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Nitrogen use efficiency trends for sustainable crop productivity in Lake Victoria basin: smallholder farmers' perspectives on nitrogen cycling

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Abstract

Nitrogen Use Efficiency (NUE) is one of the established metrics for benchmarking management of Nitrogen (N) in various systems. Numerous approaches to calculate NUE exist, making it difficult to compare the performances of systems depending on the methodology used. This study adopted the conceptualized framework by European Union Nitrogen Expert Panel (EUNEP) to calculate NUE values for cereal crops to determine future trends for the first time in the Lake Victoria region. Data were collected through in-person interviews among maize and rice smallholder farmers within the Lake Victoria region. A total of 293 observations were recorded. 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. Significant differences in maize grain yield for both fertilized and unfertilized farms were observed with very low yields of 2.4 t ha^{-1} (fertilized) and 1.4 t ha^{-1} (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^{-1}) and less than 5 t ha^{-1} maize crop yield over the years. For rice farmers, Nyando and Nzoia catchments had surpassed the set target of both yield (6 t ha^{-1}) and N input (50 kg N ha^{-1}). However, NUE values remain higher than the optimal ranges of 50%–90% (127.14%−267.57%), indicating risks of depleting soil N status. The unbalanced N fertilization also showed a trend below the linear neutrality option and the average N output for good N management for both crops. Therefore, farmers need to explore various crop management options that could increase N use efficiencies. This should be coupled with policies that promote farmers to access more N input and advocate for optimal management of N and improved quality of the cereals.

1. Introduction

Nitrogen (N) plays a critical role in cropping system productivity and environmental sustainability (Guo *et al* 2020, Ladha *et al* 2020). Most of the reactive N (N_r) enters the global cycles through fertilizer application, making N management essential for higher yields and consequently reducing the Nr losses to the environment. Furthermore, optimizing N flows in ecosystems has been linked to a number of the Sustainable Development Goals (SDGs) (Ladha *et al* 2020). However, in Sub-Saharan Africa (SSA), farmers have not exploited the full potential of adding and optimizing N inputs into their cropping systems (Cassman and Dobermann 2021). Estimating N flows is an essential indicator in understanding and improving sustainability of the food systems (Lassaletta *et al* 2016). In Africa, majority of the smallholder farmers apply an average of 7 kg N ha^{-1} yr^{-1} due to limited purchasing power, inadequate extension services and poor infrastructure to access the inputs (Masso *et al* 2017, Elrys *et al* 2020). There is limited information on N cycling within Lake Victoria basin, according to Zhou *et al* (2014), too little use of synthetic N fertilizer, which is a key contributing factor to mining of available N stocks in the soils. However, knowledge on the extent of soil N mining within the Lake Victoria basin is scanty. Certainly, the rate of N depletion in soil stocks has been associated with environmental threats such as degradation of the soil fertility (Zhou *et al* 2014, LVEMP 2003). According to Reis *et al* (2016), soil mining in Lake Victoria basin from the net anthropogenic nitrogen input (NANI) model analysis is due to little use of mineral fertilizer or lack of feed/food import into the region. In addition, crop yields in most African countries have stagnated due to low N supply, nutrient mining and loss of fertility. Thus, practical management practices of Nr are recommended; - including increasing use of synthetic fertilizers and use of manure among other sustainable sources of N input.

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). Cereal production within the Lake Victoria basin is dominated by smallholder farmers with average size of land of 1 ha (Tittonell and Giller 2013). Main sources of N input into the cropping system include synthetic N fertilizer, atmospheric deposition of N, livestock manure and biological N fixation in systems where intercropping is practiced. However, due to lack of awareness on proper management, most of the available N is lost to the environment and less is taken up by the crops or converted into potential yield. Negative environmental impacts associated with poor management of the N input include air, water and land/ soil pollution (Ghaly and Ramakrishnan 2015). African union states made recommendations to increase fertilizer use from 8 kg N ha^{-1} to 50 kg N ha^{-1} by 2015 to enable SSA to achieve food sufficiency and eradicate poverty while improving the soil fertility level (African Unions 2014). However, the recommendations failed to consider increasing the impact of increasing N inputs on the overall NUE as an indicator of improved N soil fertility. NUE can be estimated through various methodologies documented in the literature, creating variations in definitions and understanding of N cycling across multiple systems and regions (Antille and Moody 2021). According to Doberman (2007) and Gweyi-Onyango *et al* (2021), NUE can be used as a reasonable indicator of what can be targeted with good management and close simulation of the farmers' actual practices. Several studies (Powell *et al* 2010, Mosier *et al* 2013, de Klein *et al* 2017, Quemada *et al* 2020), 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. However, recently the European Nitrogen Expert Panel (EUNEP) has suggested a graphical approach to present NUE, N output, and N surplus (EUNEP 2016). This entails, use of a two-dimensional input and output diagram to indicate the differences between the actual and target values as a standard methodology applied at global levels (EUNEP 2016).

