victoria basin?
- ii) Does NUE and N surplus/ deficit vary in selected different crops and farms in Lake Victoria basin?

- iii) How do simulated N use scenarios affect crop yield and nitrogen balance indicators in maize cropping systems?
- iv) Does application of N fertilizers and liming practices have effects on GHG fluxes and nitrogen availability in lowland and upland soils?

### **1.6 Justification of the study**

Managing N in agricultural systems is challenging without data on actual N flows. Specific management practices should be tailored to improving the efficiency and productivity of the farms (Spiertz, 2009). It is expected that improved N management would have a multiplier effect of promoting and improving soil health, conservation of resources and reduction of the reactive N to the environment, hence a need for a detailed study to narrow the knowledge gap. The information on the determination of Nitrogen Balance for farms/crops in the Lake Victoria catchment are crucial, and particularly forms platform for identifications of pools of excess or little N and eventually develop strategies for preventing build up and losses. The current study is the first to quantify the NB and the quantification of NB therefore forms the first step towards improved N management as it helps in identifying major N sources and sink in the region. It is widely accepted that NUE can be used as a reasonable indicator for good management and close simulation of the farmers' actual practices and the argument hence partially informed the current study. Improving NUE has a potential of improving and/or reducing the current yield gap of  $1.4 \text{ t ha}^{-1}$  to a more sustainable yield for feeding the growing population (Mueller *et al.*, 2012). Soil acidity is another challenge towards attainment of potential crop productivity within Lake Victoria basin

and most parts of SSA regions. To this end, liming has been adopted as an agricultural practice that enhances crop productivity through neutralizing acidification in soils and simulating nutrient cycling (Senbayram *et al.*, 2019). Whereas this has been practiced for a long time, knowledge about liming, particularly in combination with acidic fertilizer have been considered as contributing factors to enrichment of GHG. Assessment of effects of liming material to enhance N availability in acid soils are relevant for sustainability of the ecosystems, particularly in regards to emissions (Smith *et al.*, 2007) but should be considered in context of GHG emissions. Therefore, quantification and management remain critical in managing the air quality and reducing the harmful environmental impact from use of N fertilizers.

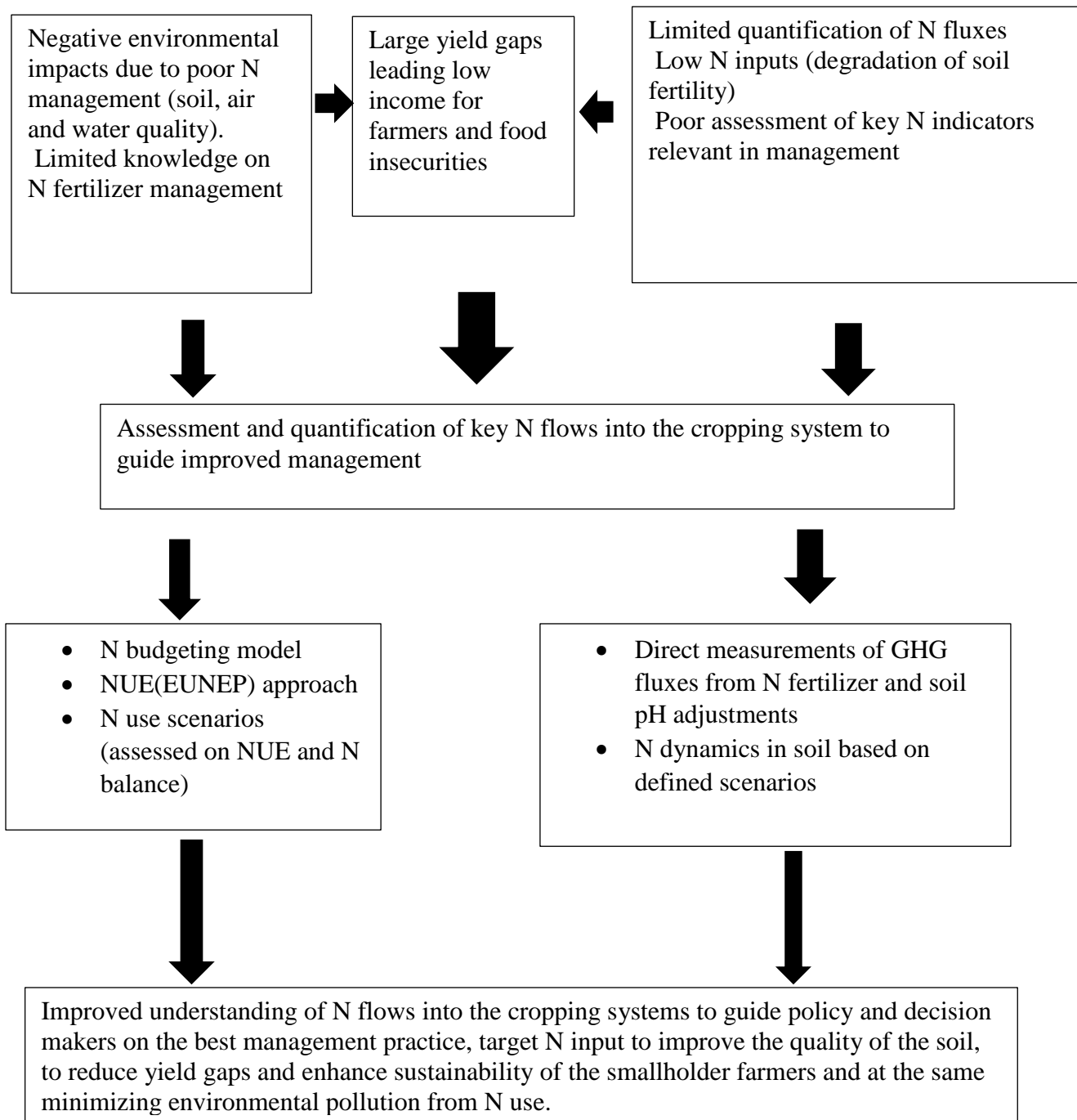
### **1.7 Significance of the study**

This research will generate data on N cycling by providing NB and NUE, which are important indicators for crop productivity and environmental sustainability. Farmers will have the right guidance on which type of fertilizer to apply and when to maximize yield while maintaining safe operating boundaries in terms of N management if they understand NUE and soil balances.

Nutrient modeling has not been prioritized in the region in order to provide predictions on the future of specific N as well as mechanisms that must be implemented in order to maximize the efficient use of applied soil and crop inputs. To achieve better nitrogen management practices, mechanistic soil and crop models that provide an adequate understanding and best quantification of various N pools in different cropping systems are needed. The study will also make generalized projections from different policy recommendations, which will be narrowed down to the local level on expected yield

and N balance if recommended management practices are followed. Data generated from field experiments on N use scenarios will be useful in demonstrating the transition of farmers to N use and changes in NUE indicators in order to provide a guide to decision makers on more sustainable practices. It is expected that with the proper management practices, yield will increase and the environment will be more secure with less pollution. The study will also provide information on the use of fertilization and its contribution to the global greenhouse gas budget, as well as the extent of global warming potential of the various management practices used by farmers. Overall, the objectives of this study are linked to a number of the United Nations Sustainable Development Goals (SDGs).

## 1.8 Conceptual framework



**Figure 1.1: Conceptual framework**

## CHAPTER TWO: LITERATURE REVIEW

### 2.1 Nitrogen Budgets

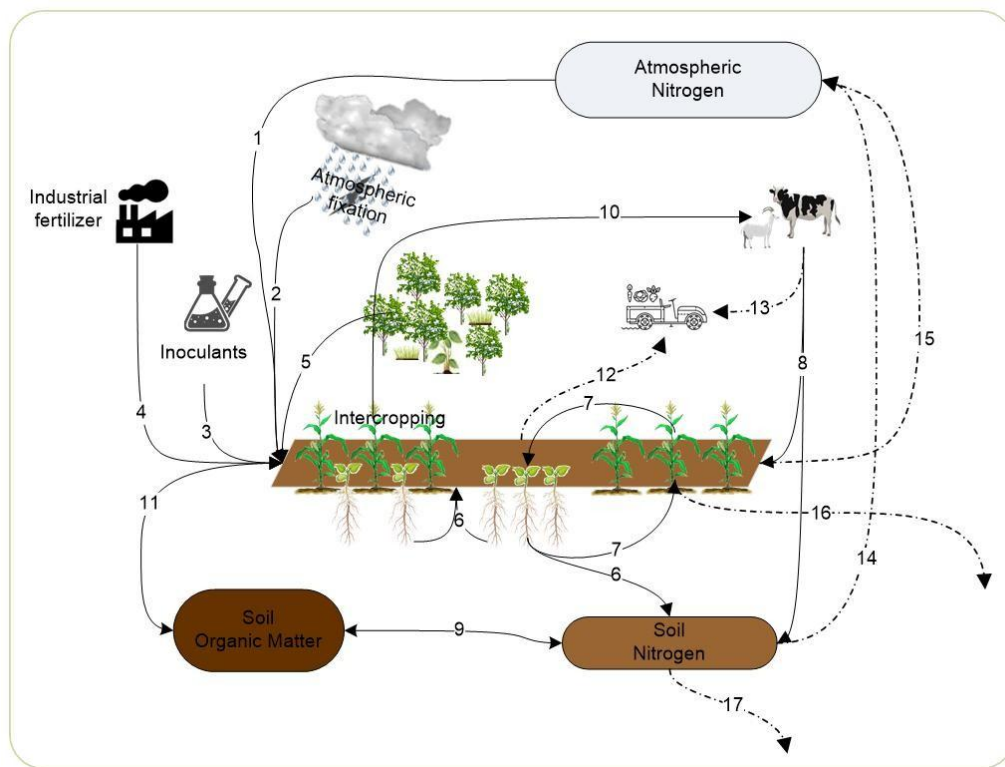
Nitrogen budgets (NB) represents a simple model to investigate the nitrogen balances in the ecosystems. Computation of N input-output budgets requires data from various sources including spatial and temporal scales (Oenema *et al.*, 2003). The key principle in nitrogen budgets is to summarize agricultural N cycle through documenting of the major flows of N as it enters and emerges from the N pools in a given agricultural system. N budgets also help in identification of N surplus within the cropping system and can be used in prediction of N management practices that can reduce nitrogen losses in potential agricultural land (Dalgaard *et al.*, 2017, Kros *et al.*, 2018). Understanding N budgets of agro-ecosystems is crucial towards increasing scientific understanding in N turnover in agriculture through raising awareness and regulating and monitoring instrument polices towards environmental policies for pollution reduction. For determining the farm-gate budget, all the sources and amount of nutrients that are entering and leaving the farm gate should be taken into account (Watson *et al.*, 2002). The surplus or deficit in N represents the difference between inputs and outputs within a farming system and is a measure of the total nutrient losses from the inputs applied (de Vries *et al.*, 2017). The farm-gate budget is essential in regulating the total nutrient losses from the agro-ecosystem through integrating both crop and animal production. A soil surface budget considers takes into account all the nutrients that are entering the soil surface and that are leaving the soil through crop uptake (Murphy *et al.*, 2019). On the other hand, the soil system budget includes all nutrient inputs and outputs accounting for all nutrients gains and losses within and from the soil (Paré and

Thiffault, 2016; Ntinyari *et al.*, 2022d). This kind of system approach allows partitioning between various nutrient loss pathways, storage and nutrient compartments within a system. N budgets gives a prediction of the N surplus, which is an essential indicator for nutrient loss from the cropping system and is a raising concern. A positive N Surplus Intensity (NSI) is an indication for residual N in the soils that may constitute to a potential environmental risk (de Vries and Kros, 2016). Inputs for N budgets includes: chemical fertilizer, which is one of the largest sources of N added in the agricultural ecosystem, atmospheric deposition, agricultural biological N fixation, manure, N from crop residue decomposition, purchased feeds into the farm, livestock and beddings. Whereas, N outputs in the farm budgets include crop harvest, ammonia volatilization losses, nitrification denitrification losses, leaching, and surface runoff (Hu *et al.*, 2018).

## **2.2 Nitrogen Budgets in Africa**

In sub-Saharan Africa (SSA), N budgets have been reported to be negative, which implies that soil N mining is a major problem in the region (Masso *et al.*, 2017). In the past, N mining has been estimated to average  $660 \text{ kg ha}^{-1}\text{yr}^{-1}$ , with losses of up to  $130 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  in the East African Highlands (Zheng *et al.*, 2018). For instance, in the Central Highlands of Kenya and croplands in the Sahel, losses of  $36 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $10 \text{ N kg ha}^{-1} \text{ yr}^{-1}$ , respectively, have been reported. According to Henao and Baanate, (1999) on annual nutrient balance from 44 sub-Saharan Africa (SSA) countries showed a negative N balance of up to  $1121 \text{ kg N ha}^{-1}$ . Due to the growing concern of N decline in SSA, different technologies with soil fertility ameliorating abilities have been developed (Feder and Savastano, 2017). This has also triggered extensive studies on N

budgets in various African farming systems. These studies include inoculation of grain legumes, efficient use of locally available organic resources such as manure, intercropping, improved soil erosion control using living barriers or micro-catchments green manuring, cover cropping, using low levels of N on maize and beans and stable isotopes to estimate nitrogen recovery fractions in crops (Dinesh, 2016; Milka *et al.*, 2019).



**Figure 2.1: Estimated N budgets and flows in Africa smallholder farming system. Arrows represent flows, with solid lines representing N inputs and transformations, and dotted lines N losses. (Source: Kiboi *et al.*, 2019)**

From Figure 2, it can be concluded that most flows are directed towards the farm. Most of the inputs such as mineral fertilizers and crop residues are directly added to the field,

while others pass through intermediate system components, such as animal manure and biological nitrogen fixation (BNF). Except for the countries, where governments provide subsidized fertilizers for cereal production, inorganic fertilizers both subsidized and individual farmers purchase (Figure 2.1) account for about one-third of the N inputs in Africa. Consequently, inorganic fertilizers are mostly used in mechanized and commercial agriculture. On the other hand, results of a meta-analysis showed that in Europe there is more organic farming which promotes lower nutrient losses (nitrogen leaching, nitrous oxide emissions, and ammonia emissions) per unit of field area (Bell *et al.*, 2016). A study by Meng *et al.* (2017) revealed that generally organic farms have positive nutrient budgets compared with non-organic farms in China and Brazil. Due to the high price of fertilizers, smallholder farmers in SSA apply insufficient N fertilizer leading to reduced crop yield (Gweyi-Onyango and Ntinyari, 2022). Garrity (2004) reported that fertilizer prices were two to six folds higher in Africa than in Europe and Asia. It is estimated that the farmers from SSA apply about 12- 15 kg N ha<sup>-1</sup> compared to over 100 kg N ha<sup>-1</sup> in the developed countries (Rurinda *et al.*, 2021). The rates account for less than 1.8% of global fertilizer use and less than 0.1% of global fertilizer production (Snapp *et al.*, 2002). With donor driven liberalization policies of the nineties in most African countries, fertilizer purchasing, distribution, and subsidization were eliminated resulting in price increase and chronic shortages in the market (Snapp *et al.*, 2002). The high cost of using commercial fertilizer has collectively limited inorganic N fertilizer use by subsistence and small-scale farmers throughout Africa (Salami *et al.*, 2010).

### **2.3 Nitrogen Footprint and Nitrogen neutrality**

The N footprint tool is useful for identifying hotspots of N losses to the environment, simulating mitigation options, and informing policy decisions for good N management through raising awareness of social responsibilities (Sutton *et al.*, 2013). N footprint has been applied to assist consumers to possibly reduce excessive N export from their farms. N footprint includes food production and food consumption (Shibata *et al.*, 2017). The food consumption footprint represents the amount of reactive nitrogen in the food, which are consumed by human. On the other hand, food production footprints encompass loss at each stage of the food production process including fertilizer run off, manure losses and food water (Leach *et al.*, 2012). Livestock products are associated with a larger nitrogen footprint than other crops. The application of the tool showed that in many countries the largest portion of the N footprint was associated with food production, with N accumulation in selected countries like the United States of America, whereas N mining occurred in countries like Tanzania in sub-Saharan Africa (Hutton *et al.*, 2017). N footprint assessments would therefore represent a great opportunity to reduce N mining in SSA through identification of potential N available for recycling in crop production (Chianu *et al.*, 2012). However, the two major pathways in which nitrogen pollution is released to the environment is through fossil fuel combustion and food production. The N footprint analysis has been developed to estimate direct and indirect loss of reactive N to the environment through use of food, transport goods, and services (Leip *et al.*, 2015). Various studies have indicated that per capita N footprints vary widely among countries because they are influenced by several

factors such as food intake characteristics, waste water, food, self-efficiencies and others (Galloway *et al.*, 2014; Shibata *et al.*, 2015).

N-neutrality is a concept that focuses on measures to reduce or avoid release of reactive N into the environments (Leip *et al.*, 2014). The main goal of N neutrality is to achieve a zero net N<sub>r</sub> releases to the environment. In farming and food systems, achieving N-neutrality there is need to increase sustainability in food production and embrace sustainable management of land. Focus on measures to create a balance of the released reactive N into the ecosystems (Galloway *et al.*, 2014). Achieving N neutrality in managing the land sustainably integrated focus should be based on ecological footprint, good agricultural and environmental conditions of the cultivatable land and through satisfaction of the human food requirements while meeting the economic needs to the respective farmers (Chen *et al.*, 2020).

#### **2.4 Nitrogen dynamics in soil**

Inorganic N in the soil is normally derived from mineral fertilizers to supply  $\text{NH}_4^-$ -N and  $\text{NO}_3^-$ -N in the soils. Whereas soil organic nitrogen comes from mineralization of the organic materials (Myrold, 2021). However, all sources of organic N has to undergo transformations before they are utilized by plants. Available organic nitrogen in the soil found in small organic molecules that make up the dissolved organic N (DON) pool. The pools for DON are normally smaller than inorganic N in the agricultural soils (Myrold, 2021); however, in soils receiving very little N input like SSA DON is the dominant form of N (Perakis & Hedin, 2002). Two main processes in nitrogen dynamics in the soils and transformation are mineralization and immobilization of organic N forms. Mineralization leads to increases in N form in the soil while

immobilization reduces the N forms (Robertson and Groffman, 2007). Both mineralization and immobilization occur at the same time within relatively smaller soil volumes. During gross N mineralization, soluble N is produced by micro-organisms while gross immobilization, soluble N is consumed. When the gross mineralization process exceeds the gross immobilization, inorganic N in the soil increases while during gross immobilization inorganic N decreases (Robertson and Groffman, 2007). Therefore, N mineralization process is considered as a fertility indicator (Cardoso *et al.*, 2011).

Soil nitrification is an important process in N cycling as it involves oxidation of ammonium to nitrate and of relevance to plant nutrition and environmental pollution. Higher rates of nitrification rate may result to low N use efficiency and higher loss of N to the atmosphere or leaching to surface or ground waters (Meng *et al.*, 2020). Soil N also undergoes denitrification process where nitrates are converted to gaseous form (nitric oxide, nitrous oxide, dinitrogen) (Richardson *et al.*, 2009). The losses through denitrification take places in oxygen-limited conditions due to activate of anerobic bacteria. In flooded fields like for paddy rice, higher N losses due to denitrification resulting to nitrogen deficiencies (Choudhury *et al.*, 2005).

## **2.5 Nutrient Modelling and Coupled Human and Natural systems (CHANS) model**

Nutrient modelling tools are used to support the decision making and planning in agricultural systems. Modelling helps to identify essential nutrients and recommending the amount, forms and timing needed for optimal crop growth (Kollas *et al.*, 2015). Modelling also facilitates in addressing long term issues such as nutrient decline and environmental issues in nutrient leaching (Lovett *et al.*, 2018). Both crop and soil

models involving equations or sets of equations represent the behavior of an agricultural system. In effect, crop models are computer programmes that mimic the growth and development of crops (Wang *et al.*, 2002). Model simulates or imitates the behavior of a real crop by predicting the growth of its components, such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of crop production or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of the crop (Corrado *et al.*, 2018). Reactions and interactions at the level of tissues and organs are combined to form a picture of the crop's growth processes. Simulation models are tools that can be tested, evaluated, and calibrated for a specific region and can integrate the evaluation of soil crop systems and management practices (Corrado *et al.*, 2018). These models can be used to evaluate irrigation and N Uptake efficiencies, and the N dynamics and transport of  $\text{NO}_3^- \text{N}$  out of the rooting system (Ostad-Ali-Askari *et al.*, 2017, Ghane *et al.*, 2018). There are several levels of models that can be applied to a specific situation and range, which include simple index screening tools, application process models, and highly detailed research process models (Corrado *et al.*, 2018).

The Coupled Human and Natural systems (CHANS) model incorporates and integrates all  $\text{N}_r$  fluxes within a system. The basic principle of the CHANS model is mass balance within the whole system for each subsystem (Gu *et al.*, 2015). The model is defined within horizontal boundaries including cropland, grassland, forest, urban, and other several other subsystems. It lies within a vertical direction with the upper boundary defined as 1 km above the ground surface. For the lower boundary, everything above the bedrock is considered part of the system, including soil and groundwater, but

mineral resources are not included because they can enter and contribute to N cycling only after mining and burning (Gu *et al.*, 2015). N cycling starts from the entry of reactive N (Nr) that is activated from N<sub>2</sub> into the system or from Nr direct input to the system from outside, and terminates when Nr is transformed to N<sub>2</sub> or lost to outside the system (Wang *et al.*, 2020).

## **2.6 Nitrogen Use Efficiency and Agronomic Efficiency**

Nitrogen use efficiency (NUE) is an agro-environmental indicator that makes it possible to determine if a system is utilizing the applied N optimally or not, as depicted in either low or high NUE values (Quemada *et al.*, 2020; Gweyi-Onyango 2018). It provides the real measure of usefulness of plants to absorb and transform the available N into the potential yield (Huggins and Pan., 2003). NUE is an indicator that provides information about the utilization of the applied N in an agricultural production system of a county or a region (Fageria and Baligar, 2005). The two major components of NUE are the efficiency of absorption (uptake) and the efficiency with which the N is utilized to produce grain. Suitable N application rates and timing are the major practices for fulfilling plant requirements and enhancing NUE (Samonte *et al.*, 2006). Higher use of artificial fertilizer may result in soil and environmental pollution like eutrophication (Abril *et al.*, 2007). Crop rotation, soil edaphic features, temperature, soil water, N fertilizer rates and crop types are the major factors, which affect NUE (Halvorson *et al.*, 2002).

According to Halitligil *et al.* (2000) and Wang *et al.* (2021) plant NUE is affected by nitrogen fertilizers in semi-arid and variable rain-fed situations. Globally, the NUE for cereals has been estimated to be 33% (Brentrup and Pallière, 2010), and this implies

that 67% of nitrogen applied to the farms goes to wastes through other means. Therefore, NUE is an effective tool to increase nitrogen for production while reducing losses that have harm to the environment. From the N cycle, it is apparent that losses are exported from the agricultural products as well as the environmental losses, which are unavoidable. Theoretically, without any N losses to the environment, NUE of 100% would be ideal, since the inputs exactly match the outputs (Carranca, 2012). Practically, this is not possible since agriculture takes place in an open environment with a continuous exchange of nutrients between the environmental compartments such as soil, water and air (Bouraoui and Grizzetti, 2014). Therefore, losses of N are unavoidable since crops do not require all the nutrients that are cycled in the agricultural system. For instance, in cases where application rate of 96 kg N/ha and the removal in grain is almost the same 92 kg N/ha, the resulting NUE is 96% (Brentrup and Pallière, 2010). The NUE values of 90-100% show risk of soil mining, since the applied N demand for roots and straw, are not achieved by N input. Importantly, there are also unavoidable losses for example due to leaching during the off period are not compensated (Schachtman, 2015).

In Africa, N removal with crop production has been reported to permanently exceed the N input with mineral fertilizer (Rahimizadeh *et al.*, 2010). The development shows that NUE even further increases over time from 120% to about 140% in places with poor management of N due to soil mining (Brentrup and Pallière, 2010). This implies that today 40% more nitrogen is removed from the cropping system in Africa than what is replaced by mineral N fertilizer. On the contrary, other places like China, NUE has shown decrease from about 50% in 1987 to less than 40% in 2006 (Yuan *et al.*, 2006).

This corresponds with increasing crop production with even more increasing N application rates. Moreover, in Europe, NUE increased from around 40% in 1987 to more than 60% in 2006, mainly due to improved agricultural practices (Carranca, 2012). The world mean NUE values remained relatively stable at 50-55% between 1987 and 2006 (Brentrup and Pallière, 2010). It is also clear that lately, NUE has already gained increasing importance as an agro-environmental indicator (Asplund *et al.*, 2014).

Optimal cropping system NUE can be achieved by a number of fertilizers and crop management strategies. Timing of application has a substantial effect on the crop's N uptake, and splitting N fertilizer application has been proposed as a way to increase NUE (Ma *et al.*, 2021). Deep placement, usage of super granules, and foliar spray of N fertilizer are among the different techniques of N application that might improve the recovery of administered N fertilizer (Ladha *et al.*, 2005). Broadcasting nitrogen fertilizers is a widespread method that results in significant N losses, such as ammonia volatilization, and poorer nitrogen recovery (Yadav *et al.*, 2017). Deep placement of urea-based fertilizers and use of a modified kind of N fertilizer (urea super-granules). Split application of N fertilizers, with the number of splits determined by soil texture and crop types can be used to reduce leaching and denitrification losses from the soil (Fageria & Baligar, 2005).

Modification of N fertilizer products to improve the efficiency of applied nutrients by minimizing losses will be key in future. The products will be preferably be either slow-release that control the release of nutrients when needed by the plants or have nitrification inhibition that interfere with soil N transformation (Singh *et al.*, 2018). The

slow-release fertilizers enhance N recovery due to their potential to delay releases of N; a characteristic that can improve the synchrony between the crop N demand and the supplied soil N. An example of slow release is the neem-polymer coated urea (Giller *et al.*, 2004). Synchronization of N release from the fertilizer is also enhanced by N stabilizers that reduce N losses either by leaching or through denitrification (Thapa *et al.*, 2015). Nitrification inhibitors keep in check the conversion of  $\text{NH}_4\text{-N}$  to  $\text{NO}_3\text{-N}$  and ensure higher concentration of ammoniacal form to improved NUE and crop yield. Liming of acidic soils is another important practice for improving NUE (Daba *et al.*, 2021). Despite N fertilizers causing acidification to the soils that affects chemical and biological processes, alleviating the pH has been shown to improve the status of  $\text{NO}_3\text{-N}$  in the soil, making more plant-available N and therefore minimal losses (Daba *et al.*, 2021).

## **2.7 Greenhouse gas (GHGs) fluxes**

Agricultural production plays a significant role in global fluxes of greenhouse gas (GHGs) to the atmosphere. The main GHGs fluxes from agriculture include nitrous oxide ( $\text{N}_2\text{O}$ ), carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) (Gao *et al.*, 2022). According to IPCC (2014), agriculture is estimated to account for 12% of the total GHGs emissions. As population increases, land expansion becomes critical to meet food demand thus increasing intensification of agriculture that has contributed to increase in GHG (Stavi *et al.*, 2013). Moreover, soil tillage has been listed as one of the leading contributors of  $\text{CO}_2$  from agricultural land (Stavi *et al.*, 2013). However, over the next decades, if agricultural activities do not change, there will be an expected upsurge in GHGs emissions. Therefore, there is dire need to develop mitigation measures to decouple the

need for the population and minimize the GHGs impact. In SSA there is limited information on greenhouse gases and a wide uncertainty due to large and insufficient temporal and spatial representations from agricultural soils is expected (Ntinyari, & Gweyi-Onyango, 2021).

The primary source of GHG in SSA agriculture is from the use of synthetic fertilizer that has a higher potential of N<sub>2</sub>O emissions and also contributes to production of other gases such as CO<sub>2</sub> and CH<sub>4</sub> (Boateng *et al.*, 2019). From applied mineral N fertilizers, N<sub>2</sub>O is produced from microbial process of nitrification and denitrification. Indirect N<sub>2</sub>O emissions from mineral N occur during volatilization and leaching process. Although with very low concentration than either CO<sub>2</sub> or CH<sub>4</sub>, N<sub>2</sub>O is more potent than any other gas due to its longer lifetime of approximately 150 years into the atmosphere and its global warming potentials is 300 times more than that of CO<sub>2</sub> in 100-time year horizon (Chauhan *et al.*, 2014). Depending on different factors, agricultural soils can be net sink or sources of CH<sub>4</sub>. These factors include moisture levels, N fertilizations and organic matter. The production of methane by methanogens is enhanced by methanotrophs which are ubiquitous in many soils (Dendooven *et al.*, 2012). The increase in GHG concentrations in the atmospheres result in global warming due their nature to absorb outgoing radiative rays and thus increasing the global temperatures (Anderson *et al.*, 2016). According to IPCC, global warming of GHG is determined as CO<sub>2</sub> equivalence (CO<sub>2</sub> eqv). Over years, CO<sub>2</sub> concentrations in the atmosphere has been increasing as agricultural intensification and fossil burning for fuel increases. This scenario has raised the global discussion on how best to maintain production

sustainability for food-secure planet and at the same time reducing the global warming through keeping the rise of global temperatures with 2 °C (Anderson *et al.*, 2016).

## **2.8 Soil quality and nitrogen fertilizer management**

Low soil fertility is an inherent challenge in SSA agricultural systems. Due to its heterogenous nature, soil across farmlands is affected by different factors including climate, biophysical, chemical, topography parental material and biodiversity (Mugizi & Matsumoto, 2020). Poor management of soils and the fragile nature of soils in the region accounts for high nutrient losses through soil erosion and leaching from the soils to water bodies (Chukwuka, 2009). The low soil fertility is linked to low productivity and food insecurities and depletion of the soil quality. As the population grows, soil degradation has intensified leading to increase in soil mining (Vanlauwe *et al.*, 2015). Mining of agricultural soils is through increase in exportations of soil nutrients than the amount of replenishment. Nutrient imbalances can be remediated through application of the required nutrients however, this is quite difficult in SSA due to data limitation on key nutrient flows and how best to maintain the soil quality through replenishing required nutrients (Vanlauwe *et al.*, 2015). Underlying challenges to low soil fertility and degrading quality is due to limited financial access to many of the smallholder farmers to purchase adequate fertilizer inputs.

Apart from low soil fertility, soil acidity is another threat to quality of soil and crop productivity. Majority of the tropical soils are acidic and contain high levels of aluminum toxicity (Fageria, & Baligar 2008). Acidity of soil originates from precipitations, soil organic matters, transformations and uptake of nutrients, leaching, and accumulation of clay minerals like aluminum oxides and iron oxides, soluble salts

and other use of fertilizers (Crawford *et al.*, 2008). Acidic soils with soil pH below 5.0, the process of nitrification is highly affected and the mineral N becomes less available for plant uptake. Acidity limits the uptake of water and nutrients particularly, N and consequently affecting plant growth and optimization of NUE (Zhu *et al.*, 2021). Failing to address acidity within the soil profile will have a negative influence on sustainability of crop production systems.

## **2.9 Yield gaps in Kenya**

Yield gap is defined as the difference between potential yield in either irrigated or water limited (rainfed systems) and the actual yields obtainable by the farmers in the field. In SSA, most of the farmers, specifically for cereals farming rarely exceed  $0.5 \text{ t ha}^{-1}$  which is against the potential of the area of between  $6-8 \text{ t ha}^{-1}$  (Dossou-Yovo *et al.*, 2020). The current trends show that yield of the most cereal crops has been slower compared to the population and demand. Despite of the crop land areas having increased by 14% over the past 10 years, subsequent output is still very low (Van *et al.*, 2016). Narrowing the current yield gap is critical in achieving the demands of the world population. In addition, reducing the yield gaps has the implication of on food prices and food security that is linked directly to crop yields (Dzanku *et al.*, 2015). Identifying the key causes of stagnated low yield within the region will help in formulating and developing strategies that can help in alleviating the challenge of food insecurity. The yield gaps are influenced by low N inputs with smallholder farmers applying relatively low input with an average of  $12.5 \text{ kg N ha}^{-1}$ , with majority applying no mineral N (Leitner *et al.*, 2020). For SSA, it is challenging to accurately quantify the rates of applications of organic fertilizers for instance, manures or plant residues since

farmers lack knowledge and this is worsened by the absence of efficient extension services and therefore crop productivity continues to be limited by these challenges (Liu *et al.*, 2010).

## **2.10 Challenges for N management in SSA**

### **2.10.1 Low use of N in production**

In SSA, N depletion is a serious issue due to low N use in cropping systems. Most of the farmers in the region are not able to meet 50 kg nutrients ha<sup>-1</sup> of the target set by the Abuja declaration of 2006 (Masso *et al.*, 2017). The unbalanced N input to the soils has led to excessive depletion and widespread of yield gaps than in any other parts of the world. Apart from low use of N input, there is poor quality of the fertilizers particularly N sources. For instance, in Uganda fertilizer, an analysis of urea sold in market place contained 31% N less than the required amount in authentic urea product (Bold *et al.*, 2015). Besides, inputs from animal manures contains very little N due poor feed and manure management (Diogo *et al.*, 2013). With such products in the market, there is likelihood of reduced yield and profitability when farmers use the adulterated urea products. Poor quality of agricultural inputs is from factors including sub-standard formulations, poor handling and transportation and storage and weak regulatory frameworks. Improving crop productivity in the region will require proper mechanism to address the quality issues of the agricultural inputs (Jefwa *et al.*, 2014).

### **2.10.2 High N loss due to poor management**

There are significant losses of N in the agricultural land despite low N use in production. (Masso *et al.*, 2017). Apart from N depletion, high atmospheric deposition of N which is equivalent to current rate of N usage of approximately 4-15 kg N ha<sup>-1</sup> yr<sup>-1</sup>,

however if this amount ends up in water bodies it becomes risk to environment most of the N deposited in the water bodies and cannot be used by the plants (Masso *et al.*, 2017; Galy-Lacaux and Delon 2014; Vet *et al.*, 2014). N loading to water bodies leads to eutrophication and has resulted into serious issue particularly for the lakes where drastic fish population has been affected due to limited oxygen and proliferation of toxic cyanobacteria blooms (Nyenje *et al.*, 2010). Particularly for the Lake Victoria basin, high rates of eutrophication are due to soil erosion, nutrient; leaching, poor recovery of nutrient from waste water and among other sources. However, due to lack of reliable systems to monitor and quantify the actual amounts of each N source contribution it becomes quite difficult to manage N within the region (Masso *et al.*, 2017).

### **2.10.3 Poor linkage between research and policy makers**

Management of N input in smallholder farmers within SSA is limited by lack of enabling policies particularly to address the adoption of good agricultural practices. There is poor coordination of N input and management particularly for organic sources that could create a better and favorable means towards sustainability (Elrys *et al.*, 2019). There is also limited linkage between the researchers, policy makers and the farmers. In this case, new technologies are not innovative or properly communicated to farmers. Weak extension services within the region are also another challenge limiting improved management of crop nutrients (Akpan *et al.*, 2012). Majority of the farmers lack training on use of farm inputs from expert and many of them rely on personal knowledge in production. There is also limited research capacity for enhancing site-specific trials for specific crops (Sutton *et al.*, 2020). Absence of resources and full

chain allocation of NUE to enhance comprehensive data collection for accurate N budget still limits research and policy to make required impact to N management.

