Agriculture and Food

http://www.aimspress.com/journal/agriculture

AIMS Agriculture and Food, 4(2): 429–446.
DOI: 10.3934/agrfood.2019.2.429
Received: 03 February 2019
Accepted: 22 May 2019
Published: 10 June 2019

Review

Nitrogen budgets and flows in African smallholder farming systems

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Abstract: Nitrogen is often the most limiting nutrient crop production in smallholder farms in Africa. Nitrogen flows and budgets in most farming systems play a crucial role in agricultural production and may lead to either N depletion or accumulation. This review presents trends of N balances and flows in Africa's smallholder farming systems as influenced by the methods used in deriving them, the differences in farming systems and, inherent variability in soil fertility and management strategies. At the farm/household level, wide variations have ranged from negative of as low as −76 kg N ha^{-1} to positive N balance of up to +20 kg N ha^{-1} within short distances which are caused by the biased allocation of N fertilizer based on the type and value of the crop planted. The review highlights the potential application of N balance approaches as an indicator of soil nutrient mining in smallholder farming systems of sub-Saharan Africa. There is enhanced awareness of nitrogen depletion in Africa from the intensive research carried out in the field. Nevertheless, most of them are snapshot, static assessments, which give little information on the dynamics and spatial variation of nitrogen flows.

Keywords: organic resources; nutrient replenishment; nutrient management; nitrogen surplus; scaling-up

1. Introduction

Eighty percent of arable land in Africa has low soil fertility and suffers from physical soil degradation as a result of massive nutrient loss caused by unsustainable soil management practices [1]. Nitrogen (N), is responsible for crop growth and yields obtained in agricultural production. It is also the most limiting nutrient to plant growth in smallholder farms in Africa due to its susceptibility losses resulting from denitrification, leaching, volatilization, and runoff or erosion [2,3]. Additionally, land degradation also leads to adverse loss of soil nitrogen stocks [4,5]. These losses directly deplete soils fertility and productivity. Calculation of N budgets for Africa has shown that soils are highly mined of N threatening productivity and food security [6]. According to Drinkwater [7], agricultural systems require sufficient N replenishment in order to produce desired yields because conventional management practices tend to disengage energy flows and nutrient cycles in space and time. Effective management of N is a significant challenge to the farm operator compared to any other fertilizer nutrient because it can enter or leave the soil-plant system by more routes than any other [8]. It is, therefore, a challenge to build vast reserves of soil N in farming systems. Thus, management strategies that reduce losses of N are critical elements for intensive crop production [9,10].

Soil nitrogen balance studies in Africa show evidence of widespread soil N depletion through harvested crops, crop residues transported out of the fields, overgrazing and/or leaching, erosion and volatilization which altogether surpass the amount of nutrient inputs through fertilizers, atmospheric deposition, biological fixation and organic inputs [11–14]. In the past, N mining has been estimated to average 660 kg $ha^{-1}yr^{-1}$ [15], with losses of up to 130 kg N ha^{-1} yr^{-1} in the East African Highlands [16]. For example, in the Central Highlands of Kenya and croplands in the Sahel, losses of 36 kg N ha^{-1} yr^{-1} and 10 N kg ha^{-1} yr^{-1}, respectively, have been reported [17]. A study by Henao and Baanate [18], on annual nutrient balance from 44 sub-Saharan Africa (SSA) countries showed a negative N balance of up to 1121 kg N ha^{-1}. However, in developed regions such as Mississippi Basin and Northern Europe, there has been a reduction in nutrient imbalances [19]. Due to the concern of N decline in SSA, different technologies with soil fertility ameliorating abilities have been developed [20]. 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 [21] and stable isotopes to estimate nitrogen recovery fractions in crops.