Management of N requires improved strategies due to its reactive nature, leading to cascading effects into the ecosystems (Mohanty *et al* 2020). Major pathways of N loss in the cropping systems with an impact on NUE include nitrate (NO_3^-) leaching, ammonia (NH_3) volatilization, and gaseous emissions (nitrous oxide (N_2O) and nitric oxide (NOx) (Tong wane *et al* 2016, Fagodiya *et al* 2020). The losses of Nr have significant negative impacts on water and air quality. However, most of the studies have concentrated on applied and harvested N (in harvested grain) in calculating NUE, neglecting N that is lost to the environment (Zhang *et al* 2019). For instance, globally, N_2O emissions from agriculture are projected to increase by 35%–60% in 2030 due to changes in agricultural practices (Qin *et al* 2010, Reay *et al* 2012, Ahmed *et al* 2020). This is a pointer to the contributions of emissions to NUE and overall N balance which represent a surplus that has not been taken into consideration in Africa agriculture (Tubiello *et al* 2013, Ntinyari and Gweyi-Onyango 2021). Degraded soils with poor supplies of key nutrients in SSA are the main reason for un-optimal NUE values. Some of the pathways like erosion and depletion by land preparation without insufficient supply of external sources also have a significant impact to NUE (Elrys *et al* 2021).

Over the past five decades, yields of major cereal crops in SSA have stagnated at 1.5 t ha^{-1} or less, although most of the cereal crops have a potential of above 5 t ha^{-1} (Zingore *et al* 2015). Less than 1% of the farmers in SSA use fertilizers in crop production due to high costs and unavailability in the local markets (Masso *et al* 2017, Beesigamukama *et al* 2020). According to Gachene *et al* (2015), simulated analysis in SSA shows that a further crop decline of more than 10% is expected by 2055. In addition, the International Institute for Applied Systems Analysis (IIASA) projects the large N imbalances related to cereal yield decline in SSA to be in the range of 30% by 2050 (Van der *et al* 2014). The low yields are due to degraded soil fertility levels, as majority of farmers grow crops without replenishing nutrients, leading to mining and depletion of N stocks in soils (Gachene *et al* 2015).

The unbalanced application of nutrients in cereal production has contributed to significantly higher yield gaps in SSA than in other parts of the world (Masso *et al* 2017). According to Edmonds *et al* (2009), there was no single place in SSA, where cereal crops had been produced without N mining. It has widely been suggested that, increasing N inputs into the cropping systems should be aligned with higher resultant crop yields and with less pollution.

Against this background, a study was conducted with two-fold objectives: (1) To graphically conceptualize NUE for maize and rice cropping systems in Lake Victoria region to identify desirable and risky zones based on EUNEP N boundaries in food production systems and (2) To project the future trends in yield, N inputs and NUE based on farmers' insights and perspectives coupled with existing policies and scientific elucidations'

2. Materials and methods

2.1. Farm characteristics and sample size

Farm data was collected from the Lake Victoria basin at Nyando, Sondu, Yala, and Nzoia catchments (supplementary 1). The catchments characteristics are described in tables 1 and 2. Lake Victoria is the world's largest tropical lake and the largest lake in the African Great Lakes region. The mean size of cultivated land per household is 0.5 ha and 1 ha for maize and rice, respectively. Rice is grown in the region under lowland irrigation, while maize relies solely on seasonal rainfall.

Data used in this study was collected from surveys that made use of open-ended semi-structured questionnaires. The sample size comprised 293 observations of both rice and maize-growing farmers within the selected catchments. The sampling procedure was purposive (targeting maize and rice farmers) and (targeting four catchments). The farmers engaged in rice and maize cropping were thereafter randomly selected. The sample size of 293 was drawn from the population based on Fischer *et al* (1998) as equation (1).

$$N = \frac{z^2pq}{d^2} \tag{1}$$

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 growing rice and maize estimated at 50% since it is not known. q is 1-p and d is degree of accuracy (0.05). The population of those undertaking maize and rice cropping was provided by the extension officers. Interviews were conducted in the months of July-August 2020 using an Open data kit (ODK). Data collected during the survey included grain yield, size of the land, number of planted seeds, N fertilizer applied, use of manure, straw management practices, challenges in the use of N fertilizer during crop production.

2.2. Nitrogen inputs, outputs and nitrogen use efficiencies

To estimate N input from the planted seeds, the quantity of seeds planted per hectare was multiplied with N concentration in the grain (equation (2)) the mean values were 1.40 and 1.90 kg N kg^{-1} for maize and rice respectively. Other sources of N inputs considered in this study were atmospheric depositions (wet and dry), and mineral N fertilizers applied. To calculate the total N harvested (crop removal), harvested yield (kg ha^{-1}) was multiplied by grain N concentration for either maize or rice (equation (3)). The N loss through gaseous pathways was estimated using IPCC default emission factors according to equation (4) as reported by Bouwman *et al* (2002) and FAOSTAT (2017). The emission factors in NH_3 losses were different for both maize (0.19) and rice (0.21) as influenced by soil conditions where each was grown. NUE was calculated using the EUNEP methodology (equation (5)).

$$N\ input\ in\ seeds\ =\ seeds\ (kgha^{-1})\ \times\ N\ concentration \tag{2}$$

$$\text{Harvested}\ N\ =\ Yield\ (kg\ ha^{-1})\ \times\ N\ concentration \tag{3}$$

$$N_2O/NH_3\ emission\ =\ net\ applied\ N\ (kg\ N\ ha^{-1})\ \times\ Emission\ factors \tag{4}$$

$$\text{NUE} = N\ outputs\ (edible\ portion)/N\ inputs\ \times\ 100 \tag{5}$$

2.3. Projections for yield, N input, and NUE in maize and Rice cropping systems

Maize yield and N input projections were based on Climate Change Agriculture and food security (CCAFS 2019) recommendations. According to CCAFS, for SSA to achieve food security, there is a need to increase the current yield and N input by 3.5% and 7% respectively on an annual basis until attainment of optimal N application rates for specific crops. The current projections was based on a target of 5.0 t ha^{-1} for grain yields in various catchments. This is 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 bourgeoning population since it has a

Table 1. Characteristics of maize farm samples and catchments n = number of observations.

