Nitrogen management for future food security: Sub-Saharan African case-study

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Abstract

One of the definitions for food security is having sufficient, safe, and nutritious food to meet dietary needs. There is an overdue need to optimize nitrogen use for food and nutrition security in developing countries particularly in sub-Saharan Africa, while minimizing environmental risks. In the past, nitrogen related environmental issues have often been associated with excessive use; however, of recently, challenges related to 'too little' nitrogen use has been recognized. In sub-Saharan Africa, nitrogen management must address the 'too little' and 'too much' paradox. Too little nitrogen is used in food production, which has led to chronic food insecurity and malnutrition. Conversely, too much nitrogen load in water bodies due mainly to excessive soil erosion, leaching, limited nitrogen recovery from wastewater, and atmospheric deposition still contributes to eutrophication in some areas. Significant research has been conducted to improve N use for food production, whereas little has been done to effectively address the 'too much' issues. The current research gaps must be addressed, and supportive policies operationalized, to maximize on nitrogen benefits, while reducing its negative impacts on the environment. Innovation platforms involving key stakeholders are required to address the nitrogen use efficiency along the full food supply chain in sub-Saharan Africa, as well as other World regions with similar challenges.

Introduction

Africa's agricultural lands continue being degraded with an annual estimated economic cost of up to 18% of the gross domestic product (Nkonya et al, 2011) because of poor agronomic practices and nutrient depletion (Tittonell and Giller, 2013; Sutton et al., 2013). Over 80% of agricultural lands are for instance nitrogen (N) deficient (Liu et al., 2010). Barriers such as availability and costs of inputs, poor economic returns of input use due to limited market opportunities or quality of the inputs, limited financial capacity and access to credits, and insufficient extension services among others have drastically affected adoption of improved agricultural inputs including fertilizers, of which nitrogen is just one (Akpan et al., 2012a,b; Akudugu et al., 2012).

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

Continuous nitrogen depletion has contributed not only to the persistent food insecurity for both quantity and quality (Marler and Wallin, 2006), but also excessive erosion due to insufficient land cover, deforestation, and encroachment to marginal lands, and consequently N load into water bodies (Leip et al., 2014). In highly populated regions of sub-Saharan Africa like the Lake Victoria catchment, inadequate systems for municipal wastewater treatments have also resulted in excessive N load into water bodies and contributed to eutrophication of certain sections of the Lake (LVBC, 2012; Zhou et al. 2014). Atmospheric deposition also contributes to N load into the sub-Saharan African environment including surface water (Galy-Lacaux and Delon, 2014). Other sources of N load into water bodies include erosion in infrastructure construction, runoff of feed and food waste from both municipal and industrial areas, N runoff and leaching mainly from commercial farms, and insufficient treatment of wastewater from industry (e.g. fisheries) among others. 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 in Africa must take into consideration the 'too little' and 'too much'paradox. This would require focused research programs and supportive policies. Existing policies lack focus on nitrogen; in most of the cases they should be improved, strengthened, and importantly operationalized. Recent efforts have mainly been limited to improving food security and overlooked environmental challenges related to the full N cycle and various N sources. This overview of challenges and opportunities of nitrogen management in sub-Saharan Africa therefore underscores issues that must be addressed to optimize nitrogen use efficiency for food security, while minimizing environmental pollution, with reference to lessons learnt from elsewhere.

Current challenges

Low nitrogen use for production

Nitrogen depletion is a critical issue in Africa (Table 1). In certain countries, less than 1% of farmers are using fertilizers (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 following the Africa Fertilizer Summit (Fig. 1). When fertilizer is used, over 90% of the applied nutrients is N (Sutton et al. 2013), sometimes accompanied with little P and/or K, and rarely with secondary and micro- nutrients. This has led to the excessive yield gaps compared to other parts of the world (Fig. 2), which is often exacerbated by the quality of the inputs.

