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***Review***

# Dilemma of nitrogen management for future food security in sub-Saharan Africa – a review

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**Abstract.** Food security entails having sufficient, safe, and nutritious food to meet dietary needs. The need to optimise nitrogen (N) use for nutrition security while minimising environmental risks in sub-Saharan Africa (SSA) is overdue. Challenges related to managing N use in SSA can be associated with both insufficient use and excessive loss, and thus the continent must address the 'too little' and 'too much' paradox. Too little N is used in food production (80% of countries have N deficiencies), which has led to chronic food insecurity and malnutrition. Conversely, too much N load in water bodies due mainly to soil erosion, leaching, limited N recovery from wastewater, and atmospheric deposition contributes to eutrophication (152 Gg N year$^{-1}$ in Lake Victoria, East Africa). Limited research has been conducted to improve N use for food production and adoption remains low, mainly because farming is generally practiced by resource-poor smallholder farmers. In addition, little has been done to effectively address the 'too much' issues, as a consequence of limited research capacity. This research gap must be addressed, and supportive policies operationalised, to maximise N benefits, while also minimising pollution. Innovation platforms involving key stakeholders are required to address N use efficiency along the food supply chain in SSA, as well as other world regions with similar challenges.

**Additional keywords:** eutrophication, innovation platform, land degradation, nitrogen use efficiency, policy, quality standards.

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## Introduction

Africa's agricultural lands continue to be degraded, with an annual estimated economic cost of up to 18% of the gross domestic product as a consequence of soil productivity decline (Nkonya *et al*. 2011) arising from poor agronomic practices and nutrient depletion (Sutton *et al*. 2013; Tittonell and Giller 2013). Over 80% of the agricultural land is nitrogen (N) deficient (Liu *et al*. 2010) due to insufficient or non-use of N inputs. Barriers such as scarcity and high costs of inputs, poor economic returns on input use, limited financial capacity, and insufficient extension services among others, have drastically affected adoption of N fertilisers (Akpan *et al*. 2012*a*, 2012*b*; Akudugu *et al*. 2012).

Limited research capacity in most regions of sub-Saharan Africa (SSA), particularly for long-term trials, has also added to the difficulty of improving agronomic efficiency of applied N ($AE_N$). Soil acidification, poor organic matter content, deficiencies of various nutrients and reduced microbial activities are among factors affecting crop responses to applied N (Fairhurst 2012; Nezomba *et al*. 2015). Adequate diagnosis of the factors limiting application of integrated soil fertility management (ISFM) is required to optimise $AE_N$ (Giller *et al*. 2011) and increase the sustainability of agricultural intensification (Vanlauwe *et al*. 2015).

The rural–urban food market system in SSA creates nutrient depletion in rural farmlands and accumulates nutrients in urban regions and cities. Furthermore, excessive soil erosion has also contributed N load into water bodies (Leip *et al*. 2014). These processes continuously create the spatial paradox of 'too little' and 'too much' N respectively, perpetuating food insecurity quantitatively and qualitatively (Marler and Wallin 2006) and leading to environmental pollution. For example, in highly populated regions of SSA like the Lake Victoria catchment, inadequate systems for municipal wastewater treatment have resulted in excessive N load into water bodies leading to eutrophication of certain sections of the lake (LVBC 2012; Zhou *et al*. 2014). Some other sources of N overload of the

SSA environment come from (1) atmospheric deposition (Galy-Lacaux and Delon 2014), (2) N-rich runoff of organic wastes from municipal and industrial areas, (3) N leaching mainly from commercial farms, and (4) insufficient treatment of wastewater from industry (e.g. fisheries). High N load into water bodies has resulted in excessive eutrophication of fresh waters and threatened the lives of various fish species (Nyenje *et al*. 2010).

The N management for future food security in SSA must take into consideration the 'too little' and 'too much' paradox and explore how to optimise N use efficiency (NUE) along the food system. This would require focused research programs on N recovery along the loss pathways and supportive policies. Existing policies lack focus on N; in most cases they have to be improved, strengthened, and importantly operationalised. Recent efforts have mainly been limited to improving food security and have overlooked environmental challenges related to the complete N cycle and various N sources. This review highlights the challenges and opportunities of improving N management in SSA to optimise NUE for food security, while minimising environmental pollution, with reference to selected case studies.

## Current challenges

### *Low use of N in production*

Nitrogen depletion is a critical issue in Africa (Table 1). In certain countries, less than 1% of farmers are using fertilisers (Nkonya *et al*. 2011). Most of the countries have not been able to meet the target of 50 kg nutrients ha$^{-1}$ set in the 2006 Abuja Declaration (Fig. 1). Nitrogen constitutes 90% of the applied fertiliser (Sutton *et al*. 2013) and is sometimes accompanied with a little phosphorus (P) and potassium (K), but rarely with secondary or micronutrients. This unbalanced nutrient application to soils with diverse nutrient co-limitations has led to the excessive yield gaps compared with other parts of the world (Fig. 2).