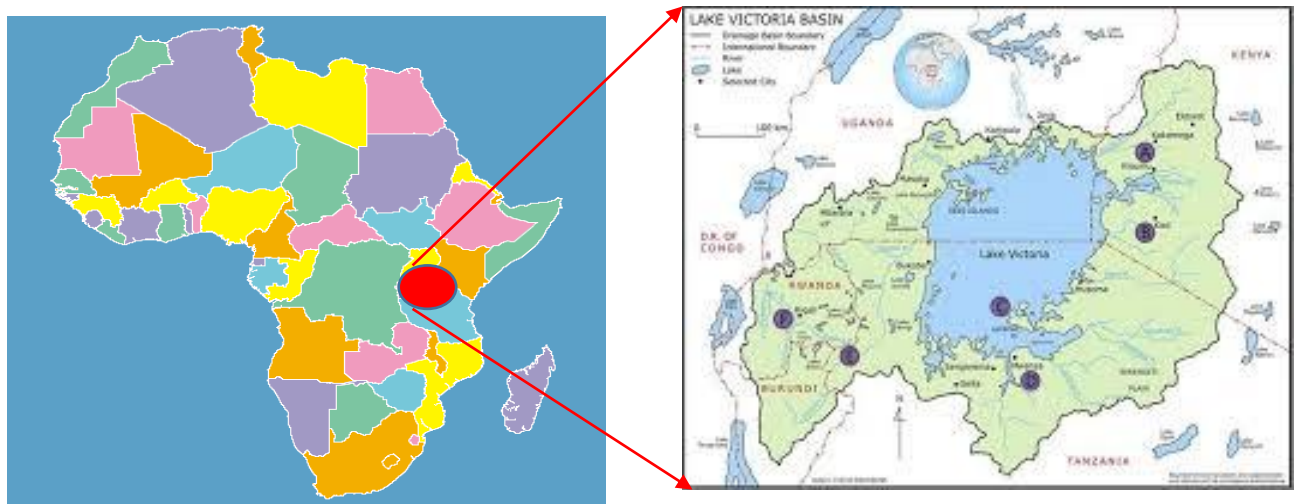
### **2.11 Opportunities for improving N management.**

Increased use of N input for improved agricultural productivity with focus on products that are affordable, sustainable, and environmentally friendly to increase NUE in the cropping systems is crucial (Elrys *et al.*, 2019). Alternative sources like animal manure, crop residues and biological nitrogen fixation should be explored and encouraged for use by the farmers. It should be noted that increasing N input without effective agronomic practices will not be sustainable but rather, the awareness should be created on use of 4R stewardship (right source, right rate, right time and right placement) of nutrient management as well as using crop varieties that are well adapted to local conditions (Roobroeck *et al.*, 2015). Development of crop-specific N applications to improve food production and minimize N loss to the environment is highly recommended. The government is encouraged to offer subsidies for the farm inputs as a way of promoting N use and creating efficient public-private partnerships for easier access of the fertilizer products (Elrys *et al.*, 2021). The quality of fertilizer inputs should be assessed by regulatory bodies for their effectiveness and enhances reduction of food contamination and environmental pollution. Conducting of comprehensive assessment of N flows at national, regional, and continental scales, such kind of assessment should focus on understanding different sources of N, agronomic and recovery efficiency, type of losses and magnitude and propose mitigation approaches to optimize food production and keep pollution levels low (Masso *et al.*, 2017).

## CHAPTER THREE: MATERIALS AND METHODS

### 3.1 Description of the Study Site

The data presented in this thesis was collected from the Lake Victoria Basin (LVB) of Kenya. The LVB extends to five Eastern African countries (Burundi, Kenya, Rwanda, Uganda, and Tanzania), covering an approximate area of 194,000 km<sup>2</sup> (Kayombo and Jorgensen, 2006) (Figure 3.1). The basin is inhabited by some of the most resource-constrained Eastern African rural populations, with an approximate population of 30 million and a projected annual increase of 6% (Kayombo and Jorgensen, 2006, Zhou *et al.*, 2014). More than 70% of the population in the basin is involved in agricultural production activities. The main staple food crops within the catchment are maize and rice growing in predominant soil types, including Ferralsols, Nitisols, Vertisol, Cambisols, and Acrisols (Nkonya *et al.*, 2015).



**Figure 3.1: Map showing the East Africa Lake Victoria catchment of the study sites (source: google maps)**

The climate is equatorial, with temperatures modified by the high elevation of lakes and mountains like Mt. Elgon.

The climate is equatorial, with temperature modified by the high elevation of lakes and mountains like Mt. Elgon. However, since the temperatures are lower than the typical tropical conditions, it is classified as humid, with temperatures ranging from 20°C to over 35°C. The LVB receives a bi-modal rainfall in a year, with long rains from March to June and short rains from September to December. On average, annual precipitation ranges from 1750 mm (Okungu *et al.*, 2005).

### **3.2 Experimental Design and Data collection**

The study was conducted using three approaches a survey and in person interviews, field trials within Lake Victoria catchment and a laboratory incubation experiment for soils collected from farmers' fields within the same region. The surveys and interviews were used to collect data for determining key data useful for estimation of the two key performance indicators i.e. Nitrogen Budgets (NBs) and Nitrogen Use Efficiency (NUEs) for selected staple crops (field level) in farms within the basin. The interviews also focused on identifying the current management practices of N among the smallholder farmers and possible barriers to improved management strategies. The field experiments were used test simulated N use scenarios reflecting actual farmers' practices and policy recommendations on N balance indicators and yield gap reduction. The final approach on an incubation studies was used to evaluate N use scenarios and liming practices impact on greenhouse gas emissions, air quality, nitrogen availability and contribution to global warming.

### 3.3 Determination of Nitrogen Budgets

Nitrogen Budgets were determined at field and farm-gate scales using the approach by Coupled Human and Natural Systems (CHANS) model version 1.3 developed by Gu *et al.* (2015). The field scale focused on rice-maize cropping systems while the farm gate focused on major inflows and outflows of N in the given farm within Lake Victoria catchment. The catchments selected for the surveys were Nyando, Sondu, Yala, and Nzoia and they represented at least 50 % of the entire land area around the lake region on the Kenyan side. Farm and field information was collected from 447 farming households during the period July- August 2020. Before the interviews, the questionnaires were pre-tested in pilot sites and updated to answer the research questions for the study. Semi-structured questionnaires were used to collect farms and field data (Appendix 1). Purposive and random sampling techniques were employed to select farmers growing maize and rice as mono-crop. At field level, i.e., farmers growing maize or rice as mono-crop were selected using purposive sampling techniques. Then, a random sampling design was employed for selected farmers for the subsequent in-person interviews. For the random sampling technique, each farm had an equal chance of being interviewed to avoid study bias.

The sample size of 447 was drawn from the population based on Fisher *et al.* (1998) as Eq 1.

$$N = \frac{z^2 pq}{d^2} \dots \dots \dots \text{Eq 1}$$

Where: N is the required sample size; z is normal deviation (1.96) which corresponds to 95% confidence interval; p is proportion in the population estimated at 50% since it is

not known.  $q$  is  $1-p$  and  $d$  is degree of accuracy (0.05). The population of farmers for maize, rice and general farmers was provided by the extension officers. Data collection was performed by trained enumerators and submitted online using Open Data Kit (ODK).

**Table 3.1: Characteristics of maize field samples and catchments  $n$  = number of observations**

Catchment	N	Soil type	Characteristic	Mean size of land (ha)	Productivity (t ha <sup>-1</sup> )
Nyando	40	Vertisols	Rainfed	0.5	1.4 low
Sondu	44	Fluvisols	Rainfed	0.6	1.2 low
Yala	37	Ferralsols	Rainfed	0.5	0.9 low
Nzoia	37	humic gleysols	Rainfed	0.5	1.1 low

**Table 3.2: Characteristics of rice fields samples and catchments  $n$  = number of observations**

Catchment	n	Soil type	Characteristic	Mean size of land (ha)	Productivity (t ha <sup>-1</sup> )
Nyando	38	Vertisols	Irrigated	0.8	6.9 high
Sondu	38	Fluvisols	Irrigated	0.5	2.2 low
Yala	-	-	-	-	-
Nzoia	59	humic gleysols	Irrigated	0.7	3.1 medium

**Table 3.3: Characteristics of farm samples and catchments  $n$  = number of observations**

Catchment	N	Soil type	Characteristic	Mean size of land (ha)	Productivity (t ha <sup>-1</sup> )
Nyando	38	Vertisols	Rainfed	0.5	2.6 low
Sondu	40	Fluvisols	Rainfed	0.5	1.6 low
Yala	38	Ferralsols	Rainfed	0.1	0.9 low
Nzoia	38	Humic glysols	Rainfed	0.7	1.4 low

Data collected from fields and farms were categorized into two: -i.e., Farmers applying mineral N fertilizers and farmers not applying mineral N fertilizers in their fields or farms. All collected data for N inputs and outputs at the field and farm levels were reported as kg N ha<sup>-1</sup>. The collected data included: land size, N inputs from fertilizers, size of land under production, the quantity of planted seeds, and seasons of crop growth, yield, legume crops grown, variety of the crops and various planted crops, use of manure, straw management practices, and challenges in the use of N fertilizer during crop production. Fields and farm characteristics are presented in tables 3.1, 3.2 and 3.3.

### **3.3.1. Farm and field sample selection**

The farmers were interviewed at field levels and farmers were defined as a maize or rice farmer depending crop grown i.e., maize and rice as monocrop was drawn from the population given by the extension officers within the local region. The sample was selected using a purposive sampling technique followed by random engagement of the farmers for subsequent in-person interviews. A similar selection approach defined at the field level was used at the farm level. Here a mixed farming system was considered, including all types of crops a farmer grows, mostly cereal-legume system and livestock and manure use practices. Data collected from fields and farms were categorized into two: -i.e., Farmers applying mineral N fertilizers and farmers not applying mineral N fertilizers in their fields or farms. All collected data for N inputs and outputs at the field and farm levels were reported as kg N ha<sup>-1</sup>. The collected data included: land size, N inputs from fertilizers, the quantity of planted seeds, crop growth seasons, yield, and various planted crops.

### 3.3.2. Data collection at field scale for maize and rice

At the field level, soil surface N budget (NB) and soil system NB approaches were used to quantify NB for maize and rice, as reported by Oenema *et al.* (2003). In each category of the N budget, there was the characterization of farmers applying and not applying mineral N. The soil surface NB considers all the significant N fluxes entering the soil via surface and only leaves the soil through crop uptake (Eq 2). The soil system NB includes all N inflows and outflows, including N uptake, exported N harvested with the crop, and losses within and from the soil surface, as reported by (EUNEP, 2016) and shown in Eq 3.

$$\text{soil surface NB} = N_{\text{inputs}} (\text{SNF} + \text{ADN} + \text{NPM}) - N_{\text{outputs}} (\text{CNR}) \quad \text{Eq 2}$$

$$\text{Soil system NB} = N_{\text{inputs}} (\text{SNF} + \text{ADN} + \text{NPM}) - N_{\text{outputs}} (\text{CNR} + \text{Lch} + \text{RF} + \text{DNT} + \text{NH}_3 + \text{N}_2\text{O}) \quad \text{Eq 3}$$

Where; *NB*- nitrogen budgets, *SNF*-synthetic N fertilizer, *AND*- atmospheric N deposition, *NPM*- nitrogen in planting materials, *CNR*- crop N removal, *Lch*-leached N, *RF*- runoff, *DNT*-Denitrification,

Data collected through field surveys included land size, N inputs as mineral fertilizers, the quantity of planted materials, yield, seasons, legume crops grown, and any other crops grown by the farmers in the fields. The actual rate of N applied from different N fertilizers sources was calculated by dividing the fertilizer application rate per ha by the proportion of N in the fertilizer used. The proportion of N in the fertilizer used is indicated in the local fertilizer grades, as shown in Table 3.1. The N in straw recycling was not considered in this budget because it is common for farmers around the catchment to burn crop residues. The N in irrigation water was not accounted for due to a lack of information on actual or estimated water supplied per hectare per growing rice

season. Livestock manure as an N input source was not included in this budget because the majority of the farmers in the catchment area were practicing communal grazing. In many cases, the livestock excreta on overnight grazing are used as fuel, and others burn the droppings. BNF fixation was excluded because leguminous crops were not integrated into the target maize and rice plots, as the focus was mainly on maize and rice monocrops.

**Table 3.4: Percentage conversion rates of N inputs from fertilizer sources (IFASTAT, 2020)**

Form/source of N fertilizer	N %
Diammonium phosphate	18
Calcium Ammonium Nitrate	27
Urea	46
Ammonium Sulphate	21
NPK	15

Wet and dry atmospheric deposition of N was obtained from direct measurements from Lake Victoria (Kayombo and Jorgensen, 2006; Bakayoko *et al.*, 2021). To calculate N input in planting material, the actual seeding rate in kg ha<sup>-1</sup> was multiplied by the N content for maize and rice seeds, while harvested N was determined by multiplying the respective N content for the specific crop and the amount of yield obtained from the fields as shown in Table 3.5. This was achieved using a tiered approach to estimate various N inputs from the planting materials and harvested products.

**Table 3.5: Parameters for calculating N inputs in seeds (Gu et al., 2015)**

<b>Crop</b>	<b>N content in harvested parts N%</b>
Rice	0.019
Maize	0.014
Wheat	0.028
Soybean	0.051
Beans	0.034
Sugarcane	0.006
peanuts	0.040
Millet	0.019
Cotton	0.0304
Potatoe	0.0026
Vegetables	0.002
Banana	0.002

**Table 3.6: Estimated rates of BNF by major legumes (adapted from Smil, 1999)**

<b>Legume</b>	<b>Rate of N fixation Kg N ha<sup>-1</sup> yr<sup>-1</sup></b>
Common bean	40
Lentils	40
Peanuts	80
Soybeans	40
Chickpea	50
Peas	40
Groundnuts	80
Cowpea	60
Other pulses	60

For soil system budget, N loss in soils from applied mineral N fertilizer through ammonia (NH<sub>3</sub>) volatilization and nitrous oxide (N<sub>2</sub>O) emissions were calculated using country-specific emission factors according to Intergovernmental Panel on Climate Change (IPCC) (FAO 2001, Bouwman *et al.*, 2002) (Table 3.7). To estimate gaseous emission, net N inputs were multiplied by the emission factors according to equation 4 (Eggleston *et al.*, 2006). Soil denitrification was estimated by the N balance method using global estimates for upland and wetland crops (Table 3.8) (Hofstra & Bouwman.,

2005), and leaching and runoff losses of applied N were estimated using the IPCC factor of 0.3 kg N ha<sup>-1</sup> of mineral N (FAO 2001, Wang *et al.*, 2019).

$$N_2O / NH_3 \text{ emission from applied SNF} = \text{Net N input applied ha}^{-1} \times EF \quad (\text{Eq4})$$

Where; *SNF*- synthetic N fertilizer, *EF*- emission factors

### 3.3.3 Farm-gate spatial scale data collection

The farm-gate N budget was determined considering all the N sources flowing into the farm-gate as N inputs and leaving the farm-gate as N output (Eqn 5). For farm-gate, all crops grown by the farmer were considered in budgeting. The parameters collected and estimated for this scale included applied mineral N fertilizers, the quantity of planted seeds, seasons for specific crops, the yield for all crops, and the total land under agricultural production. At farm-gate, BNF was determined by multiplying the crop area under legume production by the global mean rate of N<sub>2</sub> fixation for each legume type as described by (Smil, 1999) (Table 3.6). All N inputs and outputs were converted to kg N ha<sup>-1</sup>. In this study, vegetables and fruits were excluded due to a lack of data on actual yield in kgs and analyzed N contents to estimate N removal by crop. N loss via gaseous NH<sub>3</sub> and N<sub>2</sub>O emission was calculated using the same Emission Factors (EF) used for field level and denitrification rates for upland and wetland crops. There was no consideration of imported and exported feeds N because livestock were openly grazed, and feed trade was rare.

**Table 3.7: Emission factors for estimating NH<sub>3</sub> and N<sub>2</sub>O**

<b>N<sub>2</sub>O emission factors</b>			
	<b>Mineral fertilizer</b>	<b>Manure</b>	<b>Source</b>
NH <sub>3</sub>			
Wetlands	0.21	0.33	Bouwman <i>et al.</i> , (2002)
Uplands	0.19	0.36	Bouwman <i>et al.</i> , (2002)
N <sub>2</sub> O	0.132	4.56	FAO, (2017)

**Table 3.8: Denitrification estimation rate in Kg N ha<sup>-1</sup> year<sup>-1</sup> of N using the N-balance method ((Hofstra, and Bouwman, 2005)**

N application rate (Kg N ha <sup>-1</sup> )	Uplands crops	Wetland crops
0	15	32
1-75	17	36
75-150	25	54
150-225	29	62

$FNB = N \text{ inputs (including all sources of N entering a farm)}$

$$- N (N \text{ sources leaving the farm and associated N Losses}) \quad (\text{Eq 5})$$

Where; FNB- Farm N balance

### 3.3.4 Field Nitrogen Use Efficiency (NUE)

NUE in the field was determined using European Union Nitrogen Expert (EUNEP) methodology. EUNEP denotes that NUE is a ratio between harvested N in crops divided by the total sum of N inputs, including N from fertilizer, atmospheric N deposition, and N in the planted seeds (Eq 6) (EUNEP, 2016).

$$NUE = \frac{N \text{ output}}{N \text{ input}} * 100 \quad (\text{Eq 6})$$

Where; NUE- Nitrogen Use efficiency

### 3.3.5: CHANS Model Description

Coupled Human and Natural Systems (CHANS) model version 1.3 developed by Gu *et al.* (2015) in cropland subsystem was used in calculation of N budgets. The choice of this model is based on its basic principle of mass balance of N fluxes in a whole system and each subsystem as demonstrated in equation 7. In this study, CHANS model was sub-divided into two functional groups; N inputs and N outputs for cropping systems in cropland sub-system as defined in the model.

$$\sum N_{\text{inputs}} - \sum N_{\text{outputs}} = \text{NBalance} \dots \text{Eq7}$$

### 3.3.6 Projections for yield, N input, and NUE in maize and Rice cropping systems

The projection of maize yield and N inputs were based on the recommendation of Climate Change Agriculture and food security (CCAFS, 2019). According to CCAFS, for SSA to achieve food security, the current yield and N input must be increased by 3.5 % and 7% respectively on an annual basis until attainment of optimal N application rates for specific crops. The current projections were based on a target of 5.0 t ha<sup>-1</sup> for grain yields in various catchments. This was a projection by the Food and Agriculture Organization (FAO) for a food- secure SSA region, with an aim of meeting the demands of a rapidly growing population. Moreover, the increase in the population of SSA, as projected by Nigatu *et al.* (2017), requires more food to feed the burgeoning population since it has a greater growth rate of around 2.3 % which is among the highest in the world. For N input, the adopted target input by the Abuja declaration of

2006 by African Union (AU), Comprehensive Africa Agriculture Development Programme (CADDP 2016) and Malabo declaration for African green revolution at 50 kg N ha<sup>-1</sup> was used in this projection (Malabo Declaration, 2014). Change in NUE over the years due to changing yield and N input was calculated as the ratio of outputs and inputs multiplied by 100%. For rice, projections were based on the recommendations by Organization for Economic Co-operation and Development (OECD)-FAO (2016) at 3.2 % annual increment in rice yield to enhance rice grain sufficiency for a target yield as recommended by Africa Rice (2020) to achieve a base yield of 6 t/ha in 2025. For N input, it was assumed the same 7% annual increment for maize. The NUE was projected based on yield and change of N fertilizer use over the years.

### **3.4 Field experiments**

#### **3.4.1 Study Site Characteristics**

Two field experiments were carried out in two distinct catchments of the Lake Victoria basin, namely Nyando and Rangwe. Nyando is located in Kisumu County 34.912190°S, -0.148550°E at an elevation of 1154 m above sea level. The average monthly temperatures are between 24.0 °C to 25 °C. The soils in the study site are Vertisols black cotton soils with shallow depths, high organic matter, and moderate pH levels (Gachene and Kimaru, 2003). The catchment receives cumulative rainfall of 1350 mm annually. Rangwe is located in Homabay county at 34.573104°S, 0.623583°E with an elevation of 1166 m above sea level. The average monthly temperatures range between 22.1°C to 23.9 °C. The soils are Eutric Fluvisol with low organic matter and moderate pH levels. The cumulative rainfall for the catchment is 1646 mm annually.

### **3.4.2 Nitrogen fertilizer scenarios applied**

The change in N fertilizer use was assumed to be influenced by implementing various recommendations and policy interventions set aside for the Africa's Green revolution and livelihood transformation through Agriculture.

### **3.4.3 Scenario 1: Business as Usual (BAU)**

The first scenario evaluated was (BAU) representing zero N input ( $0 \text{ kg N ha}^{-1}$ ), reflecting the actual farmers' practices in the two catchments. This scenario was guided by the fact that 60% of the farmers in the region do not use N fertilizer input in their maize fields. Therefore, this scenario assumed that the farmers in this category would continue to grow crops without any N inputs over time.

### **3.4.4 Case 2: 25 % of the Abuja declaration (25 % ADS)**

The second scenario represented 25 % of the recommended rate by the Abuja declaration of 2006 on the set target of  $50 \text{ kg ha}^{-1}$  of and recommended by Africa.fertilizer.org. In this scenario, N input was set to  $12.5 \text{ kg N ha}^{-1}$  which was the average nutrient application rate by 2015 from Abuja fertilizer declaration in 2006.

### **3.4.5 Case 3: 50% of the Abuja declaration (50 % ADS)**

Scenario 3 represented 50% of the recommended rate by the Abuja declaration of 2006 on the set target of  $50 \text{ kg ha}^{-1}$  of nutrients. The N input for this scenario was  $25 \text{ kg N ha}^{-1}$  and represented a double increment and a transition from the 25 % AD scenario that was the base value in the fertilizer declaration summit. This scenario also reflected the current N inputs rates by some farmers in selected countries in sub-Saharan Africa (Sheahan *et al.*, 2014).

#### **3.4.6 Case 4: Abuja Declaration Scenario (ADS):**

This scenario used 50 kg N ha<sup>-1</sup> which was adopted during as the set target for Abuja declaration on fertilizer use. Nevertheless, many farmers are still far short of the Abuja fertilizer summit. The scenario represented 100% transition by the farmers to the “summit adopted” rate of N application. This scenario assumed that there will be changes in favor of fertilizer accessibility, hence farmers will purchase/access and apply the recommended N inputs in maize cropping systems.

#### **3.5 Experimental Design and data collection**

Maize (*Zea mays* L.) seeds of Duma-43 from the Seed Co. (hybrid variety and recommended for the Lake Victoria catchment) were sown in the fields during cropping season of September 2020-January 2021. A total of 16 plots measuring 5 m x 5 m with border widths of 0.5 m and 1 m for plots and blocks respectively were adopted and arranged in a randomized complete block design (RCBD) with four replications for each scenario. The spacing for the maize plants was 75 cm x 25 cm. Three plants per hill were planted and thinning was done to 2 seedling per hill after 2 weeks of germination. Urea, a commonly available source of nitrogen fertilizer in the region, was applied into fields except for control (BAU) and other treatments as N ha<sup>-1</sup>, 12.5 kg N ha<sup>-1</sup>, 25 kg N ha<sup>-1</sup> and 50 kg N ha<sup>-1</sup>. The N fertilizer was applied in two splits; the first split was at planting, while the second application was during the vegetative stage, which corresponded to 30 days after planting (DAP). During the experiment, the standard agronomic practices of maize crop production, including weeding and pest control, were carried out.

Data on biomass and other growth parameters were collected at three critical stages of maize production: vegetative, which was 30 days after planting (DAP), tasseling (60 DAP), and physiological maturity (90 DAP). Five plant samples were collected from the experimental plots at vegetative (V6), reproductive (R1), and (physiological maturity-R 6) harvesting stages. The samples were thoroughly washed in running water to free them from soil and any other surface impurities. The samples were separated into leaves, stems, roots, and grain at harvesting and taken to the laboratory for drying at a temperature of 70<sup>0</sup> C for 48 hrs (after achieving constant weight). The dried samples were then ground using a mechanical grinder. Powder samples of 0.3 g each were used in the analysis of N concentration (%) in the tissue following the procedures of Kjeldhal digestion (Baker & Thompson,1992).

At maturity, yield data were collected from each plot after all the ears had reached physiological maturity. Plants were harvested by cutting at ground level, and ears were threshed. Both grain and stover were air-dried and then oven-dried in the laboratory until a constant moisture content of 12.5% was reached. The yield obtained from the net plot of each N use scenario was determined and extrapolated into tons per hectare (t ha<sup>-1</sup>).

### **3.6 Laboratory Analysis Methods**

Soil samples were collected from the two experimental fields at the start of the experiment to analyze the selected chemical and physical compositions of the soils. The soils were sampled from depths (0-20 cm and 20-40 cm) for analysis of total organic N, available N (NO<sub>3</sub><sup>-</sup>) and NH<sub>4</sub><sup>+</sup>), organic carbon, available P, pH, bulk density, electrical conductivity (EC), soil texture, and exchangeable cation (K, and Ca). A soil auger was

used to collect soil samples from the experimental site, the soil samples collected were homogenized and representative samples placed in air-tight polythene bags and transported to the laboratory in ice box to prevent microbial activities and subsequent soil transformations. The analysis of the initial selected physical-chemical are shown in (Table 3.9). Electrical conductivity (EC) and pH were determined using extracts 1:2.5 [weight/volume (w/v)] for soil to distilled water. The pH and EC were then read directly using a pH (AD1000, Adwa, Romania) and EC meter (AVI, Labtech, India), respectively (Okalebo *et al.*, 2002).

**Table 3.9: Selected chemical and physical characteristics of the experimental soils**

Parameter	Nyando		Rangwe	
	0-20cm	20-40cm	0-20 cm	20-40 cm
Total N%	0.07	0.06	0.08	0.07
TOC (%)	1.35	1.16	0.56	0.82
NO <sup>3-</sup> (mg kg <sup>-1</sup> )	18.90	10.6	16.20	12.00
NH <sub>4</sub> <sup>+</sup> (mg kg <sup>-1</sup> )	22.20	36.5	45.20	32.60
pH (1:2.5 water)	5.70	5.9	6.13	6.23
EC (ms cm <sup>-1</sup> )	0.13	0.14	0.07	0.04
Available P (ppm)	28.8	62.3	7.20	9.70
Ca (cmol kg <sup>-1</sup> )	7.50	6.2	2.85	3.10
K (cmol kg <sup>-1</sup> )	1.76	1.14	1.18	0.48
Bulk density (g cm <sup>-3</sup> )	1.30	1.32	1.40	1.43

Mean values (and unit) of soil parameters of pH (0.01 mol calcium chloride), Electrical conductivity (EC), Phosphorus (P), calcium (Ca), Potassium (K), ammonium (NH<sub>4</sub><sup>+</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), Total organic carbon (TOC) and total nitrogen (TN),

The available N (NH<sub>4</sub>-N and NO<sub>3</sub>- N) was extracted from soil using 0.5 M potassium sulfate at a ratio of 1:10 (w/v). The potassium sulfate mixture was shaken for one hour using an orbital and linear shaker (KOS – 3333/KCS – 3333, MRC, UK). Filtration of the solution was done using Whatman No. 1 filter paper. The NH<sub>4</sub>-N filtrate was complexed with with sodium hydroxide, sodium hypochlorite, sodium nitroprusside,

sodium salicylate, sodium citrate and sodium tartrate while nitrate was complexed with sodium hydroxide and 5% salicylic acid. The solutions were allowed to stand for 1 hour until development of yellow color for both  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  respectively and the filtrate was used for further analysis using the colorimetric method at 655 and 419 nm as described by (Okalebo *et al.*, 2002).

Total N in soil was determined using the Kjeldahl digestion and distillation method. Exchangeable Ca and Mg were determined using Atomic Absorption Spectrometry at 422.7, and 285.2 nm, respectively (iCE 3300 AA system, Thermo Scientific, Shanghai, China), and K was determined using flame photometry. Available phosphorous was analyzed using Bray 2 method as described by Okalebo *et al.* (2002). Air-dried samples were ground using an analytical mill for N concentration in grain and plant tissues per N use scenario.

The N content in the plant tissue (grain and stover) was determined by Kjeldahl digestion procedure. A sample of 0.3 g of milled plant material were put in a digestion tube and digestion mixture 1% NaOH added and total N was determined through distillation. To determine nitrogen partitioned to roots, stem, leaves and grain, the N content obtained was divided by the total amount of N in the whole plant and later converted to a percentage through multiplying by 100.

### **3.7 Nitrogen Use Efficiency**

The calculated N use efficiency indicators, according to Fixen *et al.* (2015), were;

- a. Partial nutrient balance (PNB) was determined to show nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of “removal to use”) (Eqn 7).

$$PNB = \frac{N \text{ content of the harvested (edible portion) (kg N ha}^{-1})}{\text{Rate of N fertilization (kg N ha}^{-1})} \quad \text{Eqn 7}$$

- b. Agro-physiological N efficiency ( $APE_N$  kg grain  $\text{kg}^{-1}$ ) was calculated to determine the economic yield per unit N accumulated from each fertilizer treatment (Eqn 8);

$$APE_N = \frac{\text{yield with N (kg ha}^{-1}) - \text{yield without N (kg ha}^{-1})}{\text{biomass uptake with N (kg N ha}^{-1}) - \text{biomass uptake without N (kg N ha}^{-1})} \quad \text{Eqn 8}$$

- c. Agronomic efficiency of N ( $AE_N$  kg grain  $(\text{kg N})^{-1}$ ) was calculated to show the increase in yield per the unit of N increase applied (Eqn 9)

$$AE_N = \frac{\text{Yield N (kg N ha}^{-1}) - \text{Yield without N (kg N ha}^{-1})}{\text{Rate of N application (kg N ha}^{-1})} \quad \text{Eqn 9}$$

- d. N surplus/ deficit was calculated to show the balance between the applied N and the crop N removal (Eqn 10).

$$N \text{ surplus / deficits} = N_{\text{inputs}} (\text{kg N ha}^{-1}) - N_{\text{outputs}} (\text{kg N ha}^{-1}) \quad \text{Eqn 10}$$

### 3.8 Incubation experiment and Soil sample collection

The soil samples used in this study were collected from small scale farmers' fields in Lake Victoria basin in Kenya from 3 catchment areas Yala (0.163675° N, 34.391973° E), Nyando (0.172663° S, 34.807757° E; 0.171744° S, 34.914260° E.) and Bukura (0.22324° N, 34.61912° E). The soil samples were collected from a depth of 0-20 cm in farmers' fields. The farms where soil were collected have a history of continuous cropping of maize (rain fed) and rice (irrigated low land rice). The sample of the soils

were sorted manually to remove any objects, stones and clods bigger than 2 mm, and homogenized by hand mixing in bucket. The collected samples were air dried, crushed, and sieved to 2 mm and stored at room temperature until the start of the experiment. Before set-up of the incubation experiments selected initial physical and chemical characteristics of the soils were analyzed as shown in Table 3.10.

**Table 3.10. Initial selected soil physical and chemical characteristics for the incubation experiment**

	<b>Ferralsol 1</b>	<b>Ferralsol 2</b>	<b>Vertisol</b>
pH (0.01 m CaCl <sub>2</sub> )	4.25	4.63	5.9
EC(mS cm <sup>-1</sup> )	2.27	2.24	2.20
pH (calcium acetate)	6.27	6.09	6.43
Bulk density (g cm <sup>-3</sup> )	1.28	1.29	1.01
Texture	Sandy loam	Sandy-clay-loam	Silty clay
WHC(% w/w)	36.4	46.3	67.2
P (CAL) mg kg <sup>-1</sup>	18 (A-low)	24 (B-low)	42 (B-low)
Mg mg kg <sup>-1</sup>	33.50	90.11	180.49
K mg kg <sup>-1</sup>	94.9	89.9	614.1
NO <sub>3</sub> <sup>-</sup> (mg kg <sup>-1</sup> )	2.76	4.86	6.29
NH <sub>4</sub> <sup>+</sup> (mg kg <sup>-1</sup> )	2.33	2.11	1.51
TOC (% w/w)	0.67	1.49	1.75
TN (% w/w)	0.06	0.13	0.13
C: N ratio	11.0	11.6	13.8

Mean values (and unit) of soil parameters of pH (0.01 mol calcium chloride), Electrical conductivity (EC), Phosphorus (P), Magnesium (Mg), Potassium (K), ammonium (NH<sub>4</sub><sup>+</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), Total organic carbon (TOC), total carbon (TC) C-to-N ratio (C: N), maximum water holding capacity (WHC), total nitrogen (TN).

### 3.9 Analytical methods for incubation experiment

The soil pH was determined using extracts of 1:2.5 (weight/ volume of solution) for soil to 0.01 M Calcium chloride (CaCl<sub>2</sub>). The content were shaken and allowed to rest for 1 hour. The pH values were read directly using a pH meter (multi 340i, WTW GmbH, Weilheim, Germany and Electrical conductivity (EC), respectively. Mineral N from the soil samples were extracted with 0.01 M CaCl<sub>2</sub> (1:4 w/v) by shaking the content for 1 hr

and centrifuged at 690 relative centrifugal force (RCF) for 15 min. The supernatant was decanted into a filtration unit and filtered through a membrane filter with 0.45µm pore size (47mm diameter, Macherey-Nagel, Germany and stored at -20 °C until analysis. The concentrations of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  in soil extracts were measured by ion chromatography (Dionex DX-500, ThermoScientific, Massachusetts, USA). To extract plant accessible P and K in the soil, 2 grams of air-dried soils were weighed in 50 ml tubes, 40 ml of CAL solution were added and shaken for 1.5 hours, centrifuged at 690 relative centrifugal force (RCF) for 15 min. The supernatant was decanted into a filtration unit and filtered through a membrane filter with 0.45µm pore size (47mm diameter, Macherey-Nagel, German centrifuged at 690 relative centrifugal force (RCF) for 15 min. The supernatant was decanted into a filtration unit and filtered through a membrane filter with 0.45µm pore size (47mm diameter, Macherey-Nagel, Germany. Phosphorus was determined by inductively coupled plasma optical emission spectrometry (iCAP™ 7600 ICP-OES Analyzer, ThermoScientific, Massachusetts, USA).

The lime demand of each soil was determined as described in the LUFA methods handbook (VDLUFA, 2017). Ten (10) g of air-dried soil was mixed with 25 ml of a 0.5 M Ca acetate solution (1:2.5, w/v) and incubated overnight at room temperature. The pH in the Ca-acetate soil suspension and the pH in the 0.01 M  $\text{CaCl}_2$  soil suspension were used to estimate the lime demand at a target pH of 6.5. Based on this, we calculated the amount of  $\text{CaCO}_3$  for the treatments with lime treatment.

Maximum water holding capacity (WHC %) of the soil samples was determined using the procedure described by (Schinner *et al.*, 1996). Twenty (20) grams of air-dried soils were transferred in cylinder. The soils were saturated and allowed to drain for 24 hours. The moist soil was sampled from the cylinders, and initial wet weight was taken. The sampled amount was oven dried at 105 °C for 24 hours. The soil samples were weighed again to get the dry weight that was used in computing for 100% WHC and the values were used to calculate the amount of water to be added in 180 grams of each soil sample at 50% WHC.