Table 1 Average nitrogen balances in selected countries in sub-Saharan Africa in 2000

Country	Kg N ha^{-1} yr^{-1}	Country	Kg N ha^{-1} yr^{-1}	Country	Kg N ha^{-1} yr^{-1}
Benin	-16	Kenya	-46	Rwanda	-60
Botswana	-2	Malawi	-67	Senegal	-16
Cameroon	-21	Mali	-11	Tanzania	-32
Ethiopia	-47	Nigeria	-37	Zimbabwe	-27

Adapted from Chianu et al. (2012)

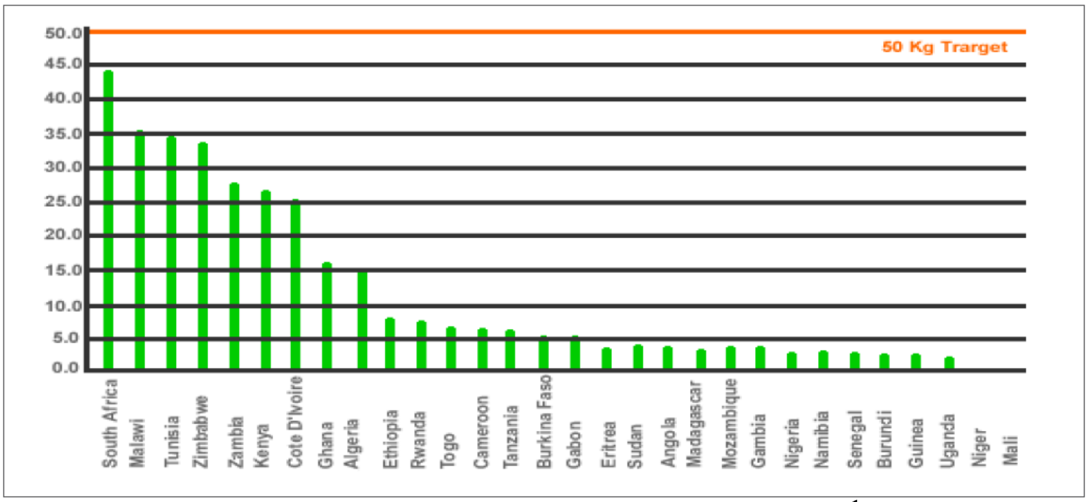

Fig.1 NPK fertilizer use compared to the target of 50 kg nutrient ha^{-1} in the 2006 Abuja declaration on fertilizers for an African green revolution (*Adapted from Wanzala 2011*)

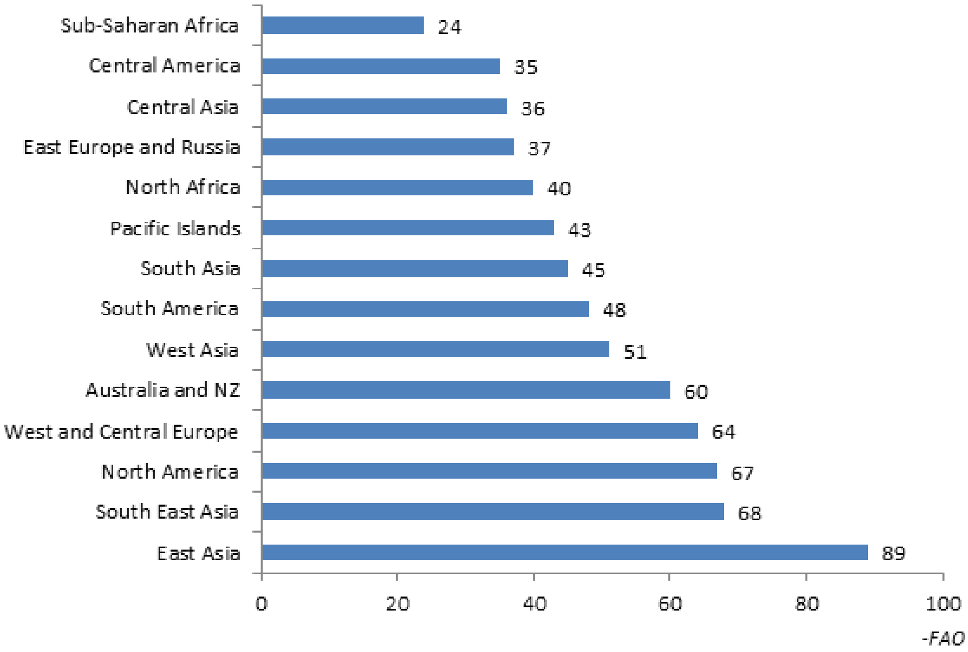

Fig.2 Average crop yields as percent of the potential across World regions (*Adapted from Argus Consulting Services; assessed 26 Jul 2016*)