### *Poor quality of N inputs*

Recent studies recognised the need to address the quality issues of agricultural inputs including N sources in SSA countries to improve crop productivity. In Uganda, for example, Bold *et al*. (2015) showed that urea sold in the fertiliser marketplace contained 31% less N on average. Analysis results for 369 samples showed all of them with N content below the authentic urea fertiliser grade (Fig. 3). They also demonstrated significant yield and profitability losses from the use of adulterated urea products in

**Table 1. Average N balances in selected countries in sub-Saharan Africa in 2000**

Negative values (kg N ha$^{-1}$ year$^{-1}$) refer to N depletion (adapted from Chianu *et al*. (2012))

| Country | N balance (kg N ha$^{-1}$ year$^{-1}$) |
|---|---|
| Botswana | –2 |
| Mali | –11 |
| Benin | –16 |
| Senegal | –16 |
| Cameroon | –21 |
| Zimbabwe | –27 |
| Tanzania | –32 |
| Nigeria | –37 |
| Kenya | –46 |
| Ethiopia | –47 |
| Rwanda | –60 |
| Malawi | –67 |

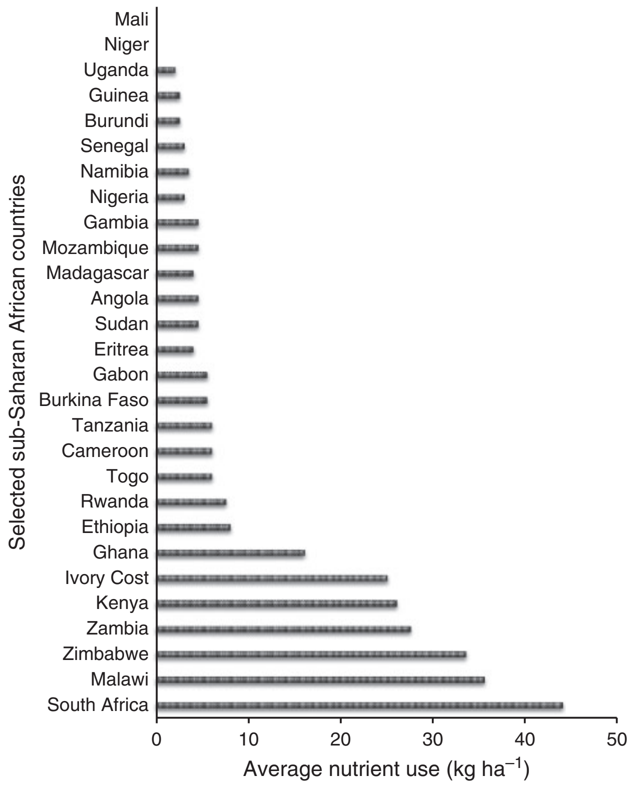


**Fig. 1.** National average nitrogen, phosphorus, and potassium fertiliser use on the basis of cultivated land in selected sub-Saharan African countries compared with the target of 50 kg nutrient ha$^{-1}$ for 2015 in the 2006 Abuja Declaration on fertilisers for an African green revolution (adapted from Wanzala 2011).

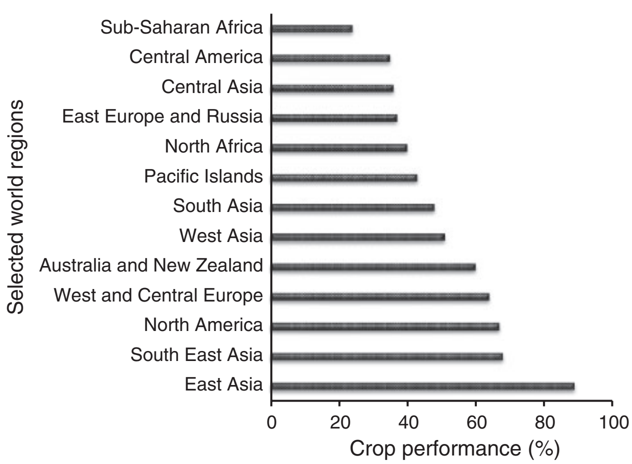


**Fig. 2.** Average crop yields as percent of the potential across world regions (adapted from Argus Consulting Services 2016).

field experiments. The quality issues also affect other N inputs like rhizobial inoculants. In a project-driven marketplace monitoring study in Ethiopia, Kenya, and Nigeria, Jefwa *et al*. (2014) evaluated over 22 rhizobial inoculants and concluded that ~40% neither contained the declared active ingredients nor performed as claimed. Other inputs such as animal manures contain little N due to poor feed quality and poor manure management (Diogo *et al*. 2013).

The poor quality of agricultural inputs stems from several factors including adulteration, sub-standard formulations, and poor handling in transportation and storage, and points to weak regulatory frameworks. Recent development initiatives have advocated for quality control of agricultural inputs through strengthening the regulatory mechanisms (Masso *et al*. 2013; AGRA 2014). However, operationalisation remains a challenge (Kargbo 2010). The use of poor quality inputs coupled with volatile input and output markets reduces the profitability associated with using agricultural inputs, and consequently the capacity to invest in N inputs.

