

Improving primary nutrients NPK soil balance and urban nutrient cycling promotes sustainable fertilizer management in Sub-Saharan Africa

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Abstract

Sustainable nutrient management in agrosystems is critical to enhance food security and soil health in Sub-Saharan Africa (SSA), where soil nutrient depletion and imbalanced fertilizer application are persistent challenges. This study comprehensively assessed the soil balance of primary nutrients, Nitrogen (N), Phosphorus (P) and Potassium (K), along with urban deposition and estimated NPK nutrient recycling potential in four selected SSA countries: Nigeria, South Africa, Ethiopia and Ghana. Country-level primary data were extracted from the FAOSTAT database over a ten-year period (2012–2022), covering nutrient inputs, agricultural usage and crop productivity. Results revealed negative NPK balances in Nigeria, Ethiopia and Ghana, while South Africa showed a positive balance, indicating excessive nutrient application. Ghana recorded the highest negative N and K balances of $-59.70 \text{ kg ha}^{-1}$ and $-34.94 \text{ kg ha}^{-1}$ respectively in 2022, while the most negative P balance of -6.15 kg ha^{-1} was observed in Ethiopia in 2019. Nigeria recorded the highest NPK urban deposition at 18.99 Tg , representing significant potential for recycling as fertilizer inputs. It is concluded that improving NPK soil balance and recycling urban waste represent promising strategies to address nutrient deficits, reduce input costs and advance sustainable agriculture across SSA. Future challenges and developmental strategies related to food security are also discussed to guide further research on nutrient balances at different spatial scales in Africa and globally.

1. INTRODUCTION

Agriculture is considered as the backbone of Sub-Saharan Africa's (SSA) economy, which provides livelihood, employment and food for millions of people in the region (Nyathi et al., 2025). However, despite its vast potential SSA faces significant challenges related to low agricultural productivity (Rafael, 2023). One of the major reasons for the low agricultural output is the imbalanced soil nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K) collectively referred as NPK, which are essential for plant growth (Dimkpa et al., 2023), and also important for maximizing crop yields and maintaining soil health (Andualem et al., 2024). Nitrogen is at the backbone of proteins, DNA and chlorophyll (Fathi, 2022). Phosphorus regulates energy transfer within the plant, is part of membranes, DNA (Khan et al., 2023). Potassium regulates water uptake, acts as charge carrier and protein stabilizer (Johnson et al., 2022).

In SSA, farmers are extensively growing crops from many years without adopting appropriate nutrient management practices, which leads to the imbalance expressed as depletion or excess (Vanlauwe et al., 2024). Usually, this is a consequence of fertilization disconnected from adequate soil testing (Jocien and Frederick, 2023). As a result, soil fertility has significantly declined, which consequently lead to lower crop productivity. Therefore, the NPK nutrient imbalance in soil has become major barrier to achieve food security and encouraging sustainable agricultural development in SSA.

Assessing the nutrient balance, as the difference between agronomic inputs and outputs, allows us to determine the nutrient flows in farm or at the country level and provide valuable information for both

growers and policymakers, respectively. Furthermore, negative nutrient balance indicates high nutrient removal from soil which may result in the depletion of soil nutrients while positive balance in soil indicates surplus of nutrients and shows inefficient nutrient utilization (Yuan et al., 2021), leading to environmental risks such as eutrophication and greenhouse gas emissions (Zhang et al., 2020; Paramesh et al., 2023). In SSA, where most of the arable soils are deficient in essential nutrient stocks, the imbalanced NPK nutrients poses a significant threat to the overall crop productivity and sustainability in farming systems (Ludemann et al., 2024).

Sub-Saharan Africa has been experiencing steep urban population growth, since food is exported from fields to urban center, cities become a plant nutrient accumulation hotspot (Saghir and Santoro, 2018; Forget et al., 2021). For a matter of fact, this source has remained virtually unexplored (Shaddel et al., 2019; Nsenga Kumwimba et al., 2023). Recycling organic waste products like food scraps, compost, sewage, and other organic debris supports the principles of circular economy, where waste is minimized and resources are reused (Kandpal et al., 2024). Thus, urban nutrient cycling might be incorporated into large agricultural systems, which promotes sustainable farming and increases crop productivity (Salomon and Cavagnaro, 2022).

The objective of this study is to (1) estimate N, P and K soil nutrient balance in selected countries of SSA, (2) quantify NPK fluxes from agriculture field to rural and urban areas and (3) to assess the NPK urban deposition and recycling for efficient nutrient reuse. The study focused on Nigeria, South Africa, Ethiopia, and Ghana because according to Magnone et al. (2022), these four countries are projected to account for more than 70% of the phosphate demand in SSA between 2020 and 2050. Since proper nutrient use requires a certain balance, we infer that this might be true also for N & K demand. Furthermore, we also provided some recommendations for development strategies to enhance the sustainable use of fertilizers and increase crop productivity in SSA. The main focus will be on how balanced soil nutrient management and urban nutrient recycling can contribute to the development of more resilient agricultural systems, fostering food security and long-term sustainability.

2. MATERIAL AND METHODS

2.1 Study area and country selection

This study focused on four Sub-Saharan African countries: Nigeria, South Africa, Ethiopia, and Ghana. These countries were selected because they are projected to account for more than 70% of phosphate demand in Sub-Saharan Africa between 2020 and 2050 (Magnone et al., 2022). In addition, they represent diverse agricultural systems, population sizes, fertilizer-use intensities, and levels of urbanization, making them suitable case studies for assessing nutrient balances and recycling opportunities.

2.2 Data sources

We gathered ten (10) year data (2012–2022) for NPK inputs applied for agricultural crop production and NPK agronomic outputs from the arable land for selected countries of Sub-Saharan Africa (i.e. Nigeria, South Africa, Ethiopia and Ghana). The required data was extracted from Food and Agriculture Organization (FAO) datasets (i.e., *FAOSTAT: Fertilizer nutrient data, 2024*) (FAO, 2024). The datasets included fertilizer nutrient use, crop production statistics, and demographic information. Additional information on nutrient recycling and urban waste management was obtained from published literature.