Poor quality of nitrogen inputs

Recent studies recognized the need to address the quality issues of agricultural inputs including N sources in sub-Saharan African countries to improve crop productivity. Bold et al (2015) showed that in the Ugandan marketplace, urea contained 31% less nitrogen on average. Furthermore, an analysis of 369 samples of the fertilizer showed that over 99% of the samples contained less than 90% of the nitrogen expected in an authentic urea product (Fig. 3). They also demonstrated through field testing significant yield and profitability losses after using adulterated urea products. The quality issue also affects other N inputs like rhizobia 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 approximately 40% did not contain the declared active ingredients or perform as claimed. Animal manure also contains little N due to poor feed quality and manure management (Diogo et al. 2013). Recent development initiatives have promoted quality control of agricultural inputs through strengthening the regulatory mechanisms (AGRA 2014; Masso et al. 2013), though operationalization remains a challenge as reported earlier by Kargbo (2010). The use of poor quality inputs coupled with volatile input and output markets reduced the profitability of agricultural inputs, and consequently the capacity to invest in improved technologies.

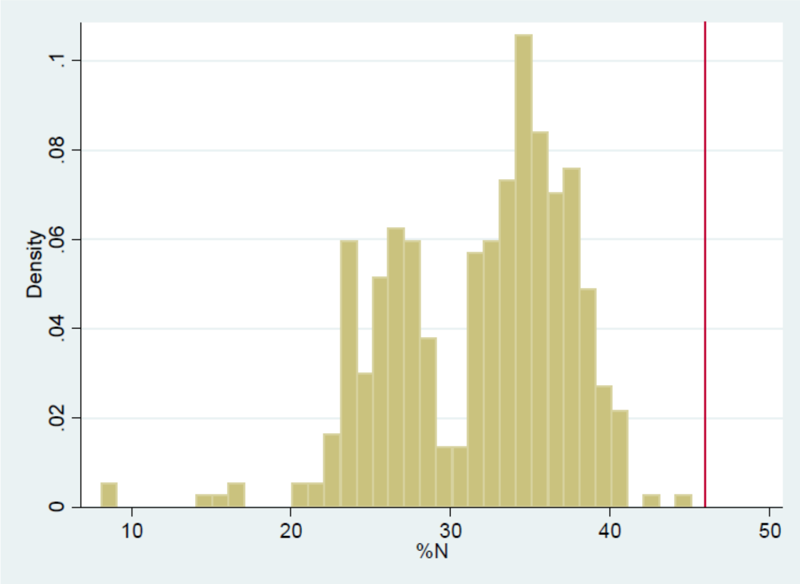

Fig. 3 Distribution of N content across 369 samples sold as urea in Uganda (*Adapted from Bold et al. 2015*)

Poor input and output markets

The accessibility, i.e. availability and affordability of fertilizers is among the factors limiting fertilizer use by smallholder farmers in sub-Saharan Africa (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 when the threshold for value cost ratio was set at 3 (Table 2). Improvement of input and output markets to increase the profitability of integrated soil fertility management practices in the smallholder farming systems would be crucial to improve productivity (Shiferaw et al. 2014), and consequently food and nutrition security.

Table 2 Costs of urea and maize prices in East African countries and implication on economic return

Country	Farm-gate urea prices[a]			Farm-gate maize prices[b]			Value-cost ratio		
	Market access								
	USD (metric ton)$^{-1}$								
	High	Med	Low	High	Med	Low	High	Med	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

Adapted from Guo et al. (2009); the application rate in the study was 35 kg N ha^{-1}

[a]Average costs in 2005

[b]Average prices in 2008

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 input would result in food crops with poor protein content as shown in the idealized model by Selles and Zentner (1998) (Fig 4). This could explain the high prevalence of undernourishment in sub-Saharan due to poor access to balanced dietary, including insufficient protein content (Fig 5).