### *Poor input and output markets*

The accessibility, i.e. availability and affordability, of fertilisers is among the factors limiting fertiliser use by smallholder farmers in SSA (Mtambanengwe and Mapfumo 2009). In a study conducted in East Africa (i.e. Burundi, Kenya, Rwanda, Tanzania, and Uganda), Guo *et al*. (2009) demonstrated that urea application to maize was only attractive for high market access in Tanzania and Uganda at a value cost ratio of greater than 3 (Table 2). Strengthening linkages to input and output markets to increase the profitability of ISFM practices in the smallholder farming systems is crucial to improve productivity (Shiferaw *et al*. 2014), and consequently food and nutrition security. The high costs of inputs and low output prices in remote areas can generally be associated with transportation costs, low availability of inputs, limited market opportunities, as well as many kinds of formal and informal taxation.

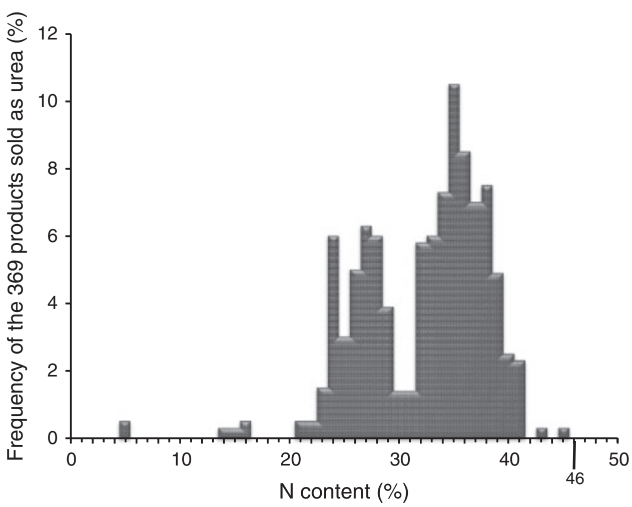


**Fig. 3.** Distribution of nitrogen (N) content across 369 products sold as urea in Uganda. All samples contained less than 46% N (adapted from Bold *et al*. 2015).

### *Malnutrition*

The insufficient use of agricultural inputs particularly N has led not only to poor yields in terms of quantity, but also in terms of quality. Nitrogen is a critical nutrient in amino acids and proteins. Hence low soil N availability or use of N inputs would result in food crops with poor protein content as shown in the idealised model by Selles and Zentner (1998), and could explain the high prevalence of undernourishment in SSA (Fig. 4).

### *High N loss to the environment*

Despite the low N use in food production, significant N losses still occur in SSA and exacerbate N depletion from agricultural lands. For instance, atmospheric deposition of N in SSA is equivalent to the current rate of fertiliser use, i.e. 4–15 kg N $ha^{-1}$ $year^{-1}$ (Galy-Lacaux and Delon 2014; Vet *et al*. 2014) (Fig. 5). The proportion of this N deposited on agricultural land represents a significant N input. It however becomes a significant risk to the environment when it ends up in water bodies or other areas where it cannot be used for plant growth. From a study by

**Table 2. Costs of urea and maize prices in East African countries and implication for economic return, i.e. value–cost ratios**

The costs of urea increase, whereas the prices of maize grain and the value–cost ratios decrease, with the distance to markets (adapted from Guo *et al*. (2009) who used an application rate of 35 kg N $ha^{-1}$)

| Country | Farm-gate urea costs[A] (USD $t^{-1}$) | | | Farm-gate maize prices[B] (USD $t^{-1}$) | | | Value–cost ratio | | |
|---|---|---|---|---|---|---|---|---|---|
| | Market access | | | | | | | | |
| | High | Medium | Low | High | Medium | Low | High | Medium | Low |
| Burundi | 659 | 684 | 693 | 234 | 200 | 185 | 2.50 | 2.00 | 2.00 |
| Kenya | 458 | 486 | 522 | 288 | 238 | 182 | 2.75 | 2.25 | 1.50 |
| Rwanda | 647 | 675 | 699 | 236 | 209 | 178 | 2.00 | 1.50 | 1.50 |
| Tanzania | 526 | 552 | 622 | 245 | 214 | 128 | 3.25 | 2.75 | 1.25 |
| Uganda | 553 | 577 | 613 | 244 | 202 | 168 | 3.00 | 2.10 | 1.75 |

[A]Average costs in 2005.
[B]Average prices in 2008.

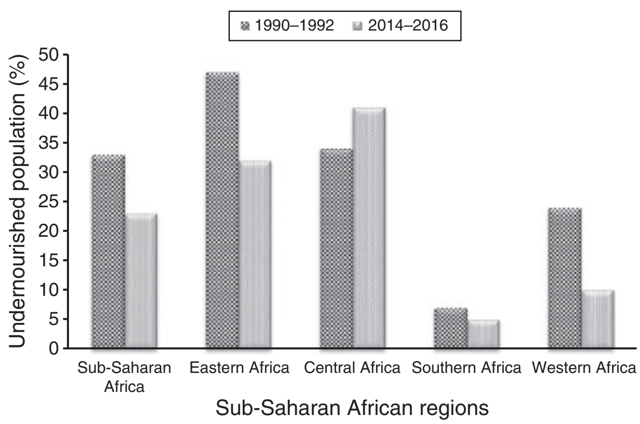


**Fig. 4.** Undernourished population in sub-Saharan Africa and selected regions of sub-Saharan Africa as percentage of the total population in the respective regions (adapted from Argus Consulting Services 2016).