Microbial biomass C ( $C_{mic}$ ) was determined at the end of the experiments for all the treatments and the soil samples using the chloroform-fumigation extraction based on Joergensen (1996). Forty (40) ml of the extracted soil was centrifuged at 690x g for 10 mins before and filtered through a 0.45- $\mu$ m polypropylene membrane filter (47-mm diameter, Macherey–Nagel, Germany). The samples in the closed desiccator were incubated at room temperature for 24 hours and the dissolved organic C (DOC) was analyzed by Total organic C (TOC) analyzer (TOC-VcPH + TNM-1 + ASI-V, Shimadzu, Japan).  $C_{mic}$  was determined as a difference of DOC of the non-fumigated blank and the fumigated samples and correction factors of kEC 0.45, as reported by Joergensen (1996)

### **3.10 The $\delta^{13}C$ -CO<sub>2</sub> analysis**

For the three soil substrates, 1 g of air-dried soil was incubated in 12-ml glass vials with soil moisture retained at 50% WHC. All the five treatments for each soil substrate described in incubation above were considered for  $\square^{13}C_{VPDB}$ . Marble granular was used as the source of CaCO<sub>3</sub>, while urea (Merck KGaA) was used as source of N. The  $\delta^{13}C$  of CO<sub>2</sub> evolving from all the treatments was determined for incubation time 0 and 48 h by measuring gas samples

on an isotope ratio mass spectrometer as described in Zhao et al. (2022). CO<sub>2</sub> evolving from each source was calculated using the 2-end-member mixing model.

### **3.11 Incubation and gas measurements**

Incubation experiment was carried out at the Institute of Bio and Geosciences, Forschungszentrum, Jülich Germany. Three soil samples were subjected to five different treatments (n=4) i.e (low N level (12.5 kg N ha<sup>-1</sup>) (SI), high N level (50 kg N ha<sup>-1</sup>) (SH), low N level (12.5 kg N ha<sup>-1</sup>) with calcium carbonate (SLC), high N level (50 kg N ha<sup>-1</sup>) with calcium carbonate (SHC), and unamended control (without N fertilizer and liming).

The fertilization with a rate of 12.5 kg N ha<sup>-1</sup> denotes the average rate currently used by farmers, while 50 kg N ha<sup>-1</sup> is the rate recommended to maintain the fertility of these soils (African Union, 2006). Soil substrates, with and without N and calcium carbonate, were thoroughly mixed, filled in incubation PVC tubes (150 mm height, 50 mm diameter) (Cao *et al.*, 2021), and recompact to the original bulk density, as reported in Table 1. Soil moisture was adjusted to 50% of the water holding capacity, and the water content was adjusted by weighing weekly and replacing the evaporative water loss by using distilled water. Urea, a commonly used form of N fertilizers by farmers in the LVB in Kenya, was used as the source for mineral N, and its equivalence per ha was calculated for the area of the incubation tubes. Throughout the incubation period, the temperature was set at 23°C, the average soil temperature in the LVB.

Gases (N<sub>2</sub>O, CO<sub>2</sub> and CH<sub>4</sub>) concentrations were analyzed automatically using an infrared laser absorption gas analyzer (G2508, Picarro, Inc., Santa Clara, USA) as

described by Cao et al. (2021). The measurements of GHG fluxes were done on incubation days 1, 2, 3, 5, 8, 15, 22, 29, 36, 43, 50, and 57.

Gas fluxes were determined using as shown by equation (Eq) 11;

$$F = \frac{\frac{\Delta C}{\Delta t} \times V \times T_o \times M}{A_{ch} (K + T) \times V_m} \quad Eq 11$$

where  $F$  represents gas emission flux, the change in gas concentration over time in ppmv for  $CO_2$  and ppbv for  $N_2O$  and  $CH_4$ ,  $V$  the headspace volume,  $M$  the molar mass of N in  $N_2O$  or C in  $CO_2$  and  $CH_4$ , respectively,  $V_m$  is the molar volume of the gases corrected for the gas sample temperature using  $K$  (273.15 K) and  $T$  (air temperature in °C).

Global warming potential among the treatments was determined as a sum of the  $CO_2$ -C and  $CO_2$ -C equivalent of  $N_2O$ . To convert  $N_2O$ - N to  $CO_2$ -C equivalent, the cumulative emissions were multiplied by 265, divided by 28 (representing the atomic mass of two N atoms of  $N_2O$ ) and multiplied by 12 (that represents the atomic mass of one atom of carbon) according to Reichel et al. (2018) and IPCC (2014) (Eq. 12):

$$GWP = CO_2 - C + (N_2O - N * \frac{265 * 12}{28}) \quad Eq 12$$

The emission factor (EF) for  $N_2O$  was determined by the difference between the treatments with N fertilizers and those without and divided by the rate of N fertilizers application ( $kg\ N\ ha^{-1}$ ) in the respective treatments (Eq. 13).

$$EF\% = \frac{(N_2O_{fertilized} - N_2O_{control})}{Rate\ N\ applied(kgNha^{-1})} \quad Eq\ 13$$

where  $EF$  (%) represents the  $N_2O$  emission factor,  $N_2O_{fertilized}$  the  $N_2O$  flux from treatments with N fertilizers, and  $N_2O_{control}$  the  $N_2O$  flux from treatments without N fertilizers.

### 3.12 Statistical Analysis

All statistical analyses were performed with R language [R Core Team, 2020]. The least Square Means were computed using "lsmeans" packages. Means were separated by adjusted 'Tukey's method using "cld" function from "multicompView" package for N inputs, N outputs, NUE and N balance ( $p < 0.001$ ). Mean distribution for N inputs, outputs, NUE, and N surplus/deficit were analyzed using the ggplot command from the ggpubr package.

The yield data of farms and fields was analyzed using the general linear model procedure. Means were compared, by the post-hoc Tukey test ( $p < 0.001$ ). Simple regression analysis was used to estimate the effect of N inputs on N outputs.

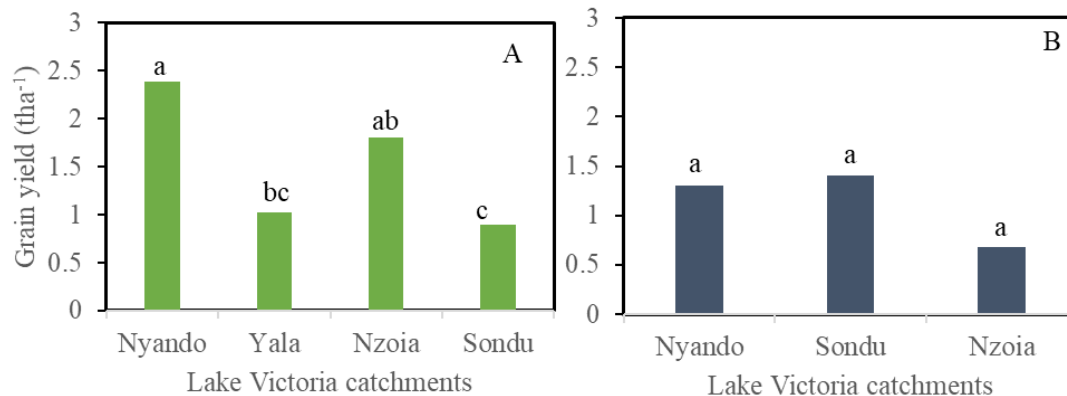
Plant biomass, N grain yield, NUE, and total nitrogen crop production were analyzed using a one-way analysis of variance test. Computation of least squares means was done using "lsmeans" package, followed by mean separation using adjusted Tukey's method at ( $p < 0.05$ ). implemented using "cld" function from the "multicompView" package. Distribution of means for grain and stover yield was done using the ggplot command from the ggpubr package (RCore Team, 2020).

Data on cumulative gas fluxes and mineral N dynamics were analyzed using one way analysis of variance. Computation of least squares means was done using "lsmeans" package, followed by mean separation using adjusted Tukey's ( $p < 0.05$ ) method implemented using "cld" from Multicomp View package.

## CHAPTER FOUR: RESULTS AND DISCUSSION

### 4.1 Grain yield in maize fields

Significant variations ( $p < 0.001$ ) in grain yield were observed between maize farms. Fertilized farms recorded higher yields than non-fertilized farms. Nyando catchment recorded the highest yield of  $2.4 \text{ t ha}^{-1}$  and  $1.4 \text{ t ha}^{-1}$  for maize with and without synthetic N application respectively. The lowest average grain yield of less than a tonne was observed in the Sondu and Nzoia catchments at  $0.9$  and  $0.5 \text{ t ha}^{-1}$  for farms with and without N applications respectively (Figure 4.1). The analysis across the sites showed that, on average, there were better yields from N applied farms than non-N applied farms and there was a positive correlation between N inputs and crop yield.



**Figure 4.1: A comparison of grain yield of maize in farms applying N fertilizers (A) and those do not apply (B) in Lake Victoria basin catchments. Different lowercase letters denote significant differences between different treatments at  $p < 0.001$**

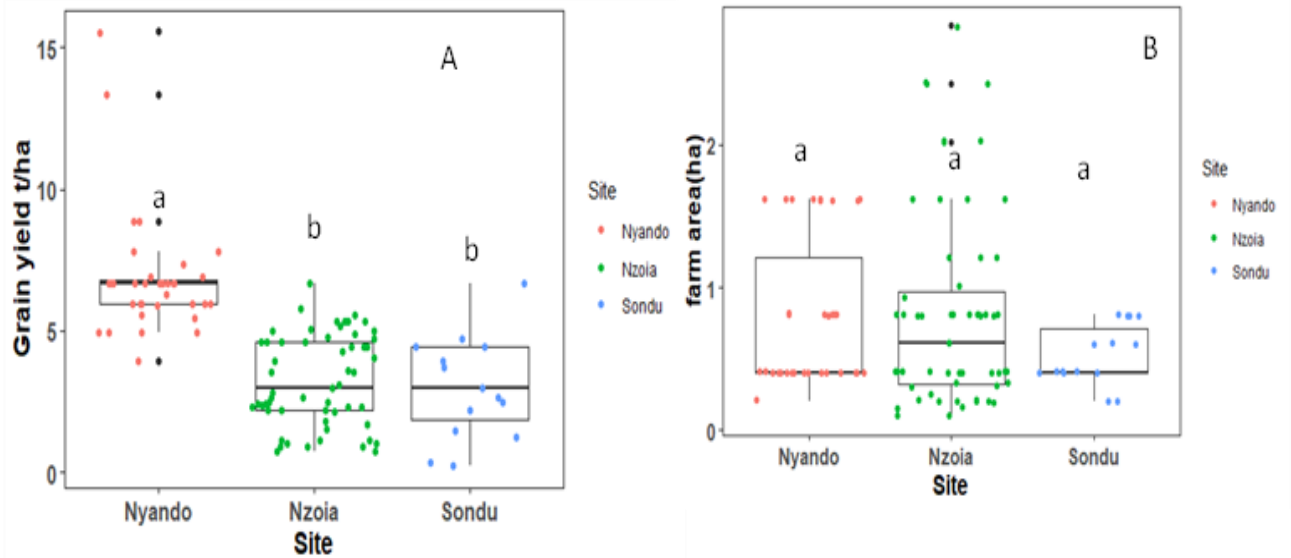
The reported maize yield was relatively low ( $< 5 \text{ t ha}^{-1}$ ), and this was evident with N application in some of the farms (Figure 4.1). This kind of results on maize yield among the small-scale farmer ranging from  $1 \text{ t ha}^{-1}$  to  $2 \text{ t ha}^{-1}$  agree with those of Tsujimoto *et*

*al.* (2019). According to Mutegi and Zingore (2014), low yield in SSA is due to low-to-zero mineral and organic fertilizers, which can be confirmed from the current findings. In addition, smallholder farms are unable to achieve higher yields because of lack of fertilizer inputs and widespread nutrient-poor soils. The continuous cropping of the land without replenishing with fertilizers contributes to the degradation of the soil quality. This may remain a challenge for SSA unless the change is enacted through policies (Chianu *et al.*, 2012). The results of Das *et al.* (2019) agree with the findings of current study that showed maize fields to be deficit in N and this could be a factor contributing to low productivity levels among small-scale farmers. The low application of N fertilizer could also be due to its prohibitive cost, coupled with other factors like poor infrastructure and low fertilizer production capacity (Masso *et al.*, 2017). The findings are also in agreement with those of Mahal *et al.* (2019), who reported an increment of maize yield by 114% in fertilized fields compared with those not fertilized. Poffenbarger *et al.* (2018) similarly reported that maize yields from fertilized plots were higher compared to those farms without N fertilization. This is, therefore, an indicator that with more increment of current N inputs, there will be an expected corresponding higher yield that could provide a solution to food insecurities within the region.

#### **4.2 Grain yield in rice fields**

There were significantly higher yield in rice systems in Nyando catchment relative to other catchments ( $p < 0.001$ ) but statistically similar yield levels for Sondu and Nzoia catchments there (Figure 4.2). Nyando recorded the highest mean value of rice grain yield of  $6.8 \text{ t ha}^{-1}$ , while the lowest mean value was in Nzoia catchments with  $3.3 \text{ t ha}^{-1}$  (Figure 4.2A). The relatively higher yield in rice could be influenced by the enhanced

access of N input by the National Irrigation Board (NIB) compared to maize farmers. Besides, in rice farming systems, the cooperatives support help farmers through various



financing mechanisms to access quality farm input.

**Figure 4.2: Box plots for rice grain yield (t/ha) (A) and farm size (B) in selected three catchment areas of Lake Victoria basin for farms with the application of synthetic fertilizer. Different lowercase letters denote significant differences between different treatments at  $p < 0.001$**

Comparatively, in rice fields where use of N fertilizers was higher compared to maize farming, a higher grain yield was recorded (Figure 4.2). This was partly due to better N uptake in rice through enhanced panicle formation and grain filling process that are key yield components (Sun *et al.*, 2018). These results agree with by Gweyi-Onyango *et al.* (2021) which suggested that more rice yields could be realized if a synchrony between the crop N demand and N availability is maintained during the growing period and this had an indirect bearing on NUEs. The higher yield in some rice farms with higher N

application is an indication that with more N inputs, the challenge of food insecurity would be solved that agrees with results from (Mafongoya *et al.*, 2006). However, increment in N usage on more integrated strategies, particularly in low land regions where rice is irrigated to minimize more losses to ground water and the atmosphere through associated gaseous emissions (Nayak *et al.*, 2015; Bhatt *et al.*, 2019; Ntinyari and Gweyi-Onyango 2021). Recent work by Elrys *et al.* (2020) showed that increasing N input from the current low rates to  $181 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  during 2016-2050, will be crucial to achieve food sufficiency for African countries, though currently out of reach by most farmers. This is particularly of importance since the basin accommodates about 40 million people with annual growth of 3.5 percent, which is among the highest growth rate in the world (Lubovich, 2009). This justifies the need for increased food production to meet the demands of the rapidly growing populations. In addition, the primary threat to the lake is land-use changes, soil degradation, and nutrients discharged from the farmlands, begging the need for proper understanding the N cycles for conservation and adoption of appropriate management strategies. Therefore, increasing N inputs should be accompanied with judicious management to avoid increasing environmental pollution through uncontrolled N losses usually associated with synthetic N fertilizer. In addition, increasing N fertilizer must also aim to strike a balance between providing optimal N to prevent depletion of N resources in Africa, which should be coupled with environmental-losses preventive measures.

### 4.3 Maize fields N balances

For the soil surface, the maize farmers who do not apply mineral N fertilizers, the atmospheric deposition represented the primary flow with an average N input of 15.0 kg N ha<sup>-1</sup> (Table 4.1). In this type of N budget, farmers without application of mineral N recorded negative balances in Nyando and Sondu with average values of -3.45 kg N ha<sup>-1</sup> and -4.29 kg N ha<sup>-1</sup>, respectively.

Similarly, farmers applying mineral N recorded negative balances for soil surface N budget in Nyando catchment. Despite the addition of N, the negative N budget in Nyando implies that more N was removed from the system than that added with fertilizers, an indicator of soil N mining. Among farmers who apply N fertilizers, positive balances were reported in three catchments, Nzoia, Yala, and Sondu, with average values of 13.27kg N ha<sup>-1</sup>, 18.04 kg N ha<sup>-1</sup>, and 19.84 kg N ha<sup>-1</sup>, respectively (Table 4.1).

**Table 4.1. Soil surface N budget for maize in fields with and without mineral N fertilizer applications in four Lake Victoria catchment.**

	Without mineral N				With mineral N			
<b>N inputs (Kg N ha<sup>-1</sup>)</b>	Nyando	Nzoia	Yala	Sondu	Nyando	Nzoia	Yala	Sondu
NPM	0.12	0.09	0.17	0.14	0.13	0.07	0.19	0.14
SNF	0	0	0	0	10.42	22.99	17.33	17.31
ADN	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Sum <sub>Ninputs</sub>	15.12	15.09	15.17	15.14	25.55	38.06	32.52	32.45
<b>N outputs (Kg N ha<sup>-1</sup>)</b>								
CNR	18.57	9.56	3.57	19.43	33.38	24.79	14.48	12.61
Sum <sub>Noutputs</sub>	18.57	9.56	3.57	19.43	33.38	24.79	14.88	12.61
N balance	-3.45	+5.53	+11.60	-4.29	-7.83	+13.27	+18.04	+19.84

**Key:** SNF- synthetic nitrogen fertilizer, NPM- Nitrogen planting materials, AND- Atmospheric Deposition Nitrogen, CNR- crop N removal

Both farmer categories were associated with negative N balances in soil system NB. In farmers not applying mineral N fertilizers, N balances ranged between -3.43 to -19.29 kg N ha<sup>-1</sup> across the four catchments areas, as shown in Table 4.2. More pronounced N losses were recorded to fertilizers associated outflows in the farmers applying mineral N categories. In Nyando balance of -67.24 kg, N ha<sup>-1</sup> was recorded, indicating severe soil N depletion and mining in the farms. Soil system had higher N losses to significant outflows from denitrification, leaching, runoff, and N<sub>2</sub>O and NH<sub>3</sub> emissions, pointing to the importance of appropriate soil management.

The negative N budget in Nyando despite addition of N implies that more N was removed from the system than that which was added with fertilizers an indicator of soil N mining. Among farmers who apply N fertilizers, positive balances were reported in three catchments, Nzoia, Yala, and Sondu, with average values of 13.27kg N ha<sup>-1</sup>, 18.04 kg N ha<sup>-1</sup> and 19.84 kg N ha<sup>-1</sup>, respectively.

**Table 4.2. Soil system N budget for maize with and without mineral N fertilizer applications in four Lake Victoria catchment**

	Without mineral N				With applied mineral N			
<b>N inputs (Kg N ha<sup>-1</sup>)</b>	Nyando	Nzoia	Yala	Sondu	Nyando	Nzoia	Yala	Sondu
SNF	0	0	0	0	10.42	22.99	17.33	17.31
NPM	0.12	0.09	0.17	0.14	0.13	0.07	0.19	0.14
ADN	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
<b>Sum<sub>Ninputs</sub></b>	15.12	15.09	15.17	15.14	25.55	38.0	32.52	32.45
<b>N outputs (Kg N ha<sup>-1</sup>)</b>								
CNR	18.57	9.56	3.57	19.43	33.38	24.79	14.48	12.61
NH <sub>3</sub> emissions SNF	-	-	-	-	10.04	4.37	3.29	3.29
N <sub>2</sub> O emissions SNF	-	-	-	-	0.69	0.30	0.22	0.22
Denitrification	15.0	15.0	15.0	15.0	17.0	17.0	17.0	17.0
Leached N	-	-	-	-	15.84	6.89	5.20	5.19
Runoff N	-	-	-	-	15.84	6.89	5.20	5.19
<b>Sum<sub>Noutputs</sub></b>	<b>33.57</b>	<b>24.56</b>	<b>18.57</b>	<b>34.43</b>	<b>92.79</b>	<b>60.24</b>	<b>45.39</b>	<b>44.21</b>
N Balance	-18.45	-9.47	-3.43	-19.29	-67.24	-	-12.87	-11.76
						22.24		

Key:.. Dash (-) means parameter could not be estimated due to data unavailability on fertilizer application, Key: SNF-synthetic nitrogen fertilizer, NPM- Nitrogen planting materials, AND- Atmospheric Deposition Nitrogen, CNR- crop N removal: Emission factors (EFs) applied for gaseous losses are only limited to applied SNF

High positive N balances are not always desirable because they indicate excess N left in the system, susceptible to losses into surface/groundwater as NO<sub>3</sub><sup>-</sup> and atmosphere as N<sub>2</sub>O, leading to environmental degradation. Chianu *et al.* (2012) recommended increasing N inputs for higher crop yield is possible but managing losses through environmentally friendly practices like site-specific nutrient recommendations, reduced tillage and integrated soil fertility management which have been shown to reduce N losses through a range loss pathways like leaching, erosion and N<sub>2</sub>O or NH<sub>3</sub> emission.

Soil system has higher N losses than the soil surface due to significant outflows from denitrification, leaching, runoff, and N<sub>2</sub>O and NH<sub>3</sub> emissions, pointing to the importance of appropriate soil management. More outstanding negative N balances

were recorded in N fertilizer using farmer category probably due to higher N losses and microbial immobilization. In Nyando balance of  $-67.24 \text{ kg N ha}^{-1}$  was recorded, indicating severe soil N depletion and mining in the farms. Export of more nutrients than those applied is one of the most important causes of negative nutrient balances and soil N depletion in African agriculture. The findings of this study agree with Nkonya *et al.* (2005) that negative N budgets could cumulatively occur over years, especially in maize fields because maize uses substantial amounts of available stocks of nutrients in soils, especially when nutrients are not replenished regularly that agrees with the current study. Another study by Hanrahan *et al.* (2019) confirmed large negative balances indicating potential risks of N depletion in the soils with a potential for causing, unsustainably low crop yield levels, increasing household food insecurity and escalating the poverty level, especially considering that over 80% of the households are mostly dependent on agriculture for food and incomes.

According to Stoorvogel *et al.*, (1990) export of more nutrients than what was applied is key factors towards negative balances has been quite prevalent in tropical soils which can be confirmed from the current study. The negative balances in maize fields is an indicator of mining and accelerates the process of soil depletion. However, without any action on increasing mineral N in the soils, nutrients pools are bound to decline and results in extreme reduction of crop yield. Large negative balances indicate higher risks of N depletion in the soils which will in return give extreme low yield levels and increase food insecurities. As reported by Tan *et al.* (2005) N imbalances in the cropping systems is coupled by inability of farmers to purchase adequate inputs and knowledge limitation on management of available N resource.

#### 4.4 Rice fields N balances

In rice fields, soil surface NB showed variabilities across the catchments (Table 4.3). N balance was more pronounced in Sondu, with a value of  $-35 \text{ kg N ha}^{-1}$ , while Nzoia showed a positive balance ( $+31.94 \text{ kg N ha}^{-1}$ ). The positive N balance in Nzoia could indicate N sufficiency Nyando and Nzoia had the highest mineral N application rates of  $102.19 \text{ kg N ha}^{-1}$  and  $77.78 \text{ kg N ha}^{-1}$ , respectively. The N in crop removal formed the largest N outflow across the three catchments in the two budget systems (Table 4.3). At soil system balance, all catchments recorded negative balances of  $-148.42$ ,  $-77.31$ , and  $-51.88 \text{ kg N ha}^{-1}$  in Nyando, Nzoia, and Sondu, respectively (Table 4.3).

**Table 4.3: Rice soil surface and soil system N budget in main rice-growing catchments in Lake Victoria basin.**

<b>Rice</b>	<b>Soil surface N budget</b>			<b>Soil system N budget</b>		
<b>N inputs (Kg N ha<sup>-1</sup>)</b>	Nyando	Nzoia	Sondu	Nyando	Nzoia	Sondu
SNF	102.19	77.78	17.44	102.19	77.78	17.44
PNM	1.1	0.95	0.39	1.1	0.95	0.39
ADN	15.0	15.0	15.0	15.0	15.0	15.0
<b>Sum<sub>Ninputs</sub></b>	<b>118.29</b>	<b>93.73</b>	<b>32.83</b>	<b>118.29</b>	<b>93.73</b>	<b>32.83</b>
<b>N outputs (Kg N ha<sup>-1</sup>)</b>						
CNR	129.93	61.79	68.29	129.93	61.79	68.29
NH <sub>3</sub> emissions SNF	-	-	-	21.46	16.33	3.66
N <sub>2</sub> O SNF	-	-	-	13.49	10.26	2.30
Leached N	-	-	-	30.66	23.33	5.23
Runoff N	-	-	-	30.66	23.33	5.23
Denitrification	-	-	-	54	36	36
<b>Sum<sub>Noutputs</sub></b>	<b>129.93</b>	<b>61.79</b>	<b>68.29</b>	<b>266.71</b>	<b>171.04</b>	<b>84.71</b>
N Balance	-11.64	+31.94	-35.46	-148.42	-77.31	-51.88.

Key:.. Dash (-) means parameter could not be estimated due to data unavailability on fertilizer application, Key: SNF-synthetic nitrogen fertilizer, NPM- Nitrogen planting materials, AND- Atmospheric Deposition Nitrogen, CNR- crop N removal: Emission factors (EFs) applied for gaseous losses are only limited to applied SNF

The negative balances could result from various mechanisms of N losses: first, these catchments are characterized by regular flooding and drying/wetting cycles. The wetness and flooding could increase leaching losses of N, and the alternate drying and wetting cycles could elicit nitrification and denitrification processes due to changing soil gas diffusivity and water-filled pore spaces leading to enhanced losses of N as N<sub>2</sub>O, according to Tan *et al.* (2013). Secondly, the sizeable negative nutrient balances could emanate from the overexploitation of soil N stocks as farmers continue to supply limited N relative to crop requirements and removal (Zingore *et al.* 2015). In addition, the negative balances could be due to N losses of the applied mineral fertilizers and the different management of nutrients by rice farmers (Wijnhoud *et al.*, (2003). The current results of this study also agree with Zingore *et al.* (2015) that large negative balances emanate from overexploitation of soil N stocks in sub-Saharan Africa as farmers continue to supply inadequate N for the crops in both organic and inorganic forms coupled with increased removal of nutrients from the harvested products and this can be confirmed in the present study

In paddy rice, denitrification (N<sub>2</sub>) also formed another greater N fluxes outflow for the soil surface budget, with the largest amount recorded in Nyando with 54 kg N ha<sup>-1</sup> (Table 4.3). Antonopoulos (2010) reported similar results on high N denitrification fluxes in paddy rice, ranging from 45.1 kg N ha<sup>-1</sup> to 47.2 Kg N ha<sup>-1</sup>. In a study by Kyaw *et al.* (2005), denitrification showed the highest pathway of N loss in irrigated rice with values of 103 kg N ha<sup>-1</sup>, which agrees with the current findings. In another study by Yoshikawa and Shiozawa (2008), high temperatures encourage denitrification due to most biochemical processes that involve soil microbes; this can be associated as

one of the causes for the region because temperatures within the Lake Victoria region are relatively high and hence can be attributed to increased N outflow in the denitrification process. Nitrous oxide emissions from applied synthetic fertilizers had the least contribution of N flow with low values of 13.49 kg N ha<sup>-1</sup> in Nyando, 10.26 kg N ha<sup>-1</sup> in Nzoia, and 2.30 kg N ha<sup>-1</sup> in Sondu (Table 4.3). According to Islam *et al.* (2018), the relatively lower emissions from the cropland could result from continuous flooding leading to anaerobic conditions hence minimal losses.

#### **4.5 Total N inputs, outputs, and NUE in maize and rice fields.**

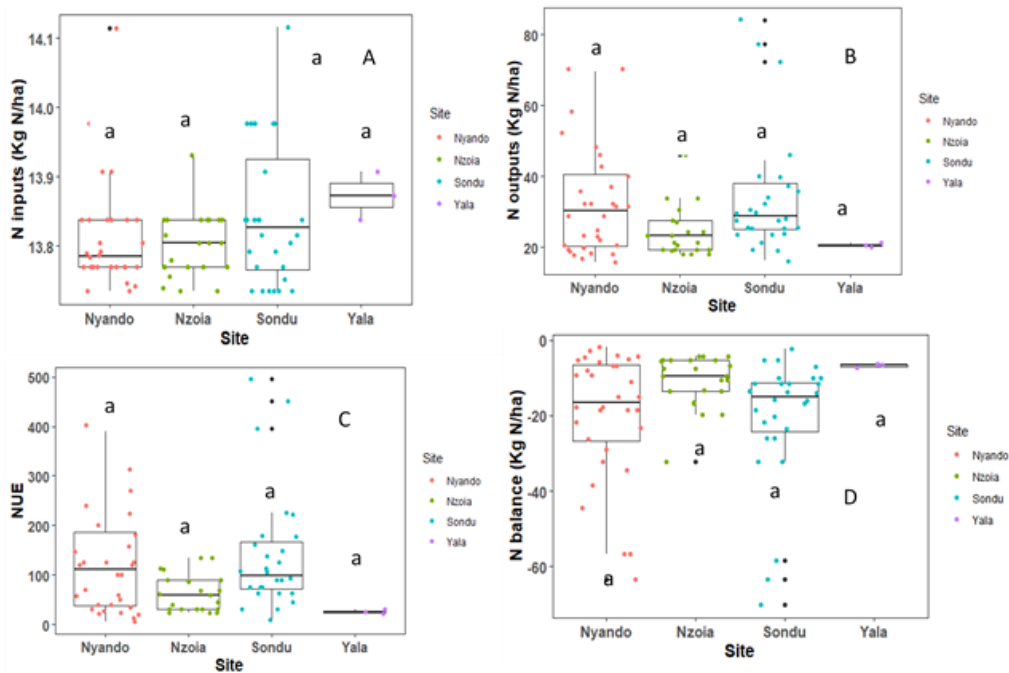
The analysis of variance did not show any significant effects on total N inputs, outputs, and NUE ( $p < 0.001$ ) for maize farms without the application of synthetic N (Table 4.4). In the data set, the mean N inputs for the catchments where farmers did not apply mineral N ranged between 15.79 and 15.87 kg N ha<sup>-1</sup> (Table 4.4). The mean inputs in this category were mainly contributed by atmospheric deposition and N in planted seeds. These findings agree with Elrys *et al.* (2019) that most other N inputs to cropping systems are still very low to support crop production. Low or no N inputs among maize farmers could be attributed lack of existing policies and interest in increasing the accessibility and use of synthetic fertilizer sources in various cropping systems (Ciceri and Allanore, 2019). Sondu catchment had the highest mean total N outputs with 34.51 kg N ha<sup>-1</sup>, while the least output was realized in Yala with 20.57 kg ha<sup>-1</sup> (Table 4.4; Figure 4.3). The highest median of total output for unfertilized plots was observed in Nyando, with 30.22 kg N ha<sup>-1</sup> in the dataset. The high N output results from crop removal for farms without applying mineral fertilizers because other N flows for this system are not considered.

**Table 4.4: Maize plots total N inputs, total N outputs, and NUE statistics for various catchments in Lake Victoria basin, Q1 and Q3 are the first and third quartiles of the probability distribution of data sets in farmers using N inputs and those not using N**

Catchments ha <sup>-1</sup> )	Total N inputs (Kg N				Total N outputs (Kg N ha <sup>-1</sup> )						NUE	
	Without synthetic N inputs											
	Mean	Median	Q1	Q3	Mean	Median	Q1	Q3	mean	media n	Q1	Q3
Nyando	15.81 <sup>a</sup>	15.78	15.77	15.92	33.57 <sup>a</sup>	30.22	20.10	41.29	134.22 <sup>a</sup>	110.37	38.63	185.79
Sondu	15.84 <sup>a</sup>	15.82	15.76	15.92	34.51 <sup>a</sup>	28.72	24.51	38.66	140.18 <sup>a</sup>	99.25	72.27	166.05
Yala	15.87 <sup>a</sup>	15.87	15.85	15.89	20.57 <sup>a</sup>	20.46	20.2	20.98	25.76 <sup>a</sup>	24.94	23.71	27.39
Nzoia	15.79 <sup>a</sup>	15.83	15.77	15.88	24.56 <sup>a</sup>	23.30	19.15	27.45	69.21 <sup>a</sup>	60.09	30.20	89.99
	With N Synthetic inputs											
	Mean	Median	Q1	Q3	Mean	Median	Q1	Q3	mean	media n	Q1	Q3
Nyando	66.66 <sup>a</sup>	27.66	21.67	120.38	96.43 <sup>a</sup>	88.22	48.47	134.7	93.33 <sup>a</sup>	55.14	38.34	144.82
Sondu	31.14 <sup>b</sup>	24.99	22.11	38.77	43.51 <sup>b</sup>	41.61	31.32	53.58	42.76 <sup>ab</sup>	34.56	21.16	39.12
Yala	31.22 <sup>b</sup>	30.29	23.65	36.07	45.40 <sup>b</sup>	41.56	33.72	55.62	44.75 <sup>b</sup>	35.86	19.41	57.53
Nzoia	36.77 <sup>b</sup>	32.44	25.83	41.56	60.80 <sup>b</sup>	52.64	40.25	76.86	76.29 <sup>ab</sup>	74.90	34.94	91.44

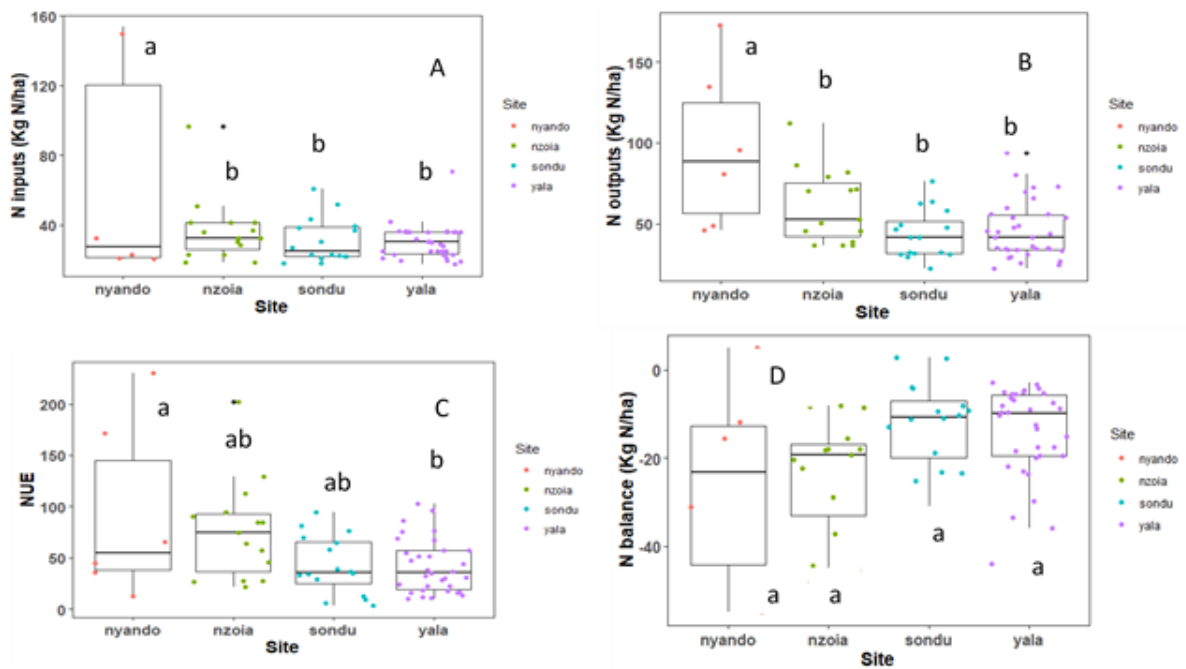
**One-way anova, followed by Tukey HSD test for pairwise (Pws) comparison for Least square means and p-value (<0.001) after adjustment for the multiple comparisons. The means with similar letters within a column are not significantly difference at the Tukeys HSD test**

Maize farms with synthetic N applied significantly on total N inputs, outputs, and NUE. Mean N inputs were highest in Nyando catchment with 66.66 kg N ha<sup>-1</sup> and the lowest was in Sondu with 31.14 kg N ha<sup>-1</sup>. Similarly, mean N output was highest in Nyando and least in Sondu, with 96.43 kg N ha<sup>-1</sup> and 43.51 kg N ha<sup>-1</sup>, respectively (Table 4.4). Mean NUE for farms without synthetic N fertilizers in Nyando and Sondu exceeded 100% with 132.22 and 140.18, respectively. In Yala, a lower mean NUE was recorded at 25.76, while Nzoia had a NUE close optimal of 69.21(Figure 4.4).