Nutrient stocks flow and budgets are increasingly being used as tools for estimating nutrient build-up and decline so as to provide an understanding of the potential and suitability of land for agricultural production [23]. Nutrient budgets are also essential tools in designing policies to support soil fertility management by smallholder farmers. According to Ngetich et al.[24], a relatively small scale nutrient budgeting can be used to evaluate the level of nutrient sources and losses, opportunities for improved use efficiency and scope for possible interventions. For instance, based on results from on-farm participatory research in Malawi and Zimbabwe, Snapp et al. [25] showed that legumes with high-quality residues and deep root systems can improve nutrient cycling. Simulation models have also been used as tools in estimating nutrient budgets and use efficiencies in Africa, (e.g., Schultz et al. [26]; Rowe et al. [27] and Tittonell et al. [28]). Kisaka et al. [29] used the Agricultural Production Systems Simulator (APSIM) model to report long-term effects of integrated N management from organic residues (goat manure, *Lantana camara*, *Tithonia diversifolia*, and *Mucuna pruriens*) and their combination with mineral fertilizers in maize production under semi-arid conditions in Kenya. Di and Cameron [22] suggested management options to curb nitrate leaching include: reducing N use rates, synchronizing N supply to plant demand, cover cropping, better timing of plowing pasture leys, enhanced stock management, and precision farming.

The nutrient budget approach in Africa became relevant since the pioneering study of Stoorvogel and Smaling [30] and still, there is a focus on the research topic [19]. Although there have been attempts to integrate the information of nutrient budget in Africa [11,31], the information is still fragmented [32]. Various studies have reported N budgets to be negative, suggesting potential problems of soil N mining. Other studies found positive balances across the continent, particularly in gardens, wealthier farmers' plots, which counter the assumption/belief that all soils in Africa are already degraded or with severe N degradation [33]. For instance, after estimating nutrient balances for small-scale farming systems in Eastern and Central Uganda, Wortmann and Kaizzi [21] found positive N balances in the banana-based land use type. Furthermore, according to Vanlauwe and Giller [34], in resource-limited smallholder agriculture, not all fields are continuously mined; some fields have very positive nutrient budgets. This is attributed to variation in the management of cultivated plots, with significant amounts of organic resources and mineral fertilizers applied on plots around the homesteads, and rarely on the fields cultivated further from the household [34]. Thus, this review shows the trends of N budgets and flows in African crop farming systems and identifies gaps for future studies on N balances.

2. Soil nitrogen inputs

N inputs to a field consist mainly of mineral fertilizers, biological N fixation, animal manures or applied composts, biomass transfer, nitrogen recovery from subsoil depths beyond the reach of crops' roots, and crop residues application [35,24]. Figure 1 is a simplified schematic presentation of a typical N budget and flows in Africa's smallholder farming system. From Figure 1, it can be deduced that most flows are directed towards the farm. Most of the inputs are directly added to the field, for instance, mineral fertilizers, crop residue application, 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 use in cereal production, inorganic fertilizers (Figure 1, arrow 4) account for about one-third of the N inputs in Africa [36]. 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 [37]. A study by Oelofse et al. [38] revealed that generally organic farms have positive nutrient budgets compared with non-organic farms in China and Brazil. In SSA, N fertilizers are produced in three countries, Nigeria, Zimbabwe, and South Africa, thus, the other countries have to import. Because of the high price of fertilizers, smallholder farmers apply insufficient N fertilizer leading to reduced crop yield [39–41]. Garrity [42] 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 9 kg ha^{-1} compared to 87 kg ha^{-1} for the developed countries. The rates account for less than 1.8% of global fertilizer use and less than 0.1% of global fertilizer production [43]. 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. The high cost of using commercial fertilizer has collectively limited inorganic N fertilizer use by subsistence and small-scale farmers throughout Africa.

In SSA, organic inputs including farmyard manure (Figure 1, arrows 5, 8 and 11) are used as a resource to enhance soil fertility. For instance, in Kenya, Omiti et al. [50] observed that between 86% and 91% of farmers use manure in the semi-arid and semi-humid agro-ecological zones. In the Central Highlands of Kenya, more than 95% of the smallholder farmers apply it to maize crop [51]. These farmers obtain manures from cattle (65%), sheep and goats (6%) and poultry (4%) [52].

Application of manure can increase crop yields significantly [53]. Manure residual effects are common when large amounts are applied [54]. Meertens et al. [55] reported that the use of cattle manure in lowland rain-fed rice production led to an overall grain yield increase of 194 kg ha^{-1} compared to the control treatment. Regarding manure amounts as an input in N budget studies, many authors have reported different values depending on the farming systems, manure availability and its use and chemical composition [21,23]. Although manure is essential for the resource-poor farmers in improving crop and soil productivity, drawbacks exist in its use as a source of N for plants. Major drawbacks include inadequate quantities produced at the farm level and low-quality manure to meet the nutritional demands for the various crop enterprises [56].