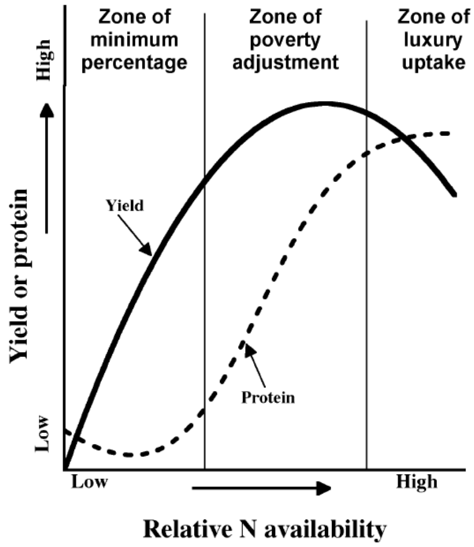

Fig. 4 Expected wheat grain yield and protein response to soil N availability (*Adapted from Selles and Zentner 1998*)

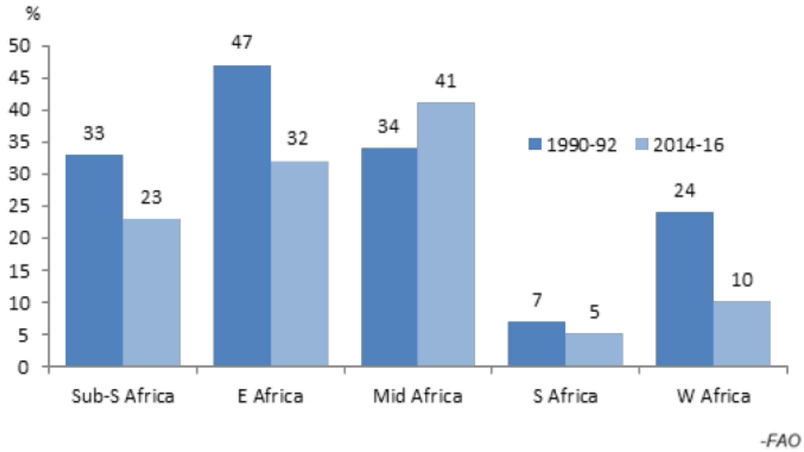

Fig. 5 Undernourished population in selected regions of sub-Saharan Africa (%) (*Adapted from Argus Consulting Services; assessed 26 Jul 2016*)

High nitrogen loss to the environment

Despite the low N use for food production, significant N losses still occur in the sub-Saharan African context, which exacerbate the nutrient depletion on agricultural lands. For instance, the N atmospheric deposition in sub-Saharan Africa is equivalent to the current rate of fertilizer use i.e. 4-15 kg N ha^{-1} $year^{-1}$ (Galy-Lacaux and Delon, 2014; Vet et al., 2014) (Fig. 6). The portion of this N that falls on agricultural lands represents a significant N input, but it 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; the beneficial portion still has to be quantified. Atmospheric N deposition is currently estimated at 80% of nitrogen load into Lake Victoria in East Africa (Fig 7). Based on 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 and N:P ratio of 7-8 on weight basis are enough for eutrophication to happen. Cultural eutrophication, which is related to anthropogenic activities, has become a serious issue in sub-Saharan Africa and has resulted in some cases in drastic reduction of dissolved oxygen and fish populations, and proliferation of toxic cyanobacteria blooms (Nyenje et al. 2010). As reported for the Lake Victoria in East Africa (Kishe 2004; Odada et al. 2004), eutrophication in sub-Saharan Africa is a result of soil erosion, nutrient leaching, atmonspheric N deposition, and poor recovery of nutrient from wastewater among other sources. Preventing eutrophication therefore requires control of both N and P loadings into water bodies (Howarth and Marino 2006).