Zhou *et al.* (2014), atmospheric N deposition accounted for 67% (i.e. 102 Gg N year$^{-1}$) of the total N loading (152 Gg N year$^{-1}$) into Lake Victoria in East Africa. At the catchment scale, N loading into the terrestrial area was estimated to be 305 Gg N year$^{-1}$ with 13.6% (i.e. 42 Gg N year$^{-1}$) of it coming from oxidised N deposition. Thus, direct atmospheric N deposition into the lake represented 71% of the total atmospheric N deposition (i.e. 144 Gg N year$^{-1}$) into the catchment (Fig. 6). Very little of the remainder (29%) benefited crop production as it was also deposited on several non-agricultural land use types such as settlements, roads, and marginal lands.

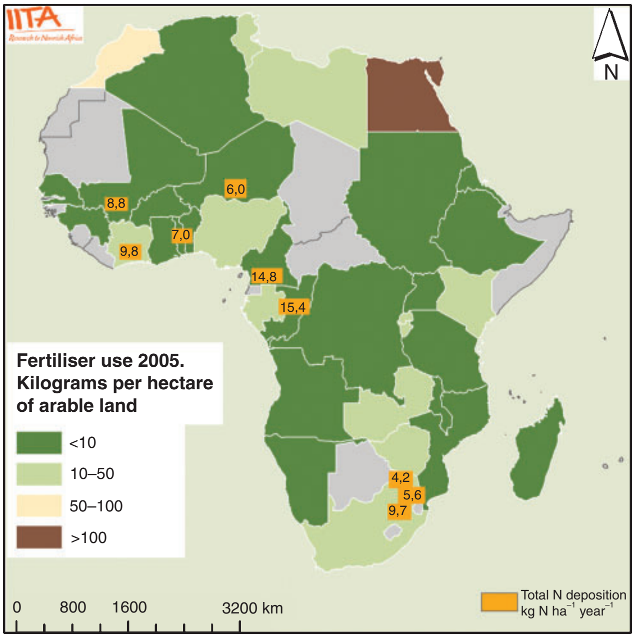


**Fig. 5.** Atmospheric N deposition fluxes superimposed on a map of fertiliser use in Africa (adapted from Galy-Lacaux and Delon 2014 and Vet *et al.* 2014).

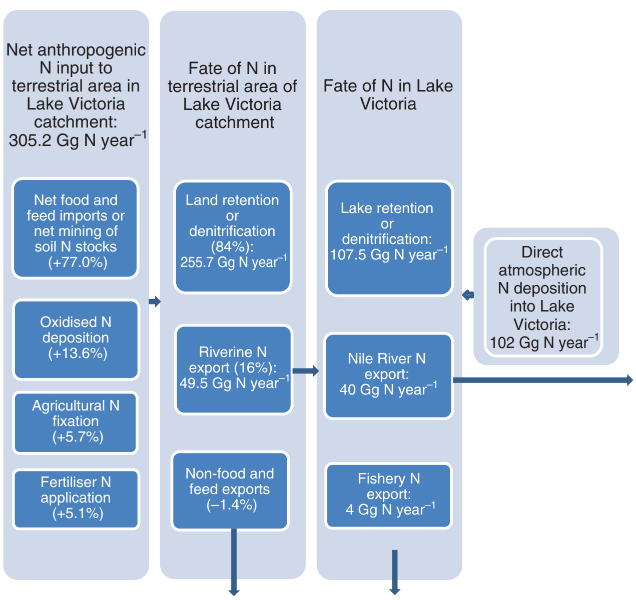


**Fig. 6.** Rough N budget for the Lake Victoria catchment in East Africa (adapted from Zhou *et al.* 2014).

Based on an assessment conducted in South Africa, Lemley *et al.* (2014) reported that when there are no other limiting factors, concentrations of 400 and 30 µg L$^{-1}$ of total dissolved N and P respectively, and an N : P ratio of 7–8 on a weight basis are enough for eutrophication to occur. Preventing eutrophication requires control of both N and P loadings into water bodies (Howarth and Marino 2006). Eutrophication related to anthropogenic activities has become a serious issue in SSA and has in some cases resulted in drastic reduction of dissolved oxygen and fish populations, and proliferation of toxic cyanobacteria blooms (Nyenje *et al.* 2010). As reported for Lake Victoria (Kishe 2004; Odada *et al.* 2004), eutrophication in SSA is mainly a result of soil erosion, nutrient leaching, atmospheric N deposition, runoff of organic wastes, and poor recovery of nutrients from wastewater among other sources. Reliable estimates of the contribution of each of these sources to N load into water bodies in SSA are generally yet to be determined to better inform policy decisions intended to reduce N losses to the environment.