Catchment	n	Soil type	Characteristic	Mean size of land (ha)	Productivity (t ha^{-1})
Nyando	40	Vertisols	Rainfed	0.5	1.4 low
Sondu	44	Fluvisols	Rainfed	0.6	1.2 low
Yala	37	Ferrasols	Rainfed	0.5	0.9 low
Nzoia	37	Humic gleysols	Rainfed	0.5	1.1 low

Table 2. Characteristics of rice farm samples and catchments n = number of observations.

Catchment	n	Soil type	Characteristic	Mean size of land (ha)	Productivity (t ha$^{-1)}$
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

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^{-1} 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, we assumed the same 7% annual increment for maize. The NUE was projected based on yield and change of N fertilizer use over the years.

2.4. Data analysis

Statistical analyses were performed with R language (R Core team 2019). The analyses consisted of yield as affected by fertilizer in various catchments for the two cereals. Analysis of variance (ANOVA) was conducted using the general linear model procedure. Means were compared, by the post-hoc Tukey test ($p < 0.05$). Simple regression analysis was used to estimate the effect of N inputs on N outputs.

3. Results

3.1. Grain yield

Variability in grain yield was observed between maize farms. Fertilized farms recorded higher yields than non-fertilized farms. Nyando catchment recorded the highest yield of 2.4 t ha^{-1} and 1.4 t ha^{-1} for maize with N 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 t ha^{-1} for farms with and without N applications respectively (figure 1). 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.

For the rice, we observed significantly higher yield in Nyando relative to other catchments ($p < 0.001$) but there were statistically similar yield levels for Sondu and Nzoia catchments there (figure 2). Nyando recorded the highest mean value of rice grain yield of 6.8 t ha$^{-1,}$ while the lowest mean value was in Nzoia catchments with 3.3 t ha^{-1} figure 2(A). 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 inputs.

3.2. Trends in yield, N inputs, and NUE

Acceptable NUE boundaries depicting the safe operating zones for maize cropping systems are shown in figures 3(A) and (B). 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 3(A). The NUE <90% occurred for the farmers supplying total inputs of >50 kg N ha$^{-1.}$ A similar scenario was also observed for the respective catchments as shown in figure 3(B). The outcome of NUE graphs call for the need to improve management of N resources for optimal NUE in maize production and productivity. 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

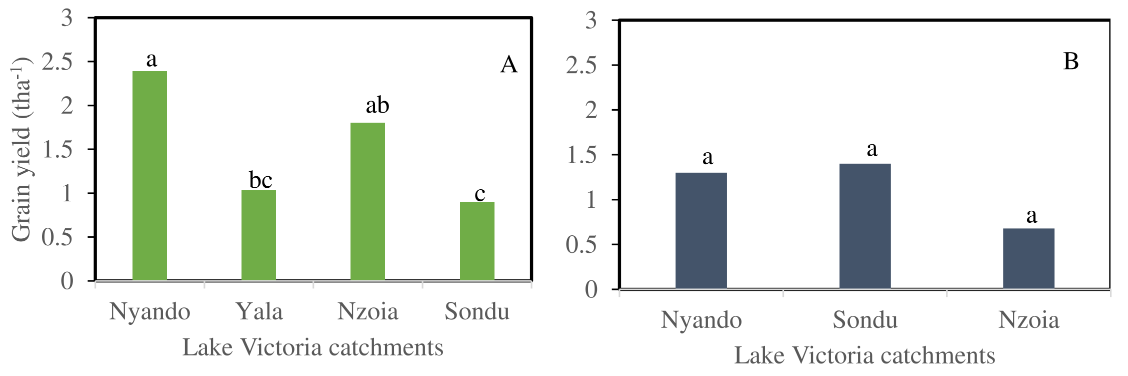

Figure 1. A comparison of grain yield of maize in farms applying N fertilizers (A) and those do not apply (B) in Lake Victoria basin catchments.