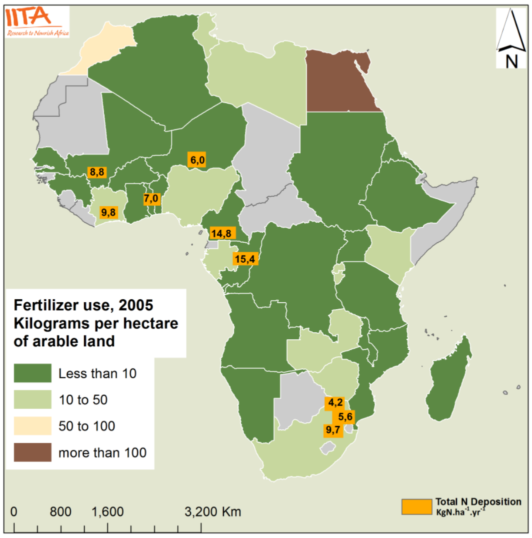

Fig. 6 Atmospheric nitrogen deposition fluxes superimposed on a map of fertilizer use in Africa (*Adapted from Galy-Lacaux and Delon, 2014 and Vet et al., 2014*)

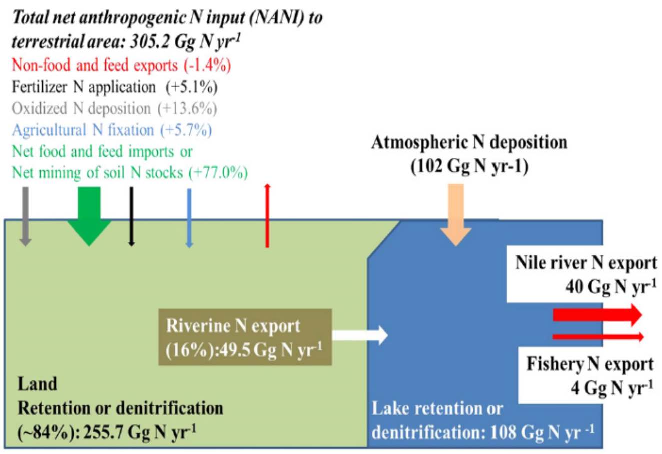

Fig. 7 Rough N budget for the Lake Victoria Catchment in East Africa (*Adapted for Zhou et al. 2016*)

Current opportunities

Nitrogen agronomic use efficiency

Nitrogen agronomic use efficiency is defined as the yield gain per unit amount of N applied, when plots with and without applied N are compared (Dobermann, 2005). In sub-Saharan Africa, it is more preferred than nitrogen use efficiency. The term N use efficiency can be misleading as straight calculations in SSA often result in estimates that exceed 100% (i.e. more N is taken up by crops than applied as fertilizer due to insufficient use of N inputs) (Edmonds et al., 2009).

Nitrogen agronomic use efficiency in smallholder farmers' fields in sub-Saharan Africa is still low because of poor agronomic practices including blanket fertilizer recommendations, too low fertilizer application rates to result in significant effect, unbalanced fertilization where the focus is put for instance on NPK without secondary and micro-nutrients (Figure 8). Even when the assessment is limited to N, P, and K fertilizers, studies conducted in multiple locations in India have demonstrated that addition of P and K to N significantly increases the N use efficiency (Table 3). Recent interventions in sub-Saharan Africa, including integrated soil fertility management (i.e. improved seeds, use of balanced fertilization, organic inputs, liming materials, water management, and appropriate tillage practices among others) showed that N agronomic use efficiency could be doubled when good agronomic practices are adopted (Figure 9; Vanlauwe et al. 2015). Such interventions could be useful to narrow the current yield gaps (Mutegi and Zingore 2014). The dilemma is that in SSA, farming is mainly practiced by resource-disadvantaged smallholder farmers who cannot afford most of the inputs at the actual market prices (Alobo Loison, 2015).