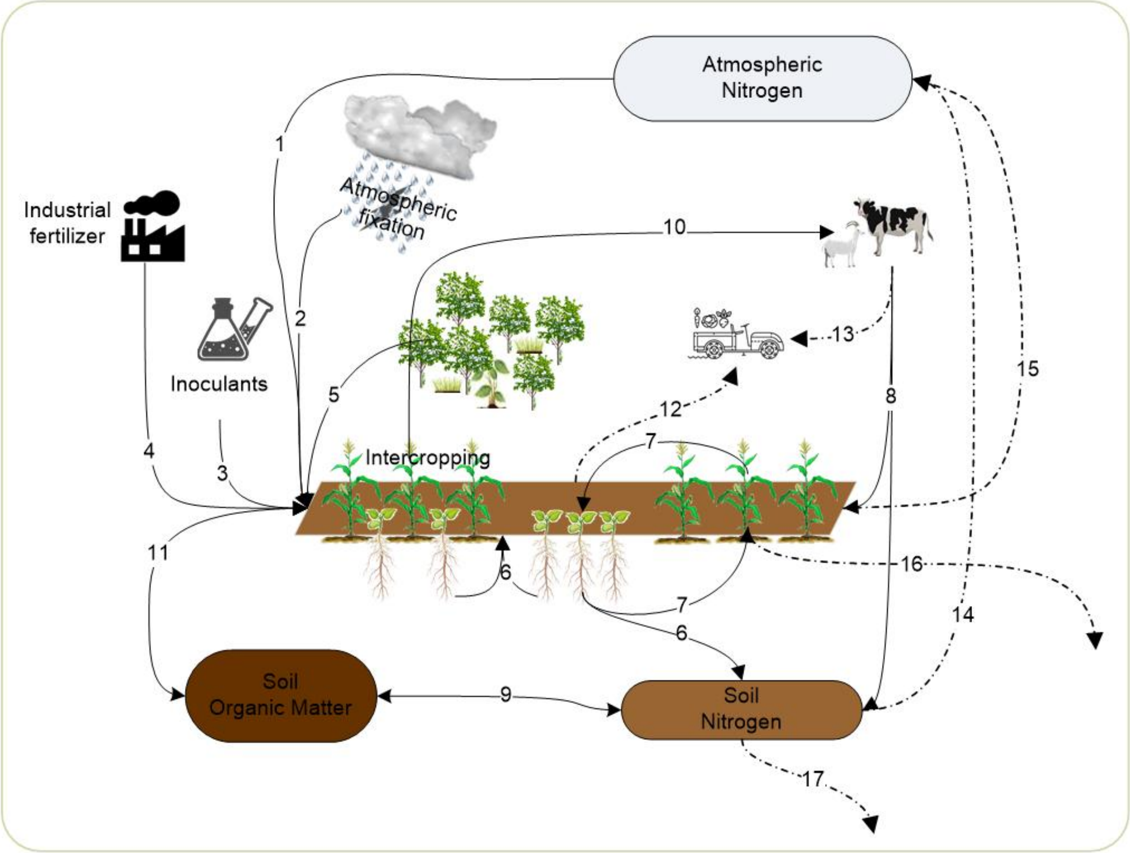

Figure 1. N budgets and flows in Africa smallholder farming system. Arrows represent flows, with solid lines representing N additions and exchanges, and dotted lines N losses. (Where 1 is biological nitrogen fixation, 2 atmospheric fixations, 3 microbial inoculations, 4 inorganic fertilizer application, 5 biomass transfer, 6 nutrient recovery, 7 crop rotation, 8 Animal manure, 9 mineralization/immobilization, 10 Animal feeds, 11 crop residues incorporated into the soil, 12 crop produce (goods), 13 livestock products, 14 denitrification, 15 volatilization, 16 runoff, and 17 leaching).