## Selected opportunities

### *NUE*

The NUE in cropping systems has been defined as the ratio of N removed in harvested product to the amount of N applied (Brentrup and Pallière 2006). In these systems, $AE_N$ is one of the commonly used indices of NUE. It is defined as yield gain per unit applied N and is a function of recovery efficiency of applied N ($RE_N$), i.e. the incremental N uptake per unit of N applied and the physiological efficiency of applied N ($PE_N$); $PE_N$ being the ratio of yield gain to incremental N uptake per unit of applied N (Dobermann 2005; Ladha *et al.* 2005; Fageria *et al.* 2010). The $AE_N$ can be affected by N application methods underpinned by the 4R nutrient stewardship principles of (1) the right source of N fertiliser, (2) the right rate, (3) the right timing of application, and (4) following the right placement (Majumdar *et al.* 2016), as well as other factors such as abiotic and biotic stresses, and crop management practices (Dobermann 2005).

### *Improved agronomic interventions*

In addition to 'too little' N use for production in most SSA countries, $AE_N$ in smallholder farmers' fields is also low because of poor agronomic practices including blanket fertiliser recommendations, fertiliser application rates that are too low to result in significant yields, and unbalanced fertilisation where the focus is put, for instance, on NPK without secondary or micronutrients (Fig. 7). Even when the assessment is limited to N, P, and K fertilisers, studies conducted in multiple locations in India have demonstrated that application of P and K in addition to N significantly increases the $AE_N$ (Table 3). Recent interventions in SSA, including ISFM (i.e. improved seeds, use of balanced fertilisation, organic inputs, liming materials, water management, and appropriate tillage practices among others) showed that $AE_N$ could be doubled when good agronomic practices were adopted (Vanlauwe *et al.* 2015). For instance, the simple adoption of improved crop varieties like maize could significantly improve $AE_N$ under conducive

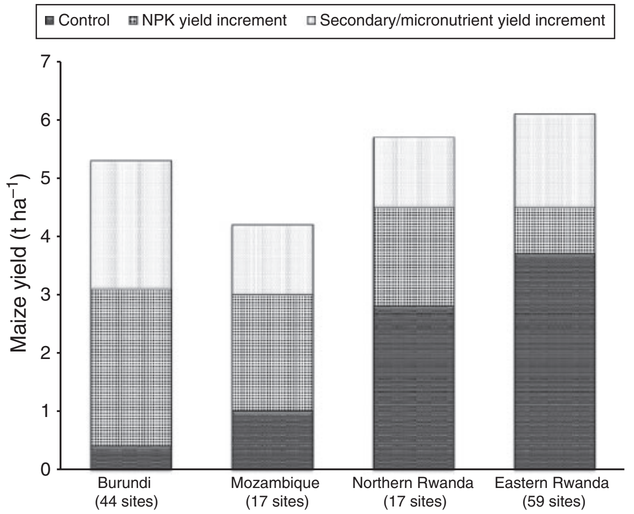


**Fig. 7.** Increment over the control of crop yields as affected by addition of nitrogen, phosphorus, and potassium (NPK) fertilisers, secondary nutrients, and micronutrients in selected sub-Saharan African countries (adapted from Wendt, pers. comm.).

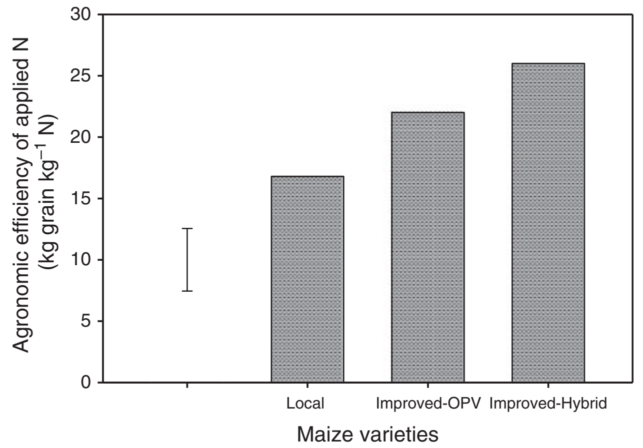


**Fig. 8.** Agronomic efficiency of applied nitrogen (N) as affected by maize varieties. OPV indicates open-pollinated variety (adapted from Vanlauwe *et al.* 2011).

**Table 3. Effect of adding phosphorus (P) and potassium (K) to nitrogen (N) fertilisation on the agronomic efficiency of applied N ($AE_N$) and yield for various crops in India**
Adapted from Ghosh *et al.* (2015)

| Crop | Yield ($t\ ha^{-1}$) | | $AE_N$ ($kg\ grain\ kg\ N^{-1}$) | |
|---|---|---|---|---|
| | N alone | N+PK | N alone | N+PK |
| Sorghum | 1.27 | 1.75 | 5.30 | 12 |
| Pearl millet | 1.05 | 1.65 | 4.70 | 15 |
| Wheat | 1.45 | 2.25 | 10.8 | 20 |
| Rice (wet season) | 3.28 | 3.82 | 13.5 | 27 |
| Maize | 1.67 | 3.23 | 19.5 | 39 |
| Rice (summer) | 3.03 | 6.27 | 10.5 | 81 |
| Sugarcane | 47.2 | 81.4 | 78.7 | 228 |

**Table 4. Effects of rates and timing of nitrogen (N) application at different stages of rice growth on head yield and protein content**
Adapted from Perez *et al.* (1996)

| N fertiliser treatment ($kg\ N\ ha^{-1}$) | | | | | Head yield ($t\ ha^{-1}$) | Protein content (%) |
|---|---|---|---|---|---|---|
| Basal | Maximum tillering | Panicle initiation | Flowering | Total | | |
| 0 | 0 | 0 | 0 | 0 | 1.97 | 5.62 |
| 120 | 0 | 60 | 0 | 180 | 4.39 | 7.58 |
| 60 | 60 | 60 | 45 | 225 | 5.69 | 9.56 |

agro-climatic conditions (Fig. 8). Therefore, ISFM could be useful for narrowing current yield gaps (Mutegi and Zingore 2014).