**Figure 4.3: Box plots for Maize (A) nitrogen inputs (kg N/ha), (B) outputs (kg N/ha), (C) NUE and (D) N balance (kg N/ha), in four catchment areas of Lake Victoria basin for farmers without application of mineral N fertilizer. Different lowercase letters denote significant differences between different sites at  $p < 0.001$**

The modest (median) value for NUE was recorded in Nyando catchment with 110.37 % (Table 4.4: Figure 4.4). As reported by EUNEP (2015), 90% NUE is the maximum value for identifying possible risks of soil N mining and degradation of soil fertility. Also, NUE of 50% and below indicate low levels of N use efficiency either as a result



of low nitrogen output or extreme losses of the available N in the cropping system. Therefore, with the current results, it is clear that in Nyando and Sondu, there is a higher level of soil degradation, and in Yala, the efficiency of N resource utilization was relatively poor.

**Figure 4.4: Box plots for Maize (A) nitrogen inputs (kg N/ha), (B) outputs (kg N/ha), (C) NUE, and (D) Balance (kg N/ha) in four catchment areas of Lake Victoria basin for farmers with the application of mineral N fertilizer. Different lowercase letters denote significant differences between different sites at  $p < 0.001$**

Significant differences ( $p < 0.001$ ) were observed in the data set for total N inputs, outputs, and NUE in fertilized rice fields (Table 4.5). The highest mean total N inputs

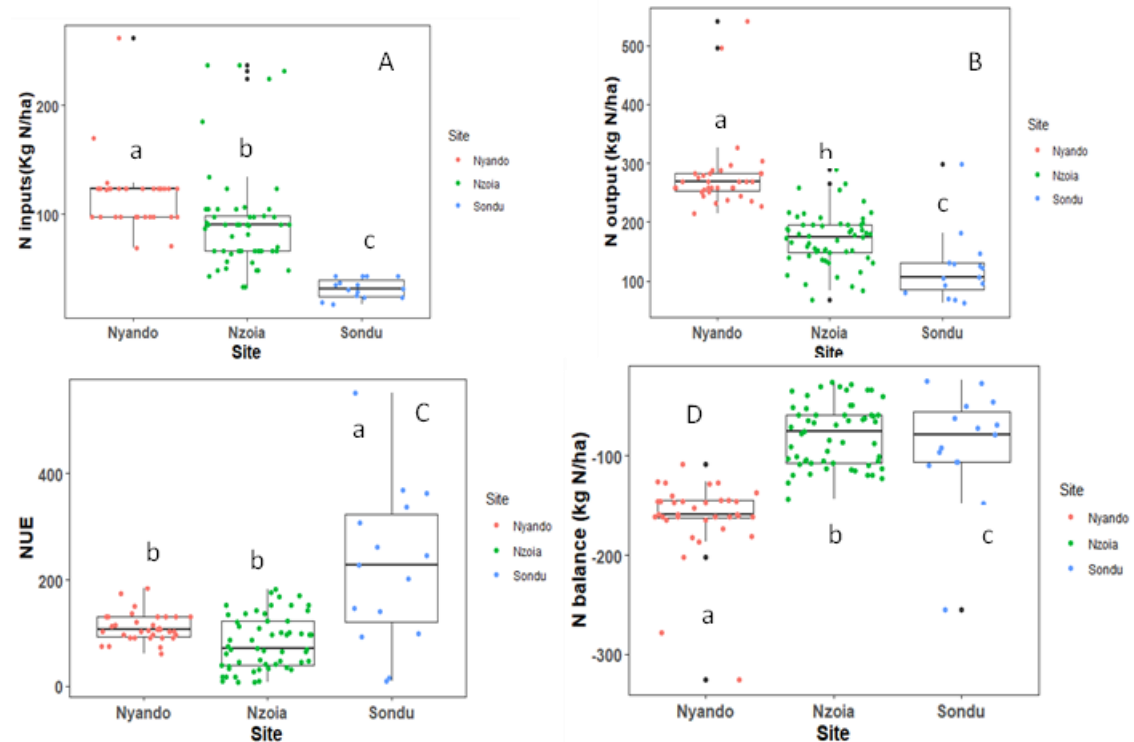
were observed in Nyando at 117.0 kg N ha<sup>-1</sup>, while the least was in Sondu with 31.53 kg N ha<sup>-1</sup> (Table 4.5). A similar trend was observed in the total N outputs data set, where Nyando had the highest mean value of 279.2 kg N ha<sup>-1</sup>, whereas Sondu had the least mean of 120.7 kg N ha<sup>-1</sup>.

**Table 4.5: Rice plots total N inputs, total outputs, and NUE statistics for various catchments in the Lake Victoria basin Q1 and Q3 are the first and third quartiles of the probability distribution of data sets**

	Total N inputs (Kg N ha <sup>-1</sup> )				Total N outputs (Kg N ha <sup>-1</sup> )				NUE			
	mean	median	Q1	Q3	mean	Median	Q1	Q3	mean	median	Q1	Q3
Nyand o	117.0 <sup>a</sup>	123.4	97.65	123.6	279.2 <sup>a</sup>	268.2	251.5	283.2	114.2 <sup>b</sup>	106.5	92.54	129.8
Sondu	31.53 <sup>c</sup>	30.80	23.77	41.09	120.7 <sup>c</sup>	105.9	82.83	130.5	224.6 <sup>a</sup>	228	109.5	329.6
Nzoia	92.43 <sup>b</sup>	90.0	66.53	99.60	171.1 <sup>b</sup>	174.1	147.2	194.9	81.92 <sup>b</sup>	70.89	39.70	122.0

**One-way anova, followed by Tukey HSD test for pairwise (Pws) comparison for Least square means and p-value (0.001) after adjustment for the multiple comparisons. The means with similar letters within the column are not significantly difference in Tukey's HSD test.**

In Nyando and Sondu, the mean NUE exceeded 100%, with Sondu having an extreme value of 224.6% (Figure 4.5 C). Low N inputs could explain the extremely high NUE values in Sondu catchment in rice systems. Severe N deficits were observed in all catchments for rice fields, with Nyando having a 2-fold highest negative balance of -162.2 kg N ha<sup>-1</sup>, relative to Sondu with -89.2 kg N ha<sup>-1</sup> and Nzoia with -78 kg N ha<sup>-1</sup> (Figure 4.5 D).



**Figure 4.5: Box plots rice (A), nitrogen input (B), and nitrogen output (C) NUE and nitrogen balance (D) with farmers with applied mineral N fertilizers. Boxes and whiskers show 5 and 95% per centiles, boxes 25 %(Q1) and 75 %(Q3) quartiles, the line in the middle is the median, while single dots indicate outlying values. Different lowercase letters denote significant differences between different sites at  $p < 0.001$**

These findings agree with Edmonds *et al.* (2009) that in SSA, estimated values of NUE are more than 100% in cereal production systems, especially in rice, due to low average application rates of mineral N that lead to a decline in soil fertility. Omara *et al.* (2009) revealed that high fertilizer applications in cereals result in lower NUE, while low or zero N inputs lead to extremely high depletion of the N pool in the soils, as reported in the current study. According to Bruuslema *et al.* (2009), it is also possible to apply sufficient N and boost N use efficiency through split application and adherence to 4R nutrient stewardship, which is crucial for closing the crop yield gaps without significantly high losses of N to the environment an adoption that applies to the results of the current study.

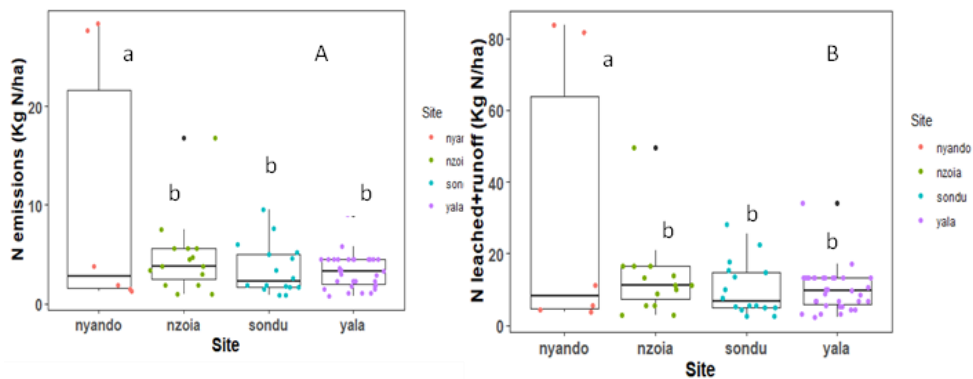
#### 4.6 N losses in maize fields

Significant differences were observed ( $p < 0.001$ ) in total emissions ( $\text{NH}_3$  and  $\text{N}_2\text{O}$ ) and leaching and runoff at all sites for maize plots with the application of synthetic fertilizers. Nyando catchment recorded the highest mean emissions, leaching, and runoff with  $15.45 \text{ kg N ha}^{-1}$  and  $45.6 \text{ kg N ha}^{-1}$ , respectively (Table 4.6, Figure 4.6).

**Table 4.6: Estimated major N loss fluxes in fertilized maize fields**

Catchment	N emissions ( $\text{Kg N ha}^{-1}$ )	Leaching and Runoff ( $\text{Kg N ha}^{-1}$ )
Nyando	15.45 <sup>a</sup>	45.6 <sup>a</sup>
Sondu	6.40 <sup>b</sup>	18.9 <sup>b</sup>
Yala	7.65 <sup>b</sup>	16.2 <sup>b</sup>
Nzoia	7.65 <sup>b</sup>	22.6 <sup>b</sup>
P Value	*** $p < 0.001$	*** $p < 0.001$

One-way ANOVA, followed by Tukey HSD test for pairwise (Pws) comparison for Least square means and p-value ( $< 0.001$ ) after adjustment for the multiple comparisons. The means with similar letters within the column are not significantly difference at Tukeys HSD test.



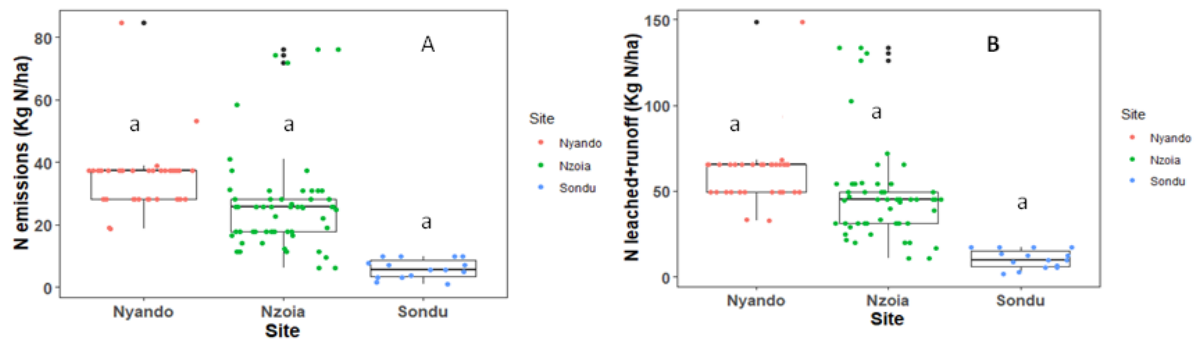
**Figure 4.6: Box plots of major N loss fluxes in maize fields; (A) total N emissions ( $\text{NH}_3+\text{N}_2\text{O}$ ) ( $\text{Kg N ha}^{-1}$ ) and (B) total leaching and runoff ( $\text{kg N ha}^{-1}$ ) from applied synthetic fertilizers. Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles, the line in the middle is the median, while single dots indicate outlying value. Different lowercase letters denote significant differences between different sites at  $p < 0.001$**

Sondu catchment recorded the lowest mean emissions of  $6.40 \text{ kg N ha}^{-1}$ , while the lowest means in leaching and runoff were observed in Yala catchment at  $16.2 \text{ kg N ha}^{-1}$ . The estimated gaseous losses ( $\text{NH}_3$ ,  $\text{N}_2\text{O}$ ) in maize agree with the findings of Elrys *et al.* (2019) on the increase of losses to  $11.6 \text{ kg N ha}^{-1}$  in some regions in sub-Saharan Africa. Accelerated N losses in maize fields within the catchments result from inadequate inorganic fertilizer application and insufficient education among farmers on controlling emissions in farming systems (Elrys *et al.*, 2019). High gaseous loss in maize fields can be attributed to low N use efficiency. Emission of gases like nitrous oxide are influenced by microbial characteristics, weather carbon sources, and other environmental factors hence the variations observed in the data set (Thomson *et al.*, 2012).

#### 4.7 N losses in rice fields

Analysis of variance showed significant differences ( $p < 0.001$ ) in total N emissions, leaching, and runoff in rice fields. The highest mean N emissions in the data set were

observed in Nyando, with  $34.95 \text{ kg N ha}^{-1}$ , while the lowest were observed in Sondu, with a mean value of  $5.97 \text{ kg N ha}^{-1}$ . (Figure 4.7 A) Similarly, total leaching and runoff in Nyando showed the largest mean value of  $61.3 \text{ kg N ha}^{-1}$  and  $10.5 \text{ kg N ha}^{-1}$  in Sondu (Figure 4.7 B) The variabilities in N leaching and runoff across the catchments resulted from soil properties and the amount of N fertilizer application.



**Figure 4.7: Box plots of major N loss fluxes in rice fields; (A) total N emissions (NH<sub>3</sub>+N<sub>2</sub>O) (Kg N ha<sup>-1</sup>) and (B) total leaching and runoff (kg N ha<sup>-1</sup>) from applied synthetic N fertilizers. Boxes and whiskers show 5 and 95% percentiles, boxes 25 % (Q1) and 75 % (Q3) quartiles, the line in the middle is the median, while single dots indicate outlying values. Different lowercase letters denote significant differences between different sites at  $p < 0.001$**

The high emissions and leaching from rice fields greatly threaten the environment to air quality, soil acidification, and water quality, which agrees with the findings of Lassaletta *et al.* (2014). According to Cao *et al.* (2014), better management practices that match the spatial and temporal supply of rice plant demand are strategic toward reducing nitrate concentration in the soil and thereby minimizing leaching losses, and this can be recommended in the present study.

#### 4.8 Farm-gate N balances

Farms without mineral N application had the main N input from atmospheric deposition ( $15.0 \text{ kg N ha}^{-1}$ ) and biological N fixation with  $6.99 \text{ kg N ha}^{-1}$ ,  $14.76 \text{ kg N ha}^{-1}$  and  $16.7$

kg N ha<sup>-1</sup> for Nyando, Nzoia, and Sondu, respectively. At the soil surface N budget, negative balances were observed in Nzoia for farms with no N fertilizer applications with a value of -0.53 kg N ha<sup>-1</sup>(Table 4.7). In contrast, in Nyando and Sondu, the N budget was +6.35 and+ 6.63 kg N ha<sup>-1</sup>, respectively. Conversely, in farms with mineral N application, positive balances of +26.59 kg N ha<sup>-1</sup> and +41.98 kg N ha<sup>-1</sup> were observed with Nzoia and Sondu, respectively. Nyando had a negative balance of -12.92 kg N ha<sup>-1</sup> (Table 4.7) due to increased N losses.

**Table 4.7: Soil surface N budget for farms with mineral N applications and without mineral N mineral application.**

	Without mineral N			With mineral N		
<b>N inputs (Kg N ha<sup>-1</sup>)</b>	Nyando	Nzoia	Sondu	Nyando	Nzoia	Sondu
NPM	0.38	0.64	0.50	1.52	0.49	1.49
SNF	0	0	0	60.34	46.07	49.42
BNF	6.99	14.76	16.7	7.5	22.07	18.88
ADN	15.0	15.0	15.0	15.0	15.0	15.0
Sum <sub>Ninputs</sub>	22.37	30.40	32.20	84.36	83.63	84.79
<b>N outputs (Kg N ha<sup>-1</sup>)</b>						
CNR	16.02	30.93	25.57	97.28	57.04	42.81
Sum <sub>Noutputs</sub>	16.02	30.93	25.57	97.28	57.04	42.81
<b>N balance</b>	<b>6.35</b>	<b>-0.53</b>	<b>6.63</b>	<b>-12.92</b>	<b>+26.59</b>	<b>+41.98</b>

**Key: SNF-synthetic nitrogen fertilizer, NPM- Nitrogen planting materials, AND- Atmospheric Deposition Nitrogen, CNR- crop N removal, BNF-biological N fixation**

In Nyando, Nzoia, and Sondu, for farmers using fertilizers, mineral N fertilizer was the dominant source of N input with 60.34 kg N ha<sup>-1</sup>, 46.07 kg N ha<sup>-1</sup> and 49.42 kg N ha<sup>-1</sup>, respectively. Farm-gate N balances were characterized by negative budgets for farm categories with and without mineral N fertilizer application. For farms without N fertilizers, the highest N balance was recorded in Nzoia, while the lowest value was in Sondu (Table 4.8). For farms where farmers applied N fertilizers, more losses and the

largest negative balances were observed in Nyando with a mean value of -78.37 and the lowest in Yala with a mean value of -13.69 kg N ha<sup>-1</sup>. In the two farm categories, the largest N outflow was recorded in crop removal (Table 4.8).

**Table 4.8. Nitrogen budget for two categories of farms with mineral N application and without mineral N application.**

Without mineral N				With mineral N			
N inputs (kg N ha <sup>-1</sup> )	Nyando	Nzoia	Sondu	Nyando	Nzoia	Yala	Sondu
SNF	0	0	0	60.34	46.07	15.87	49.42
NPM	0.38	0.64	0.51	1.52	0.49	1.05	1.49
ADN	15.0	15.0	15.0	15.0	15.0	15.0	15.0
BNF	6.99	14.76	16.7	7.5	22.07	23.22	18.88
<b>Sum N<sub>inputs</sub></b>	<b>22.37</b>	<b>30.40</b>	<b>32.20</b>	<b>84.36</b>	<b>83.63</b>	<b>55.14</b>	<b>84.79</b>
N output (kg N ha <sup>-1</sup> )							
CNR	16.02	30.93	25.57	97.28	57.04	37.81	42.81
NH <sub>3</sub> emissions SNF	-	-	-	11.46	8.75	3.01	9.39
N <sub>2</sub> O emission SNF	-	-	-	0.79	0.61	0.21	0.65
Leached N	-	-	-	18.1	13.82	4.75	14.82
Runoff N	-	-	-	18.1	13.82	4.75	14.82
Denitrification	15	15	15	17.0	17.0	17.0	17.0
<b>Sum N<sub>outputs</sub></b>	<b>31.02</b>	<b>45.93</b>	<b>40.57</b>	<b>162.73</b>	<b>111.04</b>	<b>67.53</b>	<b>99.49</b>
<b>N balance</b>	<b>-8.65</b>	<b>-15.53</b>	<b>-8.37</b>	<b>-78.37</b>	<b>-27.41</b>	<b>-12.39</b>	<b>-14.70</b>

**Key:** Key: Dash (-) means parameter could not be estimated due to data unavailability on fertilizer application, Key: SNF-synthetic nitrogen fertilizer, NPM- Nitrogen planting materials, AND- Atmospheric Deposition Nitrogen, CNR- crop N removal: Emission factors (EFs) applied for gaseous losses are only limited to applied SNF

These results are consistent with Bassanino *et al.* (2007) that mineral N was the largest contributor to N flow in farm gate N budgeting. Farm-gate N balances showed negative budgets for farm categories with and without mineral N fertilizer application. The negative N balances across farms can be attributed to poor management practices within the region, low availability, and low potential to purchase adequate N inputs, unlike other regions like Europe that have positive N balances in various farm types. Farmers in low-income countries could switch from N-depleting to accumulating scenarios by adopting best N management practices (Leip *et al.*, 2011). Regions with high inputs of

N fertilizers into their cropping systems, like China, have reported more than 300% higher N stock/balance in soils ranging from 954-1237 kg N ha<sup>-1</sup> (Oelofse *et al.* 2010). Similarly with high but more regulated N inputs for Europe, Quemada *et al.* (2020) reported positive N balances of up to 72 kg N ha<sup>-1</sup> in the Europe croplands. As reported by Watson *et al.* (2002), most of the farms studied in Denmark showed positive balances, unlike the current study, due to differences in management and availability of N resources. However, positive balances imply potential loss of N to the environment as it implies excess N is left without utilization. For regions with excessive N in the environment also require similar strategies to those without adequate N input, like the Lake Victoria basin region in East Africa, to ensure a balanced supply with minimal environmental threats.

#### **4.9 N losses fluxes in farms**

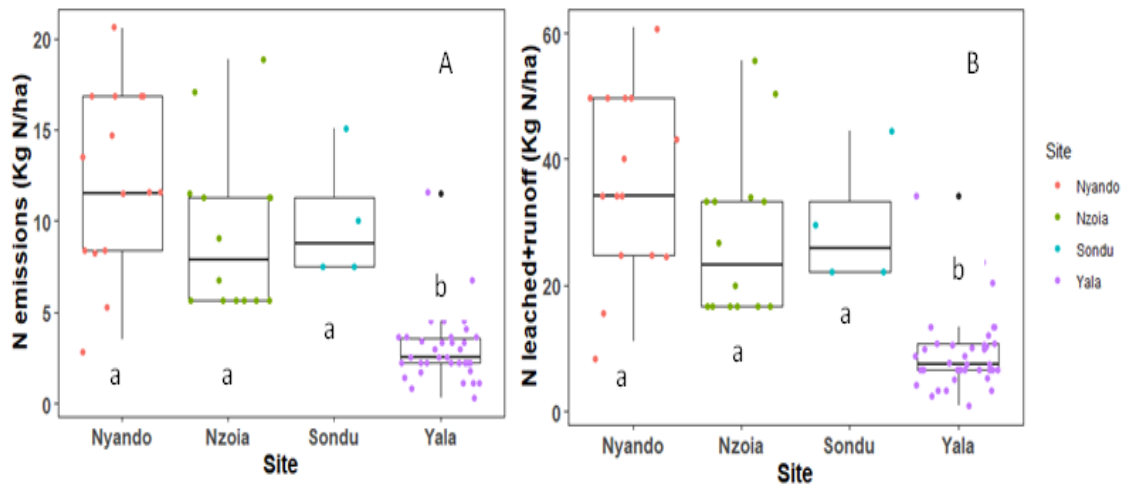
N emissions, leaching, and runoff showed significant differences ( $p < 0.001$ ) for fertilized farms in the dataset (Table 4.9). The highest mean leaching and runoff of N was observed in Nyando catchment, with 36.21 kg N ha<sup>-1</sup> and the lowest in Yala, with 9.22 kg N ha<sup>-1</sup>. Similarly, total emissions were higher in Nyando, with a mean value of 12.26 kg N ha<sup>-1</sup>, and in Yala, with the least mean of 3.22 kg N ha<sup>-1</sup> (Figure 4.8). These results agree with the findings of Ross *et al.* (2008), who reported that N losses through leaching are estimated between 5-50% of the applied N, specifically in wet and humid soils in the tropics. Losses of N through leaching can also be facilitated by favorable conditions like low soil organic matter or drought that also reduces crop N demand causing high accumulation of N in the soils hence making it more prone when conditions return to normal (Pimentel *et al.*, 2005).

**Table 4.9: Estimated N losses in fertilized farm**

Catchment	Leaching and runoff N (kg N ha <sup>-1</sup> )	Emission (Kg N ha <sup>-1</sup> )
Nyando	36.21 <sup>a</sup>	12.26 <sup>a</sup>
Sondu	29.65 <sup>a</sup>	10.04 <sup>a</sup>
Yala	9.52 <sup>b</sup>	3.22 <sup>b</sup>
Nzoia	27.64 <sup>a</sup>	9.36 <sup>a</sup>
Pvalue	***p < 0.001	***p < 0.001

One-

way anova, followed by Tukey HSD test for pairwise (Pws) comparison for Least square means and p-value(<0.001) after adjustment for the multiple comparisons. The means with similar letters within the column are not significantly difference at Tukey's HSD test.



**Figure 4.8: Box plots of N loss in farms; total N emissions (NH<sub>3</sub>+N<sub>2</sub>O) (A) (Kg N ha<sup>-1</sup>) and total leaching and runoff (kg N ha<sup>-1</sup>) (B) from applied synthetic Nitrogen fertilizers. Boxes and whiskers show 5 and 95% percentiles, boxes 25 % (Q1) and 75 % (Q3) quartiles, the line in the middle is the median, while single dots indicate outlying value. Different lowercase letters denote significant differences between different sites at p < 0.001**

The data of this study agree with those of Shang *et al.* (2020) that increased emissions of N<sub>2</sub>O rates have been reported to be high in upland crops since anaerobic conditions encourage the denitrification process, resulting in high fluxes from the applied

fertilizers. The current results show that emissions of gaseous seem to be low and do not match the current debates on impacts of agricultural activities on the accumulation of greenhouse gases in the atmosphere. There are some gaps in the methods of quantification from the IPCC inventories and emission factors (Wang *et al.*, 2020), specifically the emission factors for East Africa, due to data limitations that could not give the actual contribution of the gases to air quality. As reported by Yue *et al.* (2018), developing more robust models will enable better prediction of the agricultural farms N<sub>2</sub>O emission and provide better regional nitrogen management.

#### **4.10 Implications and practical recommendations for N Use and Management**

The results of this study show atmospheric deposition as the primary source of N in the Lake Victoria region in the majority of farms and fields where farmers do not use any mineral N. Managing N sources from atmospheric deposition could be challenging since a significant proportion may end up in unintended areas, for instance, water bodies or uncultivated land where runoff is more likely causing more pollution to the environment. Given that the N use of fertilizer in sub-Saharan Africa is low, with many cases of no use, these results indicate a need for improved use of fertilizers to change farm N balances to +ve. Across the two cropping systems, the soil system registered higher N losses than the soil surface, implying significant outflows from denitrification, leaching, runoff, and N<sub>2</sub>O and NH<sub>3</sub> emissions and pointing to a need for improved N management. These results affect environmental management, policy-making, and optimal agricultural resource management. These results could potentially be applied in projecting N dynamics for over 3 million hectares where maize and rice are grown in this region.

Several cases presented herein have indicated significantly higher negative balances in the N-applied farms relative to non-N applied plots. The results indicate significant losses of applied N to the environment with a potential to pollute water bodies and contribute to increased N<sub>2</sub>O emission (Furthermore, negative balances imply poor management, which results in the extraction of available N resources. This implies that farmers will require widespread capacity building to implement NUE optimizing practices. Furthermore, good agronomic practices, such as integrated soil fertility management to improve nutrient balance, could be managed by managing N losses.

An integrated approach is relevant to reducing N losses in cropping systems to ensure a reduced negative impact on the environment and soil degradation. These include promoting balanced nutrient management, the 4R nutrient stewardship, and integrated soil fertility management. As in recent studies by IFDC (2018), over 50% of fertilizers used in East Africa supply only N and P. Such nutrient imbalance alters crop uptake of N, contributing to losses and optimal NUE. A better-balanced application of fertilizers; ensures the availability of all essential nutrients is crucial for optimal N uptake, leading to minimizing losses. Additionally, whereas most farmers apply most N fertilizers at planting, the 4R nutrient stewardship framework recommends splitting N application to 2- or 3-times during crop growth to match N supply with N demand by the crop, thus reducing the accumulation of N in soil and reducing such losses.

The results revealed relatively low to no N use, particularly in maize fields, while in rice fields, most farmers had access to fertilizers. However, both categories did not imply proper management due to higher NUE than optimal values and negative N balance. Therefore, decision support tools that guide farmers on the rate and time of

application of nutrients to reduce excess N in the soil and match crop requirements with available N quantities, thus reducing the outflow of N from the agricultural system, should be given priority in this region. Some of the practical examples of decision support tools like the Nutrient Expert (NE) and Nutrient Manager for Rice (NMR) support the implementation of site-specific fertilizer management, leading to improved NUE (Rurinda, 2020; Sharma *et al.*, 2019). Decision support tools make it possible to significantly manage N fertilizer application rates through improved NUE while sustaining or increasing crop yield levels (Wang *et al.*, 2019).

#### **4.11 Limitations and study assumptions in the determination of N budgets at smaller spatial scales**

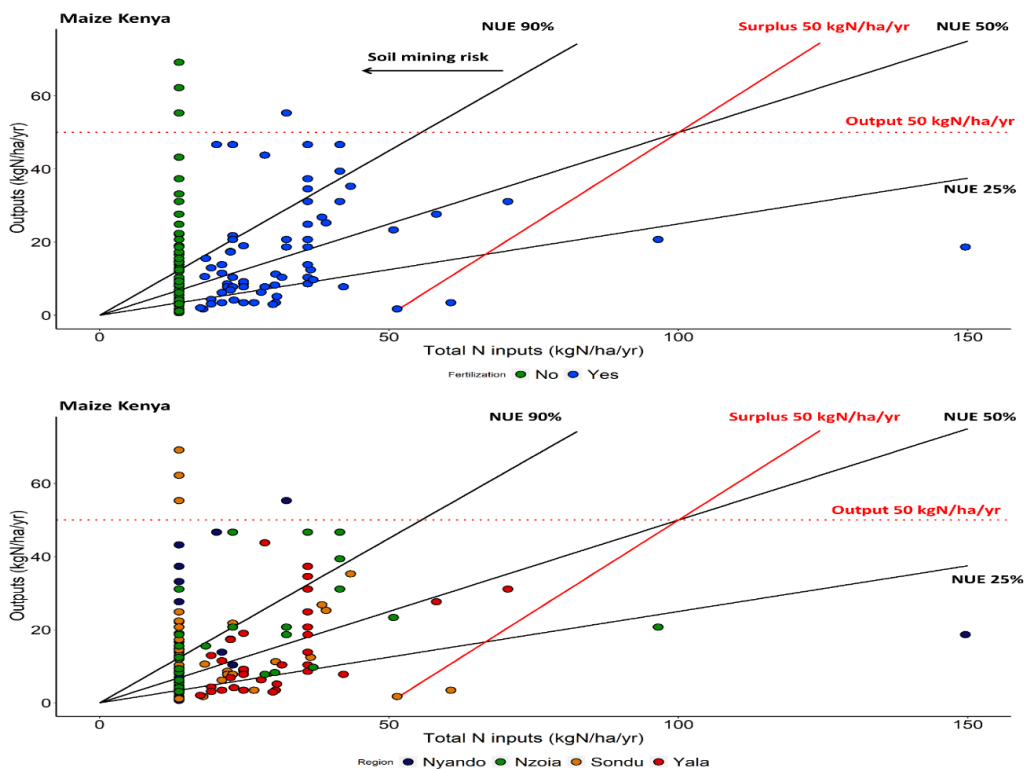
The calculation of agricultural N budgets includes generalizations and assumptions (Lassaletta *et al.*, 2014). Particularly in Africa, with limited data on the quantification of N flows at the field and farm level due to a lack of specialized systems for monitoring N fluxes. We relied on specific conversion factors to calculate crop N removal and BNF, which could produce some uncertainties due to crop variations and adaptations to local environmental conditions. For instance, BNF is determined based on the crop area of the legume using global N<sub>2</sub> fixation rates. Losses on leaching and runoff adopted a unified co-efficient for all regions according to IPCC; gaseous losses were also estimated using territorial emission factors (FAO, 2001, Bouwman *et al.*, 2002) for different cropping systems (lowland or upland). These N loss pathways could vary even in the same farm. Similarly, losses via denitrification were determined on fixed factors based on the amount of N fertilizer application.

Livestock manure was excluded from the N budget estimations due to the farmers practices of burning manure or grazing the animals along the road. Burning and random grazing have an overall effect in N cycling due to the associated losses of  $\text{NH}_3$  and  $\text{N}_2\text{O}$  that could be very high without proper manure management. At farm level, imported feeds was also omitted from the N budgeting method due to economic limitation of the farmers to buy feeds for their livestock also there is scanty information on availability of the N co-efficient for manure More public knowledge and policy advocacy on manure management and its implications for N cycling are crucial. In addition, the role of straw management in N cycling should be emphasized to encourage farmers leave crop residues in the field other than burning to enhance sustainability of the system in regard to nutrient cycling. N in irrigation water particularly in rice systems was omitted in the budgeting due lack of data on N contents concentration and the amount of water supplied in the growing season, this could vary due to limitations in irrigation water. Leguminous trees in the farms were also not accounted for the estimation due to absence of N fixation rates to make the estimation.

Despite these limitations the current data of study provides a comprehensive scenario on the N budgets status at field and farm level. Future studies on N budgeting within Lake Victoria basin should focus on establishing long term experiments at field and farm level for accurate measurements for transformation of N in soil gradients under specific rates of N fertilization to reduce existing uncertainties in such studies (Elrys *et al.*, 2019).

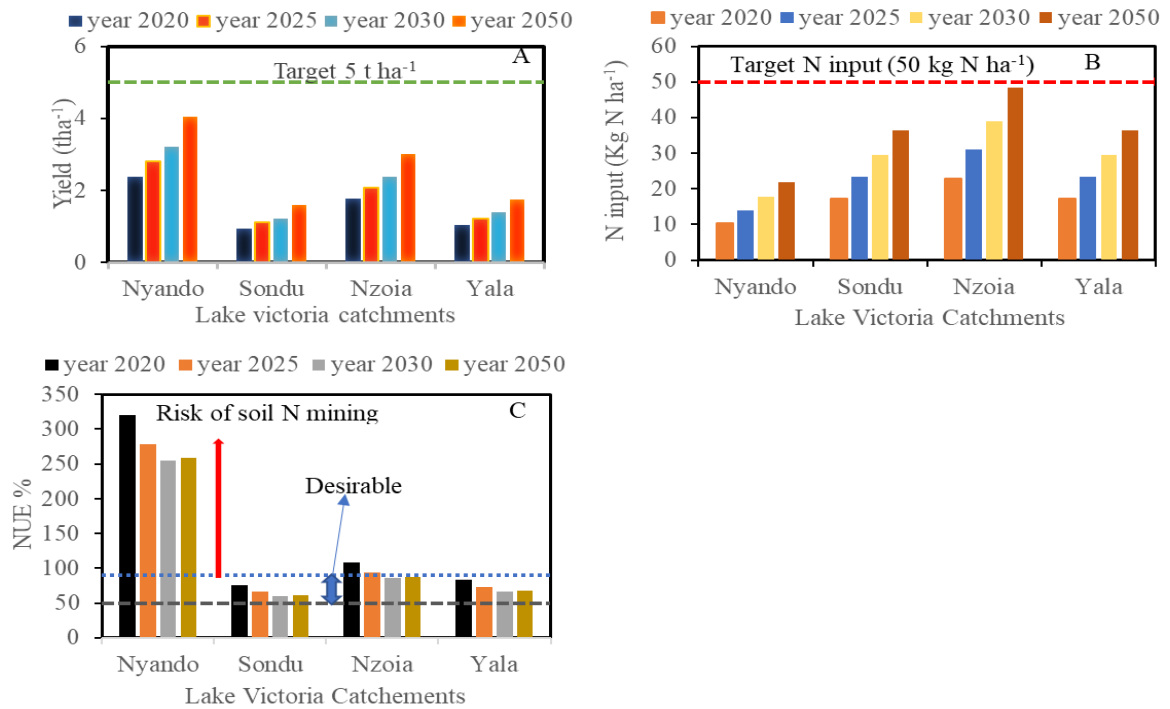
#### 4.12 Trends in yield, N inputs, and NUE

Acceptable NUE boundaries depicting the safe operating zones for maize cropping systems are shown in Figures 4.11 A and 4.11B. The NUE values for the farms not applying N fertilizers lay in the “risk area” and is likely to be prone to soil degradation and mining as the values were above 90% (Figure 4.9). The  $NUE < 90\%$  occurred for the farmers supplying total inputs of  $> 50 \text{ kg N ha}^{-1}$ . A similar scenario was also observed for the respective catchments as shown in Figure 4.9. The results of NUE graphs call for the need to improve management of N resources for optimal NUE in maize production and productivity.