2.3 Estimation of NPK soil nutrient balance

For the calculation of NPK agronomic output, the total crop production was calculated for the ten years (2012–2022) for each selected country. For Nigeria, the top thirteen (13) crops were selected (i.e. cassava, cow pea, wheat, soybean, taro, yams, maize, banana, millet, potatoes, rice, sorghum and tomato) on the basis of their high production covering approximately 79% of the total crop production per year. For South Africa, Ethiopia and Ghana, the top 17, 21 and 16 crops were selected which covers around 89%, 74% and 82% of the total crop production respectively recorded in a year. Furthermore, the NPK removal from the soil by the crop was calculated according to the estimate potential of each crop to remove N, P and K separately from the soil as per its biomass production in a year. The total NPK removal by the crops in a year is termed as the “NPK agronomic output”, which was further used to determine the NPK soil nutrient balance. The same dataset was organized for the ten year (2012–2022) following same procedure to understand NPK soil nutrient balance trend in the selected countries. The following Eq. 1 was used to calculate the N, P and K balance in the soil.

$$\text{Nutrient balance} = \text{Nutrient input} - \text{Nutrient agronomic output} \quad \text{Eq. 1}$$

where nutrient input represents the total annual N, P, and K fertilizer applied per hectare, and nutrient output represents nutrient removal through harvested crops.

For each country, major crops contributing approximately 75–90% of total crop production were selected. Crop-specific nutrient removal coefficients obtained from published literature were used to estimate nutrient extraction by harvested biomass. The total nutrient output was calculated using Eq. 2.

$$\text{Nutrient Output} = \sum (\text{Crop Yield} \times \text{Nutrient Removal Coefficient}) \quad \text{Eq. 2}$$

The annual nutrient balance was then expressed in kg ha^{-1} for nitrogen, phosphorus, and potassium.

2.4 Assessment of crop productivity and nutrient inputs

Country-level average crop yields (kg ha^{-1}) were compared with annual NPK fertilizer inputs. Relationships between fertilizer application and crop productivity were evaluated using correlation analysis to identify trends between nutrient use and agricultural output.

2.5 Estimation of urban nutrient deposition

Nutrient flows from agricultural production to rural and urban populations were estimated using crop production and population distribution data. The transfer of nutrients was assumed to occur through

food consumption and biomass utilization. Urban nutrient deposition was estimated based on the proportion of agricultural production consumed in urban areas and accumulated in organic waste streams, including food waste, sewage sludge, and municipal organic residues.

2.6 Estimation of nutrient recycling potential

Potential nutrient recovery was estimated by assuming different recycling scenarios for urban organic waste. A conservative recycling efficiency scenario of 30% was used to estimate the amount of N, P, and K that could potentially be recovered and returned to agricultural systems. The nutrient recovery potential was calculated through Eq. 3.

$$\text{Nutrient Recovery} = (\text{Urban Nutrient Deposition} \times \text{Recycling Efficiency}) \text{ Eq. 3}$$

where recycling efficiency was assumed to be 30%.

2.7 Data analysis and visualization

All calculations were performed using Microsoft Excel and graphical analyses were conducted to illustrate trends in nutrient balances, fertilizer inputs, crop productivity, nutrient transfers, and recycling potential during the study period (2012–2022).

3. RESULTS

3.1 NPK soil nutrient balance in selected SSA countries

3.1.1 Nitrogen balance

The results showed significant nutrient imbalance for all four countries (Fig. 1). For N balance in soil, Nigeria, Ethiopia and Ghana showed significant N deficit from soil, maximum negative N balance of $-30.84 \text{ kg ha}^{-1}$, $-24.02 \text{ kg ha}^{-1}$ and $-59.70 \text{ kg ha}^{-1}$ were recorded for the four countries, respectively. South Africa showed maximum positive N balance of 32.43 kg ha^{-1} in 2019, indicating excess N application and potential N losses from soil. However, the contribution of N fixation by legumes is likely minimal in these countries. Legumes accounted for only about 3–4% of total crop production in these countries during 2012–2022, suggesting a negligible impact on overall soil nitrogen balance (Fig. 1A).

3.1.2 Phosphorus balance

The same trend was observed for the P balance in soil, Nigeria showed maximum negative P balance of -3.71 kg ha^{-1} in 2012, Ethiopia showed maximum negative P balance of -6.15 kg ha^{-1} in 2019 and Ghana showed highest negative P balance of -3.13 kg ha^{-1} in 2018, while only South Africa showed positive P balance ranging from 3.54 – 13.11 kg ha^{-1} during 2012–2022 (Fig. 1B).

3.1.3 Potassium balance

Figure 1C reveals substantial differences in soil potassium balance among the selected Sub-Saharan African countries. Ghana recorded the most severe potassium deficit, which increased from approximately -22 kg ha^{-1} in 2012 to nearly -35 kg ha^{-1} in 2022, indicating progressive depletion of soil K reserves. Nigeria and Ethiopia also exhibited consistently negative potassium balances throughout the study period, suggesting that crop removal exceeded fertilizer replenishment. In contrast, South Africa transitioned from negative to positive potassium balances after 2017, reflecting higher fertilizer inputs and improved nutrient replacement. These findings indicate that potassium depletion remains a major challenge in most SSA countries and may constrain future agricultural productivity if corrective nutrient management strategies are not implemented.

Furthermore, Ghana exhibited an increasing trend of negative N and K balances, indicating that more N and K are being removed from soils than replenished. This pattern likely reflects continuous and intensive cropping on the same arable land, leading to progressive soil nutrient depletion over time. However, the South Africa has shown negative K balance up to 2017 and then it comes to positive balance during the years 2018–2022, which indicated its high fertilizer inputs as compared to their nutrient removal from soils, the same trend was observed for N and P during the whole study period (2012–2022).

3.2 Relationship between NPK inputs and crop productivity

3.2.1 Trends in fertilizer inputs and crop yield

The results shown in Figure showed a positive correlation between NPK inputs and crop yield in all four countries, indicating the importance of optimizing soil nutrition in sustaining crop productivity. While comparing the studied four countries during the year 2012–2022, South Africa showed highest NPK inputs ($94.81\text{--}160.99 \text{ kg ha}^{-1}$) as compared to others and produced highest yield of $6870\text{--}8800 \text{ kg ha}^{-1}$ among four countries with a positive correlation ($R = 0.66$). However, Ethiopia has applied the lowest NPK input ($14.08\text{--}38.33 \text{ kg ha}^{-1}$) and produced lowest yield of $2030\text{--}2880 \text{ kg ha}^{-1}$ with positive correlation ($R = 0.52$). Among Nigeria, Ethiopia, and Ghana that produced negative NPK balance in soil as shown in Fig. 1, the Ghana produced the highest yield range ($5140\text{--}7090 \text{ kg ha}^{-1}$) with minimum NPK input ($8.63\text{--}22.87 \text{ kg ha}^{-1}$), which indicated that Ghana is depleting the soil nutrient faster than all other countries. Furthermore, among NPK application rates, all countries has applied more N fertilizers as compared to P and K. The Ethiopia have applied highest proportion (81%) of N fertilizer followed by Nigeria (78%), while Ghana applied only 52% of N out of total NPK application. Nigeria, South Africa, and Ghana applied the least P proportion of 8%, 16% and 18%, respectively, out of total NPK application while Ethiopia applied very minimal K application during 2012–2022. This clearly showed the imbalance in nutrient application, which is one of the major reasons explaining the yield gap and inefficient use of nutrient in these countries.