In addition to applying the right rate of N in the context of ISFM, timing of N fertiliser including split applications, can both improve yields and protein content (Table 4). Effective split application reduces N losses as the timing and rate for each application are adjusted to target the various demand peaks for N by the crop of interest during the growing season. Conversely, utilisation of high N rates to meet the crop N requirement in one single application generally results in increased N leaching and reduced crop $RE_N$ (Fig. 9). As smallholder farmers in selected SSA countries like Kenya have started adopting the practice of split application of N for some crops such as maize, there is a need for more investments in capacity building for farmers and supportive institutional systems that will enhance proper fertiliser N application and consequently $AE_N$.

However, the dilemma is that in SSA, farming is mainly practiced by resource-poor smallholder farmers who cannot afford most of the inputs at the actual market prices (Alobo Loison 2015). Similarly, there are no systematic policies to encourage (1) recycling of organic wastes from cities, (2) recovering nutrients from wastewater, and (3) collecting municipal sewage sludge for use on agricultural lands where they are needed. The N from those sources is either lost to landfill or discharged to water bodies and contributes to environmental pollution. Quantification of such N losses to inform policy decisions related to N recycling in food production is required.

## *N budgets and N footprint*

In addition to $AE_N$, indices related to environmental sustainability like N budgets (Leip *et al.* 2011; Eurostat 2013; Özbek and Leip 2015) and N footprint (Galloway *et al.* 2014; Hutton *et al.* 2017) are important for informing practices and policies intended to minimise N loss to the environment, while optimising crop and energy production. Good N management must therefore reduce both N accumulation (Vitousek *et al.* 2009; Leip *et al.* 2011) and N mining (Edmonds *et al.* 2009; Bekunda *et al.* 2010; Kihara *et al.* 2015), which can be detected through N budgets, as both have negative environmental impacts. The former could result in losses to the environment and contributing to greenhouse gases, soil acidification, and eutrophication among others, whereas the latter could result in low crop productivity. Comprehensive quantification of all inputs and outputs is required to construct accurate N budgets and to estimate $AE_N$. For instance, Özbek and Leip (2015)

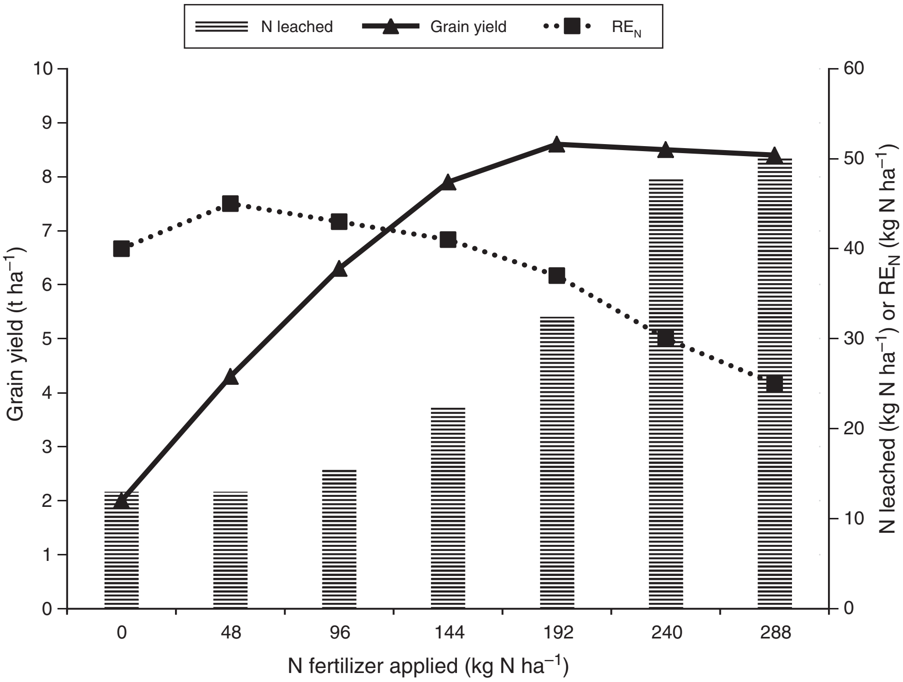


**Fig. 9.** Impact of nitrogen (N) fertiliser application on winter wheat yield (solid line), N leaching (bar chart), and estimated crop recovery efficiency of applied N ($RE_N$; dashed line) (adapted from Hawkesford 2014).

demonstrated the importance of including soil N stock change in N budgets to minimise overestimation of N surplus and underestimating NUE. Soil N mining could be overestimated if N inputs from irrigation water, rainfall, crop residue, biological N fixation, and atmospheric deposition are ignored, but could be underestimated if losses through leaching, erosion, runoff, volatilisation, and denitrification are ignored (Majumdar *et al*. 2016).