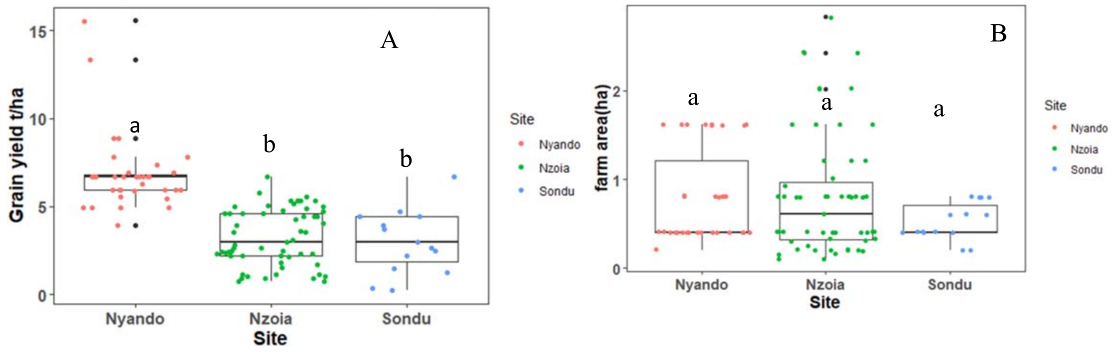

Figure 2. Box plots for rice grain yield (t/ha) (A) and farm size (B) in selected three catchment areas of Lake Victoria basin for farms with the application of synthetic fertilizer.

farms, despite, high N input and low NUE, the yields were still relatively low, implying a risk of N loss to the environment figures 3(A) and (B).

From the projections, it is clear that increments in both maize and rice grains will be realized as N fertilizer use increases. For maize, none of the catchments is expected to have achieved the targeted yield of 5 t ha^{-1} with the current recommendation of annual yield increment of 3.5%. figure 4(A). Yields in Nyando catchment will be closer to the targeted yield by 2050; with an average of 4.05 t ha^{-1}, which is 76.11% increment from the current average yield of 2.3 t ha^{-1}. On the other hand, the average yield for the Yala catchment will be approximately 1.76 t ha^{-1} representing an increase of 70.1% from the current yield level of about 1.03 t ha^{-1} by 2050.

The projected increase in N inputs in maize shows that farmers will continue applying sub-optimal amounts of synthetic N fertilizer in their fields as their application rates are still far from the targets based on current assumptions. In 2050, N inputs for Nzoia will be approaching the recommended rate of 50 Kg N ha^{-1}, with the values of 48.3 kg N ha^{-1} representing over 100% increment from the current application rates figure 4(B). The least N increment will be realized in Nyando (21.88 kg N ha^{-1}) in 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(C) and 4A. 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 5) 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'. 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 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 t ha^{-1} respectively by 2050 (figure 6A). N input in Nyando and Nzoia have already crossed the mark for 50 kg N ha^{-1} and the projected increase in N inputs will be beneficial in enhancing crop yield and lowering NUE