3.2.2 Implications of nutrient imbalance for yield gaps

3.3 Crop composition and implications for nutrient management

The proportion of different types of crops grown by each studied country during 2012–2022 is shown in Fig. 3. When comparing the NPK input by each country during the same period (Fig. 2, Nigeria and Ghana produced 75% and 83% of their total crop production from root and tuber crops, respectively. However, Nigeria and Ghana applied 78% and 52% of the total NPK inputs as N, respectively. Ethiopia produced about 75% of cereals out of total production which generally required large amount N application and for that reason Ethiopia applied highest proportion of N (81%) as compared to other countries. However, Ethiopia applied negligible amount of K which creates imbalance in nutrient application and reduced crop productivity. South Africa produced highest proportion of fruit and vegetables (56%) followed by cereals (36%) which required high amount of NPK nutrients. For that reason, South Africa likely applied highest amount of NPK as compared to other countries but the imbalance in nutrient application, as shown in Fig. 1, leads to the positive soil nutrient balance which promotes nutrient losses by runoff, erosion and causes environmental risks like greenhouse gas emissions and eutrophication.

Moreover, legumes are the least grown crop type (3% – 4%) across all countries, despite their nutritional and economic value. Their ability to fix atmospheric nitrogen could help reduce excessive N inputs and promoting a balanced soil nutrient application. As discussed earlier, countries like Nigeria, Ethiopia, and Ghana face negative nitrogen balances in their soils. Crop production data from 2012 to 2022 reveal that Nigeria and Ghana focus heavily on root and tuber crops, which account for 75% and 83% of total crop production, respectively, while Ethiopia allocates 75% of its cropping area to cereals.

3.4 Estimated transfer of NPK to rural and urban areas

The rural–urban split in the estimated production of agronomic K, N, P has shifted from 2012 to 2022 (Fig. 4). In Nigeria, South Africa and Ghana, it was found that nutrient transfer shifted towards urban areas while Ethiopia had a higher proportion of nutrient transfer towards rural areas. The estimated transfer was higher in 2012 on the rural side of the divide in Nigeria, but it grew steadily over time on the urban side of the divide. Nigeria had the highest estimated NPK transfer to urban areas in 2022 (1,860 Gg) while Ghana had the second highest value of 529 Gg. Nigeria also had the largest cumulative NPK deposition (estimated at 15,118 Gg by 2021), followed by South Africa (4,001 Gg)..

3.5 Urban nutrient deposition and recycling potential

The estimated NPK fluxes in the agricultural systems of Nigeria, Ghana, South Africa and Ethiopia for 2012–2022 are shown in Fig. 5. The estimated nutrient deposition in rural areas was highest in Nigeria while the same was observed for the urban areas among the four countries. Of this, 3.62 Tg N, 0.38 Tg P and 0.64 Tg K were added to agricultural soils in Nigeria. An estimated 10.27 Tg of N, 1.19 Tg of P, and 5.52 Tg of K were exported from agriculture to cities, respectively.

The nutrient imports via animal and crop products were estimated as 0.11 and 1.91 Tg of NPK, respectively. The total nutrient deposition into the urban areas was estimated to be 11.66, 1.47 and 5.86 Tg of N, P and K, respectively, after subtracting the amount of nutrients produced by domestic agriculture and imported products. These nutrients have been linked to urban waste streams, such as sewage sludge and organic waste. With the assumed recycling rate of 30% it is estimated that Nigeria could be able to recover around 3.50 Tg of N, 0.44 Tg of P and 1.76 Tg of K from urban waste (Fig. 5). The amount of nutrients recovered was greater than the amount of NPK supplied to the country through agriculture at present.

4. DISCUSSION

The study could focus on the national NPK balances, NPK inputs, productivity, composition of crops, nutrient transfers from rural to urban areas, and the possible recovery of N, P, and K from urban waste in Nigeria, South Africa, Ethiopia and Ghana. There are three findings which are of particular interest. Firstly, Nigeria and Ethiopia had an ongoing deficit in nutrients while in South Africa, nutrients generally had surplus, particularly for N and P. Secondly, more positive association between crop productivity and fertilizer inputs was found, and differences between countries indicated that the effect of fertilizer quantity on the performance of crop productivity was not sufficient. Thirdly, a significant amount of nutrients was removed from agricultural areas and delivered to urban centers, especially in Nigeria, which created a nutrient loss problem for the agricultural soils and a chance for recovery in the urban waste. The results of this study suggest that improving nutrient security in Sub-Saharan Africa will require more than just more fertilizer, but also a better balance between N, P, and K inputs, enhancing nutrient-use efficiency, and connecting urban waste streams to agricultural production.

4.1 NPK balances and implications for soil fertility

The consistently negative NPK balances of all three countries in Nigeria, Ethiopia and Ghana suggest that the nutrients removed in harvested crops were greater than the nutrients added in fertilizer inputs in this study. Prolonged negative balances may lead to progressive loss of soil nutrient reserves, soil fertility, and crop productivity (Abuye et al., 2021; Rawal et al., 2022). Ghana had the biggest N and K deficiency, and Ethiopia had the highest P deficiency. The patterns indicate that N-based fertilizer programs are unlikely to compensate for the amount of P and K taken out by the crop. In another situation, high levels of N application with low levels of P and K can also lead to reduced nutrient-use efficiency, as the deficiency of one nutrient (P) effects the uptake of the other nutrients supplied (K) (Fageria, 2016).

In contrast, South Africa had mainly positive N and P balances, and a change from negative to positive K balance following 2017. Soils with positive balances might be able to maintain fertility, if soils are low in nutrients; however, the continuous positive balances also suggest that nutrient supply may be greater than crop removal. These excesses can lead to higher loss rates of nutrients through runoff, leaching, erosion and gaseous emissions, especially when rates of application exceed crop requirements (Zhang

et al., 2020; Paramesh et al., 2023). The divergent national trends are then reflected by the fact that one national strategy for fertilizer use would be unsuitable. Improved nutrient replenishment is needed in Nigeria, Ethiopia and Ghana while increasing the attention to nutrient-use efficiency and the environmental impact of nutrient surpluses is needed in South Africa.

The balances should, however, be viewed as national agronomic rather than as measures of soil nutrient stocks changes. Major differences in the data by crop, soil, farm system and area can be masked by the national averages. Also, the estimates do not fully consider the biological fixation of nitrogen, manure, recycling of crop residues, atmospheric deposition, erosion, or other flows of nutrients. These results are consequently most relevant for determining general nutrient-management pressures and priorities, which should then be explored using field- and subnational-scale data.