Various factors such as source, herd size, and management system influences the quality and quantity of manure available to a farmer [54]. Animal manure production depends on the herd size and seasonal climatic changes which determine the availability of feeds to livestock. Given that external/free range grazing is the predominant livestock system, manure quality with regard to N release and crop uptake is poor posing a challenge to smallholder farmers. Besides livestock-system dependent manure challenges, differences in manure quality can be linked to its management from the point of production to application in the field [3,25,57]. For instance, manure stored in pits can have significantly higher N amounts compared to heaped manure [54,53]. This could be due to ammonia losses that occur throughout the decomposition period and leaching of nitrates from the uncovered manure [58]. The quality of manure could be improved through the provision of high-quality feed such as *calliandra* and *leucaena* to the animal and better management of manure [59]. In intensively managed smallholder farms in Kisii County (formerly Kisii District) in Kenya, use of manures from cattle enclosures (bomas) to the fields averaged 23 kg N ha^{-1}, which is equivalent to one-third of the total N inputs [36]. Under smallholder livestock farming system with limited use of external feeds (concentrates), manure application is a process of nutrient transfer from one part of the farming system to another rather than a replacement of nutrients exported in harvested products, and therefore its use may not significantly improve the farm-level nutrient balance [60].

Substantial N input into agriculture comes from N_2 fixation worldwide (Figure 1, arrow 1). Moreover, the global rate of N fixation has doubled during the last few decades, through agricultural activities such as the use of N-fixing crops [44]. Biological N fixation becomes an input when atmospheric N_2 gas is converted into plant N by symbiotic plants followed by the addition of N from plants into the soil. Biologically fixed N is a critical N input into tropical African agro-ecosystems where legumes constitute a significant portion of the farming systems [45]. The incorporation of legumes (e.g., pigeon pea, cowpea, beans, and soybean) into cereal cropping systems either as an intercrop or in the rotation is a common practice throughout sub-Saharan Africa. The contribution of N into the soil by legumes has a sparing effect on the amounts of additional fertilizers required for high cereal yields. However, legumes' nodule functions are affected by environmental conditions. For instances, drought can decrease nodule functioning in symbiotic legumes through the drought-induced collapse of lenticels and can directly affect the longevity of introduced rhizobia [46].

Consequently, due to low soil moisture content and desiccation, nodulation can fail to occur through loss of infection sites due to induced changes in the morphology of infectible root hairs. Where indigenous rhizobia are less effective or ineffective in N_2 fixation with the legume than selected inoculant strains, or in the absence of compatible rhizobia and where their population is low, legumes need inoculation (Figure 1, arrow 3) [46]. This requires knowledge of the abundance and effectiveness of the indigenous rhizobia population in the soil [47]. If inoculants are available, they are cheaper relative to the other costs of production, hence, the use of inoculants is a potential yield enhancing tactic. It can substantially contribute to the promotion and adoption of cereal-grain legume cropping systems as a soil fertility management approach.

Under cereal-legume intercropping (Figure 1, arrow 7), the contribution to soil fertility depends on the amount of N_2 fixed in relation to the amount mined from the system during crop harvest, reflected in the N harvest index [45]. Despite its benefits, the system is faced with different constraints such as inadequate soil moisture, soil fertility status and rhizobia related issues that affect N_2 fixation of field legumes. Multifunctional legumes have a potential for adoption and can contribute to soil fertility enhancement when incorporated within the farming system. Development and promotion of 'promiscuous' varieties of legumes that are highly effective in fixing N_2 can be a good substitute for smallholder farmers than relying on legumes that need inoculation [48]. The grain legumes, especially soybean, efficiently translocate N to the grain, thus leaving behind only a small portion of N in the stover [49]. If legume stover is not returned to the soil at harvest, then there will be a significant removal of soil N from the system by the legume crop. Consequently, grain legumes such as soybean and common beans, have been reported to deplete N present in the soil [45].

Biomass transfer is another source of N input in smallholder farms in sub-Saharan Africa, although it is considered as an internal flow in the N budgeting (Figure 1. arrow 5). The technology involves ex-situ production of biomass for example on designated areas, hedges around or within the farm [61,62]. Examples of plants suitable for biomass transfer include *Leucaena leucocephala, Tithonia diversifolia Leucaena trichandra, Mucuna pruriens, Calliandra calothyrsus, Sesbania sesban, Crotolaria,* among others. For instance, *Tithonia diversifolia* is rich in nutrients content, particularly N, and others such as phosphorus, potassium, and magnesium, and may prevent other nutrient deficiencies such as micronutrients [63]. Except for the N fixing plant species, the biomass transfer approach offers an opportunity for intensifying agricultural production as N is transferred from one portion of the land to another.