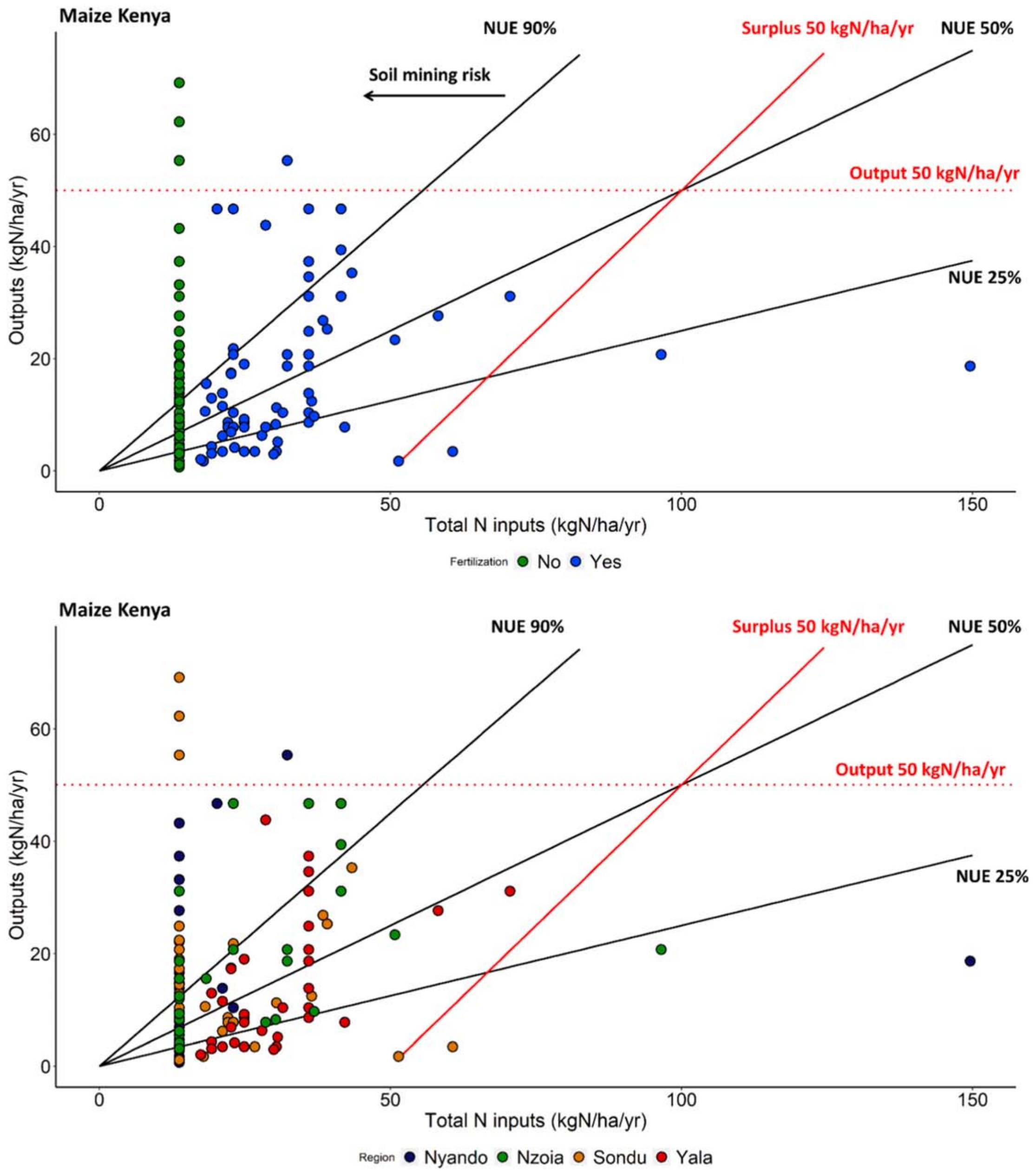

Figure 3. Graphical representation of maize NUE critical regions for Lake Victoria catchment in Kenya for two categories of farmers using mineral N and those not using any mineral N.

values to the desirable range (figure 6B). N input will increase from 102.19 kg N ha^{-1} to 245 kg N ha^{-1} by 2050 in Nyando, while in Nzoia, the increment will be from 78 kg N ha^{-1} to 186 kg N ha^{-1}. Projections show that the values for Sondu catchment will remain relatively low by 2050 at about 42 kg N ha^{-1} from the current rate of 17.44 kg N ha^{-1}. Similarly, in rice, increasing N inputs and yield will lower NUE values for Nyando and Nzoia catchments to desirable ranges, as shown in figure 6(C). As indicated in figure 5, for rice production, 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.

3.3. 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 7). 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

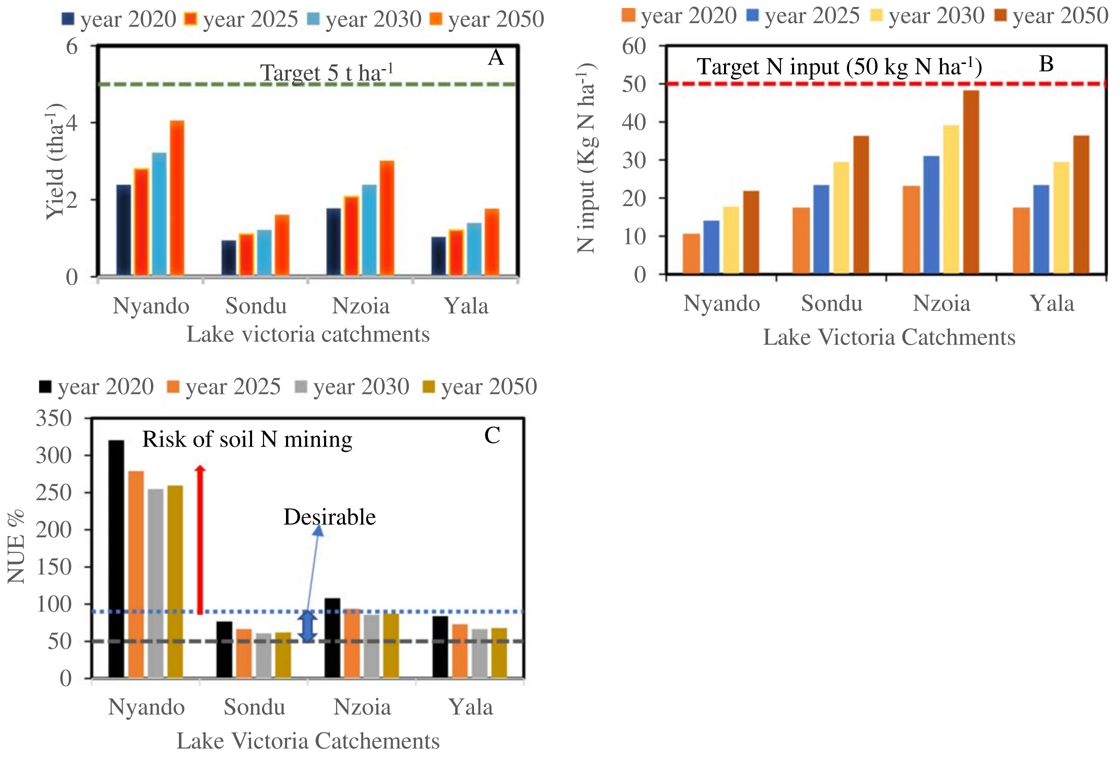

Figure 4. Projected trends in maize yield t ha^{-1} (A), N input Kg N ha^{-1} (B), and NUE % (C) in selected catchments for Lake Victoria Basin for 2025, 2030 and 2050.