**Figure 4.9:** Graphical representation of maize NUE critical regions for Lake Victoria catchment in Kenya for two categories of farmers using mineral N and those not using any mineral N.

The analyses also reveal that in farms with low N input, low yields, as well as high NUE surprisingly present a higher risk of soil mining. However, in few of the farms, despite, high N input and low NUE, the yields were still relatively low, implying a risk of N loss to the environment. The projections showed that increments in both maize and rice grains will be realized as N fertilizer use increases. For maize, none of the catchments is expected have achieved the targeted yield of 5 t ha<sup>-1</sup> with the current recommendation of annual yield increment of 3.5 %. (Figure 4.10 A). Yields in Nyando catchment will be closer to the targeted yield by 2050; with an average of 4.05 t ha<sup>-1</sup>, which is 76.11% increment from the current average yield of 2.3 t ha<sup>-1</sup>. On the other hand, the average yield for the Yala catchment will be approximately 1.76 t ha<sup>-1</sup> representing an increase of 70.1 % from the current yield level of about 1.03 t ha<sup>-1</sup> by 2050.



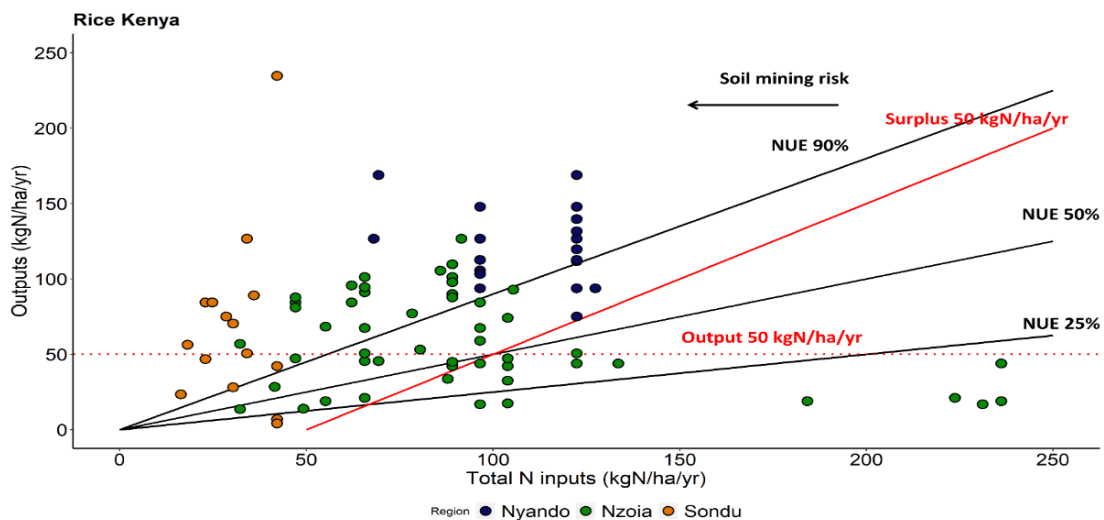
**Figure 4.10: Projected trends in maize yield t ha<sup>-1</sup> (A), N input Kg N ha<sup>-1</sup> (B), and NUE % (C) in selected catchments for Lake Victoria Basin for 2025, 2030 and 2050.**

Increasing N inputs and yield will lower the current values of NUE in both maize and rice production systems. Under maize production, Sondu, Nzoia, and Yala catchments will remain in desirable NUE range of between 50-90%, a contrast of the current NUE (higher) values in the region between the years 2025-2030 (Figure 4.10 C). However, in Nyando, although the NUE values will decrease with an increase in both yield and N inputs, they still remain at high risk of soil mining, depletion and loss of soil fertility as depicted by values in excess of 100% that are expected to be 320.38 % and 259.35 % in 2020 and 2025 respectively.

The NUE graphical representations (Figure 4.13) show that most of the catchments under rice are currently in the risky region of nutrient mining since the NUE values surpass the “safe operating zone”.

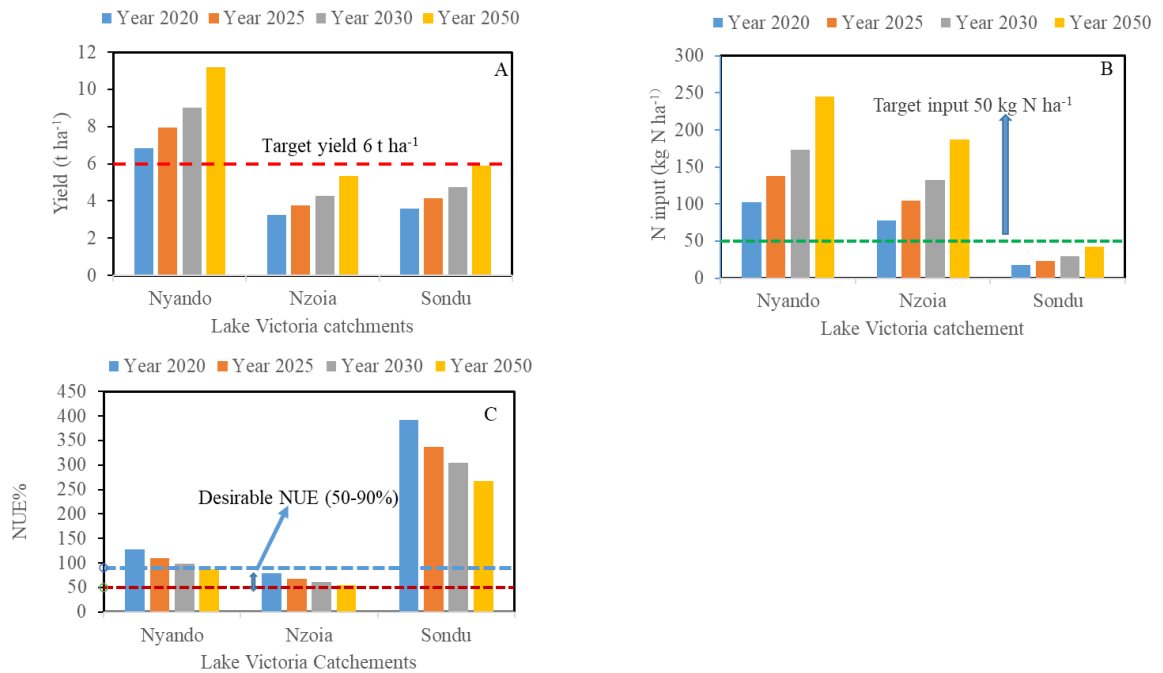
**Figure 4.11: Graphical representation of rice NUE critical regions for Lake Victoria catchment in Kenya**

Despite being endowed with ability to access more N inputs than maize farmers, optimization of NUE by rice farmers in the respective catchments remains elusive



though quite critical. In rice cropping, the Nyando catchment surpassed the current yield targets of  $6 \text{ t ha}^{-1}$ , but other catchments remain below the target. From the projection, both Nzoia and Sondu will be nearing the target with yields of  $5.3$  and  $5.9 \text{ t ha}^{-1}$  respectively by 2050 (Figure 4.12A). N input in Nyando and Nzoia have already crossed the mark for  $50 \text{ kg N ha}^{-1}$  and the projected increase in N inputs will be beneficial in enhancing crop yield and lowering NUE values to the desirable range

(Figure 4.12 B). N input will increase from 102.19 kg N ha<sup>-1</sup> to 245 kg N ha<sup>-1</sup> by 2050 in Nyando, while in Nzoia, the increment will be from 78 kg N ha<sup>-1</sup> to 186 kg N ha<sup>-1</sup>.



**Figure 4:12: Projected trends in rice yield t ha<sup>-1</sup> (A), N input Kg N ha<sup>-1</sup> (B), and NUE % (C) in selected catchments for Lake Victoria Basin for 2025, 2030 and 2050**

Projections show that the values for Sondu catchment will remain relatively low by 2050 at about 42 kg N ha<sup>-1</sup> from the current rate of 17.44 kg N ha<sup>-1</sup>. Similarly, in rice, increasing N inputs and yield will lower NUE values for Nyando and Nzoia catchments to desirable ranges, as shown in figure 4.12 C. From these results, most of the farms in the three catchments lay in the NUE ranges >90%, which is a sign of soil mining. A few farmers operated in the region referred to as the “safe operating zone” for NUE, with the optimal NUE being 50- 80%. Moreover, a number of the farms were also below the 50% threshold, which indicates the inefficient use of N inputs. From the projections, the NUE values in Nyando will decrease from 127% to 87% within 2020-

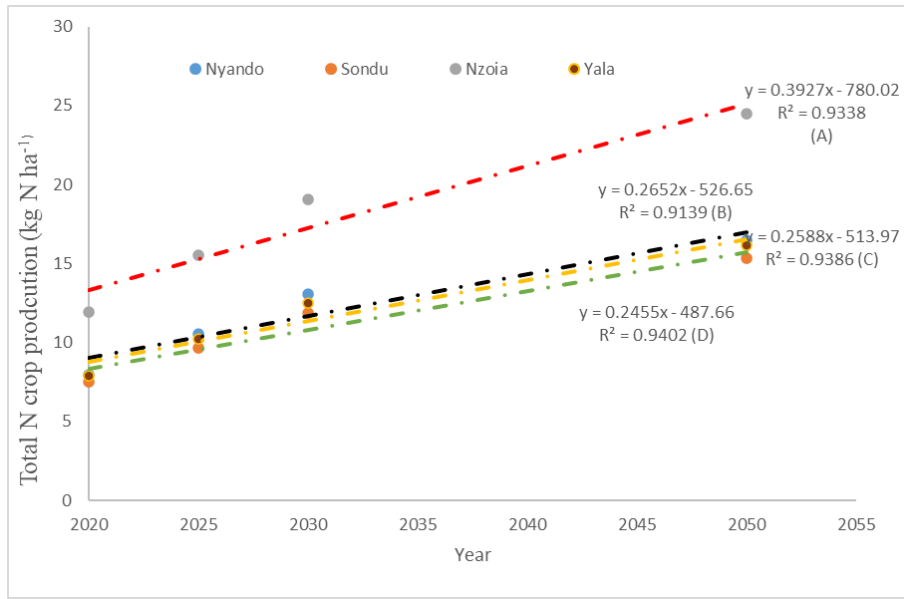
2050 period. This implies that with current recommended changes, optimization of NUE will be possible for the Nyando catchment.

This study has revealed that most rice and maize farms are at risk of “soil mining” zone on the NUE graphical representations (Figures 4.10 & 4.11). The findings demonstrate the need for more effort for the farmers to operate within the optimal boundaries of N in food production. The findings of this study agree with those of Yuan and Peng (2017) that reported optimization of NUE with increased supply of soil N in cropping systems. According to Gweyi-Onyango *et al.* (2021), increasing N input combined with the 4 R (right source, right rate, right placement, and right timing) stewardship of nutrients could also offer a sustainable solution to optimizing NUE particularly in rice cropping system and can be adopted in the current study. The results agree with the findings of Chianu *et al.* (2012) who reported poor soil fertility and failed agricultural practices as a critical driver to poor NUE in African countries, including Botswana, Mauritius, and Zambia. The NUE values greater than 90% was also observed in Algeria, Tanzania, Uganda, Cameroon, Benni, and Togo by Elrys *et al.* (2019), which is a clear indication that most African countries are still experiencing severe N depletion and agrees with the current study. Similar findings have been confirmed by Lassaletta *et al.* (2014) that reported higher crop removal with minimal N input in SSA which is linked to soil mining. The soil mining leads to unbalanced soil N, associated with poor NUE values. Therefore, due to the existing challenges among the small-scale farmers in Africa, low N input and NUE remain critical areas of research, requiring more research emphasis, coupled with prioritized technological innovation for improved and sustainable management of N. Furthermore, lack of fertilizer recommendations for particular crops

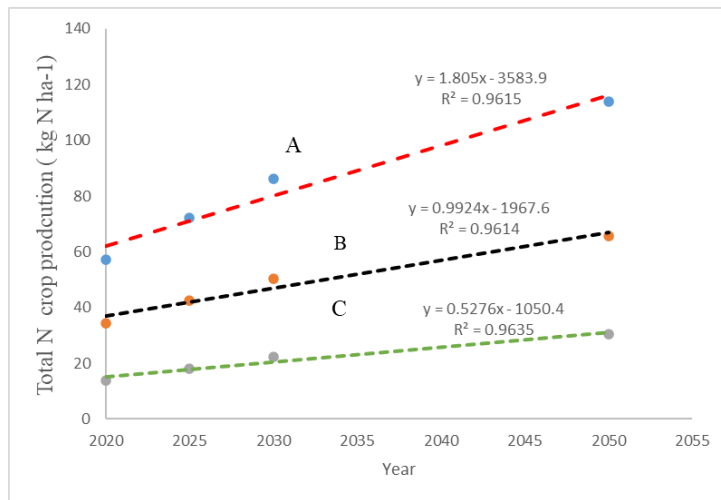
is also another cause of poor NUE values in African agriculture (Masso *et al.*, 2017; Gweyi-Onyango *et al.*, 2021) that could be confirmed from the current study.

#### **4.13 Total nitrogen crop production (TNCP)**

TNCP will increase linearly in rice crop production, with Nyando having the highest value of 57.20 to 114.02 kg N ha<sup>-1</sup>. Sondu catchment will have the least increment on TNCP with 13.89 to 30.46 kg N ha<sup>-1</sup> (Figure 4.13). Both Sondu and Nzoia will not have reached a target of 100 kg N ha<sup>-1</sup> by the year 2050 following the current recommendations. In maize, a similar linear change was observed; however, the values were lower than the change in rice farms. TNCP in the Nzoia catchment will change from 11.92 kg N ha<sup>-1</sup> in 2020 to 24.46 kg N ha<sup>-1</sup> in 2050. Sondu will have the least change of TNCP from 7.49 to 15.30 in 2020 and 2050, respectively (Figure 4.13). Furthermore, with the current projected increase, all the catchments will be below 100 kg N ha<sup>-1</sup> on TNCP over time.



**Figure 4.13: Changes in rice grain total N production in selected catchments over the years (A) for Nyando, (B) for Nzoia, and (C) for Sondu.**



**Figure 4.14: Changes in maize grain total N production in selected catchments over the years (A) for Nzoia (B) for Nyando, (C) for Yala, and (D) Sondu**

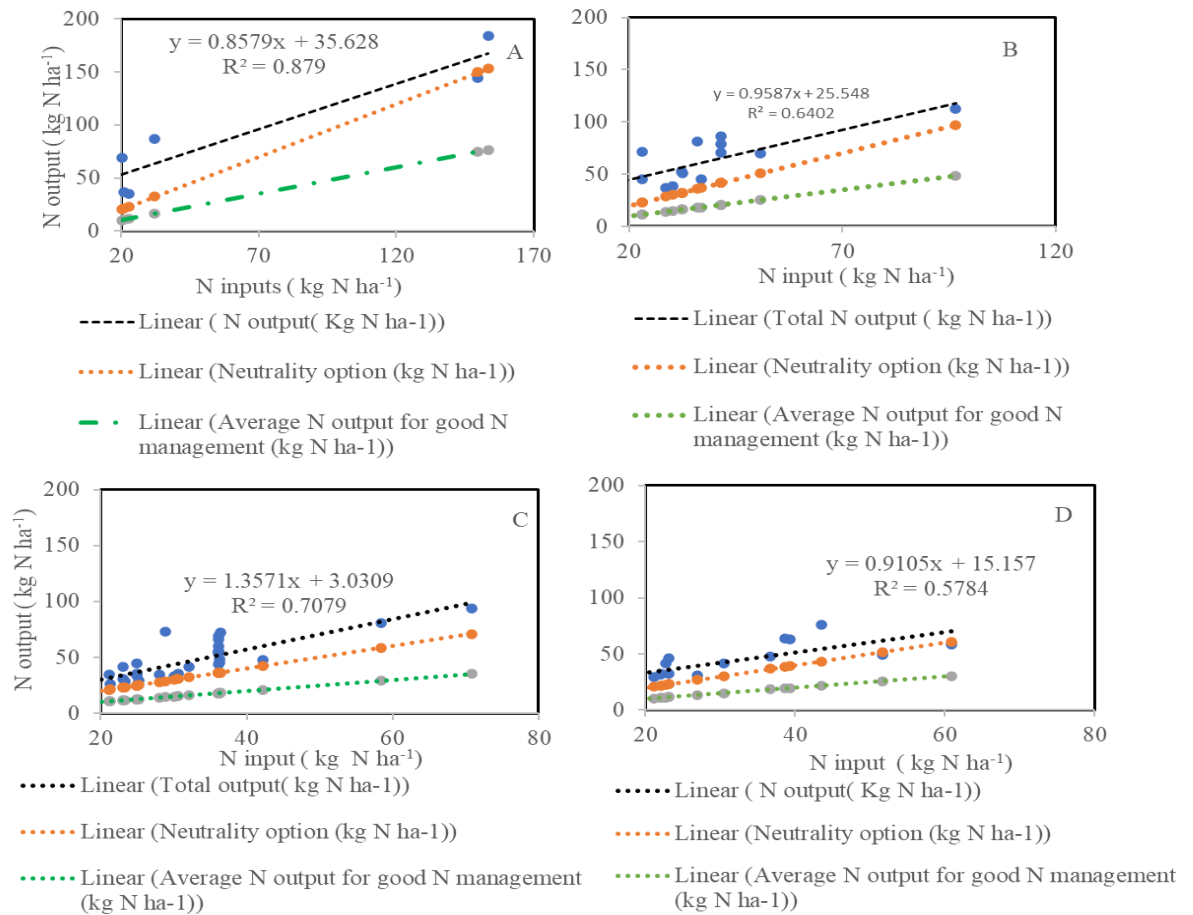
There will be an increase in TNCP for both maize and Rice in respective catchments as N inputs increase (Figures 4.14). Increasing TNCP is an agronomic performance

indicator and has significance towards food security. In East Africa specifically where food security remains a challenge for, many households to meet the dietary recommendations, improving and optimizing use of N in cropping systems remains critical. Currently, per capita, protein consumption is  $3.78 \text{ kg N cap}^{-1} \text{ yr}^{-1}$ , below the healthy recommended rate of  $4.0 \text{ kg cap}^{-1} \text{ yr}^{-1}$  (Food Security Information Network, 2018). Therefore, these findings show a clear connection of the widespread undernourishment in Africa due to the poor content of proteins in the locally grown food. Notably, in Eastern Africa, more than one-third of the population is undernourished, showing the need to improve TNCP in grain quality. The findings of this study agree with those of Elrys *et al.* (2020), who reported an increase in TNCP for African countries based on business as usual and equitable diet scenarios. From this finding, it was also reported that most of the nations would be less than  $100 \text{ kg N ha}^{-1}$  except Egypt, Malawi, South Africa, Mauritius, and Seychelles that will record a range of 209-105.  $\text{Kg N ha}^{-1}$ . N is a primary component of protein and amino acids, therefore possessing a solid linkage between increased N fertilization and quality of the foods for the population in SSA (Masso *et al.*, 2017).

#### **4.14 Relationship between N input and output**

The results revealed a positive relationship between N output and N input for farms with fertilization in maize cropping systems (Figure 4.15). The results also demonstrate the actual range of neutrality when N input equals the N output that strikes a system balance of the inputs. In addition, an average N output expected from the systems under good N management is also presented. Although a positive relationship between N outputs and N inputs ( $y= bx+c$ ) in all fertilized farms for the four catchments for maize

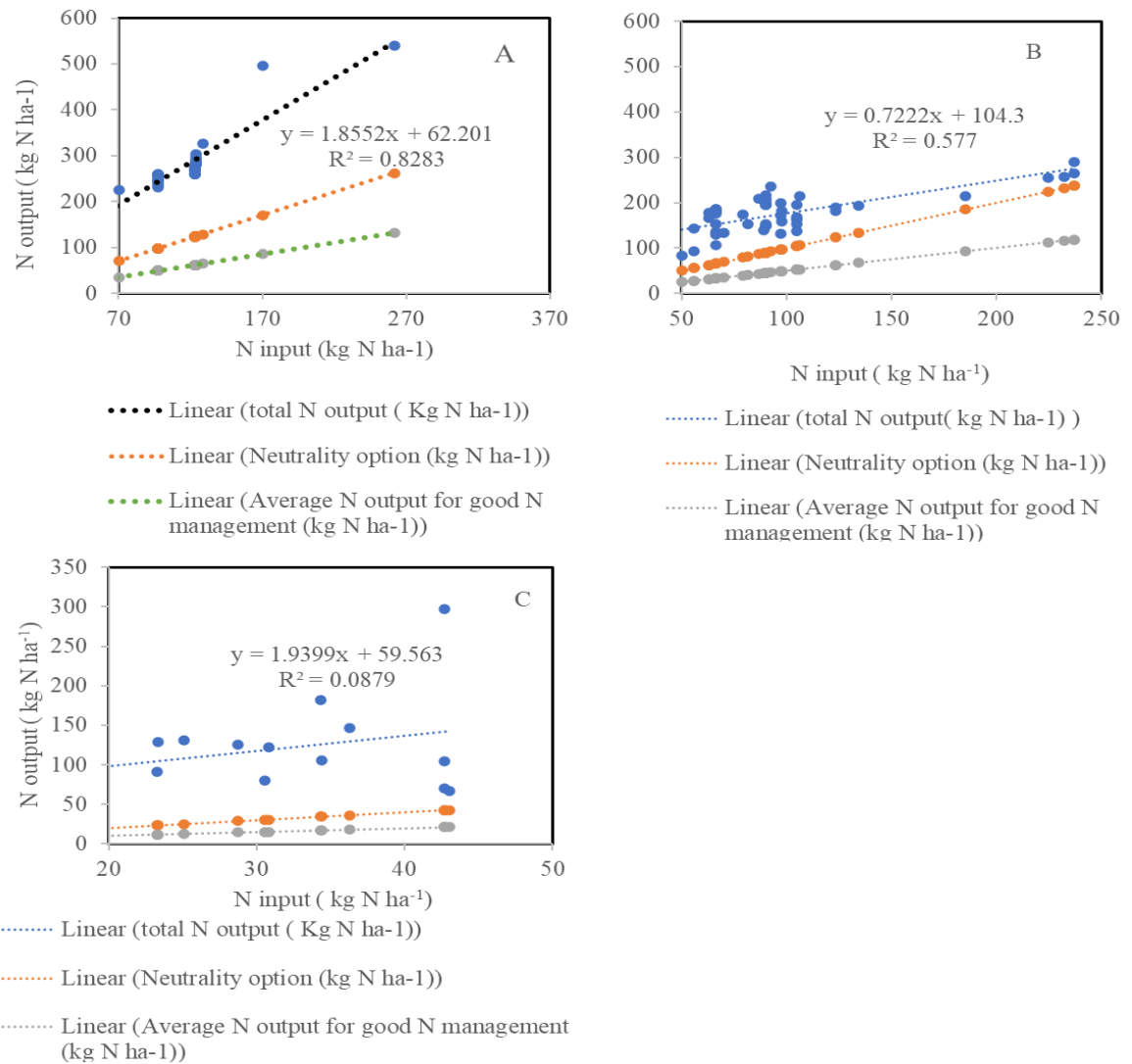
crops with  $r^2$  values ranging from  $r^2 = 0.88$  to  $r^2 = 0.58$ , depicting N imbalance in the system; - represented as ( $y=x$ ) (Figure 4.15).



**Figure 4.15: linear regression model between total N outputs (Kg N ha-1) and total N inputs (Kg N ha-1) in fertilized maize fields in Lake Victoria basin catchment; (A) Nyando; (B) Nzoia, (C) Yala; (D) Sondu**

All the observed values for all the catchments lay above the neutrality option ( $y= x$ ), illustrating N imbalances in the systems and scenarios of higher N removal than the input. The regression analyses revealed positive increase in N outputs with increasing N inputs. Indeed, having a higher nutrient removal than the applied amount has detrimental effects on the quality of soil due to continued depletion of available N

stocks. Moreover, the predicted N output average of good N management lies way below the actual regression line, a clear pointer that improved management strategies are critical for the LVB to strike a balance in the specific cropping systems



**Figure 4.16: linear regression model between total N outputs (Kg N ha-1) and total N inputs (Kg N ha-1) in fertilized rice fields in Lake Victoria basin catchment; (a) Nyando; (b) Nzoia, (c) Sundu.**

In rice cropping system, a similar scenario was observed with a positive linear relationship between N output and input ( $y = bx+c$ ) of the data set with varying  $r^2$  values ( $r^2 = 0.82$  and  $r^2 = 0.58$ ) in Nyando and Nzoia catchments respectively (Figure 4.16). However, the estimated values for neutrality of N output ( $y = x$ ) lay below the actual regression line. This is also a pointer of high removal N than the N input. In catchments with higher use of N fertilizer like Nyando, this could be due to lack of proper management of the available N for optimal NUE while in regions of low N input, increased soil N mining could be the reason (Figure 4.16). The low  $r^2$  values in Sondu catchment could be as result low N input evident in the site. Apart from the low N input, other factors including temperature, moisture and varieties influencing N uptake, yield and NUE. A beneficial increase would be realized if crop harvest were to increase as N inputs increase in a more integrated way to promote food security, ensure balanced systems, and prevent continued soil fertility depletion (Jones *et al.*, 2013). However, an increase in N inputs does not necessarily translate to a positive input-output relationship, and this could be due to the presence of other interacting factors such as rainfall, previous crop, crop N demand, field management, soil properties, and application methods that are dependent on the individual farm or specific regions (Tao *et al.*, 2018). In addition, there is need to integrate individual soil characteristics with field-specific fertilizer management practices for different crops to balance of nutrient is achieved (Tsujimoto *et al.*, 2019).

#### **4.15 Straw management practices and implications in N cycling**

Farmers within the selected catchments adopted various straw management strategies in their fields. The most dominant method of managing maize straws was feeding

livestock, as shown in Table 3. More than 85% of the Nyando and Nzoia farmers fed the maize straw to the livestock (Table 4.11). A significantly lower number of farmers either burn or sell their maize straw. Across the catchment, the proportion of farmers who manage maize straw from burning range between 7 and 25% (Table 4.11). The strategies for rice straw management included livestock feeding, burning and selling. In contrast, majority of the farmers especially, in Nyando (100%) and Nzoia (75%) burnt their rice straw (Table 3). There were no farmers, reported leaving straw in the field for the two crops.

**Table 4.10: Common straw management practices by farmers in various catchments (% percentage)**

	Catchment	Maize crop				Total
		N	Feed to livestock	Burn	Sell out	
Nyando	40	92.5	7.5	0	0	100
Nzoia	37	86.84	7.9	5.26	0	100
Sondu	44	70.45	25	4.55	0	100
Yala	37	72.97	24.32	2.71	0	100
		Rice crop				
Nyando	38	0	100	0	0	100
Nzoia	59	25.42	74.58	0	0	100
	38	39.47	28.95	31.58	0	100
Yala	-	-	-	-	-	-

**Key: Zero (0) -means there were no such practice for straw management, Dash (-) indicates no data was available for the specific catchment for rice crop. – indicate n in each catchment**

Feeding maize stover to livestock, especially under communal grazing system implies that N in the maize straws is exported out of the field, and the recycling process is neglected (Table 4.10). However, this could have been effective if farmers consider livestock manure as a source of nutrients in the cropping systems, as it would form a

viable strategy of developing a closed nutrient cycling system (Adegbeye *et al.*, 2020). The activity of burning the crop residues is associated with the emission of large amounts of GHG, including methane (CH<sub>4</sub>) and N<sub>2</sub>O, that are harmful to the environment (Romasanta *et al.*, 2017). Dobermann and Fairhurst (2002) demonstrated that burning rice straws resulted in an increase of N loss by 25% and, therefore, affecting the overall nutrient cycling process. With the current findings, policies and recommendations within the Lake Victoria Basin should focus on more sustainable methods of straw management to reduce pollution and the exportation of N from the farms. Some of the practices that could be useful in replenishing and recycling N in the soils include incorporating the straws into the field to improve soil quality through sequestration of carbon and soil nutrient buildup (Guan *et al.*, 2020; Ntinyari and Gweyi-Onyango, 2021). Limited knowledge on the best source of N fertilizer due to the lack/ weak extension services within the region also affects the potential of farmers in applying mineral N in their cropping systems. There are definitely gaps on good agronomic practices for farmers to adopt and enhance improved N utilization, for example composting or burying the crop stovers in the field to enhance N cycling over time.

#### **4.16 Implications and available opportunities**

According to this study, increasing the status of N in the soil to promote yield and optimize NUE is critical for the studied East Africa region. This has been revealed from the current NUE values representing various farmers into critical zones including “soil mining”, “safe operating zone,” and “region of inefficient N use”. From this study, it is evident that farmers use very low N input, hence most farms were aggregated into

the “soil mining” domain of the graphical presentation. The projections also show that poor NUE values will continue to be a serious threat in African cropping systems, which is associated with unbalanced fertilization, unless proper practices are encouraged. The unbalanced fertilization in both rice and maize cropping systems depicted a relationship operating above the expected and predicted range as result of poor management practices. Therefore, the optimization of NUE requires several practices like increasing the availability of N for plant uptake, for instance, using modified fertilizers, slow release, more efficient application of N fertilizer, and adopting site-specific N management (Yuan and Peng, 2017). There is need to focus more on crop N demand and uptake, possibly by genetic improvements to enhance N utilization, synchrony of growth season, N availability and demand as well as influence on NUE (Yadav *et al.*, 2017; Gweyi-Onyango 2021). In addition, balanced crop nutrition recommendations should be incorporated into soil fertility management practices, including organic applications (Masso *et al.*, 2017). Elrys *et al.* (2019) reported that solving soil fertility in African regions is not possible without using synthetic fertilizers. However, such progress requires effective agronomic management practices being put forward in all dimensions, including improved crop varieties. To increase the current low N inputs in cropping systems, better access to finance should be made available, and farmers encouraged to use them to access farm inputs. Alternative sources of N input such as organic manures, biofertilizers and biological nitrogen fixation can be explored to eliminate dependency on synthetic N sources (Ladha *et al.*, 2020). Regular trainings on methods to improve the application of N inputs in ways that limit losses need to be put into place (Elrys *et al.*, 2019). Through extension and training, farmers

can be encouraged to embrace the 4R stewardship, involving the right source, right time, right rate, and right placement methods of N fertilizer to increase N resource use efficiency. Creation of strong linkages and coordination between farmers, researchers, and policy-makers to improve the dissemination and implementation of new technologies on the overall management of farm nutrients are vital (Camara and Heinemann, 2006). Designing and strengthening policies to create an enabling environment for small-scale farmers to intensify their production systems can be done through implementation of fertilizers subsidy program and provide a chance to increase N input supplies.

#### **4.17 Uncertainties in the study**

Part of results presented in this type of study were obtained through in-person interviews with farmers, so all of the presented information was based on values reported by farmers rather than direct measurements in the field. The N concentration values are compared to the region's previous experiments (though quite limited). Farmers in the region practice communal grazing in open fields and along roads, making estimating manure inflows into the cropping system difficult. Simultaneously, a few people who keep animals in enclosed systems burn their manure. These factors make estimating N input from livestock manure difficult, and the assumptions on (N losses to air/water) affect potential NUE calculations.

Temperatures are expected to affect emissions, as is the stage of N supply to rice if done in splits, which is a challenge because the practice is not uniform across the three catchments. The method of application varies as well because broadcasting has the potential to contribute to more volatilization than deep placement or incorporation into

the soils, and these are not uniform across the three catchments. In addition, , there are gaps in this area, exacerbated by limited data on N flows in and across Africa.

On the contrary, there may be even more N depositions (from the air) within the catchments, particularly in the Nyando catchment, which is near Kisumu city and contains a number of industries, including three sugarcane processing factories. The assumption could be that particle sizes are smaller and more evenly distributed throughout the catchments in question. The N losses in irrigation water are also limited, but this can be partially offset by the contribution of N from farmlands where the rivers pass before reaching the study catchments' targeted farmers.

#### 4.18 Biomass accumulation, grain yield, and N partitioning

Biomass accumulation varied significantly ( $p \leq 0.05$ ) among the N use scenarios during vegetative (V6), reproductive (R1), and (physiological maturity (R 6) stages of maize production (Table 4.11).

**Table 4.11: Biomass accumulation of maize as influenced by various N use scenarios during maize phenological stages**

		Biomass accumulation (t ha <sup>-1</sup> )					
		Nyando			Rangwe		
N scenarios	Kg N ha <sup>-1</sup>	(v 6)	(R1)	(R 6)	(V 6)	(R 1)	(R 6)
BAU	0	0.17 <sup>c</sup>	2.45 <sup>b</sup>	5.47 <sup>b</sup>	0.13 <sup>c</sup>	2.68 <sup>b</sup>	4.44 <sup>b</sup>
25 %	12.5	0.39 <sup>b</sup>	3.25 <sup>b</sup>	8.91 <sup>a</sup>	0.35 <sup>ab</sup>	3.10 <sup>b</sup>	4.66 <sup>b</sup>
ADS							
50%	25	0.76 <sup>a</sup>	4.65 <sup>ab</sup>	10.17 <sup>a</sup>	0.37 <sup>ab</sup>	4.86 <sup>ab</sup>	6.62 <sup>ab</sup>
ADS							
ADS	50	0.72 <sup>a</sup>	7.00 <sup>a</sup>	10.42 <sup>a</sup>	0.42 <sup>a</sup>	6.27 <sup>a</sup>	8.62 <sup>a</sup>
<i>P-value</i>		0.002	0.002	0.004	0.04	0.03	0.004

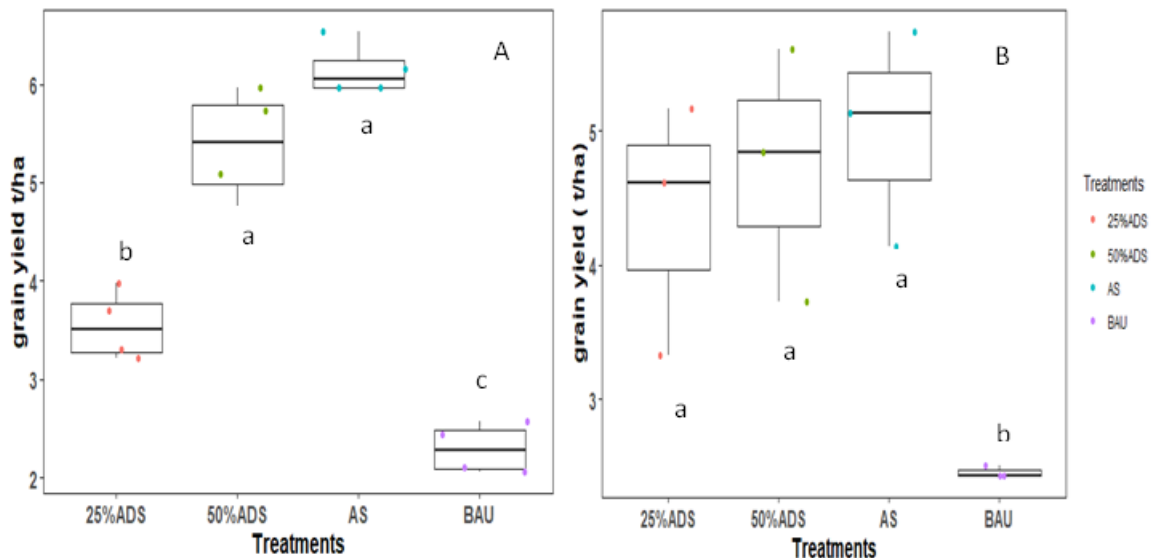
**Key** BAU- Business as Usual, 25 % ADS- Abuja declaration scenario AS- Abuja scenario; vegetative, reproductive, and harvesting = 30, 60, and 90 days after planting, respectively. V6 – vegetative stage, R1 -reproductive stage, R 6- Harvesting stage. In the same column, means with the same letter superscripts are not significantly different.