4.2 Fertilizer inputs, crop productivity, and yield gaps

The positive correlations of the NPK inputs with crop yield for the four countries indicate the need for proper supply of nutrients for agricultural productivity. South Africa had the highest levels of fertilizer input and average yield while Ethiopia had the lowest level of fertilizer input and yield. However, it is observed from the differences between the two countries, Ghana and Ethiopia, that similar levels of fertilizer inputs can be accompanied by significantly varying yields. The amount of fertilizer, therefore, is not the only factor which determines productivity in the country. The yield response to nutrient application per unit area of nutrient applied can be affected by soil condition, nutrient balance, crop type, rainfall, irrigation, management practices, soil testing facilities, and the timing and placement of the nutrient application.

This outcome is in line with the broader yield-gap findings for Sub-Saharan Africa. Constraints of the nutrients, soils, climate, technology and socio-economic factors of the farm interact and can affect the gap between what can be achieved and what is actually obtained (Miti et al., 2024). The negative impact of soil degradation, soil erosion, low organic matter, soil acidity, variable rainfall, and limited irrigation can limit crop responses even after fertilization in Ethiopia (Erkossa et al., 2022; Solomon et al., 2024). The factors cited above are plausible explanations of the lower yield found in Ethiopia than in Ghana; however, the results presented in this paper do not allow the identification of the individual contributions of these factors. The comparison should then be understood as an indicator for the integration of soil and water management in the fertilizer recommendations, and not as proof of an influence of a specific factor on the difference.

Responses to the crop may also be restricted by imbalance fertilization. Excessive N can cause excessive vegetative growth, lodging, susceptibility to pests and disease, delayed maturity and soil acidification and P deficiency will affect root growth and energy metabolism, deficiency of K will cause plant to dry easily and reduce the quality of the crop (Malhotra et al., 2018; Wu et al., 2019; Liu et al., 2021; Zhang et al., 2022). Therefore, fertilizer policy should go beyond encouraging higher total fertilizer inputs to specifying specific N, P, and K application combinations and the timing of those inputs, as well as integrated soil-fertility management that can enhance yield and nutrient-use efficiency.

4.3 Crop composition and nutrient-management priorities

Part of the variation in the nutrient balance for the nations is due to differences in crop composition. Nigeria and Ghana had the majority of root and tuber crops and both countries had the majority of fertilizer inputs in the form of N. Harvested root and tubers (RTs) tend to draw significant amount of K and P from the soil and this can exacerbate the deficiency (Tein et al., 2014; Laxminarayana et al., 2016; Setu, 2022). Therefore, the high K deficiency found in Ghana and the low K balance throughout Nigeria is consistent with the root-and-tuber based production and low K application. The importance of crop specific removal of P and K in balanced formulations should not be underestimated and should be considered more than just N fertilizer. Ethiopia's production was dominated by cereals and this is one of the reasons for its relatively large percentage of N fertilizer use. The relatively low K input and negative balances of the P and K pools, however, indicate that this N-dominant fertilization approach might be limiting productivity in the long term. Within South Africa, higher application of fertilizers in total production occurred in the larger proportions of fruits, vegetable and cereal production. The positive balances indicate a higher nutrient replacement, but also emphasize the importance of synchronization with the nutrient requirements of the crop and reduction of nutrient losses.

The share of legumes production was small in all four countries. If their suitable use in rotations, intercroops or green-manure systems could supply a portion of synthetic N, enhance soil organic matter and contribute biologically fixed N (Córdova et al., 2019; Mudare et al., 2022). However, the results from various production systems suggest that legume integration could boost subsequent crop yields and decrease the reliance on N-fertilizer, depending on the legume species, biomass production, soil nitrate availability, legume residue management, climate, and the effectiveness of the legume symbiotic microorganisms (de Sousa et al., 2016; Gatsios et al., 2021; Pipai et al., 2023; Flohr et al., 2024). Balanced fertilization should therefore not be a substitute for legumes, but be complemented by them, and use be adjusted to local farming practice.

4.4 Urbanization and the redistribution of agricultural nutrients

The spatial distribution of nutrients in food and agriculture biomass is evolving with the growing population and urbanization. By 2050, the population of Africa is expected to grow significantly (United Nations, 2015), driving the increased transport of food products from the rural sector to the urban sectors. This one-way flow can lead to nutrient depletion in agricultural regions while at the same time adding to nutrient loads in urban waste streams, unless the nutrients in these products are recovered and returned to the land via agriculture. This can be seen from the results in Nigeria, South Africa and Ghana, where the proportion of agronomic NPK production in urban areas rose from 2012 to 2022. The highest estimated urban transfer and cumulative deposition in Nigeria with an appreciable rural share in Ethiopia. The differences in the numbers are likely due to differences in population size and urbanization, but the current analysis does not account for the individual impact of any of the demographic or economic parameters. However, the observed pattern shows that nutrient management will not be

simply considered at the farm level at a national level. Food distribution, food consumption and food sanitation, as well as waste management, are part of a nutrient system.

The accumulation of nutrients in urban areas is an environmental problem and a recovery opportunity. When not properly managed, food waste, human excreta, sewage sludge and other organic wastes can add nutrients to water and the atmosphere. On the other hand, these streams are also sources for secondary fertilizer if collected, treated, tested and re-distributed safely without harm to man or nature. This is a rural-urban nutrient loop that, if closed, would decrease nutrient losses, partly mitigate the demand for fertilizers and link urban use with agriculture.

4.5 Potential contribution of urban nutrient recycling

The amount of NPK estimated that accumulates in urban centres of Nigeria shows that there is considerable theoretical potential for nutrient recovery. These amounts are relatively large, representing about 3.50 Tg N, 0.44 Tg P, and 1.76 Tg K, respectively, of urban waste that could be recovered using the 30% recycling scenario applied in this study and, compared with the fertilizer inputs considered in this study, may provide a significant additional source of nutrients. However, the scenario should be read as a possible recovery rate and not as an actual recovery rate. Not every nutrient entering into the cities is recovered in recoverable waste flows and not all nutrients recovered during recovery survive storage and treatment or are available for crops. Actual recovery will be based on extent of collection, source separation, processing efficiency, nutrient losses, product quality, contaminant levels, transportation distances, market demand, and farmer and consumer acceptance. However, caution must be taken in making comparisons with current inputs of fertilizers, as recovered organic nutrients and mineral fertilizers vary in concentration, availability, release rate, handling requirements, etc.