3. Nitrogen flows and balances

As expounded by Vlaming et al. [64], the concept of nutrient depletion is derived from quantification of nutrient flows resulting in nutrient balances and stocks. Nitrogen input processes are biological N fixation, application of mineral fertilizer and organic manure, biomass transfer, atmospheric deposition, and sedimentation by irrigation and flooding [23]. N internal flows within a system include household waste feeds, crop residues, grazing of vegetation, animal manure and farm products to a household. The potential supply of mineral-N by soil is determined by factors such as the mineralization-immobilization and N-loss mechanisms operating during the cropping season [65]. Addition of organic inputs promotes N immobilization and mineralization. As observed by Jenkinson [66] and Balkcom et al. [67], organic compounds with relatively high carbon C to N ratios tend to stimulate immobilization more than mineralization of N until the ‘‘turning point’’ occurs, and then mineralization becomes more prevalent than immobilization.

N output processes include removal of crop product and residues, leaching, gaseous losses, runoff and erosion [68] (Table 1 and Figure 1). Rainfall amounts, soil hydraulic properties, amount of N applied [69], soil type [70] and management decisions such as choice of crop rotation [71] affect N movement in the root zone. When N inputs exceed the outputs, it’s referred to as surplus N accumulation, while the vice-versa is termed as N depletion [24]. Although a number of N flows can easily be quantified and valued through partial balance approach, some flows are hard to quantify calling for estimations transfer functions. Table 1 lists the nutrient inputs and outputs that play a role in the Africa smallholder farming systems.

Numerous studies have been carried out on both partial and full N balances in many African countries, and the results show variations (Table 2). Partial balance approach has a shortcoming in that it excludes flows (e.g., N fixation, erosion) which could have high relative importance, especially in low external input agriculture [73]. After comparing both partial and full N balances, Cobo et al.[33] reported that partial balance estimates were significantly higher than their respective full balances. The variations in the amounts of N balances can be attributed to many factors such as the methods used in deriving them, the variability in farming systems, inherent variability in soil fertility and decomposition rates of the inputs applied. For instance, in an on-farm experiment conducted in the highlands of Ethiopia, Bedada et al. [74] found a positive N balance at plot levels in treatments with compost (+20 kg N ha^{-1} yr^{-1}) and a negative balance under fertilizer (−65 kg N ha^{-1} yr^{-1}), half compost and half fertilizer (−33 kg N ha^{-1} yr^{-1}) and control (−76 kg N ha^{-1} yr^{-1}). Tully et al. [75] found that N balances differed both among farms and between years, which emphasizes the importance of tracking inputs and outputs on multiple farms over multiple years before drawing conclusions about nutrient management, soil fertility outcomes, and food production. Lederer et al. [14] concluded that recycling of hitherto unused municipal solid waste had much lower quantitative potential than the recycling of human excrement to reduce soil nutrient deficits. Therefore, in the effort to improve agricultural productivity there should be a focus on measures such as soil conservation and mineral fertilizer application. Besides the biophysical factors, socio-economic characteristics (education, herd size, crop diversity, and non-farm activities) also contribute to variations in N flows and balances [35].

According to Faerge and Magid [76], the main problem in the calculation of nutrient balances is the estimation of flows that are difficult to measure, for example, losses by leaching or erosion, or the flows generated by denitrification, deposition, and N_2-fixation. Approaches used in the calculation of N balances (from partial balances using farmers' estimations to the modeling of complex processes to simulate different N losses) vary from farm to farm and across regions and are difficult to validate [28]. A model by Sheldrick and Lingard [77], designed to carry out soil nutrient audits, showed that, in Africa and several African countries, the nutrient decline has been increasing which was estimated to be approximately 3.5 million tonnes N (17.4 kg N ha^{-1} yr^{-1}) in 1998 alone.

Table 1. Nitrogen flows at farm level in Africa smallholder farming system (after Smaling et al. [72]).

Flows	Nutrients
Inputs	Mineral fertilizers
	Organic inputs including
	• Animal/farmyard manures
	• Applied composts
	• crop residues application
	Biological N fixation
	• Intercropping
	• Inoculant application
	Atmospheric N
	Biomass transfer
Output	Harvested crops
	Crop residues removal
	Runoff and erosion
	Leaching below the root zone
	Gaseous losses
	• Volatilization
	• Denitrification

Table 2. Regional and national N balances of some African countries as reported in various studies.