There was a significant increase in biomass accumulation from vegetative, reproductive, and maturity in the two catchments area (Table 4.12), with ADS (50 kg N ha<sup>-1</sup>) having the highest biomass accumulation of 0.72 – 10.42 t ha<sup>-1</sup> in Nyando and 0.42- 8.62 t ha<sup>-1</sup> in Rangwe across all the three phenological stages. The results indicate that more biomass could be achieved at higher N application.

These findings imply that increasing N fertilization reflected in the scenarios adopted in this study could result in more grain yield. Thus, this confirms that farmers need to change their current practices of little (or lack of) fertilizer application to more improved practices for higher yields to achieve food sufficiency and reduce the yield gap. Although the ADS of 50 kg ha<sup>-1</sup> results in incremental grain yield, exploring more alternative sources like animal manure and biological nitrogen fixation may be critical for the region for more sustainable production. These results are in concurrence with findings of others (Abbasi *et al.*, 2013; Hammad *et al.*, 2017; Chen *et al.*, 2017; Srivastava *et al.*, 2018) who reported an increasing trend on yield and growth under influence of N application. The lower biomass accumulation at the vegetative stage reported in this study agrees with Mueller and Vyn, (2018) who associated the low dry weight to reduced N uptake at vegetative as compared to silking and tasseling stages. Sen *et al.* (2016) also reported reduced biomass accumulation in maize crops grown in low N status than those supplied with N fertilizers. The higher biomass accumulation at the tasseling stage could be due to an increase in soil N status upon the second split application of the slow-release urea at the vegetative stage and the increased demand of N by the plants stage. Moreover, Nasielski and Deen, (2019) and Wang *et al.* (2017)

also reported a higher biomass accumulation of maize at reproductive stages under different N applications.

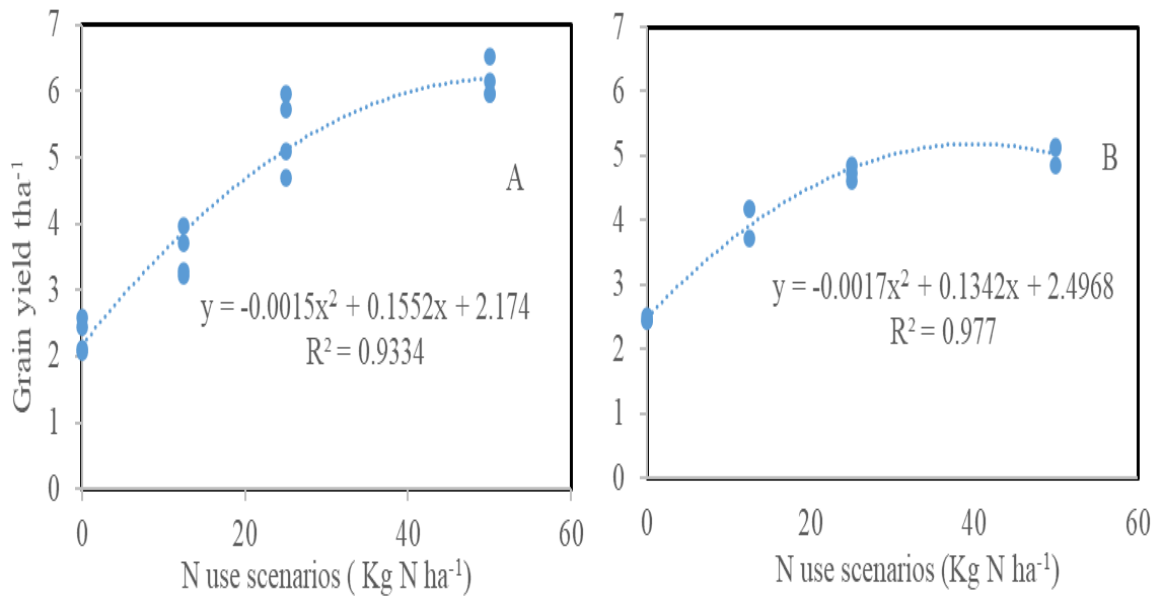
The different N use scenarios showed significant differences ( $p < 0.001$ ) in maize grain yield in the two catchments (Figure 4.19). A positive trend on grain yield increase with increasing N application rates was observed. In Nyando, a significant ( $p < 0.001$ ) difference was observed across the scenarios, with ADS 50 kg N ha<sup>-1</sup> having the highest yield of 6.15 t ha<sup>-1</sup> which was 167.39 % higher compared with the BAU (0 kg N ha<sup>-1</sup>) (Figure 4.17 A).



**Figure 4.17: Box plots of maize grain yield (A for Nyando and B for Rangwe) influenced by N use scenarios. Boxes and whiskers show 5 and 95% percentiles, boxes 25 % (Q1) and 75 % (Q3) quartiles, the line in the middle is the median while single dots indicate outlying values. Different lowercase letters denote significant differences between different treatments at  $p < 0.05$**

In Rangwe, a similar trend of maize yield was observed with ADS at 50 Kg N ha<sup>-1</sup>, recording the yield of 5.00 t ha<sup>-1</sup> which was 103.25 % higher than the BAU (0 kg N ha<sup>-1</sup>)

1). However, the yield differences were not significantly different between AS and the other two N scenarios (i.25% and 50 % ADS) in Rangwe. The regression analyses (Figure 4.18 A) showed that grain yield increased with N rates, and the response assumed polynomial function, with  $R^2$  values of 0.93 and 0.98 for Nyando and Rangwe, respectively. However, in Rangwe (Figure 4.18 B), the curve seems to plateau that could result from other factors, including calcium and potassium that were relatively low in the site, hence affecting N in the test variety.



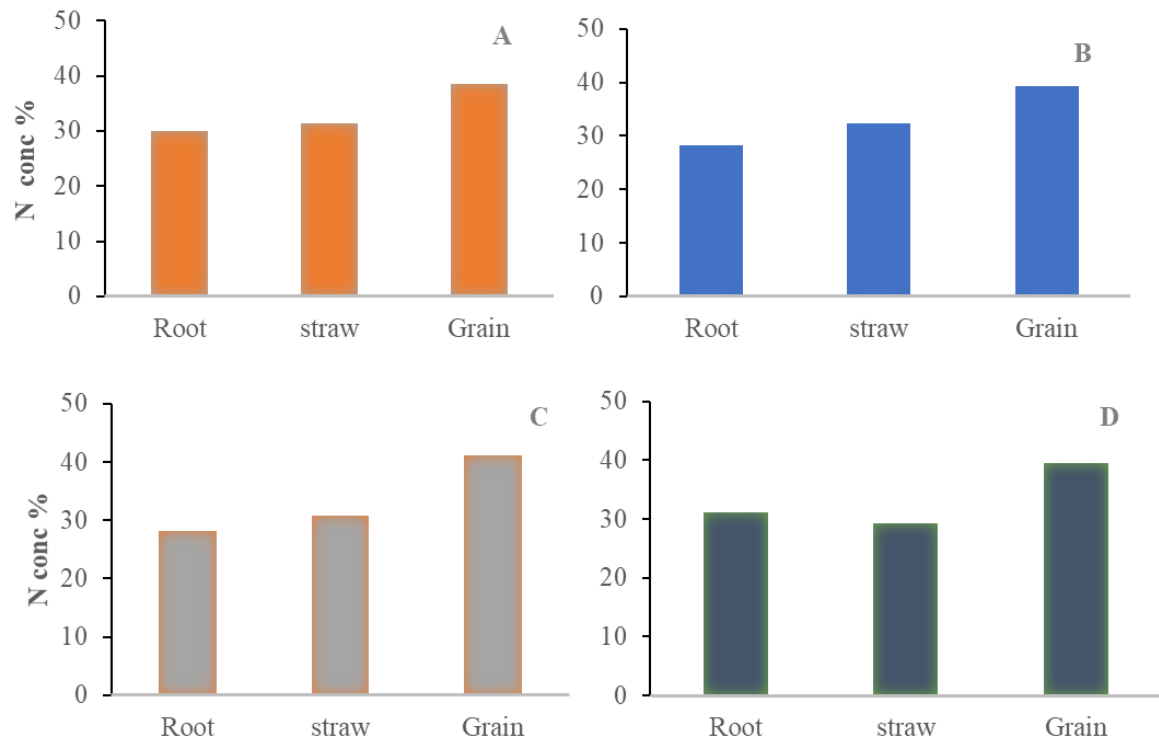
**Figure 4.18: Maize grain yield fertilizer as a polynomial function to N use scenarios in two catchments (A) Nyando and B-(Rangwe).**

The increase in yield without any plateaus in the regression lines signifies the need for more N to achieve food sufficiency. However, in Rangwe (Figure 4.18 B), the curve seems to plateau that could result from other factors, including calcium (Ca) and potassium (K) that were relatively low in the site, hence affecting N in the test variety.

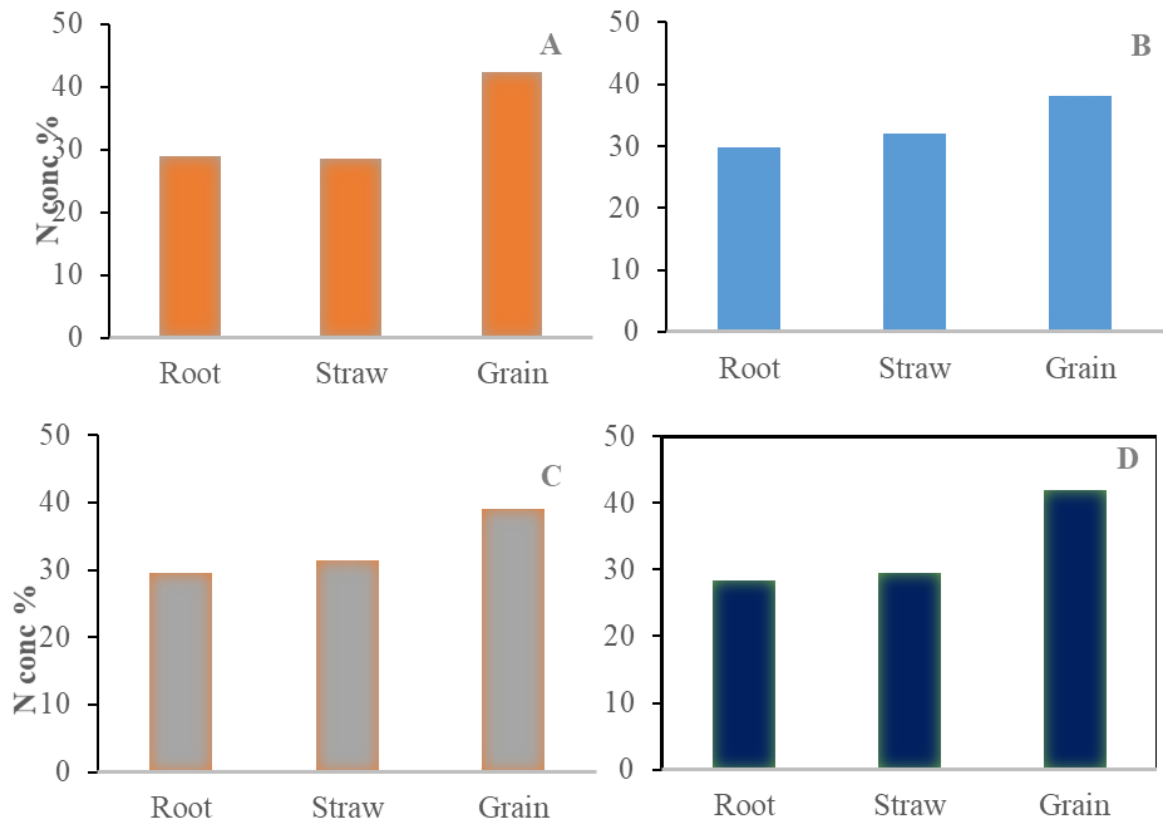
The significant increase in grain yield with N rates confirmed the potential of meeting the food needs and reducing the yield gap if more N fertilizers were used (Pasley *et al.*, 2019). In addition, the lack of a plateau in the yield response model indicates that the increasing N fertilizers to 50 kg N ha<sup>-1</sup> could not be optimum, specifically for soils reported to have negative N balances like the case of SSA (Figure 4.18 A). The variety (Sc Duma-43) used could also be more effective in scavenging for the available nutrients to promote growth and consequent positive increment in yield. Besides, the variety could be more effectively utilizing N use effectively although the rates used are lower to match the need for the crop. This may be a pointer that the rates used by the farmers are well below the plants' demands, which partially agrees with the low NUE in these sites. With optimal N management through proper application timing, specifically for slow-release fertilizers, there is a higher chance of obtaining a significant increase in yield (Grant *et al.*, 2012; Davies *et al.*, 2020). Although increasing application of N fertilizers may have a positive increase in both grain and stover yields, it may be difficult for some farmers in SSA due to financial constraints and therefore need for exploring alternative sources of N (Pasley *et al.*, 2019; Elrys *et al.*, 2020; IFDC, 2013). However, this can be made possible by increasing availability and subsidizing the cost of fertilizers, and exploring more organic sources of N. Therefore, policy instruments, including extension services, are critical for the region to offer technical efficiency in reducing the yield gap. This can be achieved by addressing N inputs management, including the timing for application for maximum yield as knowledge is limited (van *et al.*, 2020).

#### 4.19 Nitrogen partitioning

In all the N use scenarios, in both catchments, the highest N concentration was partitioned to the grain; representing 39.01- 42.07 % and 38.62-41.09 % of the entire plant uptake in both Nyando and Rangwe catchment areas (Figure 4.19 & 4.20). The results indicate that approximately 40% of N uptake removed from the field with the grain harvested for all nitrogen use scenarios. The lowest partitioning of N concentration was observed in the roots with mean percentage ranges of 28.19-31.19% and 28.41-29.85% in Rangwe, and Nyando respectively (Figure 4.19).



**Figure 4.19: Nitrogen partitioning as influenced by nitrogen use scenario A for BAU, B for 25% ADS, C for 50% ADS, D for Abuja Declaration scenario (ADS) in Rangwe catchment**



**Figure 4.20 Nitrogen partitioning as influenced by nitrogen use scenario A for BAU, B for 25% ADS, C for 50% ADS, D for Abuja Declaration scenario (ADS) in Nyando catchment**

The partitioning of about 50% of nitrogen into the root and the straw is an indicator practice of N recycling specifically for farms where ploughing is done to incorporate both the straw and the roots in the soils after harvest (Figure 4.19 & 4.20). These findings can be used to guide policy and decision-making on straw management as a way of improving N management sustainability. Enlightening farmers through local extension services on the benefits of incorporating straws into the soils other than burning or feeding to livestock would be a milestone towards increasing nitrogen recycling into the cropping systems for the region. The higher concentration of N in the

grain is an indicator of N recovery from the cropping systems and the proportion of N that is exported from the field. According to Yesuf, and Balcha, (2014) having a higher NHI is a measure of higher nitrogen transformed to the grain. However, this does not mean there is sufficient fertilization particularly in the case of this study where unfertilized plot had almost similar NHI values with fertilized plot. Similar results were reported by Ntinyari, (2018) and Gweyi-Onyango, (2018) where there no significant differences on NHI in harvested rice crops due to reduced reserves of N in the soil during the crop growth season. The findings agree with Ning *et al.* (2017), who reported a significant decrease in N concentration in the stover and a higher increase of N concentration in the grain of maize both under low and high nitrogen inputs.

#### **4.20 Nitrogen balance indicators**

Agro-Physiological Nitrogen Efficiency ( $APE_N$ ) was not significantly ( $p < 0.05$ ) different among the N use scenarios in the two catchments. However, there was a clear trend with the highest N inputs (ADS-  $50 \text{ kg N ha}^{-1}$ ) having higher  $APE_N$  values. The lack of differences could be influenced by the N scenario adopted in this study being too low to affect maize grain significantly. Moreover, degraded soils could have contributed to the lack of differences and N inputs being too low. The ADS scenario at  $50 \text{ kg N ha}^{-1}$  recorded the highest  $APE_N$ , with a mean value of  $57.60 \text{ kg grain kg}^{-1} \text{ N}$  in Rangwe and  $51.7 \text{ kg grain kg}^{-1}$  in Nyando catchment. In both catchments, all N use scenarios achieved the recommended  $APE_N$  level of between  $40\text{-}60 \text{ kg grain kg}^{-1} \text{ N}$  (Table 4.12).

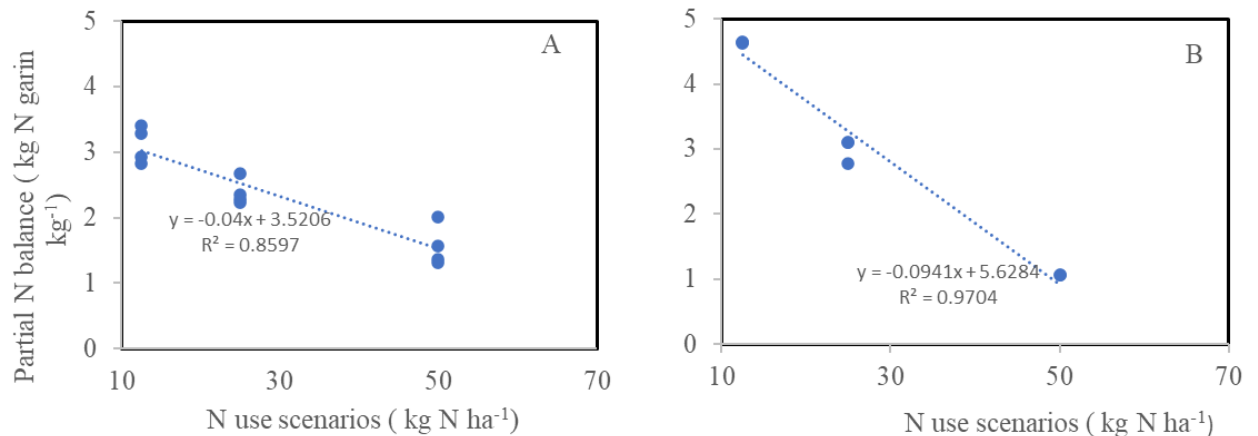
**Table 4.12: Effects N use scenarios fertilizers on nitrogen use efficiencies and partial N balance maize**

N use Scenarios	Kg ha <sup>-1</sup>	Nitrogen use efficiency					
		Nyando			Rangwe		
		N	APE <sub>N</sub>	PNB	NS /D	APE <sub>N</sub>	PNB
BAU	0	n.a	n.a	-66.6 <sup>a</sup>	n.a	n.a	-62.5 <sup>a</sup>
25 % ADS	12.5	47.4 <sup>a</sup>	3.11 <sup>a</sup>	-109.1 <sup>b</sup>	52.4 <sup>a</sup>	4.64 <sup>a</sup>	-82.4 <sup>ab</sup>
50 % ADS	25	48.9 <sup>a</sup>	2.39 <sup>b</sup>	-125.7 <sup>b</sup>	45.4 <sup>a</sup>	2.99 <sup>ab</sup>	-105.4 <sup>b</sup>
ADS	50	51.7 <sup>a</sup>	1.56 <sup>c</sup>	-119.6 <sup>b</sup>	57.6 <sup>a</sup>	1.10 <sup>b</sup>	-63.30 <sup>a</sup>
P Value		0.030	0.001	0.001	0.75	0.013	0.001

**Key: BAU- Business as Usual, 25 % ADS- Abuja declaration scenario ADS- Abuja scenario; APE<sub>N</sub>- Agro Physiological Nitrogen Efficiency, PNB-Partial N Budget, NS/D- Nitrogen surplus/deficit n.a- not applicable. In the same column, means with the same letter are not significantly different**

Agro-Physiological Nitrogen Efficiency (APE<sub>N</sub>) of maize across the scenarios varied in the two catchments expressing the plants' ability to transform nutrients applied into economic yield (Table 4.12). The increasing trend in APE<sub>N</sub> values obtained in this study could suggest that an additional supply of more N inputs into the soils would lead to a positive contribution of the maize crop to transform the acquired N into economic yield. Therefore, achieving an optimal NUE for maize crops requires increment of N inputs as confirmed in this study and also agrees with the projection's analysis for Elyrs *et al.* (2020) on Africa achieving food sufficiency in 2050. The APE<sub>N</sub> values for ADS (50 kg N ha<sup>-1</sup>) results in the Rangwe catchment agreed with Fixen *et al.* (2015), who reported APE<sub>N</sub> optimal values of 40-60 kg grain kg<sup>-1</sup>. The results are also supported by the findings of Snyder & Bruulsema (2007), who suggested that APE<sub>N</sub> values >50 kg/kg could be obtained in low N use in some of the properly managed systems.

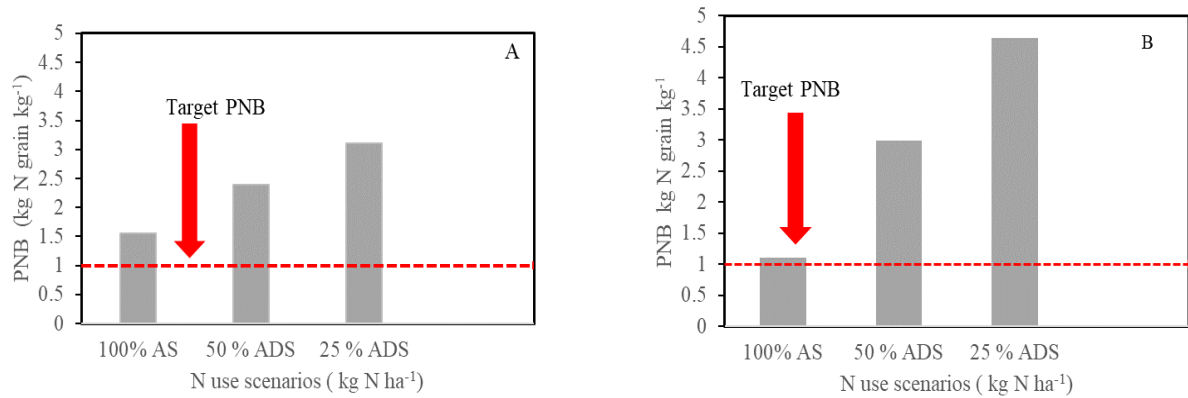
N surplus/ deficit of maize varied significantly ( $p < 0.001$ ) across all the scenarios in the two catchments evaluated (Table 4.13). The 50 % ADS ( $25 \text{ kg N ha}^{-1}$ ) had the largest N deficit of  $-125$  and  $-105 \text{ kg N ha}^{-1}$  in Nyando and Rangwe catchments. This indicates the addition of more N input could optimize N and reduce the negative imbalances in the soils; however, the  $50 \text{ kg N ha}^{-1}$  suggested at the Abuja fertilizer summit is still very low for maize crop to contribute to the optimization of overall NUE. Negative values of N balance observed in all the scenarios in the two catchments (Table 4.13), implied higher crop removal of N compared to N input, a process that is likely to contribute to extreme depletion of the soil N status. The N deficits indicate that even with the implementation of the Abuja recommendation, the soil fertility will still decline due to continuous mining.



**Figure 4.21: Relationship between Nitrogen use scenarios and partial N balance for two study catchments A for Nyando and B for Rangwe**

The partial Nitrogen balance (PNB) of maize varied significantly ( $p < 0.001$ ) across all the N use scenarios evaluated in the two catchments (Table 4.13). The 25 % ADS ( $12.5 \text{ kg N ha}^{-1}$ ) had the highest values of PNB of  $3.11 \text{ kg grain N (kg N)}^{-1}$  in Nyando, while

50 % ADS (25 kg N ha<sup>-1</sup>) and AS (50 kg N ha<sup>-1</sup>) had 2.39 and 1.56 kg grain N (kg N)<sup>-1</sup> PNB, respectively.



**Figure 4.22: Graphical representation of Partial N balance across the N use scenarios and the target values A for Nyando catchment, B for Rangwe catchment**

A similar reducing trend of PNB with an increase N was also observed at Rangwe. The declining trend of PNB with N was linear (Figure 4.22, Table 3). Moreover, ADS (50 kg N ha<sup>-1</sup>) fertilizer application resulted in a near-optimal PNB of 1.10 kg grain N (kg N)<sup>-1</sup> (Figure 4.22). The higher N application rate resulted in values closer to optimal PNB, while the low N rates had higher values, far from the optimal range. Figure 4.23 confirmed a strong association between nitrogen scenarios and Partial N balance for both Nyando and Rangwe study sites. The increase of N application rates as defined by the N use scenarios resulted in lowering partial N balance with  $r^2 = 0.86$  and  $0.97$  for Nyando and Rangwe, respectively (Figure 4.21). Partial Nitrogen Balance (PNB) that expressed the nutrient output per unit of nutrient input varied significantly across the scenarios. The values observed in this study were above the typically optimal range that indicates insufficient or low N level of the applied fertilizer. The PNB showed that the amount of N used was not sufficient to supply the required quantity of N to optimize

NUE hence a need for an increased application. Increasing the N rate from the current AS scenario could lead to more sustainable PNB in the region, a fact that is supported by the positive regression in Figure 4.22. With no plateaus observed in the regression lines, it may be an indication that increasing more N for the two regions would result in desirable PNB values (lower than <1) (Figure 4.22). Besides, the high PNB values >1 imply that more nutrients were being removed from the plot than what was applied: a situation of soil N mining. Therefore, there is lack of a mass balance between N used and N removed in the crop, with precise/optimal ranges shown in Figure 4.22. The current findings agree with those of Snyder and Bruulsema (2007), who suggested that a PNB value close to 1 is an indicator of the nutrient's mass balance and higher than one shows extreme deficits in the systems. However, this was not achieved in the current experiment, and this could probably mean more N input needs to be added to correct the existing deficiencies of mineral N inputs. Similar results of higher PNB greater than 1 were also reported by Fixen *et al.* (2015) in the global PNB analysis, with SSA having the highest values.

#### **4.21 Agronomic performance**

Agronomic Efficiency of Nitrogen ( $AE_N$ ) had significant differences across the N use scenarios in the two catchments.  $AE_N$  depicts the efficiency of N recovery from the applied fertilizers in grain yield. In all the N use scenarios, the  $AE_N$  obtained was greater than the common values of 10-30 kg grain ( $\text{kg N}^{-1}$ ) (Table 4.14). Total Nitrogen crop Production (TNCP) increased significantly at  $p < 0.001$  across N use scenarios in the two catchments. The ADS at  $50 \text{ kg N ha}^{-1}$  recorded the highest TNCP ( $30.30 \text{ kg N ha}^{-1}$  in Nyando) and  $25.3 \text{ Kg N ha}^{-1}$  in Rangwe catchments (Table 4.14). Shifting from

the Intermediate scenario (12.5 kg N ha<sup>-1</sup>) to the Abuja scenario would lead to 154.27 % and 214.21 % increment on the TNCP in Rangwe and Nyando catchment, respectively.

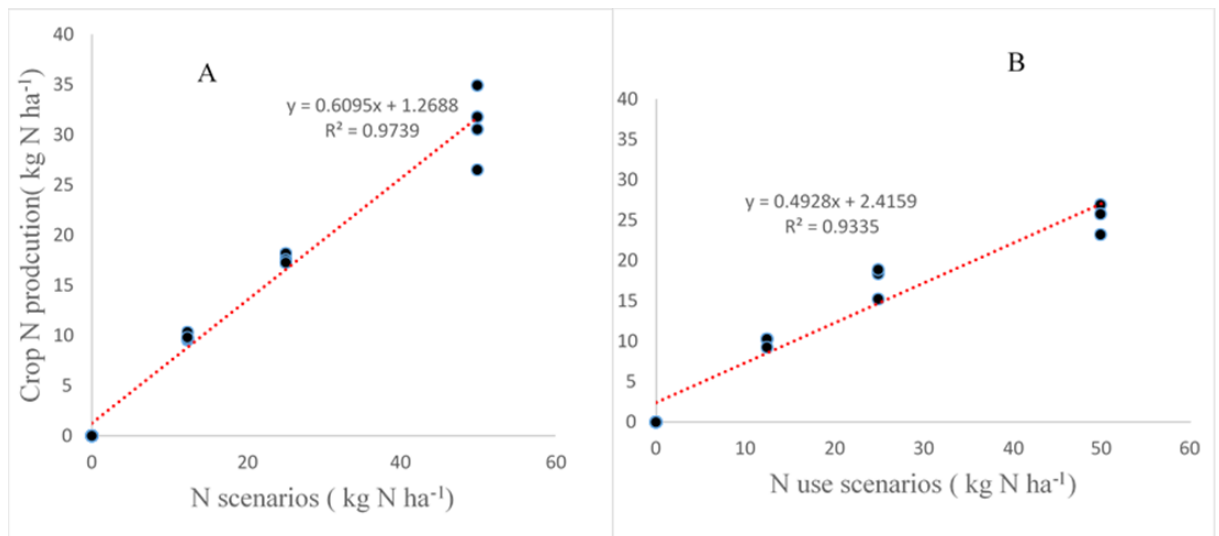
**Table 4.13 Effects N use scenarios fertilizers on Agronomic Nitrogen Efficiency (AEN) on maize**

	Nyando			Rangwe		
	TNCP	AE	IEN	TNCP	AE <sub>N</sub>	IEN
BAU	-	-	-	-	-	-
25 % ADS	9.45 <sup>c</sup>	118.7 <sup>ab</sup>	43.19 <sup>a</sup>	9.95 <sup>c</sup>	154.3 <sup>a</sup>	34.37 <sup>a</sup>
50 % ADS	17.60 <sup>b</sup>	132.1 <sup>a</sup>	42.45 <sup>a</sup>	17.51 <sup>b</sup>	103.0 <sup>a</sup>	31.97 <sup>a</sup>
ADS	30.30 <sup>a</sup>	81.7 <sup>b</sup>	49.38 <sup>a</sup>	25.3 <sup>a</sup>	45.4 <sup>b</sup>	33.83 <sup>a</sup>
P -value	***	0.02	0.30	***0.001	0.01	0.88
	0.001					

**Key; TNCP/ total nitrogen crop production, AE- Agronomic efficiency, IEN-Internal utilization efficiency of N. BAU- Business as Usual, ADS- Abuja declaration scenario AS- Abuja scenario; In the same column, means with the same letter are not significantly different. AE<sub>N</sub>- Agronomic efficiency of nitrogen. TNCP- total nitrogen crop production, IEN- internal utilization efficiency of N (-dash means- parameter could not be estimated)**

The values obtained were between 81.7 -118.7 kg grain (kg N)<sup>-1</sup>) in Nyando and 45.4-154.3 kg grain (kg N)<sup>-1</sup>) in Rangwe catchment, which are higher values than 30 kg grain (kg N)<sup>-1</sup>) implying the amount of N fertilizer supplied were very low to optimize AE<sub>N</sub>. The results on AE<sub>N</sub> showed that by increasing the N fertilization rate to 50 kg ha<sup>-1</sup> as the recommendation in the Abuja Fertilizer summit, there is a possibility of optimizing AE<sub>N</sub> (Table 4.13), particularly for Rangwe site though the optimal range was not achieved, there was a significant milestone towards enhanced insights on the sustainability of the agricultural system. The decreasing trend of AE<sub>N</sub> with increase in N fertilizer application rates indicates that with more N, there are possibilities of achieving an optimal value of AE<sub>N</sub> for cereal crops between 10- 30 kg grain (kg N)<sup>-1</sup>). The AE<sub>N</sub> values greater than 30 kg grain (kg N)<sup>-1</sup>) as reported by Vanlauwe *et al.* (2011)

demonstrated that lower N rates resulted in higher  $AE_N$  in the African context that strongly agrees with the findings of this experiment. In addition to increasing N fertilizer input, hybrid maize varieties are also recommended to optimize  $AE_N$  for the region. Narrowing the agronomic use efficiency gap for the region can be achieved by increasing addition of N input coupled with improved management practices.



**Figure 4.23: Relationship of Nitrogen use Scenarios and Total Crop production (kg N ha<sup>-1</sup>) in A- Nyando and B- Rangwe catchments**

According to Ahrens *et al.* (2010) higher values of  $AE_N$  result from fields with depleted soil N pools and due to less fertilization, which is an implication that the current study did not achieve adequate N input to obtain optimized  $AE_N$  values. In addition, there is need to understand other factors contributing to high  $AE_N$  beyond the optimal values at farm level as way of addressing the existing gap for example by including improving fertilization (Ahrens *et al.* 2010). The increasing total Nitrogen crop production (TNCP) with increasing N input, (Figure 4.22) has a favorable implication on the human diet

(high protein content), specifically for sub-Saharan Africa, where malnutrition is a severe challenge. However, although there is an increase in TNCP in AS scenario, the study shows that the transition to the recommended rate of 50 kg N ha<sup>-1</sup>, will still result in a TNCP below 100 kg N ha<sup>-1</sup> (Elrys *et al.*, 2020). Therefore, a shift to increase N fertilization for increased yield is required to optimize NUE for the Lake Victoria region. In the approach to determine TNCP, the assumption is that N is the critical limiting factor in crop production, although other factors like water availability, crop mix, and other macro and micronutrients may affect the agronomic performance of the crop. Similar findings were reported by Elrys *et al.* (2020), who reported an increase in TNCP from 15- 22 kg N ha<sup>-1</sup> in Africa with an increase in N fertilizer inputs; considering different socio-economic scenarios. In addition, Lassaleta *et al.* (2016) suggested that increasing TNCP could be possible by adopting improved agronomic practices for production.