There is still limited use of organic waste recycling in many parts of Sub-Saharan Africa. Many composting, vermicomposting, anaerobic-digestion and urban-agriculture programs are small, or informal, and only a small percentage of urban organic waste is formally composted (Ddiba et al., 2022; Rubagumya et al., 2023). The recovery would then need investments in collection and treatment plants, quality standards of recovered products, extension support, and transport facilities from the urban sources to the nutrient poor agricultural areas. Assess economic feasibility at the local level, as capital and operating costs, fertilizer prices, policy incentives and travel distances can make a theoretically recoverable nutrient stream actually impractical.

The recycling of manure also provides an example of the need for spatial coordination. Although a land area may be adequate for the nutrients it provides, nutrients can still be lacking in areas where livestock is concentrated or in urban centers (Van Dijk et al., 2016), which means there are limitations to reuse. Integrated planning therefore should take into account the amount and position of nutrients that can be recovered. Some parts of the organic streams can use decentralized composting or digestion, while other concentrated wastewater or sludge streams might warrant larger treatment facilities.

4.6 Technologies for nutrient recovery

The right recovery technology will vary based on the waste stream, nutrient content, the desired quality of the recovered product, the infrastructure, and the available financial and technical resources in the region. The options that are available are composting, anaerobic digestion, enhanced biological phosphorus removal, ammonia stripping, membrane filtration, crystallization, chemical precipitation, and recovering phosphorus from sewage sludge or ash (Egle et al., 2015). Traditionally, the aim with wastewater treatment has been to reduce organic material and nutrients to prevent eutrophication in receiving waters, rather than to generate reusable fertilizers. It must also take into account the nutrient concentration, safety of the product, its agricultural value and the possibility of transporting and applying the recovered material.

Treated effluent, anaerobic-digester supernatant, sewage sludge and sludge ash may be used for phosphorus recovery. The crystallization and precipitation processes can transform the dissolved P into concentrated products and the wet-chemical and thermochemical processes can extract P from ash (Egle et al., 2015; Carrillo et al., 2020; Magrí et al., 2020). Wastewater composition varies and there is the possibility of P being present as dissolved P, biologically bound P, or chemically bound P, complicating process selection (Melia et al., 2017). Products from sludge or ash may also be restricted in their agricultural applications due to heavy metals and other contaminants, which can only be effectively prevented or removed through purification, product testing and regulatory standards.

High recovery rates can be obtained by advanced technologies but these can be very capital intensive, energy intensive, require a high level of expertise, and need centralized infrastructure. In resource-limited areas, less expensive strategies such as source separation, composting of food waste and manure, and anaerobic digestion might be more viable, but still pose challenges due to pathogen control, plastic, pharmaceutical and other contaminant issues (Macura et al., 2021; Xiong et al., 2023). The introduction of technology in Sub-Saharan Africa should therefore be driven by waste streams in the region and not recovery efficiency alone, as costs for the whole technology life cycle, including waste streams, must also be considered.

4.7 Agricultural use of recovered nutrients

Nutrient-recovery will only contribute to improving nutrient balance in agriculture if the nutrients can be provided in the right form and at the right time. Compost may help to enhance soil structure, water holding capacity and biological activity but may also release nutrients slowly and in an unpredictable way compared to mineral fertilizers. (Zhao et al., 2022) found that in most cases, yield was lower with compost than with mineral fertilizer, but higher when compost was supplemented with mineral fertilizer. This enables an integrated form of solution where recovered organic products are not simply used as a substitute for well-considered mineral fertilizers. Organomineral fertilizers' nutrient-use efficiency is also influenced by their formulation. Toprak and Seferoğlu (2024) observed that the lower formulations of the organic-matter and P rates resulted in higher P-use efficiency as compared to the higher formulations. The result is that the higher the levels of organic material or P added, the worse the agronomic performance (nutrient immobilization and imbalanced supply). Before recommending rates of use for

recovered products, total nutrient content, plant available nutrients, stability, salinity, pathogens and contaminants should be determined.

There is a wide range of nitrogen available, especially among organic amendments. During the period evaluated, mineralization from guano and feather meal was high, and release of mineral N from relatively stable materials (vermicompost, yard-waste compost) was < 10%, while release from poultry manure (PM) and poultry-manure compost (PMC) was intermediate (Geisseler et al., 2021). Total N in an urban waste product is therefore not synonymous with "immediately-available" fertilizer N so that application recommendations must take into account the rate of mineralization, maturity of the amendment, the needs of the crop, soil conditions, and the timing of application.

These agronomic constraints qualify the national recycling estimates. The amount of the nutrient that can be used to substitute mineral fertilizer in a specific growing season could also be significantly lower, even when high concentrations of NPK are found in urban wastes. In addition to the short-term benefits to nutrient supply, the long-term benefits to soil organic matter and soil physical condition should also be taken into account, and contaminant control and product consistency should be required to ensure soil, crop and human health.

4.8 Study limitations and future research

The study provides a national assessment of nutrient balances and urban recycling potential, but several limitations should guide interpretation. First, the balance calculations depend on FAOSTAT data and literature-derived crop-removal coefficients, which may not capture subnational variation in production, soils, crop varieties, and management. Second, some nutrient inputs and losses, including manure, biological N fixation, atmospheric deposition, crop-residue return, erosion, leaching, runoff, and gaseous emissions, may be incompletely represented. Third, allocating nutrient transfers using rural and urban population shares provides an approximation of nutrient movement rather than a direct measurement of food flows and waste generation. Fourth, the 30% recycling scenario does not account fully for collection losses, processing losses, nutrient bioavailability, contamination, or economic feasibility.

Future research should develop subnational nutrient budgets, quantify actual urban waste streams, and determine the recoverable and plant-available fractions of N, P, and K. Spatial analysis is needed to connect urban nutrient sources with agricultural areas experiencing the largest deficits and to estimate transport requirements. Field experiments should compare recovered products with mineral fertilizers under representative soil and climatic conditions, while economic assessments should include collection, processing, quality control, transport, and farmer adoption. These steps would allow the theoretical recycling potential identified here to be translated into safe, economically viable, and locally appropriate nutrient-management strategies.

5. CONCLUSION

The study assessed soil balance of primary nutrients – N, P, and K; nutrient use patterns; crop productivity; urban nutrient deposition and nutrient recycling potential in four sub-Saharan African countries – Nigeria, South Africa, Ethiopia and Ghana. Results showed significant nutrient management imbalances throughout the region. Nigeria, Ethiopia and Ghana had consistently recorded negative nutrient balances for NPK suggesting removal of nutrients through crop removal was greater than the nutrients that were added. South Africa on the other hand had mostly positive nutrient balances, with more intensive nutrient use and higher fertilizer inputs generally. The results also showed positive relationship between the use of NPK fertilizer with productivity of the crops. There are, however, large variations in yield between countries which imply that fertilizer alone cannot close yield gaps. Agricultural productivity is also influenced by soil quality, nutrient-use efficiency, climatic conditions and soil management practices. The high proportion of root and tuber crops to cereal crops in Nigeria and Ghana, combined with low potassium replenishment, led to low levels of potassium supply, and Ethiopia was the country with a high proportion of cereal crops, high dependency on nitrogen and limited potassium application.