Country	Average N balance (Kg/Ha)	Type of balance	Soil classification	Source
Sub-Saharan Africa (38 countries)	−22	*Full*		Stoorvogel and Smaling [30]
Mali (Southern)	−25	Full		Van der Pol [87]
Kenya (Kisii District)	−112	Full	Humic to Dystro-mollic Nitisols and Chromo-luvic Phaeozems; Ando-luvic Phaeozems; Nito-rhodic Ferralsols; Mollic Nitisols; Chromo-luvic Phaeozems and Mollic Nitisols	Smaling et al. [88]
Tanzania (Sukumaland)	−36.5	Full		Budelman [89]
Mali (Southern)	−9.2	Full	Plinthic-ferric Lixisols (Plinthic Haplustalfs)	Ramisch [90]
Burkina Faso	−49.5	Full	Ferric Lixisol	Zougmoré et al. [13]
Kenya (Western)	−76	Full	Kaolinitic Ferralsols and Nitisols, Acrisols	Shepherd et al. [91]
Uganda (Palisa location)	−208	Full	Eutric Nitosols	Wortmann and Kaizzi [21]
Uganda (Kamuli, Iganga and Mpigi locations)	−67	Full	Orthic Ferralsols	Wortmann and Kaizzi [21]
Mozambique	−32.9	Full		Folmer et al. [92]
Nigeria (Northern)	−13	Full	Brown to reddish-brown soils	Harris [51]
Ghana (Nkawie and Wassa Amenfi)	−27	Full	Ferralsols and Acrisols	FAO [81]
Kenya (Embu)	−151	Full	Andosol/Nitisol	FAO [81]
Mali (Koutiala)	−26	Full	Luvisols	FAO [81]
Tanzania (Bukoba)	−12.8	**Partial**	Ferralsols, Fluvisols, Arenosols and Gleysols	Baijukya et al. [93]
Kenya (Machakos)	−12.8	Partial		Gachimbi et al. [94]
Ethiopia (Central Highlands)	−38.7	Partial	Luvisols and Vertisols	Haileslassie et al. [95]
Kenya (Kisii, Kagamega and Embu)	−71	Partial		De Jager et al. [96]
Kenya (Embu and Nyeri)	−59.5	Partial		De Jager et al. [68]
Uganda (Busia)	−33	Partial	Lixic Ferrasols and Petric Plinthosols	Lederer et al. [14]

Full nutrient balances included additionally environmental flows (i.e. inputs from wet/atmospheric deposition, nitrogen fixation, and sedimentation; and outputs from leaching, gaseous losses, and soil erosion) [97]; **Partial** nutrient balances were defined as the difference between the inflows to a system from mineral and organic fertilizers, and its respective outflows from harvested products and crop residues removed [33].

4. Nitrogen balance under semi-arid cropping systems

Nitrogen is one of the major factors limiting agricultural productivity in SSA because of growing population segments, variable rainfall amounts and timing during the year making agricultural productivity under the agricultural systems extremely variable. This has had a greater impact on the semi-arid cropping systems practiced in the continent. Additionally, soil type and crops grown in the Sahel region, e.g. millet in Northern Burkina Faso largely contribute to N loss from the fields [78]. A study conducted in the semi-arid of Burkina Faso found that N losses through sorghum exports and soil erosion were the two main factors leading to negative N balances [13]. In their studies on the analysis of nutrient balances of four mixed farming systems in Mali and two in Niger Powell and Coulibaly [79] and Buerkert et al. [80] indicated that croplands lack an internal capacity to replenish N removed with grain and crop residues. Low economic returns to most agricultural production under semi-arid conditions and high market and weather-related risks reduce the use of external inputs [81].