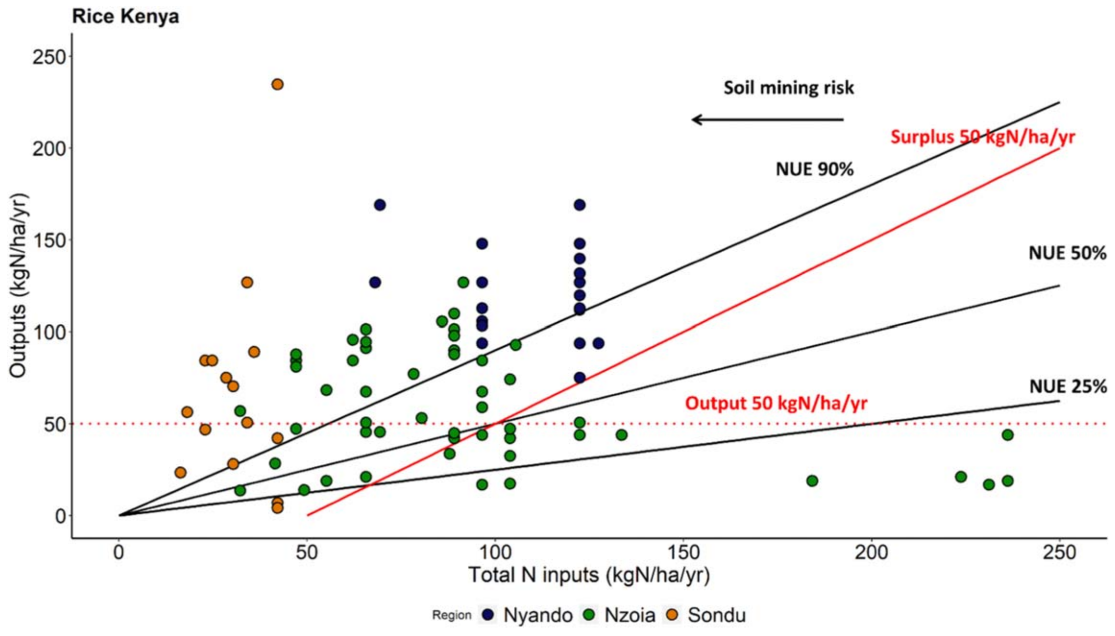

Figure 5. Graphical representation of rice NUE critical regions for Lake Victoria catchment in Kenya.

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 ($y = x$). 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.

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 8). However, the estimated values for neutrality of N output ($y = x$) lay below

Figure 6. Projected trends in rice yield t ha^{-1} (A), N input Kg N ha^{-1} (B), and NUE % (C) in selected catchments for Lake Victoria Basin for 2025, 2030 and 2050.