The study also emphasized the increasing transfer and accumulation of nutrients in urban areas due to the rapid urbanization. The nutrient deposition was highest in Nigeria, suggesting that there is significant potential for nutrient recovery and reuse in the city. The scenarios showed that the recycling potential of the different urban organic waste streams is significant even if only a portion of the nutrients is recovered, resulting in a shift from synthetic fertilizers, better nutrient balances in agriculture, and reduced dependence on fertilizers. In general, better nutrient management of NPK and better nutrient recycling in the cities are potential ways to improve soil fertility, agricultural production and food security in Sub-Saharan Africa. Strategies for balancing fertiliser use, more integration of legumes in cropping systems, investments in nutrient recovery technologies and the creation of nutrient circular economies to reconnect the urban waste flows with the agriculture production should be emphasized in future. These strategies can work to enhance the efficiency of resource use, alleviate environmental pressures, and advance sustainable agriculture in the region, all at once.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

W.I. conceived the study, conducted the investigation, collected the data, performed the formal analysis, and prepared the original draft of the manuscript. S.K. contributed to the study design, methodology, interpretation of the results, and critically reviewed and edited the manuscript. S.E.S. contributed to the conceptualization, methodology, formal analysis, interpretation of the findings, and manuscript writing, review, and editing. A.S. assisted with data curation, literature review, validation, and manuscript revision. H.W.P.C. supervised the research, contributed to the conceptual framework, interpretation of the results, and critically reviewed and edited the manuscript.

Data Availability

Data will be made available on request.

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Figures

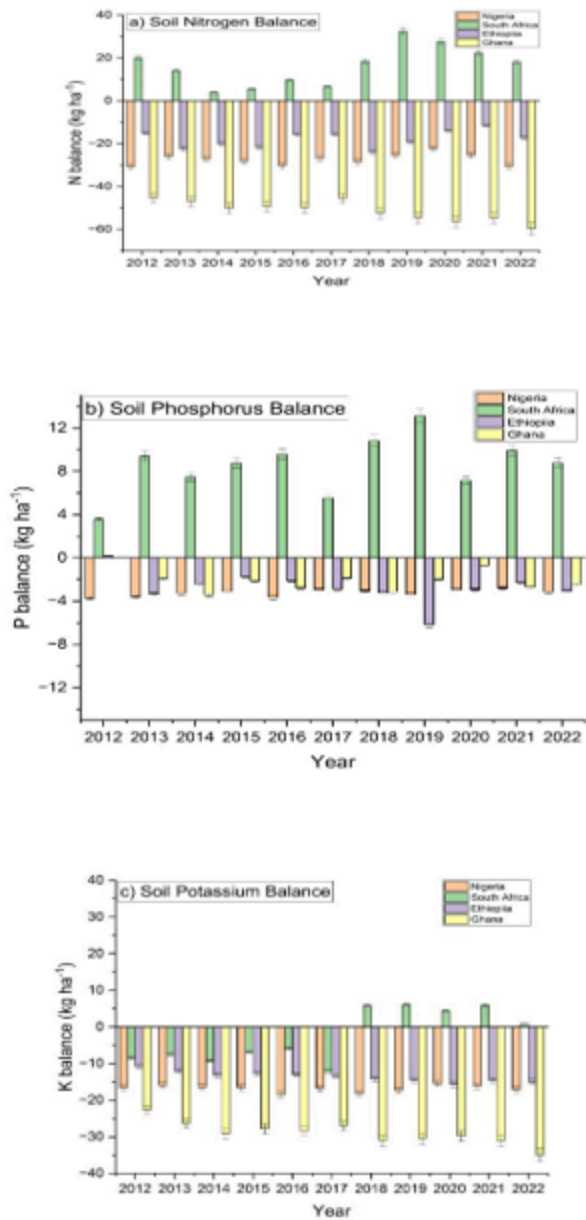


Figure 1

Soil nutrient balance a) Nitrogen b) Phosphorus c) Potassium estimation in Nigeria, South Africa, Ethiopia, Ghana from 2012-2022. Between 2012 and 2022 the average balance was: Nigeria (N: -27.48; P: -3.25; K: -16.82), South Africa (N: +16.26; P: +8.55; K: -2.47), Ethiopia (N: -17.97; P: -2.74; K: -13.59), and Ghana (N: -51.43; P: -2.10; K: -28.96).