To enhance or maintain the quality of the environment and conserve natural resources, alternative low-external-input approaches which involve utilization of organic inputs have been developed for use by farmers [68]. Use of livestock for nutrient cycling and transfer to agricultural land presents another option of enhancing N recycling in the semi-arid conditions. It has been shown that livestock can recycle up to 48% of N intake as manure, which amounts to yearly average use on the cropped land of 1.2 kg ha^{-1} N [30]. Most of the livestock are kept by communities who live in the semi-arid regions of Africa where farmers can produce on average 3 to 14 Mg ha^{-1} of manure, equivalent to 43 to 199 kg ha^{-1} of N [82]. In free-range grazing systems, livestock nutrient deficiencies can be enhanced by moving the animals to better grazing areas. However, in Sahel countries, population growth exceeds 3%, and as a result, pastoralists are increasingly forced into already degraded rangelands which limit the flexibility of livestock movement [83]. Hence, the benefits of applying N under semi-arid conditions depend on the frequency and intensity of drought as well as the amounts and timing of N applications. Zougmoré et al. [13] conducted a study at Saria in semi-arid Burkina Faso in a sorghum-based cropping system and concluded that N depletion in poor fertile soils could be mitigated through the combination of soil water conservation and nutrient management strategies. However, most of these researches in the Sahel region have been conducted in on-station experiments [84–86] with little being reported from on-farm sites [78].

5. Cases of nitrogen imbalances in Africa

Regional and national estimates of N balances are negative in most of sub-Saharan Africa region. Numerous studies focusing on N balance, have consistently reported negative national averages (Table 2) which can be ascribed to the several N losses channels especially through harvest, soil erosion and low or non-use of external soil inputs.

For instance, Stoorvogel et al. [98] estimated N losses from arable land to be 31, 68, 112 and 27 kg ha^{-1} yr^{-1} in Zimbabwe, Malawi, Kisii, Kenya, and Tanzania, respectively. Similar results have been found in Mali [99]. In Niger, N losses of up to 91 kg ha^{-1} have been attributed to leaching [100]. For Africa as a whole, low level of inputs relative to outputs results in a consistently negative balance [98].

6. Plot and farm nitrogen balances

Nitrogen balance variability cuts across the regional, national and household level. Most studies have reported huge variations, sometimes ranging from very negative to very positive N balance within the same locality. For example, Haileslassie et al. [95] in a study to explore effects of land-use strategies and access to resources, reported N balance results in some study sites that were inconsistent to their average N balance and national balances where even maize had a partial N balance of 18 kg ha^{-1}. Zingore et al. [101], in a study in Murewa, Northeast Zimbabwe, though they reported overall negative N balances in most farms, significant differences in N balances existed between fields within a farm with some fields showing positive balances, resulting in substantial differences in soil fertility status between those fields (Table 3).

Table 3. Nitrogen balances at farm/plot scale in different cropping systems.

Crop	N Balance in Kg ha^{-1}			
	Folmer et al. [92]	Wortman and Kaizi [21]	De Jager et al. [96]	Haileslassie et al. [95]
Maize	−47.1	−1.2	−44	−34
Sorghum	−18.2	0.5		
Cassava	−48.1	0.3		
Legumes/Beans	−24.3	0.7		−9
Coffee		−3.6	−4	
Tea			−26	
Banana		−1.1		

Zones close to homesteads showed tendencies of N accumulation with soil fertility decline along a gradient with increasing distance from the homestead [28]. Furthermore, N balances in most wealthy farms were positive while those for medium and poor farms were close to zero or negative. Apart from the assumption that fields near the homesteads are zones of nutrient accumulation and distant fields are zones of depletion, N balances also depend on the value of the crop grown as perceived by the farmers and the intensity of soil management practices [95,102,103]. At the crop level, Zingore et al. [101] reported higher inflows of both inorganic and organic fertilizers for maize compared with groundnut, as farmers invariably applied more fertilizers to the maize crops with little or nothing to the groundnuts. As a consequence, N balances were mostly positive for maize and negative for groundnuts. Depending on the soil characteristics and crop type, large additions of N, though it can lead to high productivity do not obviously translate into positive balances. The high crop productivity can lead to higher N requirement and hence higher efficiency in N uptake leading to soil mining through N export during harvest. Allocation of nutrient resources is also influenced by the type of crop planted. Studies have shown that cash crops receive more nutrients compared to food crops [16]. Soil fertility heterogeneity might not be solely the source of variability in yields. The diversity in the intensity and timing of certain agronomic practices, such as planting and weeding, which are often associated with the perceived fertility of different fields [104], also play a crucial role in N use efficiency