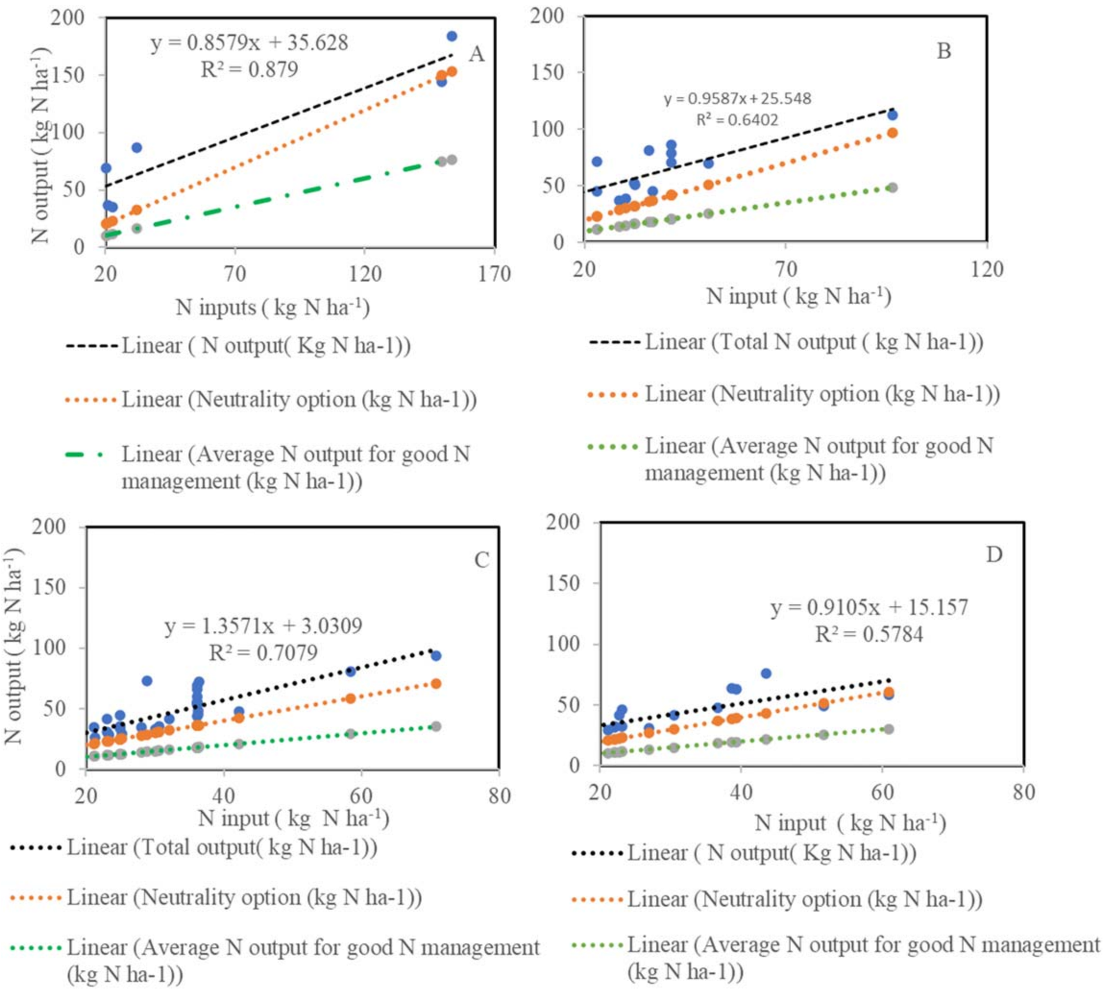

Figure 7. Linear regression model between total N outputs (Kg N ha^{-1}) and total N inputs (Kg N ha^{-1}) in fertilized maize fields in Lake Victoria basin catchment; (A) Nyando; (B) Nzoia, (C) Yala; (D) Sondu.

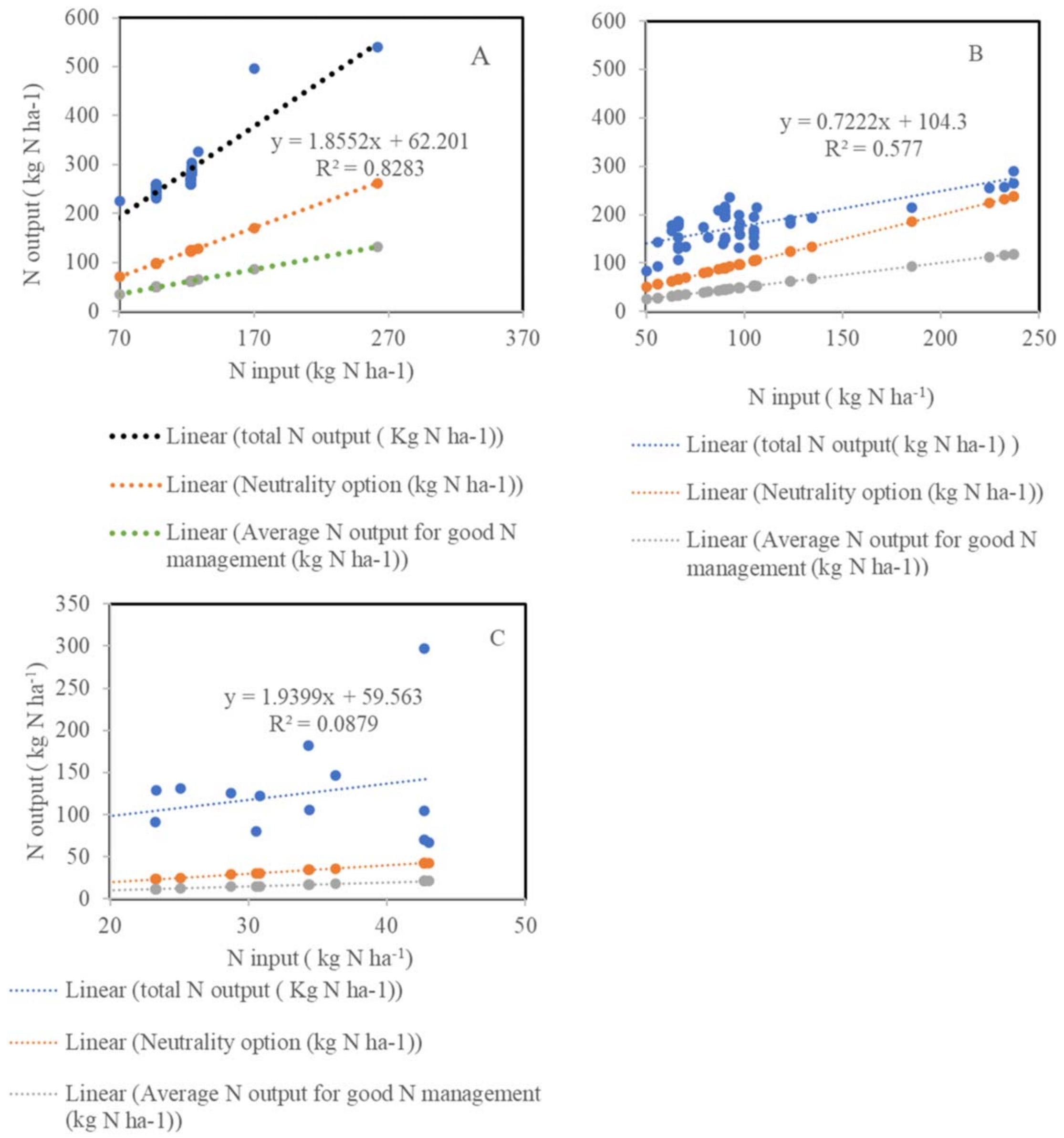

Figure 8. Linear regression model between total N outputs (Kg N ha^{-1}) and total N inputs (Kg N ha^{-1}) in fertilized rice fields in Lake Victoria basin catchment; (a) Nyando; (b) Nzoia, (c) Sondu.