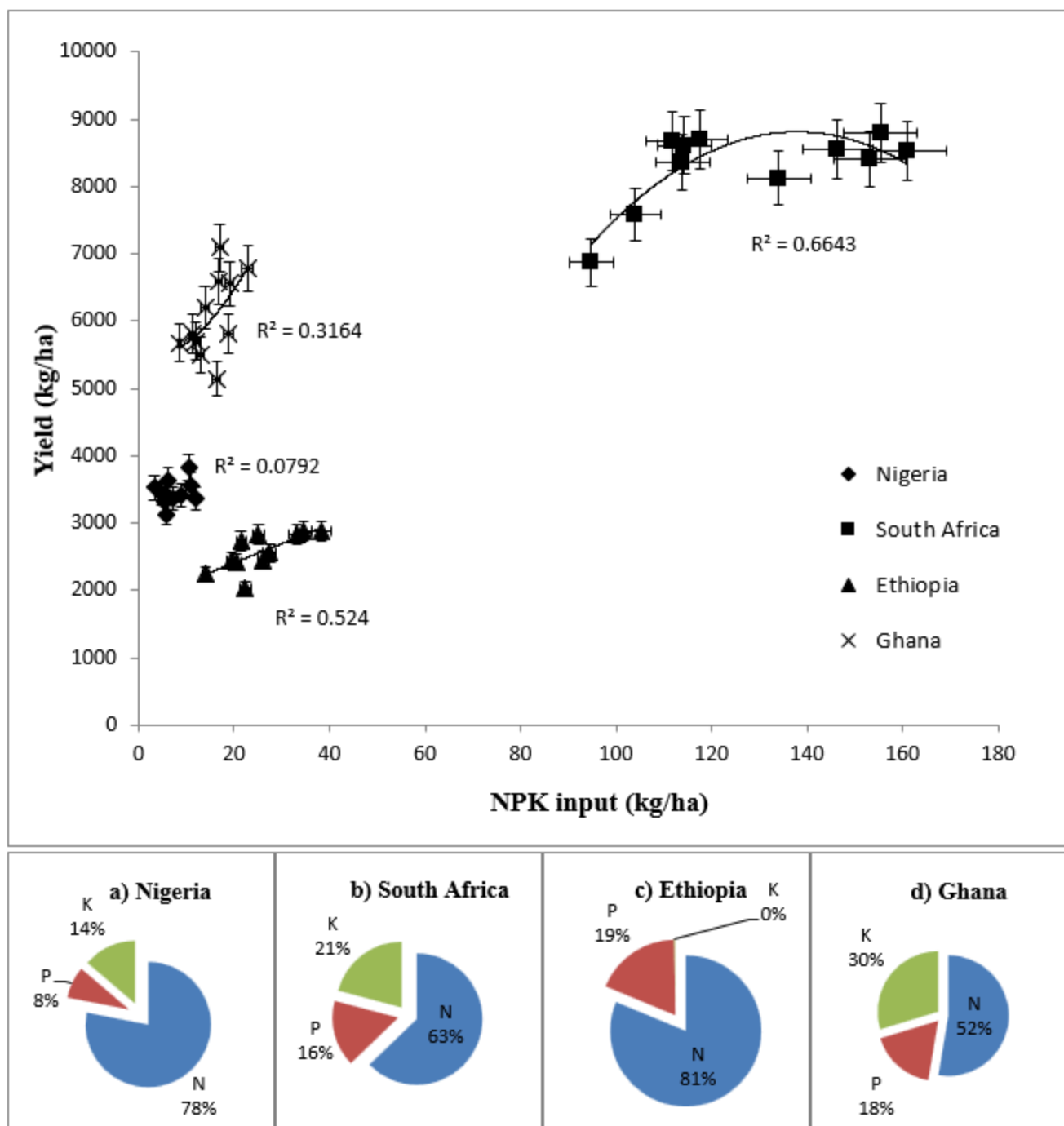


Figure 2

NPK input vs Yield and proportion of N, P and K as input fertilizer in Nigeria, South Africa, Ethiopia, and Ghana

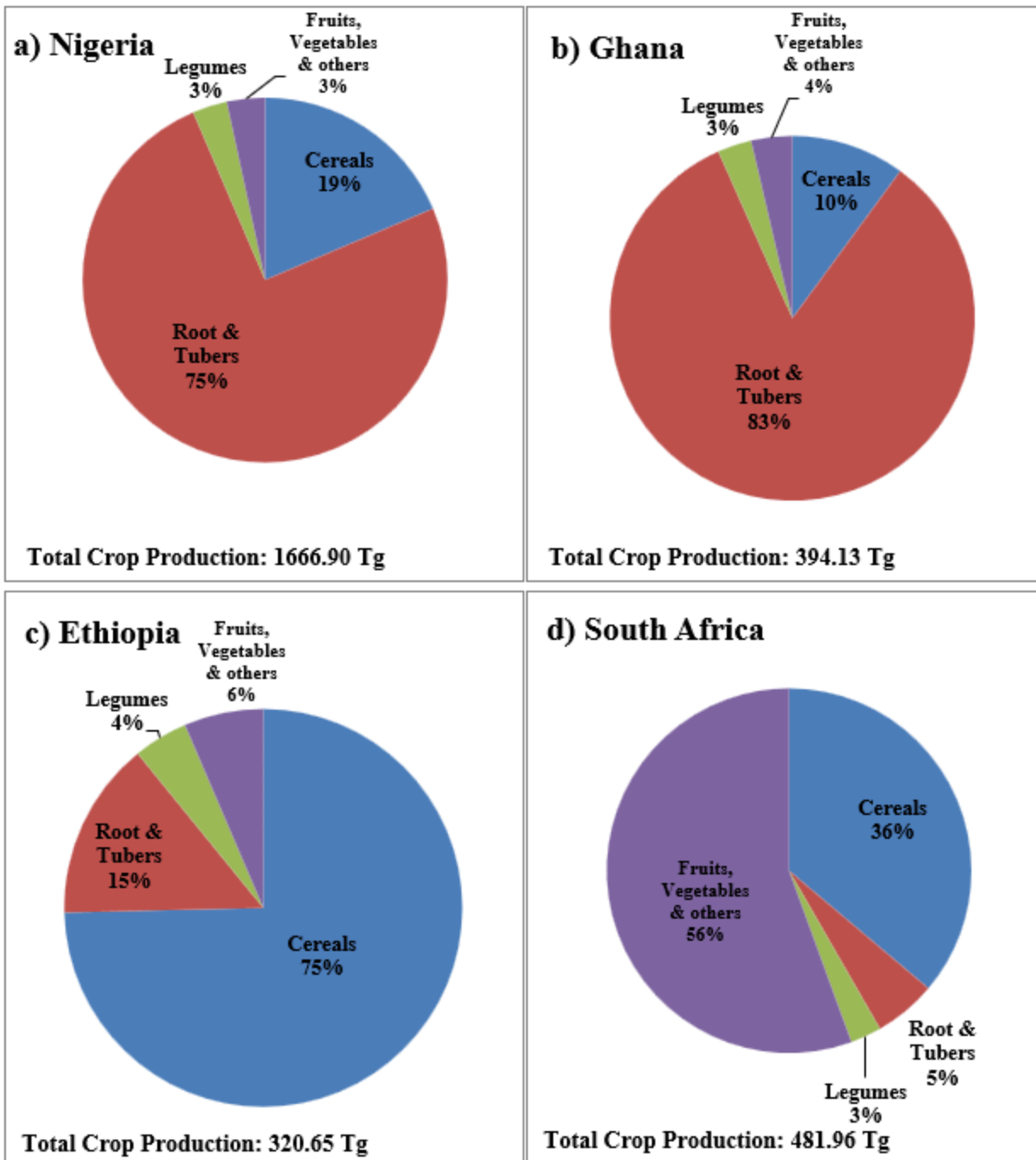


Figure 3

Proportion of crops produced in a) Nigeria b) South Africa c) Ethiopia and d) Ghana during 2012- 2022