The N footprint tool is useful for identifying hotspots of N losses to the environment, simulating mitigation options, and informing policy decisions for good N management through raising awareness of social responsibilities (Galloway *et al*. 2014; Davidson *et al*. 2016). The application of the tool showed that in many countries the largest portion of the N footprint was associated with food production, with N accumulation in selected countries like the United States of America, whereas N mining occurred in countries like Tanzania in SSA (Hutton *et al*. 2017). Nitrogen footprint assessments would therefore represent a great opportunity to reduce N mining in SSA through identification of potential N available for recycling in crop production.

### *Innovation advances*

In addition to adoption of good agronomic practices like ISFM to improve $AE_N$, exploration of innovations that are cost effective to maximise the return on investment would be critical in the context of resource-poor smallholder farmers. One of the innovations that has proven cost effective in smallholder farming systems is the use of 'urea briquettes' mainly in rice production, although similar results have been reported in maize (Table 5). The potential has not only been shown in SSA, but also in Asian countries like Bangladesh (Huda *et al*. 2016). Although the innovation is labour-intense, the improved canopy reduces the labour required for weeding. Other slow N release innovations (e.g. inhibitors and N coating) represent a comparative advantage; however, their costs would generally represent a challenge for resource-poor smallholder farmers in SSA.

**Table 5. Comparative advantage of urea briquettes versus conventional urea granules under smallholder farmer conditions in selected SSA countries**
Adapted from J. Wendt (pers. comm.). $Yd^+$, yield increment

| Country | Crops | $Yd^+$ (t ha$^{-1}$) |
|---|---|---|
| Togo | Rice | 1.0 |
| Rwanda | Rice | 1.1 |
| Rwanda | Maize | 1.1 |
| Ethiopia | Maize | 1.3 |
| Niger | Rice | 1.5 |
| Mali | Rice | 1.6 |
| Senegal | Rice | 1.6 |
| Burkina Faso | Rice | 1.7 |
| Madagascar | Rice | 2.0 |
| Nigeria | Rice | 2.5 |

Another innovation gaining momentum in SSA is the incorporation of bio-fertilisers such as rhizobial inoculants in ISFM practices, which not only benefit legume crops, but also subsequent crops in the rotation. Under conducive conditions, legume crops can fix more N than they require, and therefore leave behind residual N (Table 6, Fig. 10). The performance of biological N fixation (BNF), however, depends on the

**Table 6. Potential N fixation through symbiotic associations of rhizobia and legume crops under conducive environments**
Adapted from FAO (1984)

| Legume crop (scientific name) | N fixed[A] (kg $ha^{-1}$ $year^{-1}$) |
|---|---|
| Bean (*Phaseolus vulgaris*) | 40–70 |
| Pea (*Pisum sativum*) | 52–77 |
| Lentil (*Lens esculentum*) | 88–114 |
| Groundnut (*Arachis hypogaea*) | 72–124 |
| Soybean (*Glycine max*) | 60–168 |
| Stylo (*Stylosanthes* spp.) | 34–220 |
| Pigeon pea (*Cajanus cajan*) | 168–280 |
| Alfalfa (*Medicago sativa*) | 229–290 |
| Mung bean (*Vigna mungo*) | 63–342 |
| Cowpea (*Vigna unguiculata*) | 73–354 |
| Centro (*Centrosema pubescens*) | 126–398 |
| Calapo (*Calapogonium mucunoides*) | 370–450 |
| Horse bean (*Vicia faba*) | 45–552 |
| Leucaena (*Leucaena leucocephala*) | 74–584 |

[A]The values represent the range based on the legume genotype, rhizobium strain, environmental conditions, and legume crop management practices.

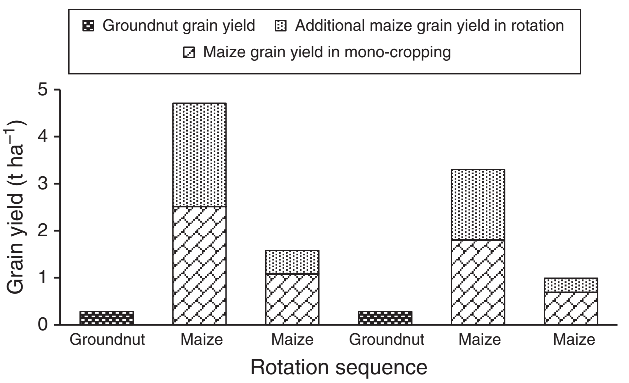


**Fig. 10.** Grain yields of groundnut and maize in two cycles of a groundnut–maize–maize–groundnut rotation without fertiliser at Domboshava Station, Harare, Zimbabwe, 1994–2001, with a standard error of difference for maize of 0.62 t $ha^{-1}$ (adapted from Waddington *et al.* 2004).

interaction of legume genotype, rhizobium strain, environmental conditions like soil fertility, and crop management such as planting dates, weeding, and spacing (Woomer *et al*. 2014). Low BNF, i.e. <5 kg $ha^{-1}$, has been reported when soil fertility is poor and no-amendment is applied (Mapfumo 2011). The success of rhizobial inoculation in SSA will therefore depend on proper diagnosis of BNF-limiting factors for local adaptation and availability of effective strains for widely grown grain legumes. This would require enabling policies to facilitate smallholder farmers' access to high quality inputs and awareness creation about good agronomic practices to optimise the performance of inputs.