Internal utilization efficiency N (IE<sub>N</sub>) did not show any significant ( $p < 0.05$ ) differences among the N use scenarios evaluated. In Nyando catchment, the highest IE<sub>N</sub> of maize was observed in ADS (50 kg N ha<sup>-1</sup>) at 49.38, representing 16.32 % and 14.02 % higher than 50 % ADS and 25% ADS, respectively (Table 4.14). In rangwe catchment, the highest IE<sub>N</sub> was observed in an intermediate scenario with 34.37, while the lowest was 50% ADS with 31.97. Furthermore, the IE<sub>N</sub> was within the recommended range of 30-90 in the two catchments, but none achieved optimal recommended values (55-65). IEN values observed in this study in Nyando study sites (Table 4.13) were within the range, showing the ability of the plant to acquire and transform N applied from other sources. In the current study, the 40-60 kg/kg range

agrees with those of Brentrup and Pallière, (2010) and EUNEP, 2015). In Rangwe study site, IE values were relatively lower and suggested that the N scenarios resulted in the poor internal conversion of N due to existing deficiencies in the soils.

#### **4.22 Nitrogen uptake and mineral N dynamics**

Nitrogen uptake by the maize crop varied significantly ( $p < 0.05$ ) across the three growth stages, vegetative, reproductive, and maturity, in the two catchments. In Nyando, the N accumulation at the vegetative stage increased significantly ( $p < 0.05$ ) from (3.85- 16.25 Kg N ha<sup>-1</sup>) to (59.0 to 209 .1 kg N ha<sup>-1</sup>) at tasseling and silking stages (Table 4.14). A significant ( $p < 0.05$ ) decrease in N uptake was observed at the maturity stage for the different N use scenarios. However, the highest mean of N uptake was observed in ADS at 50 kg N ha<sup>-1</sup> with 86.9 kg N ha<sup>-1</sup> while the lowest mean was with BAU at 0 kg N ha<sup>-1</sup> with 49.3 kg N ha<sup>-1</sup>. In Rangwe catchment, a similar trend was observed with a significant ( $p < 0.05$ ) increase in N uptake from the vegetative state (3.07- 8.42 kg N ha<sup>-1</sup>) to (52.4-202.8 kg N ha<sup>-1</sup>) during tasseling. A decline in N uptake was observed at maturity at ADS with 110.9 kg N ha<sup>-1</sup> (Table 4.14). At the vegetative and maturity stage, the unfertilized scenario (0 kg N ha<sup>-1</sup>) had the lowest N accumulation than other N use scenarios with values ranging from 3.07 kg N ha<sup>-1</sup> and 89.4 kg N ha<sup>-1</sup>. A significantly higher whole plant N uptake was observed as the N fertilizer rate increased and played a critical role in maize crop growth (Table 4.14). At early vegetative stages, the N uptake was due to the availability of essential nutrients in the maize kernel, facilitating development hence making the available soil N not quite critical.

**Table 4.14: Mean Nitrogen uptake (kg N ha<sup>-1</sup>) at different maize growth stages**

N uptake kg N ha <sup>-1</sup>								
N scenarios	use	Kg N ha <sup>-1</sup>	Nyando			Rangwe		
			(V 6)	(R1)	(R 6)	(V 6)	(R1)	(R 6)
BAU	0	3.85 <sup>b</sup>	59.0 <sup>bc</sup>	49.25 <sup>b</sup>	3.07 <sup>b</sup>	87.7 <sup>b</sup>	89.4 <sup>a</sup>	
25% ADS	12.5	8.48 <sup>ab</sup>	66.6 <sup>c</sup>	65.8 <sup>ab</sup>	7.53 <sup>a</sup>	52.4 <sup>b</sup>	98.3 <sup>a</sup>	
50% ADS	25	15.60 <sup>a</sup>	160.6 <sup>b</sup>	68.71 <sup>ab</sup>	7.92 <sup>a</sup>	117.9 <sup>ab</sup>	118.5 <sup>a</sup>	
AS	50	16.25 <sup>a</sup>	209.1 <sup>a</sup>	86.9 <sup>a</sup>	8.42 <sup>a</sup>	202.8 <sup>a</sup>	110.9 <sup>a</sup>	
P value		0.02	0.04	0.05	0.04	0.01	0.61	

**Key BAU- Business as Usual, 25 % ADS- Abuja declaration scenario AS- Abuja scenario; vegetative, reproductive, and harvesting = 30, 60, and 90 days after planting, respectively. V6 – vegetative stage, R1 -reproductive stage, R 6- Harvesting stage. In the same column, means with the same letter superscripts are not significantly different.**

Similar arguments are in line with the finding of Montemurro *et al.* (2006) with minimal uptake of N at vegetative stages of maize growth. The significant increase in N uptake at reproductive stages is due to the high demand by the plant to meet the N nutrition requirements for tasseling and silking. Therefore, it implies that more available N is required to match the crop N demands and create a balance to eliminate mining and depletion of the soil N status. Improving this synchrony between N supply and crop N uptake is key to enhancing overall NUE. The high N uptake observed at the reproductive stage could also be influenced by increased remobilization of N from the stalks and leaves to the grain during the grain-filling process (Yang *et al.*, 2016). The decrease in N uptake at maturity is supported by the findings of Asibi *et al.* (2019), which could be due to N supply that decreases the dry matter partitioning to grain. Therefore, increasing N input rate and timing are critical to match the specific crop N demands, as revealed in this study.

There were variations of mineral N (NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>) in the soil during different growth stages of maize in the two catchment areas. A variation was also evident in different

depths (20cm and 40 cm) in mineral N concentration (Table 4.15 and 4.16). The  $\text{NH}_4^+$  concentration was more dominant during the vegetative stage in both depths 20 cm and 40 cm in the two catchments. There was no statistical significance ( $p < 0.05$ ) in mineral N concentration during the growth stages except for Ahero during reproductive stages, where  $\text{NH}_4^+$  showed significant differences across the different N use scenarios with 50 % ASD having a concentration of  $75.7 \text{ mg N kg}^{-1}$

**Table 4.15: Mineral N dynamics at depths (0-20 cm, 20-40 cm) and different growth stages.**

soil depth 20cm)						
Nyando	V6		R1		R6	
Treatments	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )
BAU	108.0 <sup>a</sup>	47.6 <sup>a</sup>	60.5 <sup>ab</sup>	22.1 <sup>a</sup>	23.7 <sup>a</sup>	14.9 <sup>a</sup>
25% ASD	100.0 <sup>a</sup>	46.5 <sup>a</sup>	42.3 <sup>b</sup>	20.9 <sup>a</sup>	24.4 <sup>a</sup>	18.6 <sup>a</sup>
50% ASD	96.0 <sup>a</sup>	50.4 <sup>a</sup>	75.7 <sup>a</sup>	28.2 <sup>a</sup>	28.5 <sup>a</sup>	21.5 <sup>a</sup>
100% ASD	108.0 <sup>a</sup>	47.5 <sup>a</sup>	51.9 <sup>ab</sup>	22.1 <sup>a</sup>	21.2 <sup>a</sup>	17.5 <sup>a</sup>
Soil depth 40cm						
	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )
BAU	108.0 <sup>a</sup>	43.8 <sup>a</sup>	41.5 <sup>a</sup>	18.9 <sup>a</sup>	23.1 <sup>a</sup>	18.5 <sup>a</sup>
25% ASD	100.7 <sup>a</sup>	46.0 <sup>a</sup>	43.8 <sup>a</sup>	21.0 <sup>a</sup>	24.6 <sup>a</sup>	18.4 <sup>a</sup>
50% ASD	96.3 <sup>a</sup>	47.3 <sup>a</sup>	48.3 <sup>a</sup>	21.4 <sup>a</sup>	25.1 <sup>a</sup>	18.5 <sup>a</sup>
100% ASD	102.1 <sup>a</sup>	48.1 <sup>a</sup>	50.3 <sup>a</sup>	23.6 <sup>a</sup>	26.4 <sup>a</sup>	18.8 <sup>a</sup>

**Key BAU- Business as Usual, 25 % ADS- Abuja declaration scenario AS- Abuja scenario; vegetative, reproductive, and harvesting = 30, 60, and 90 days after planting, respectively. V6 – vegetative stage, R1 -reproductive stage, R 6- Harvesting stage. In the same column, means with the same letter superscripts are not significantly different.**

**Table 4.16: Mineral N dynamics at depths (0-20 cm , 20-40 cm) and different growth stages at rangwe catchment.**

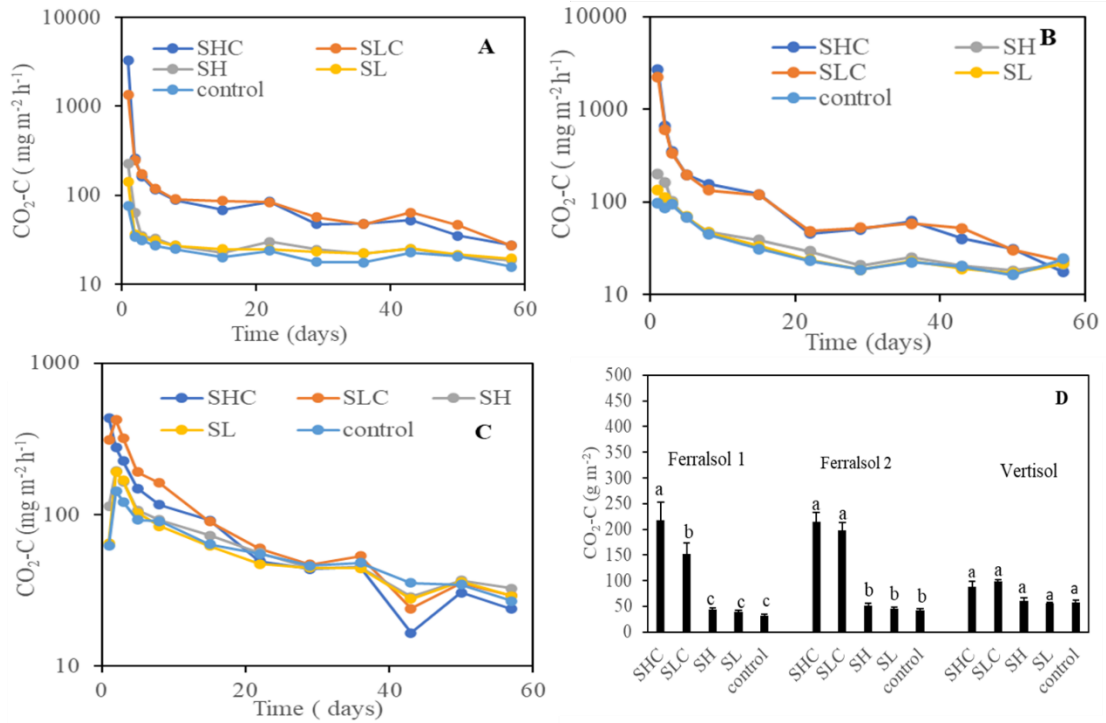
Rangwe	V6		R 1		R6	
	soil depth (20cm)					
Treatments	NH <sup>+</sup> <sub>4</sub> (mg N kg <sup>-1</sup> )	NO <sup>-</sup> <sub>3</sub> (mg N kg <sup>-1</sup> )	NH <sup>+</sup> <sub>4</sub> (mg N kg <sup>-1</sup> )	NO <sup>-</sup> <sub>3</sub> (mg N kg <sup>-1</sup> )	NH <sup>+</sup> <sub>4</sub> (mg N kg <sup>-1</sup> )	NO <sup>-</sup> <sub>3</sub> (mg N kg <sup>-1</sup> )
BAU	133.0 <sup>a</sup>	46.7 <sup>a</sup>	54.7 <sup>a</sup>	20.6 <sup>a</sup>	27.6 <sup>a</sup>	11.6 <sup>a</sup>
25% ASD	126.0 <sup>a</sup>	49.6 <sup>a</sup>	74.9 <sup>a</sup>	28.0 <sup>a</sup>	33.1 <sup>a</sup>	10.1 <sup>a</sup>
50% ASD	118.0 <sup>a</sup>	48.1 <sup>a</sup>	59.7 <sup>a</sup>	24.5 <sup>a</sup>	23.9 <sup>a</sup>	10.3 <sup>a</sup>
100% ASD	115.0 <sup>a</sup>	49.6 <sup>a</sup>	45.8 <sup>a</sup>	18.4 <sup>a</sup>	24.2 <sup>a</sup>	13.4 <sup>a</sup>
soil depth (40cm)						
	NH <sup>+</sup> <sub>4</sub> (mg N kg <sup>-1</sup> )	NO <sup>-</sup> <sub>3</sub> (mg N kg <sup>-1</sup> )	NH <sup>+</sup> <sub>4</sub> (mg N kg <sup>-1</sup> )	NO <sup>-</sup> <sub>3</sub> (mg N kg <sup>-1</sup> )	NH <sup>+</sup> <sub>4</sub> (mg N kg <sup>-1</sup> )	NO <sup>-</sup> <sub>3</sub> (mg N kg <sup>-1</sup> )
BAU	122.0 <sup>a</sup>	46.1 <sup>a</sup>	45.2 <sup>a</sup>	17.1 <sup>a</sup>	25.9 <sup>a</sup>	8.43 <sup>a</sup>
25% ASD	132.0 <sup>a</sup>	55.5 <sup>a</sup>	62.8 <sup>a</sup>	23.7 <sup>a</sup>	25.1 <sup>a</sup>	7.55 <sup>a</sup>
50% ASD	101.0 <sup>a</sup>	46.6 <sup>a</sup>	39.4 <sup>a</sup>	17.8 <sup>a</sup>	24.4 <sup>a</sup>	10.77 <sup>a</sup>
100% ASD	108.0 <sup>a</sup>	48.4 <sup>a</sup>	44.4 <sup>a</sup>	19.5 <sup>a</sup>	24.9 <sup>a</sup>	12.5 <sup>a</sup>

**Key BAU- Business as Usual, 25 % ADS- Abuja declaration scenario AS- Abuja scenario; vegetative, reproductive, and harvesting = 30, 60, and 90 days after planting, respectively. V6 – vegetative stage, R1 -reproductive stage, R 6- Harvesting stage. In the same column, means with the same letter superscripts are not significantly different.**

Across all the scenarios, for the two catchments, mineral N concentration decreased throughout the growing period for the growth stages. A higher concentration of  $\text{NH}_4^+$  during the vegetative stage could be due to less demand for the crops to uptake the available N in the soil and transform for various growth processes. A higher  $\text{NH}_4^+$  accumulation in the soil during the vegetative stage could lead to more volatilization and gaseous loss to the environment. The high  $\text{NH}_4^+$  in the fertilized plots could be due to the hydrolysis of applied urea-N and contributing. The fact that the soils are low in N and possibly limited diversity of the micro-organisms limited the nitrification process hence lower concentration of  $\text{NO}_3^-$  in all growth stages (Guo et al., 2021).

#### **4.23 CO<sub>2</sub>-C fluxes and cumulative emissions**

The highest  $\text{CO}_2$  fluxes occurred during day 1 of the incubation in all soil substrates. Mean  $\text{CO}_2\text{-C}$  values on the first day of measurements for F1 and F2 with SHC treatments were 3271 and 2672  $\text{mg m}^{-2} \text{h}^{-1}$ , while the mean values of the control were 98 and 75  $\text{mg m}^{-2} \text{h}^{-1}$  for F1 and F2, respectively (Figure 4.24 A, B).



**Figure 4.24: Mean values CO<sub>2</sub>-C daily trends during the 8 weeks incubation period in different treatments (SHC- high N +CaCO<sub>3</sub>, SLC (low N+ CaCO<sub>3</sub>, SH- high N and SL- Low N. A-Ferralsol 1, B-Ferralsol 2: C –vertisol.**

The treatment with nitrogen only also had an effect on initial CO<sub>2</sub> fluxes with 50 kg N ha<sup>-1</sup> (SH) having mean value of 224. 8 and 202. 8 mg m<sup>-2</sup> h<sup>-1</sup> which was 14 & 13 times less than the same amount in SHC for the two Ferralsol. Overall, in all treatments CO<sub>2</sub> fluxes decreased gradually over the incubation period in all the treatments for the two soil samples.

The cumulative emission significantly varied in the two Ferralsols samples across the treatments. In figure 4. 24 SHC had significantly higher emissions of CO<sub>2</sub> with a mean value of 217,237.8 mg m<sup>-2</sup> which represented 30. 23 % high emissions compared to low N + CaCO<sub>3</sub> (SLC). N fertilization alone did not show any significant differences when

compared to low N and the control. However, the application of both SH and SL increased cumulative emissions by 26.4 % and 17.5% respectively when compared to control.

In Ferralsol 2, application both SHC and SLC significantly increased CO<sub>2</sub> emissions by three folds when compared to treatments without CaCO<sub>3</sub> (Figure 4.24). Application of CaCO<sub>3</sub> increased, although no significant differences were recorded in treatments with SH and SL there was an increase of cumulative emissions of CO<sub>2</sub> by 15.8% and 6.8 % respectively compared to unfertilized treatments.

In Vertisols CO<sub>2</sub> fluxes and cumulative emissions were lower compared to Ferralsol 1 & 2. During the first day the mean value of SHC and SLC was 434.5 and 311.6 mg m<sup>-2</sup> h<sup>-1</sup> respectively (Fig 4.24). In the 2<sup>nd</sup> day of measurement there was peak increase of CO<sub>2</sub> fluxes in all treatments except SHC and on the third day the fluxes declined gradually until the end of the incubation period. Both SHC and SLC had significant differences in CO<sub>2</sub> cumulative emissions compared to N treatments with CaCO<sub>3</sub> representing 46.1% and 75.2 % increment respectively (Figure 4.24).

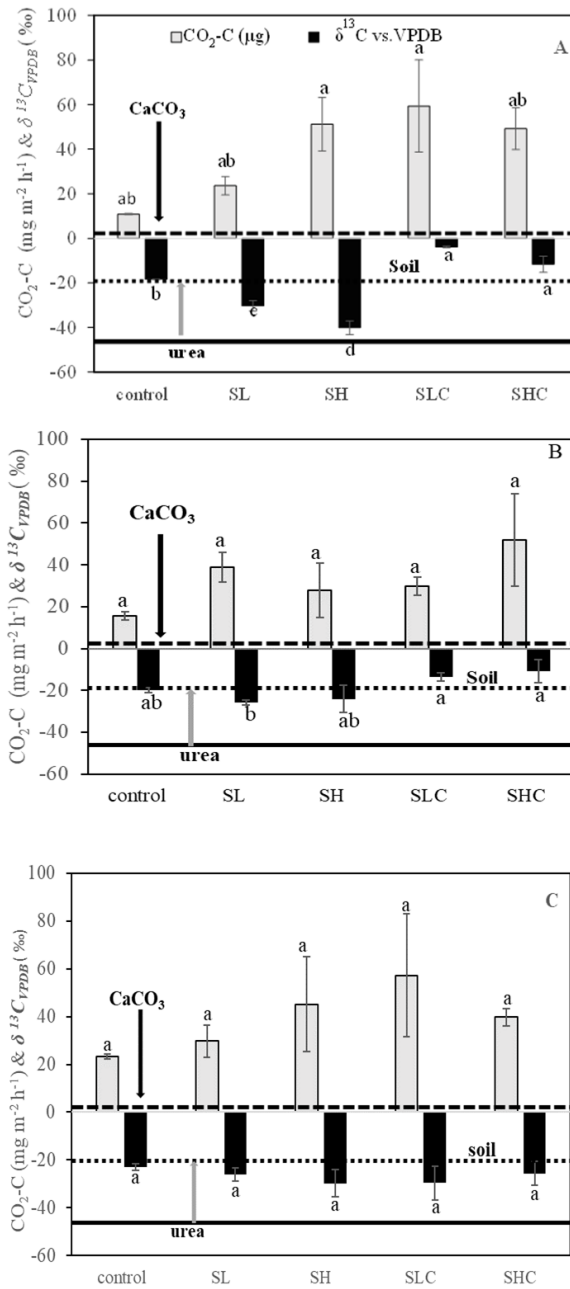
The combination of liming and N fertilization increased CO<sub>2</sub> emissions compared to samples without lime and control (Figure 4.24). The data from this study revealed that the most acidic soil had the highest emission of CO<sub>2</sub> is due to the dissolution of CaCO<sub>3</sub> in the acids (Figure 4.26). Previously, IPCC (2006) recognized liming as one of the sources of CO<sub>2</sub> in calculating GHG emissions in the global budget. Due to this, countries/regions are obliged to report CO<sub>2</sub> emissions from limestone in the annual national GHG inventories, particularly for developing nations without specialized

equipment for GHG measurement (IPCC, 2006). N fertilization contributed to changes in inorganic stocks of in the soils and therefore increased the efflux of CO<sub>2</sub> to the atmosphere (Zamanian, Zarebanadkouki & Kuzyakov, 2018). In addition, N fertilization induces more acidity to the soil increasing the dissolution of CaCO<sub>3</sub> contributing to more CO<sub>2</sub> efflux. Amendment of agricultural soils with urea stimulates microbial activity hence stimulates emission of CO<sub>2</sub> (Serrano-Silva *et al.*, 2011). Urea hydrolysis could also be another reason for CO<sub>2</sub> emission in N fertilizer plots. The increase in CO<sub>2</sub> fluxes by liming is due to optimized soil pH leased to more labile organic C and facilitates microbial activities (Wu *et al.*, 2020). Liming by CaCO<sub>3</sub> enhances mineralization of organic matter in the soil limited by low pH, thereby increasing bio-available C that is easily stimulated by microbial activities, hence higher CO<sub>2</sub> emissions. These results agree with Adnan *et al.* (2018); Shaaban *et al.* (2017) who reported that liming increases soil respiration and microbial biomass contents and consequently CO<sub>2</sub> is released to the atmosphere. When CaCO<sub>3</sub> is added to acid soils it serves as net source of CO<sub>2</sub> besides, in strongly acidic soils CO<sub>2</sub> is released from the reaction of CaCO<sub>3</sub> and protons released from nitrification process (Kunhikrishnan *et al.*, 2016). Similar results to this study were reported by Fuentes *et al.* (2006); Dumale *et al.*, 2011) with high rates of CO<sub>2</sub> emissions during the first days and later a decrease during an incubation experiment following lime application.

#### **4.24 Isotopic signatures ( $\delta^{13}\text{C}$ ) of CO<sub>2</sub>**

The analysis of  $\delta^{13}\text{C}$  of CO<sub>2</sub> from the different soils and treatments in our experiment helped to discriminate the fraction of CO<sub>2</sub> originating from SOM, urea (N fertilizer), and CaCO<sub>3</sub> (liming material). The dominant sources of  $\delta^{13}\text{C}$  variation from our

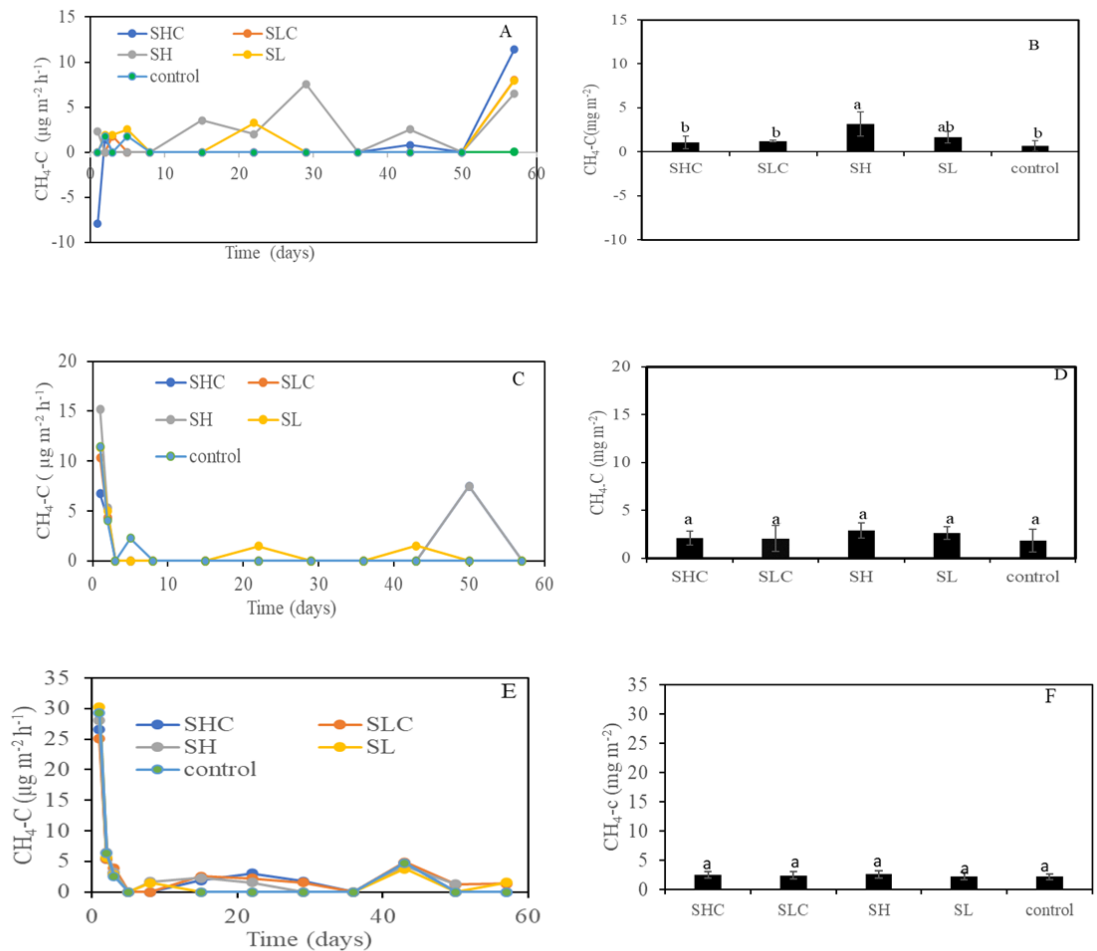
experiment were liming ( $\text{CaCO}_3$ ) and N fertilization applied at different levels, specifically for the two Ferralsols (Figure 4.25) with  $\text{CO}_2$  evolving from SOM, urea (N fertilizers) and  $\text{CaCO}_3$ . The results emphasize the relevance of liming ( $\text{CaCO}_3$ ) for total  $\text{CO}_2$  efflux of limed acidic soils and their potential contribution to the global GHG budget (Bertrand *et al.*, 2007), thus posing an important dilemma as both liming and N fertilization are crucial for improving the productivity of acidic tropical soils. In addition, the  $\delta^{13}\text{C}-\text{CO}_2$  results suggest a contribution of protons from nitrification of ammoniacal N fertilizers to the increased  $\text{CO}_2$  emission from the Ferralsols, which enhance the dissolution of  $\text{CaCO}_3$  compared to the soils without any amendments. Similar findings were reported by Tamir *et al.* (2011) on the production of  $\text{CO}_2$  through carbonate dissolution in soils and due to mineralization of N fertilizers. In addition, Perrin *et al.* (2008) reported the potential impact of nitrogenous fertilizers to increase  $\text{CO}_2$  budget from dissolution of agricultural lime ( $\text{CaCO}_3$ ).



**Figure 4.25: The <sup>13</sup>C signatures (δ<sup>13</sup>C vs.VPDB) of the CO<sub>2</sub> evolved from the experimental treatments in three soils ( A- Ferralsol 1, B- Ferralsol 2, C-vertisol. (SHC- high N +CaCO<sub>3</sub>, SLC (low N+ CaCO<sub>3</sub>, SH- high N and SL- Low N. Different lowercase letters denote significant differences between different treatments at p < 0.05**

#### 4.25 CH<sub>4</sub>-C fluxes and cumulative emission

The CH<sub>4</sub> fluxes for the Ferralsol 1 were very low in the first day with a negative flux - 7.87  $\mu\text{g m}^{-2} \text{h}^{-1}$  recorded in the treatment with SHC. There were different peaks in different treatments with the highest flux being recorded on the last day of incubation in SHC at 11.43  $\mu\text{g m}^{-2} \text{h}^{-1}$  (Figure 4.26).



**Figure 4.26 Mean CH<sub>4</sub>-C daily trends A- Ferralsol 1, C-Ferralsol 2: D –Vertisol (paddy rice) and cumulative CH<sub>4</sub>-C emissions B- Ferralsol 1, D-Ferralsol 2: F– Vertisol (paddy rice) during the 8 weeks incubation period in different treatments (SHC- high N +CaCO<sub>3</sub>, SLC (low N+ CaCO<sub>3</sub>, SH- high N and SL- Low N. Different lowercase letters denote significant differences between different treatments at p < 0.05**

There were higher CH<sub>4</sub> fluxes during the 1<sup>st</sup> day of measurement in Ferralsol 2 with the highest flux recorded in SH at 50 kg N ha<sup>-1</sup> treatment with a mean value of 15.2 μg m<sup>-2</sup> h<sup>-1</sup> followed by the control at 11.47 μg m<sup>-2</sup> h<sup>-1</sup> while the least CH<sub>4</sub> fluxes were recorded in SHC at 6.75 μg m<sup>-2</sup> h<sup>-1</sup>. After the 1<sup>st</sup> day there was a decline in the CH<sub>4</sub> fluxes for all treatments with different peaks throughout the incubation period. The high flux on high N treatment agree with findings of Yuan *et al.* (2018) that N fertilization increases the abundance of methanogens hence leading to higher CH<sub>4</sub> fluxes. In the Vertisol, there was relatively higher CH<sub>4</sub> fluxes compared to Ferralsol 1 and 2. The highest CH<sub>4</sub> fluxes were observed in the first day with an average of 30.21 μg m<sup>-2</sup> h<sup>-1</sup> for low N to 25.04 μg m<sup>-2</sup> h<sup>-1</sup> for the SLC. The fluxes decreased but with peaks at different measurement days throughout the incubation period. In cumulative emission there were significant differences (p < 0.05) observed in Ferralsol 1 (Figure 4.26 B) while no significant differences were observed in Ferralsol and the Vertisol (Figures 4.26 D and F). The production of CH<sub>4</sub> in soils is influenced by anaerobic conditions through which methanogens are influenced activated. Through application of lime, pH buffering offers favorable conditions for CH<sub>4</sub> production (Jiang *et al.*, 2018). Similar results to this study have been reported by Murakami *et al.* (2005) that showed stimulated CH<sub>4</sub> production when pH is increased through liming in peatland. From this study, it can be confirmed that liming has higher influence on production and emission of CH<sub>4</sub> in paddy rice soils.

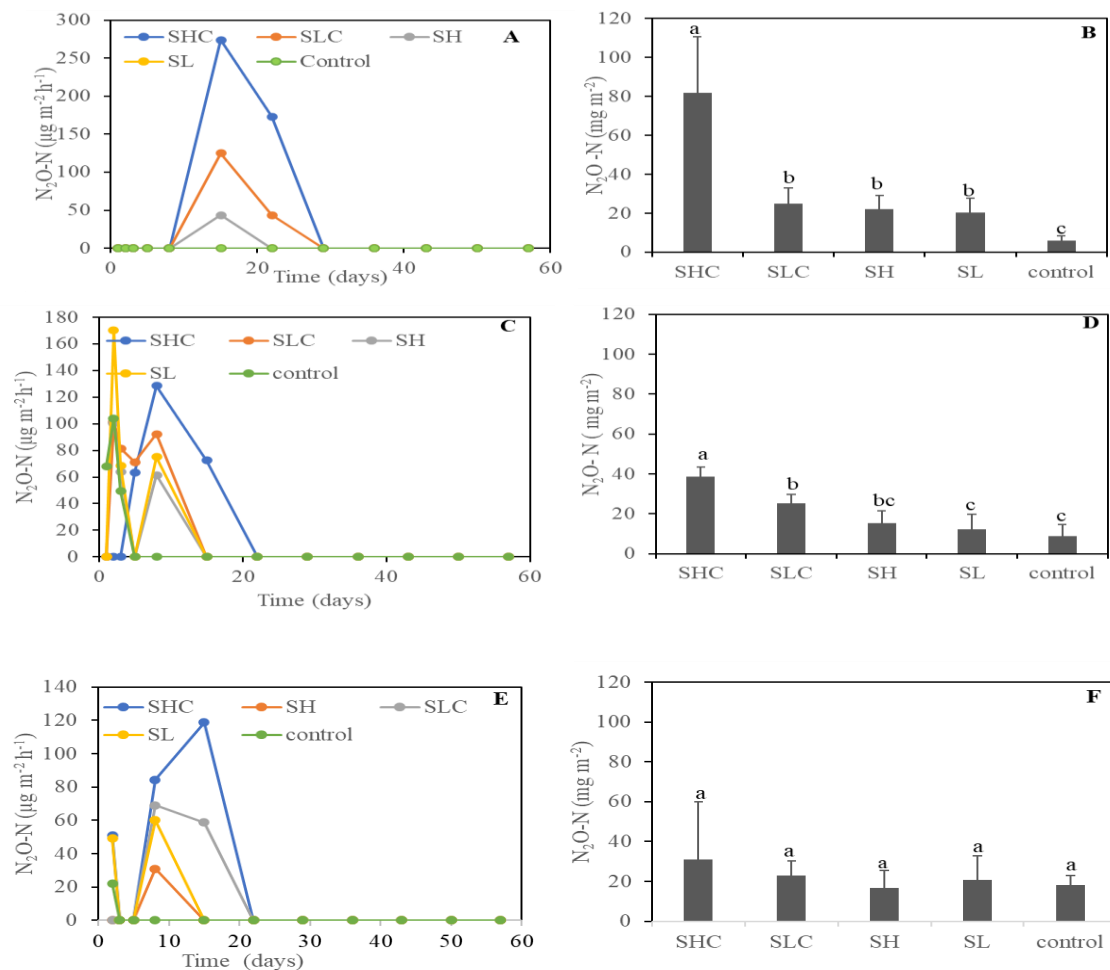
#### 4.26 N<sub>2</sub>O-N fluxes and Cumulative emissions

During the first week of incubation, there was no N<sub>2</sub>O-N fluxes detected from all the treatments for Ferralsol 1 & 2. However, at the 15<sup>th</sup> and 22<sup>nd</sup> day week there was a peak of N<sub>2</sub>O-N fluxes with the SHC having the highest mean values of 274 and 173  $\mu\text{g m}^{-2} \text{h}^{-1}$  respectively (Figure 4.27). A similar peak was observed in SLC and SHC treatments. In the Ferralsol 2, with an initial flush of N<sub>2</sub>O- N during the first day of measurement, followed by a decline and another peak at day 8 and 15 with SHC having mean values of 84.3 and 118.9  $\mu\text{g m}^{-2} \text{h}^{-1}$  respectively.

Overall, combination of N+ CaCO<sub>3</sub> significantly increased N<sub>2</sub>O-N cumulative emission. For the Ferralsol 1, the highest mean values were recorded in high N + CaCO<sub>3</sub> at 81.74 which was 4 times higher compared to SH. At lower SLC N<sub>2</sub>O-N emissions were 25.9  $\text{mg m}^{-2}$  that had no significant differences with high and low N application. The control had the least cumulative emissions with mean value of 5.9  $\text{mg m}^{-2}$  (Figure 4.27 B). In Ferralsol 2 similar trend was evident with significant differences between the treatments. The treatment having SHC had significantly higher cumulative fluxes when compared with control of mean value of 38.5  $\text{mg m}^{-2}$  while the control had the lowest mean value of 8.9  $\text{mg m}^{-2}$ .