In a study on the diversity of soil fertility management practices in smallholder farms of western Kenya, Tittonell et al. [105] reported negative N balances in most farms and fields. In the study, the pattern of N allocation from fields close to the homestead to the remote fields was explained mainly by the pattern of organic resources allocation with the former receiving more inputs than the latter. The distribution of mineral fertilizers was mainly influenced by resource endowment level of the farmers, with wealthy farmers distributing fertilizers more evenly on farms compared to the more impoverished farmers [105]. The distribution of N added through organic inputs was chiefly affected by field type (i.e., home fields, mid-fields, and outfields), reflecting the distance from the homestead. Overall, the partial N balance was negative in most fields of all case-study farms, ranging from about −35 to −110 kg ha^{-1} [105]. Only in the home fields of the wealthiest farmers was the partial N balance positive. The N balance tends to be more negative in those fields where the highest yields were attained, especially in the more impoverished farms indicating that the negative balances were mainly as a result of nutrient mining through harvested products. However, other continents report positive N balances. Pilbeam et al. [106] reported N balance in a hypothetical household holding 1 ha of land in the mid-hills of Nepal with inputs across the boundary of about 26 kg Na^{-1} (mainly in fertilizer) and losses, excluding gases, of about 60 kg Na^{-1} (mainly under crop removal). In India, Rego et al. [107] reported nutrient balance under sorghum-castor rotation cropping system at farmers' field level whereby the N input was at 87 kg N ha^{-1} compared with an output of 77 kg N ha^{-1} thus a net gain of +10 kg N ha^{-1}.

7. Conclusion

Research on N flows and balances has been carried out in African countries including Kenya, Ethiopia, Mali, Uganda, Tanzania, Zimbabwe, and Malawi. However, most of the studies were conducted to assess the condition of different agro-ecosystems with nutrient balances calculated from experimental plots and after scenario simulations. N balance results from most studies, spatial scale and units notwithstanding, indicate that most systems have negative N balances. These observations were consistent with the general claim of nutrient mining across the continent [72]. As input use in Africa is the lowest in the world, soil nutrient balances are often negative [31]. This situation can be critical in regions where land users are extensively mining soil resources for their livelihoods. Despite the overall negative trend in N balances in Africa, positive balances are also found in small patches within smallholder farms on the continent.

Although there is enhanced awareness on N depletion in African countries through intensive research and studies in the field, most of them are snapshot, static assessments, which give little information on the dynamics and spatial variation of N flows. The use and extrapolations from such findings might be misleading. There is a need to develop methodologies that can be used continuously to monitor changes in soil nutrient status [108] both temporally and spatially. This will require well-documented and broadly accepted procedures and guidelines for nutrient budgeting and for analyzing uncertainties by ensuring that nutrient budgeting approach and data acquisition strategies are in harmony with the purpose of the studies.

Research on up-scaling methods and accurate estimation of N flows at the primary spatial units should be a priority, because N use efficiencies and farm scales are profoundly affected by spatial heterogeneity [102]. Also, inter-disciplinary collaboration and the convenient use of newly available techniques in SSA in the fields of agronomy, ecology, mathematics, (geo) statistics, modeling, and geographical information systems, are also crucial in this quest [33]. The results from these techniques should be accompanied by efficient dissemination to the smallholder farmers as the target beneficiaries. Antonopoulos [109] showed that using RICEWNB model gives adequate information on the water and nitrogen balances in rice fields in Northern Greece. Using the nonseasonal Box-Jenkins model or exponential models Bo et al. [110] projected the N surplus for the total cultivated land in China.

There is also a great need for integration of effective environmental policies with agricultural and socio-economic policies, at global, continental, regional and local levels. Governments in countries experiencing nutrient decline should offer adequate support on integrated, multiscale biogeochemical research that yields policy-relevant information on nutrient balances and their implications. For instance, fertilizer prices subsidies and review of taxation costs which impose a constraint on agricultural production in many nutrient deficit developing countries [32]. It is also important to increase capacity building so as to encourage the smallholder farmers to practice nutrient management for improved and sustainable agricultural production in tropical agro-ecosystems. Lastly, more effort in the analysis and documentation of spatial diversity of management practices affecting N dynamics, crop productivity and the complex interactions with other factors, such as labor allocation is needed [105].

Acknowledgements

We are grateful to the editor and the two anonymous reviewers for their exceptionally helpful comments and suggestions during the review process.

Conflict of interest

No author of this paper has a conflict of interest, including specific financial interests, relationships, and/or affiliations relevant to the subject matter or materials included in this manuscript.

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