## *Policies and innovation platforms to improve $AE_N$*

Enabling policies targeting resource-poor smallholder farmers in SSA would be critical to addressing the barriers to adoption of good agricultural practices aimed at increasing $AE_N$. Most of the constraints are of agronomic or socioeconomic nature. Agronomic policies must for instance address the following:

- *weak extension services* to ensure good agronomic practices are understood and adopted by farmers (Akpan *et al*. 2012*a*, 2012*b*; Kiptot *et al*. 2016)
- *poor quality of agricultural inputs* not only for enhancing efficiency but also ensuring that farmers gain confidence in the products (Masso *et al*. 2013; Bold *et al*. 2015)
- *blanket fertiliser recommendations* by investing in research to generate site and crop-specific recommendations (Mutegi and Zingore 2014)
- *N recycling from various organic wastes and N recovery from wastewater for use on agricultural lands* importantly, returning N from cities to rural agricultural areas, from where N is generally exported in food products

Similarly, socioeconomic policies are required to improve:

- *market opportunities* by controlling input costs and output prices to increase the profitability of using N inputs and reduce the volatility of produce prices, thereby minimising risks, and consequently triggering adoption (Kelly 2006; Dittoh *et al*. 2012)
- *the supply chain of inputs and outputs* through improved market systems and reduced transportation costs and losses (Bumb *et al*. 2011; Akpan *et al*. 2012*a*)
- *infrastructure conditions* to cut input and output transportation costs and enhance storage conditions to minimise input deterioration and post-harvest losses
- *the financial capacity or access to credit for resource-poor smallholder farmers* (Akudugu *et al*. 2012)
- *land tenure systems for farmers* to ensure ownership and thus create incentive for farmers to move towards sustainable intensification (TerrAfrica 2009)

Currently, some of the policies have been developed in selected SSA countries, but operationalisation remains a critical issue (TerrAfrica 2009; Kargbo 2010). Future interventions must ensure that novel and existing policies are strengthened and effectively implemented. Hence, innovation platforms would be crucial to inform policy decisions in a participatory manner to improve accessibility to, and proper use of, high quality agricultural inputs including N for sustainable intensification as well as production of sufficient, nutritious, and safe food.

## *Research capacity and future perspectives*

In SSA, limited life-cycle assessment of N has been undertaken as a consequence of poor research capacity and the research priorities of most national and international research organisations. In general, human choices in terms of food consumption drive N use, particularly for food production (Sutton *et al*. 2013). Selected investigations in SSA have been made to improve $AE_N$; however, quantification of N flows in the whole food supply chain has been too scarce to be representative, which has resulted in many uncertainties in N budgets (Rufino *et al*. 2014; Zhou *et al*. 2014). Consequently, key intervention areas to optimise $AE_N$ and minimise N losses to the environment are often not well understood, particularly at national, regional, and continental scales. Based on current challenges and opportunities related to N management in SSA, priorities to improve food security could, among others, include the following:

- using a participatory approach to determine segments of the whole food supply chain with low NUE (i.e. N footprint) and developing solutions to address the underlying causes to optimise food production
- developing crop-specific N application rates in the context of ISFM to improve food production and quality, while minimising environmental pollution
- developing smart subsidies for N inputs that promote N use, conducive to public–private partnerships, and minimise dependence on public support over time
- advocating for market policies conducive to increased profitability of N use for food production
- conducting comprehensive national, regional, and continental N budgets to determine (1) the various sources of N, (2) $RE_N$ and $AE_N$ for each source of N, (3) the types of N losses (i.e. N loss pathways) and magnitude, and (4) effective mitigation approaches for each type of loss to optimise food production, while minimising pollution
- assessing the quality of emerging N inputs (e.g. bio-fertilisers) to improve effectiveness, while preventing food contamination and environmental pollution

## Conclusion

Sub-Saharan Africa is facing a challenge of ‘too little’ N for food production and ‘too much’ N lost to the environment. Appropriate interventions are required to reverse the trend and so meet the food demand of this region, which has the highest global population growth. This is particularly critical as the population pressure will exacerbate land degradation and N depletion if adequate solutions are not implemented. Participatory development of solutions for improved N management would be crucial to inform market policies intended to support resource-poor smallholder farmers and increase the profitability of N use for food production. Importantly, in addition to improving accessibility to N inputs, farmers will have to be empowered with relevant knowledge and the know-how and financing opportunities for the adoption of N inputs in the context of ISFM to be able to produce enough nutritious food, and diversify production systems to meet dietary needs. Public–private partnerships would therefore be critical to ensure that the private sector contributes to the capacity building of farmers and extension services, and that governments increase agricultural budgets, to effectively increase $AE_N$, while minimising environmental pollution.

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