In Vertisol, N<sub>2</sub>O-N fluxes had an initial peak in the first 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> days of measurements with mean value of 68.19, 104.01 and 49.23  $\mu\text{g m}^{-2} \text{h}^{-1}$  and later no N<sub>2</sub>O-N fluxes were measured throughout the incubation period. For the treatments with high and low N, they had a peak of N<sub>2</sub>O-N in 2<sup>nd</sup>, 3<sup>rd</sup> and 8<sup>th</sup> day of measurement and thereafter no detectable N<sub>2</sub>O-N fluxes were measured until the end of the experiment. In the treatment with SHC the highest mean value was 128.49  $\mu\text{g m}^{-2} \text{h}^{-1}$  on the 8th day

of measurement while for SLC the highest fluxes were on 2<sup>nd</sup> day with a mean value of 101.4  $\mu\text{g m}^{-2} \text{h}^{-1}$ . There were no significant effects on cumulative emissions for  $\text{N}_2\text{O-N}$  in treatments and mean values ranged between 31.06 to 16.74  $\text{mg m}^{-2}$  (Figure 4.27F). The current results showed higher  $\text{N}_2\text{O}$  emission in liming and N fertilizer application. Soil pH is a critical factor influencing emissions of  $\text{N}_2\text{O}$  from the soil. N fertilizer use enhances soil  $\text{N}_2\text{O}$  emissions through increased nitrification and denitrification rates.



**Figure 4.27: Mean  $\text{N}_2\text{O-N}$  daily trends A- Ferralsol 1, C- Ferralsol 2: D – Vertisol and cumulative  $\text{N}_2\text{O-N}$  emissions B- Ferralsol 1, D-Ferralsol 2: F– Vertisol during the 8 weeks incubation period in different treatments (SHC- high N +  $\text{CaCO}_3$ , SLC (low N+  $\text{CaCO}_3$ , SH- high N and SL- Low N. Different lowercase letters denote significant differences between different treatments at  $p < 0.05$**

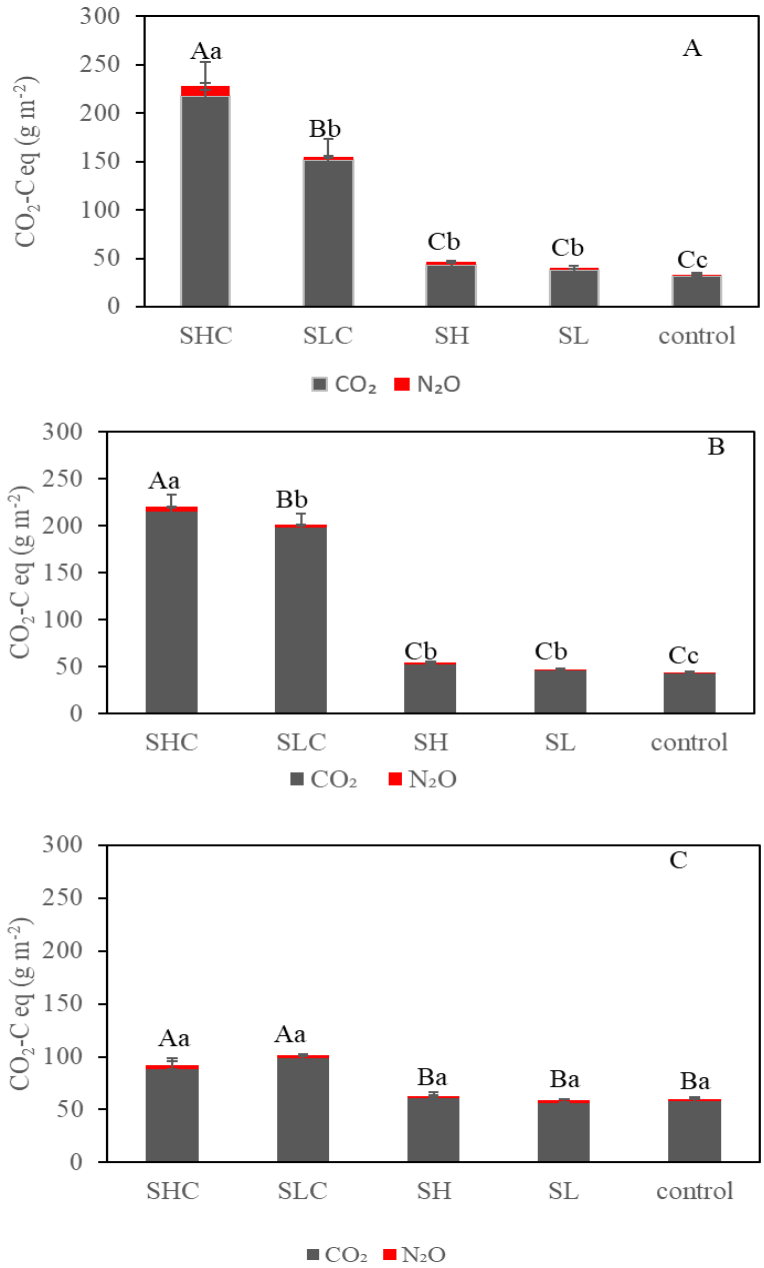
There was an increase in N<sub>2</sub>O fluxes with higher N combination with CaCO<sub>3</sub> in both daily trends and cumulative emission (Figure 4.27). Moreover, when urea is added to soil, it is hydrolyzed to form NH<sub>4</sub><sup>+</sup> which is oxidized by nitrifies and thereby leading to formation of N<sub>2</sub>O during nitrification process. This experiment showed that tropical soils have minimal emissions of N<sub>2</sub>O fluxes, possibly due to depletion of N stocks in the soil and relatively low rates of N fertilization. N<sub>2</sub>O peaks were different for the different soil's types with Ferralsol 1 having the highest daily fluxes for the treatment with SHC (274 and 173 μg m<sup>-2</sup> h<sup>-1</sup>) on 15<sup>th</sup> and 22<sup>nd</sup> (Figure 4.267A).

The different peaks were influenced by the level of N concentration in the soils which was very low and therefore the no potential development of significant amount of N<sub>2</sub>O during the experimental period. To add on, the N fertilizer applied by the farmers in the fields is very low and this study revealed that currently there is little contribution of N fertilizer to N<sub>2</sub>O emissions. The increase in N<sub>2</sub>O emission on application of lime could be due to favoring of the ammonia oxidizing bacteria (AOB) that has higher production of N<sub>2</sub>O per mole compared to the ammonia oxidizing archaea (AOA) (Abalos *et al.*, 2020). Similar results have been reported by Brummer *et al.* (2008) where low emission of N<sub>2</sub>O were reported in Savanna grassland with depleted N levels. The effect of urea N fertilizers on N<sub>2</sub>O emission is due to hydrolysis that leads to higher mineral N concentration providing a substrate for bacteria responsible production of N<sub>2</sub>O (Ullah *et al.*, 2016). Comparatively, to what has been recommended for the region for food security and to correct the depletion levels on soil fertility an increment on N fertilizer will definitely lead to an increase on N<sub>2</sub>O emissions although with no significant differences. However, raising the soil pH to an optimal range of 6.5 will have a

significant increase on N<sub>2</sub>O emission as revealed from current study. The findings of this study agree with Galbally *et al.* (2010) that N<sub>2</sub>O emission in soil could increase by 10 % when soil pH is increased up to 7.3. Liming creates a favorable environment for denitrifies and significantly increase the fluxes of N<sub>2</sub>O. As observed from the study elevated pH led to higher N<sub>2</sub>O production at different peaks for different soil types. According to Wang *et al.* (2021), liming acidic soils stimulate N<sub>2</sub>O emissions due to increased nitrification and nitrifiers producing N<sub>2</sub>O and also increase NO<sub>3</sub><sup>-</sup> availability, a substance for N<sub>2</sub>O production through the process of nitrification. Liming has also been reported to increase denitrification rate in acidic soils due to rapid depletion of available soil NO<sub>3</sub><sup>-</sup> at denitrifying microsites (Senbayram *et al.*, 2019). Increasing soil pH leads to an exponential increase N/N<sub>2</sub>O due to higher activity of nitrous oxide reductase.

#### **4.27 Global warming potential**

Liming and N fertilization in three soils evaluated in the study showed significance difference in CO<sub>2</sub>-C equivalence (Figure 4.28). In Ferralsol 1 SHC had the significantly higher CO<sub>2</sub>-C eqv compared to other treatments with a mean value of 227,690. 19 mg m<sup>-2</sup> while the least was in control with mean value of 32,626.84 mg m<sup>-2</sup> (Figure 4.28A). Similarly, the Ferralsol 2 had significant difference on CO<sub>2</sub>-C equivalence with high and SLC combination having the highest contribution with mean values of 220,112.9 and 201, 087.9 mg m<sup>-2</sup> respectively (Figure 4.28B).



**Figure 4.28: Mean CO<sub>2</sub>-C Eqv A-Ferralsol 1, B-Ferralsol 2: C -vertisol. and cumulative CO<sub>2</sub>-C emissions (SHC- high N +CaCO<sub>3</sub>, SLC (low N+ CaCO<sub>3</sub>, SH- high N and SL- Low N. Different uppercase letters denote significant differences between the contribution of CO<sub>2</sub> from different treatments. Different lowercase letters denote significant differences between the contribution of N<sub>2</sub>O from different treatments p < 0.05**

In vertisols soils CO<sub>2</sub>-C eqv was relatively lower compared to the other two soils from maize crops (Figure 4.28 C) with treatments having SHC and SLC having mean values of 92,288.9 and 101, 148 mg m<sup>-2</sup> respectively. According to Peng *et al.* (2010) increasing N fertilization into the cropping systems has an effect on global warming due to increase emissions of N<sub>2</sub>O which is a more potent GHG. In another study by Pittelkow *et al.* (2014) contribution of N<sub>2</sub>O to GWP was estimated at 10-18% being very little as confirmed from this study however, it should not be overlooked since its concentration into the atmospheres will tend to increase as farmers increase their farm inputs hence better mitigation potential should be explored.

#### **4.28 Mineral N dynamics at the end of incubation**

In the three soil there was significantly higher NO<sub>3</sub><sup>-</sup> (mg N kg<sup>-1</sup>) in treatment with SHC 127.4, 152.3 and 168.0 mg N kg<sup>-1</sup> for Ferralsol 1,2 and the Vertisol respectively compared to high N without liming (Table 4.18). Similarly, in SLC there was higher NO<sub>3</sub><sup>-</sup> (mg N kg<sup>-1</sup>) with 93. 8. 107.0 and 97.8 mg N kg<sup>-1</sup> for Ferralsol 1, 2 & Vertisol respectively compared to SL. The lowest NO<sub>3</sub><sup>-</sup> concentrations were recorded in the control for all the soils in the experiment. In Ferralsol 1 SH had the high significance on NH<sub>4</sub><sup>+</sup> concentration (3.24 mg N kg<sup>-1</sup>) while the other treatments did not show any significance differences when compared to the control. In Ferralsol 2 & vertisol, NH<sub>4</sub><sup>+</sup> concentrations did not have any significant differences at the end of the incubation period. There was higher N (NO<sub>3</sub><sup>-</sup>) retention in the limed treatment when compared to non-limed plots (Table 4.17). The higher retention of N is beneficial to soil and offers a viable management strategy for the acidic soils in Lake Victoria basin. Moreover, for crop productivity, more N will be available for plant uptake for growth and

development. The results of this study confirm that raising soil pH promoted nitrification and induced the accumulation of nitrate in soils.

**Table 4.17: Nitrate (NO<sub>3</sub><sup>-</sup>) and ammonium (NH<sub>4</sub><sup>+</sup>) concentrations in different soil samples at the end of incubation period**

Ferralsol 1	Treatments	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )
	SHC	0.18 <sup>b</sup>	127.4 <sup>a</sup>
	SLC	0.11 <sup>b</sup>	93.8 <sup>b</sup>
	SH	3.24 <sup>a</sup>	98.4 <sup>b</sup>
	SL	0.11 <sup>b</sup>	67.5 <sup>c</sup>
	Control	0.11 <sup>b</sup>	42.8 <sup>d</sup>
Ferralsol 2			
	SHC	0.12 <sup>a</sup>	152.3 <sup>a</sup>
	SLC	0.12 <sup>a</sup>	107.0 <sup>bc</sup>
	SH	0.12 <sup>a</sup>	120.3 <sup>b</sup>
	SL	0.11 <sup>a</sup>	88.1 <sup>c</sup>
	Control	0.11 <sup>a</sup>	62.5 <sup>d</sup>
Vertisol			
	SHC	0.13 <sup>a</sup>	168.0 <sup>a</sup>
	SLC	0.12 <sup>a</sup>	97.8 <sup>b</sup>
	SH	0.12 <sup>a</sup>	127.2 <sup>b</sup>
	SL	0.12 <sup>a</sup>	85.4 <sup>c</sup>
	Control	0.12 <sup>a</sup>	63.2 <sup>d</sup>

**Means followed by the similar letters within a column are not statistically significant the p < 0.05 level between treatments. (SHC- high N +CaCO<sub>3</sub>, SLC (low N+ CaCO<sub>3</sub>, SH- high N and SL- Low N).**

Liming increases availability of NO<sub>3</sub><sup>-</sup> indicating less loss of the applied N and therefore effective in enhancing nitrogen use efficiency. The higher concentration of NO<sub>3</sub><sup>-</sup> was due to enhanced environment for growth and development of nitrifiers in higher pH leading to nitrification of applied urea. As reported by Sahrawat, (2008) application of CaCO<sub>3</sub> initiates formation of nitrate when pH is raised as confirmed from current study.

According to Senbayram *et al.* (2019) liming in acidic soils stimulates nitrification resulting to higher  $\text{NO}_3^-$  in the soil. Liming has been reported to improve efficiency of fertilizers and the activities of soil micro-organisms to enhance releases of organic N and other crop N nutrients (Krešmane *et al.*, 2016). With more N retained in soil, liming can be used to add the beneficial effects of minimizing N input into the cropping systems due to improved N mineralization (Holland *et al.*, 2018).

#### 4.29 Microbial biomass C

There were no significant differences ( $p < 0.05$ ) observed for microbial biomass carbon (MBC) at the end of the incubation experiment. Therefore, both N fertilization and liming did not influence soil microbial biomass. Overall, Vertisol had the highest accumulation of MBC in all the treatments with the highest value recorded in low N at  $149.0 \mu\text{g g}^{-1}$  (Table 4.18).

**Table 4.18: Microbial biomass C in the three soils at the end of the experiment**

	MBC $\mu\text{g g}^{-1}$		
	Ferralsol 1	Ferralsol 2	Vertisol
SHC	68.8 <sup>a</sup>	103.7 <sup>a</sup>	140.0 <sup>a</sup>
SLC	83.8 <sup>a</sup>	96.09 <sup>a</sup>	127.0 <sup>a</sup>
SH	57.0 <sup>a</sup>	94.1 <sup>a</sup>	123.0 <sup>a</sup>
SL	69.5 <sup>a</sup>	94.8 <sup>a</sup>	149.0 <sup>a</sup>
Control	74.5 <sup>a</sup>	94.6 <sup>a</sup>	142.0 <sup>a</sup>

Means followed by the same letter within a column are not statistically significant at  $p < 0.05$  level between treatments. (SHC- high N +  $\text{CaCO}_3$ , SLC (low N+  $\text{CaCO}_3$ , SH- high N and SL- Low N)

According to Fuentes *et al.* (2006) some systems consisting of high organic matter tend to have higher microbial biomass contents due to availability of the proffered sources of energy for the micro-organisms like the case of Vertisol. In Ferralsol 1, the higher

MBC was recorded in SLC at  $83.8 \mu\text{g g}^{-1}$ . In Ferralsol 2 the SHC had the highest value of  $103.7 \mu\text{g g}^{-1}$ . These findings agree with the Fuentes *et al.* (2006) that application of lime could increase the quality of C sources creating a greater proportion of microbes but the total MBC is not is affected.

## CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

1. There is unbalanced N use in the study region where the majority of farms have negative N budgets and are above the safe operating boundaries, although there are uncertainties with current existing systems.
2. Increasing N input for smallholder farmers will increase yield, although not to the targeted amount required to achieve optimal NUE for improved N management in the dominant smallholder farms.
3. The current study established that fertilizer increments to 50 kg ha<sup>-1</sup>, as spelt out in the Abuja declaration, will slightly improve the growth and yield of maize but is not sufficient to overcome the soil fertility decline. Negative N balances were also evident from this analysis, an indicator of higher N removal than the N input, indicating the presence of low N status that leads to soil N mining and degradation of the overall fertility and quality of the soil.
4. Increasing N fertilizer use and liming will lead to more CO<sub>2</sub> and N<sub>2</sub>O emissions but will increase N availability in the soil, which is critical for increasing nutrient availability and optimising NUE.

### 5.2 Recommendations

1. Improving the current low use of N fertilizers in the cropping systems will require effective policies targeting to improve the current low to zero N input through increasing the availability of fertilizers and affordable prices and encouraging the use of organic sources of N to increase sustainability in farms.

2. The decision-makers to focus on more integrated approaches to provide alternative tools and opportunities like increasing access to controlled-release fertilizers, nitrification inhibitors, manures, and composting for improving soil fertility and increasing crop productivity and, at the same time, optimizing NUE.
3. The study recommends formulating new targets, particularly N input above 50 kg N ha<sup>-1</sup>, to optimize NUE, reduce the yield gap for sustainability, and focus more on integrated soil fertility as a package for nutrient management in cropping systems.
4. Farmers can increase their use of N fertilizers to raise the fertility of the soils but require an alternative to liming materials other than CaCO<sub>3</sub> to manage the challenge of soil acidity and minimize environmental pollution by reducing GHG emissions.

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## APPENDICES

### Appendix I: Questionnaire

#### **NITROGEN BUDGET (BALANCE BETWEEN INPUTS AND OUTPUTS) AT PLOT IN LAKE VICTORIA CATHCMENT, EAST AFRICA.**

Nitrogen (N) is a critical mineral nutrient in agricultural systems. In East Africa, there lacks data on quantification of the N pools from the cropland hence representing a key challenge towards improved N management within the region. This questionnaire seeks to understand the balances (input an outputs) of N in cropland at plot scale in maize-rice cropping systems within lake victoria catchement. The information obtained from the activity will be used to make future projections and give insights on how to best manage nitrogen in maize cropping systems.

We thank you very much for the minutes you will spend in filling in this form and we are very gratefull to receive your inputs to this study.

Date	
Name of Farmer	
Longitudes	
Latitudes	
Sub-location	
Location	
County	
Country	

**1. Gender \***

Female

Male

**2. Age:** \_\_\_\_\_

**3. Marital status**

Single

Married

**4. Education Level**

Pre-school/pre-primary

Primary education

Secondary education

Bachelors or equivalent level

Master's or equivalent level

Doctoral or equivalent level

Other

(specify): \_\_\_\_\_

**5. What is the total size of your land -----acres( convert into ha)**

**(5a) How many plots of maize do you have in your farm ( Specify the size of land under maize production?)**

**(5b) Which are the planting seasons for maize plots**

**(5c) What have you been growing in your plots for the last 5 years (history of the cropping systems in respective plots )**

**(5c) Which variety of maize do you use in your plots**

**(5d) Where do you obtain your seeds from**

- a) Agrovat
- b) Previous harvest
- c) Borrow from neighbours
- d) Any other source

**(5e) What quantity of seeds do you plant in you maize plots ----- kg (per hectare per year)**

**(5f) The largest part of the total area you cultivate is:**

- (a) Owned
- (b) Rented
- (c) Other type of tenure

**(5g) How many years of farming experience do you have**

- (a) Less than 5 years
- (b) 6-10 years
- (c) 11-20 years
- (d) More than 20 years

**6. Do you use Nitrogenous fertilizers in your maize plots**

- a) Yes
- b) No

**(6a) If yes, which sources do you use for maize plots**

- (a) Ammonium sulphate
- (b) calcium ammonium sulphate
- (d) urea
- (c) Ammonium sulphate ammonium
- (d) calcium ammonium nitrate
- (e) NPK
- (f) Diammonium phosphate
- (e) Any other-

**(6b) Why do you prefer use of specific fertilizer in maize plots**

- a) It is cheap
- b) readily available
- c) recommended for use in specific rice/maize
- d) easy to handle
- e) easy to store (does not cake)
- f) Is the only type available in the market

**(6c) What rate of Nitrogen fertilizers do you apply in each maize plots(per hectare/acre per year)**

- a) 0 kg/ha(No fertilizer application)
- b) 25 kg N /ha
- c) 50 kg N/ha
- d) 75 kg N/ha
- e) 100 kg N/ ha,
- (f) Any other amount

**(6d)What method of Nitrogen application do you use in your maize plots**

- (a) full dose(all fertilizer at once)
- (b) split method

**(6e) If split how many splits per season you use in maize plots**

- a) one
- b) twice
- c) thrice

**(6f)Why do you use this specific type of fertilizer in maize?**

- a) Rich in nutrients
- b) Easy to apply
- c) Cheap
- d) Readily available

**(6g) Where do you acquire your fertilizers from?**

- a) Agro dealers
- b) cooperatives
- c) Directly from manufacturing companies

**(6h) How do you transport the fertilizer from the area of purchase to your plots?**

- a) By foot
- b) motorbike
- c) using a vehicle

**(6i) For how long have you been using N fertilizers in maize farming**

- a. Less than 5 years
- b. 6-10 years
- c. 11-20 years
- d. More than 20 years

**(6j) Do you have a production contract that specifies the type of nitrogen fertilizers you must use in maize?**

- a) Yes
- b) NO

**7. How much yield do you obtain from your plots maize (kg/ha per year) ?**

**8. How many people rely on your plot produce?**

- a) less than 2
- b) 3-5
- c) 6-10
- d) above 11

**9. What fraction of your plot's maize produce do you sell per year?**

- a) None
- b) 50 kg
- c) 100 kg
- d) Any other------(specify number of bags)

**10. Do you use livestock manure in maize plots**

- (a) Yes
- (b) NO

**(10a). If yes, what is the source of your manure that you use maize plots**

- (a) from own farm (specify quantity produced)
- (b) purchase from outside ( specify qauntity produced)

**(11b) If yes, what type(s) of manure do you mostly apply your plots and in what quantity**

- (a) Cattle
- (b) Poultry
- (c) Pig

**(11c). If yes, how many kg of manure do you apply in plot per year**

**(11d) Which method do you use to apply manure in your plots**

- (a) Broadcasting on the surface
- (b) Broadcasting and mixing with the soils
- (c) planting hole

**(11c) How long do you store your manure before applying to the plots?**

- a) Less than a month
- b) One month
- c) Two months
- d) Any other

**12. Do you recycle straws in your plots**

- (a) Yes
- (b) NO

**(12a) If yes, where do you take you crops straws**

- a) feed to livestock
- b) Sell out
- c) Burn

**13. Do you irrigate your maize/ rice plots**

- (a) Yes
- (b) No

**(13a) If yes, what is the source of water**

**(13b) If is irrigation**

- (a) continous
- (b) intermittent

**(13c) how long does it take before net cycle of irrigation**

- (i) less than 3 days
- (ii) (ii) 3-4 days (more than 4 days)
- (iii) One week
- (iv) Two weeks

**14. What are the challenges you face in using of nitrogen fertilizers in your maize plot ?**

- a) lack of labour to apply,
- b) lack of subsidy,
- c) fear of fertilizer adulteration,
- d) lack of correct and affordable packages,
- e) packages used are non-degradable etc

**15. Do you follow the advises concerning N fertilization in your maize/rice plots provide by County personell or extension, NGOs, NIB (in case of rice)**

- (a) Yes
- (b) No

**(15a) Do you think that you could use nitrogen more efficiently and reduce the losses?**

- (a) Yes
- (b) No
- (c) I don't know

**(15b) Do you know about N fertilizer management techniques that reduce fertilizer losses?**

(a) Yes, but I don't apply any measures

(b) Yes, and I apply all the measures that I can to reduce losses

(c) No

**Appendix II: Nitrogen Budget (Balance Between Inputs And Outputs) At Farmagate Level In Lake Victoria Cathcment, East Africa.**

Nitrogen (N) is a critical mineral nutrient in agricultural systems. In East Africa, there lacks data on quantification of the N pools from the cropland hence representing a key challenge towards improved N management within the region. This questionnaire seeks to understand the balances (input an outputs) of N in cropland at farmagate scale in cropping systems. The information obtained from the ativity will be used to make future projections and give insights on how to best manage nitrogen in cropping systems.

We thank you very much for the minutes you will spend in filling in this form and we are very gratefull to receive your inputs to this study.

Date	
Name of Farmer	
Longitudes	
Latitudes	
Sub-location	
Location	
County	
Country	

**5. Gender \***

Female

Male

6. Age: \_\_\_\_\_

**7. Marital status**

Married

Single

**8. Education level:**

Pre-school/pre-primary

Primary education

Secondary education

Bachelors or equivalent level

Master's or equivalent level

Doctoral or equivalent level

Other (specify): \_\_\_\_\_

**9. What is the total size of your land -----acres**

**(5a) Which are the planting seasons for crops in various plots e.g maize-----**

--

**(5b) What have you been growing in your plots for the last 5 years (history of the cropping systems in respective plots )**

**10. The largest part of the total area you cultivate is:**

- (a) Owned
- (b) Rented
- (c) Other type of tenure

**11. How many years of farming experience do you have**

- (a) Less than 5 years
- (b) 6-10 years
- (c) 11-20 years
- (d) More than 20 years

**12. What kind of cropping system do you normally use for crops /plots in your farm?**

- a) Monocropping
- b) Intercropping
- c) Crop rotation
- d) Fallow
- e) Others

**13. Do you use Nitrogenous fertilizers in your farm for all crops/plots**

(1) Yes

(2) No

**(10a) If yes, which sources do you use for each crop/plot you grow in your farm**

- a) Ammonium sulphate
- b) calcium ammonium sulphate
- c) urea
- d) NPK
- e) Ammonium sulphate ammonium
- f) calcium ammonium nitrate
- g) Diammonium phosphate
- h) Any other-

**(10b) Why do you prefer use of specific fertilizer in your farm or in respective plots**

- a) It is cheap
- b) readily available
- c) recommended for use in specific crops/plots
- d) Easy to handle
- e) Easy to store(does not cake)
- f) Is the only type available in market

**14. Which crops(leguminous and nonleguminous) do you grow in your farm and how much yield do you get from each of them?**

Crop/plots	Size of the land occupied (acres)	Type of N fertilizer applied	Amount of N used in each(kg/ha) per yr-1	Source of plantin g seed	Quantity of planting seeds	Yield obtained (kg/ha)
1.						
2.						
3.						
4.						
5.						
6.						
7.						
8.						
9.						
10.						
11						
12						
13						

**(11a)What method of Nitrogen application do you use in your crops (specify which method for each crop you grow)**

(a) full dose(all fertilizer at once)

(b) split method

**(10b) If split how many splits per season you use for each crop you grow in your farm (specify which method for each each crop/plot)**

(1) one

(2) twice

(3) thrice

**(10c)Why do you use this specific type of fertilizer for all crops /plots in your farm?**

(a)Rich in nutrients

(b) Easy to apply

(c) Cheap

(d) Readily available

**(10d) Where do you acquire your fertilizers from?**

- (a) Agro dealers
- (b) cooperatives
- (c) Directly from manufacturing companies

**(10e). How do you transport the fertilizer from the area of purchase to your farm?**

- (a) By foot
- (b) motorbike
- (c) using a vehicle

**(10f). For how long have you been using N fertilizers in your farms**

- (a) Less than 5 years
- (b) 6-10 years
- (c) 11-20 years
- (d) More than 20 years

**(10g) Do you have a production contract THAT specifies the type of nitrogen fertilizers you MUST use?**

- (a) Yes
- (b) No

**(10h) Which are the planting seasons for various crops/ plots in your farm**

**15. How many people rely on your farm produce?**

- a) less than 2
- b) 3-5
- c) 6-10
- d) above 11

**16. What fraction of your farms produce (specific crops) do you sell?**

- e) None
- f) 50 kg
- g) 100 kg
- h) Over 100 kg
- i) Any other------(specify number of bags)

**17. Do you use livestock manure in crops**

- (a) Yes
- (b) NO

**(13a). If yes, what is the source of your manure**

- (a) from own farm(specify quantity produced)
- (b) purchase from outside( specify quantity purchased)

**(13b) If yes, what type(s) of manure do you mostly apply in your plots (specific for which crop)**

- (a) Cattle
- (b) Poultry
- (c) Pig

**(13c). If yes, how many kg of manure do you apply in farm per planting season for each crop you grow**

- 1.
- 2.
- 3.
- 4.
- 5.
- 6.
- 7.

**(13d) Which method do you use to apply manure in your crops**

- (a) Broadcasting on the surface
- (b) Broadcasting and mixing with the soils

**(13e) How long do you store your manure before applying to the plots?**

- e) Less than a month
- f) One month
- g) Two months
- h) Any other

**(13e). Do you sell any manure from you produce**

- (a) Yes
- (b) NO

**18. Do you recycle straws in your farm**

- (a) Yes
- (b) NO

**(14a). If yes, for which crops**

- 1.
- 2.
- 3.
- 4.
- 5.
- 6.
- 7.

**(14b) If no, where do you take you crops straws**

- a) Feed to livestock
- b) Sell out
- c) Burn

**19. Do you irrigate your plots( specific crops within the farm)**

- (a) Yes
- (b) No

**(15a) If yes, what is the source of water**

**(15a) If yes, what is the source of water**

**(15b) If is irrigation**

- (a) continuous
- (b) intermittent

**(15c) how long does it take before net cycle of irrigation**

- (v) less than 3 days
- (vi) (ii) 3-4 days (more than 4 days)
- (vii) One week
- (viii) Two weeks

**20. What are the challenges you face in using of nitrogen fertilizers in your farm ?**

- f) lack of labour to apply,
- g) lack of subsidy,
- h) fear of fertilizer adulteration,
- i) lack of correct and affordable packages,
- j) packages used are non-degradable etc

**21. Do you follow the advises concerning N fertilization given by County personell or extension, NGOs, NIB (in case of rice)?**

- (a)Yes
- (b) No

**22. Do you think that you could use nitrogen more efficiently and reduce the losses?**

- (a)Yes
- (b)No
- (c)I don't know

**23. Do you know about N fertilizer management techniques that reduce fertilizer losses?**

- (a)Yes, but I don't apply any measures
- (b)Yes, and I apply all the measures that I can to reduce losses
- (c)No

**24. Do you purchase animal feeds in your farm**

- (a) Yes
- (b) No

20a) What is the type of animal rearing do you practice

- a) Zero grazing
  - b) Grazing on communal land
  - c) Grazing along the road
- (20 a) **if yes, in what quantities in kg?(specify the type of feed you purchase)**
- a) Concentrates
  - b) Feed supplement
  - c) Feed additives

### Appendix III: Publications emanating from the thesis

1. Ntinyari, W., Gweyi-Onyango, J., Giweta, M., Mochoge, B., Mutegi, J., Nziguheba, G., and Masso, C. (2022). Nitrogen use efficiency trends for sustainable crop productivity in Lake Victoria basin: smallholder farmers' perspectives on nitrogen cycling. *Environmental Research Communications*, 4(1), 015004. <https://doi.org/10.1088/2515-7620/ac40f2>
2. Ntinyari, W., Giweta, M., Gweyi-Onyango, J., Mochoge, B., Mutegi, J., Nziguheba, G., and Masso, C. (2022). Assessment of the 2006 Abuja fertilizer declaration with emphasis on nitrogen use efficiency to reduce yield gaps in maize production. *Front. Sustain. Food Syst.* <https://doi.org/10.3389/fsufs.2021.758724>
3. Ntinyari, W., Giweta, M., Gweyi-Onyango, J., Mochoge, B., Mutegi, J., Nziguheba, G., and Masso, C (2022) Nitrogen budgets and Nitrogen use efficiency as agricultural performance indicators in Lake Victoria basin. *Front. Sustain. Food Syst* DOI: 10.3389/fsufs.2022.1023579
4. Ntinyari W., Reichel, Mochoge, B. Wissel, H Gweyi-Onyango, J., Giweta, M.; Bol, R., Masso, C and Brüggemann., N (2022). Nitrogen Fertilization and agricultural liming increase greenhouse gas emissions and nitrogen availability in tropical soils- *Draft in preparation to be submitted to Agronomy for Sustainable Development by springer*

**Appendix IV: Pictorial of field experiments**



**Plate 1: |Experimental sites and different stages of data collection**

## Appendix V: Pictorial of lab experiment

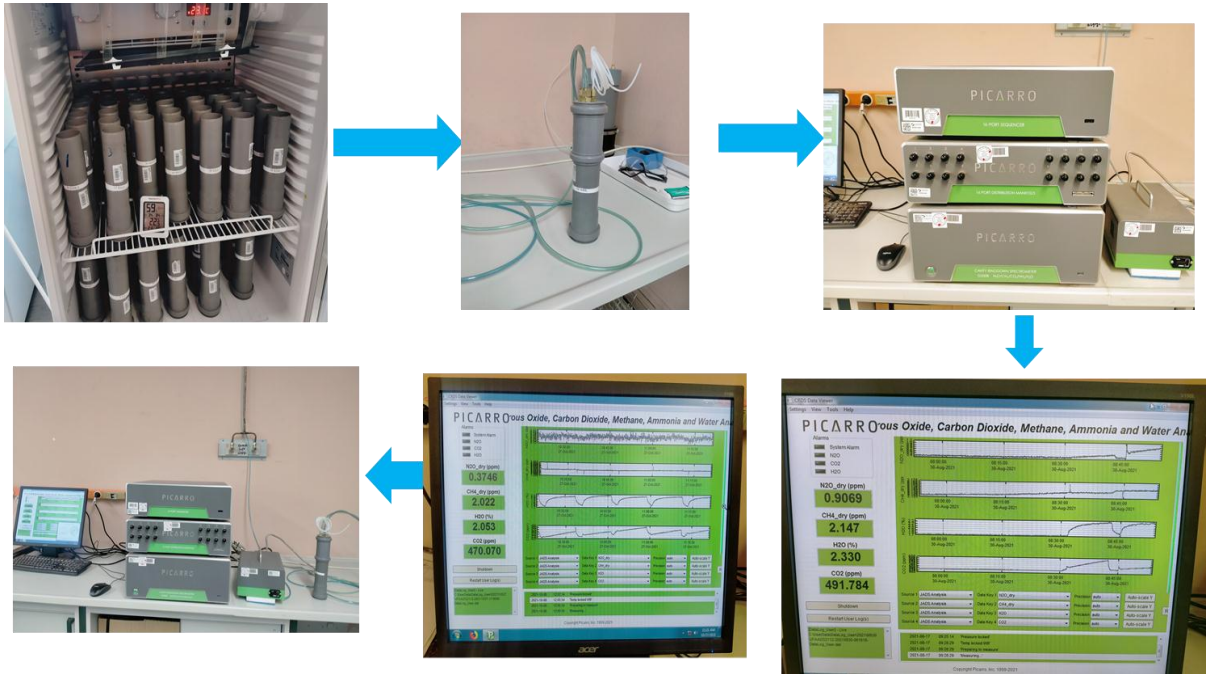


Plate 2: Incubation experiment on GHG measurements



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National Commission for Science, Technology and Innovation  
off Waiyaki Way, Upper Kabete,  
P. O. Box 30623, 00100 Nairobi, KENYA  
Land line: 020 4007000, 020 2241349, 020 3310571, 020 8001077  
Mobile: 0713 788 787 / 0735 404 245  
E-mail: [dg@nacosti.go.ke](mailto:dg@nacosti.go.ke) / [registry@nacosti.go.ke](mailto:registry@nacosti.go.ke)  
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