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 8). The low r^2 values in Sondu catchment could be as result of 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.

3.4. 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 3). A significantly lower number of farmers either burn or sell their maize straw. Across the catchment, the proportion of farmers who better manage maize straw instead of burning range between 7 and 25% (table 3). 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 3. Common straw management practices by farmers in various catchments (% percentage).

	Catchment N	Maize crop Feed to livestock	Burn	Sell out	Left in field (recycled)	Total
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
YalaY	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.

4. Discussions

4.1. Current maize and rice grain yield

The reported maize yield was relatively low (< 5 t ha^{-1}), (figures 1 and 2) and this evident with N application in some of the farms (figure 1). This kind of results on maize yield among the small-scale farmer ranging from 1 t ha^{-1} to 2 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. Comparatively, in rice fields where use of N fertilizers was higher compared to maize farming, a higher grain yield was record (figure 2). This was partly due to better N use influences in rice through enhanced panicle formation and grain filling process that are key yield components (Sun *et al* 2018). Gweyi-Onyango *et al* (2021) suggested that more yield in rice 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 (Mafongoya *et al* 2006). However, increment in N usages should focus 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 of 35 kg N ha^{-1} yr^{-1} to 181 kg N ha^{-1} 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 of the N cycles for conservation and adoption of appropriate management strategies. However, 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.

4.2. Trends and variations in yield, N input and NUE

Our study shows that increasing N input with current recommendations for Africa can optimize NUE (50%–90%) in some catchments. The study has also revealed that most rice and maize farms are at risk of 'soil mining' zone on the NUE graphical representations (figures 3 and 5). 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. Chianu *et al* (2012) 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. This has been confirmed by the current study. Lassaletta *et al* (2014) 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 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).

Our regression analyses revealed positive increase in N outputs with increasing N inputs (figures 7 and 8). 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. 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).

4.3. Stover management practices and existing challenges in N cycling in cereals

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 3). 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_4) and N_2O, 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). Identifiable vital challenges contributing to none or low use of mineral N inputs in agricultural activities within the region include the high cost of fertilizers and limiting power to purchase an adequate amount of fertilizer that to sustain crop productivity (Masso *et al* 2017, Tsujimoto *et al* 2019). The high prices in fertilizers are attributed to a lack of subsidies or tax reduction on the products that contribute to increased purchasing power of farmers. Proper fertilizer packaging with smaller and reasonable amounts is another barrier limiting farmers in accessing fertilizers. Some of the farmers using little N were also wary of buying fake or adulterated fertilizers bought from opened bags and sold in smaller amounts and this is complicated by the fact that there are several middlemen with different brands (Masso *et al* 2017). Lack of labor to apply, especially where farmers are need to use a specific application method, also came out as one of the challenges for farmers using mineral N fertilizers. 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.

4.4. Implications and available opportunities

According to our 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 (figures 3–6). 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 *et al* 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.

4.5. Sources of uncertainty

Data used in the study was obtained from in person interviews with the farmers and therefore all the presented information relied on values reported by farmers rather than direct measurements in the field. The N concentration values compare to literature values on previous experiments (though quite limited) we have done in the region. Farmers in the region practice communal grazing in open fields and along the roads and hence difficult to estimate manure inflows into the cropping system. At the same time, a few who keep animals in enclosed systems burn their manure. These factors make it difficult to estimate N input from livestock manure. It is true that the assumptions on (N losses to air/ water) affect the potential calculations of NUE. The emissions are expected to be affected by temperatures, the stage of N supply to rice if done in splits and this is a challenge since the practice is not uniform across the three catchments. Method of application also vary since broadcasting has potential of contributing to more volatilization as compared to deep placement or incorporation into the soils and these are not uniform across the three catchments. It is true there are gaps in this area and this further hampered by limited data on N flows in this area and Africa at large. On the contrary there could be even more N depositions within the catchments (from air) particularly in Nyando catchment that is near Kisumu city with a number of industries especially three sugarcane processing factories. The assumption could be that the particle sizes are smaller and easily spread out more evenly throughout the catchments in question. The N losses in irrigation water is also limited but this can partly be cancelled by the contribution of N from the farmlands where the rivers pass before reaching the targeted farmers in our study catchments.

5. Conclusions

This is the first study to quantify N deficits and NUE trends in the region for two cereals crops with critical N boundaries in food production systems, including soil mining, safe operating zone, and inefficient use of available N in Lake Victoria Basin. We conclude that with the changes in N input as recommended by various policies and stakeholders for SSA, there are likely changes in both current yield and NUE values in future. However, most of the small-scale farmers will continue to experience low yields, specifically in maize with less than 5 t ha^{-1} by 2050, which implies overall challenge of food security for the rapidly growing population. In addition, NUE will also remain in the soil mining zone (>90%) but would be nearing optimal ranges of

50%–90% as N input increases. Besides, increase in N input with the recommended annual growth will also remain below 50 kg N ha^{-1} which is an indicator that most of the maize farmers will continue to use insufficient N inputs in their crops. Our results can be instrumental in informing policy on the changes of N management, particularly concerning sustainability and food security and the need for better recommendations. Therefore, based on our results, we suggest that decision-makers 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.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files). Data will be available from 1 August 2021.

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