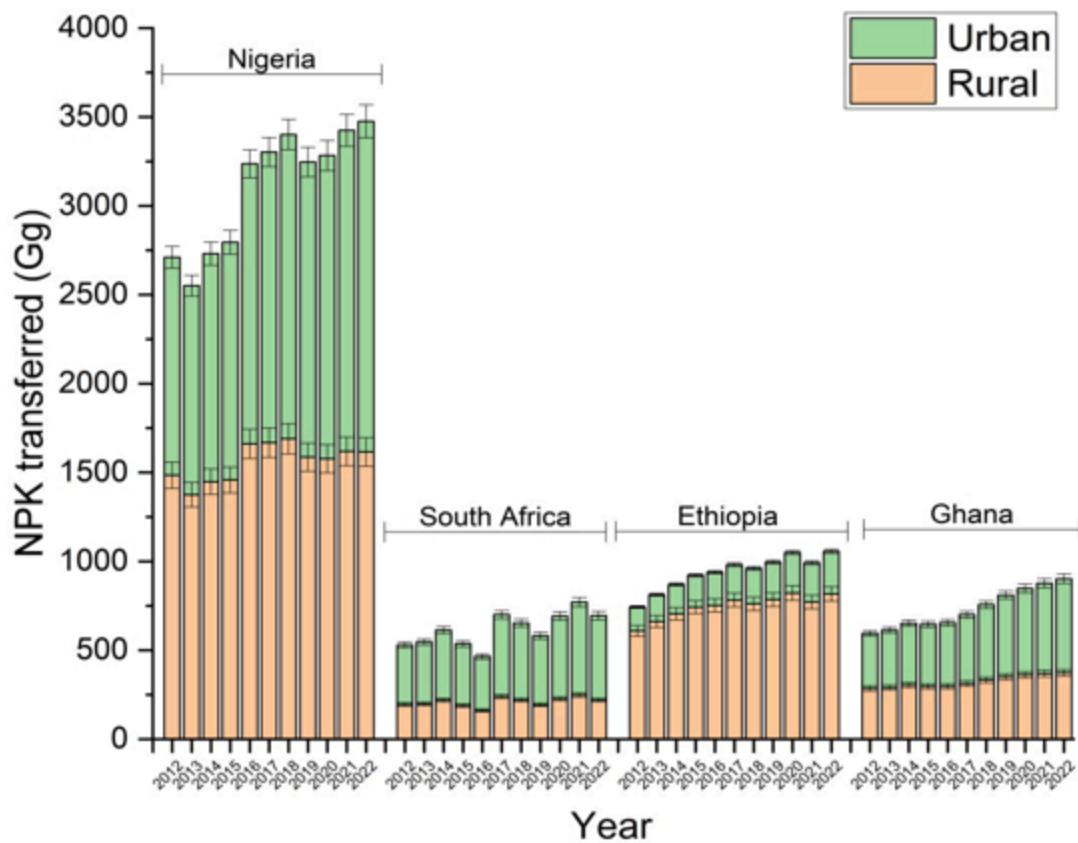


Figure 4

Agronomic NPK output and its estimated transfer and deposition to rural and urban area in Nigeria, South Africa, Ethiopia and Ghana during 2012-2022.

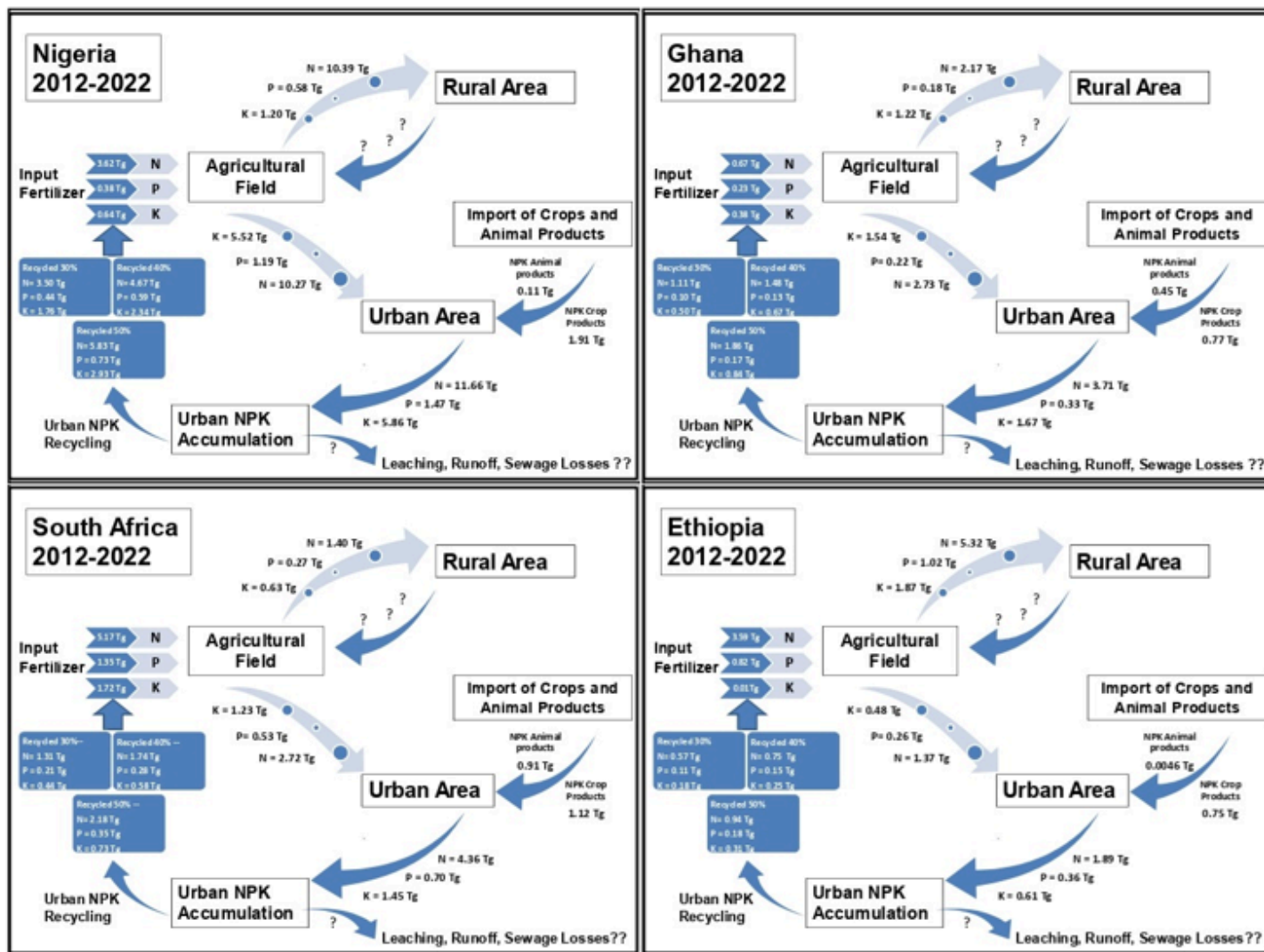


Figure 5

Graphical representation of NPK fluxes in agri-system, its urban deposition and estimated recycling in Nigeria, Ghana, South Africa and Ethiopia during 2012-2022.