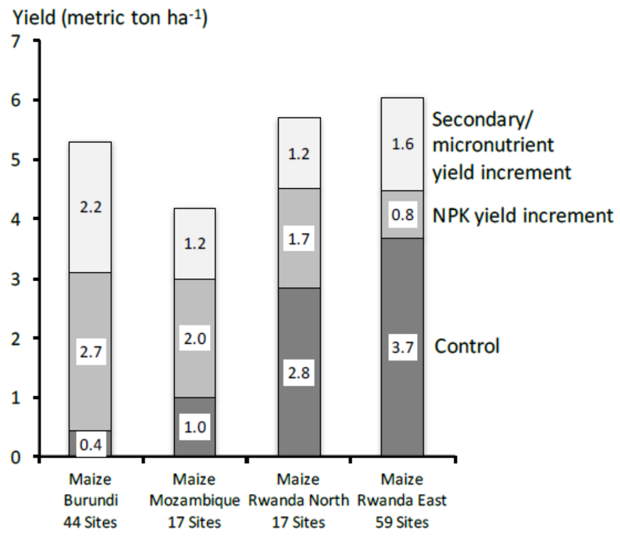

Fig. 8. Increment over the control of crop yields as affected by addition of NPK fertilizers and/or secondary/micronutrients and its spatial variability (*Adapted from Wendt, 2014; personal communication)*

Table 3 Effect of adding P&K to N fertilization on N agronomic efficiency for various crops in India (*Adapted from Ghosh et al. 2015*)

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

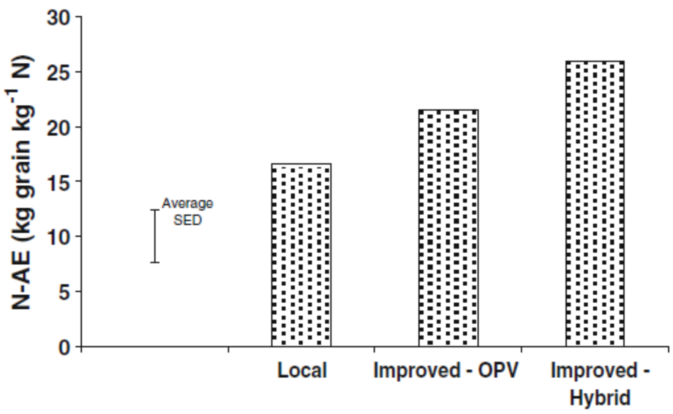

Fig. 9 Nitrogen agronomic use efficiency as affected by maize varieties, where OPV stands for open-pollinated variety (Adapted from *Vanlauwe et al. 2011*).

In addition to applying adequate amount of N inputs in the context of integrated soil fertility management, timing of N fertilizer including split application, not only can improve yields, but also protein content (Table 4). Smallholder farmers in selected sub-Saharan African countries have started adopting the practices. Split application contributes to reduce N losses, as in general N leaching increases and N use efficiency decreases with the application rate (Fig. 10).

Table 4 Rates and timing of N application rice yield and protein content

N Fertilizer treatment (kg N ha^{-1})					Head rice 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

Adapted from Perez et al. (1996)

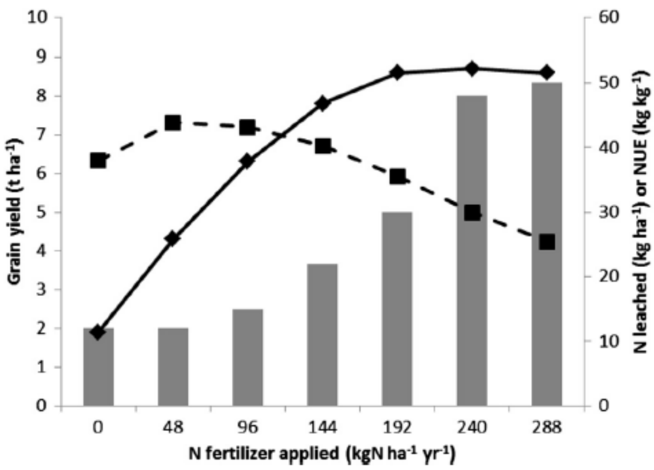

Fig. 10. Impact of N fertilizer application on winter wheat yield (solid line, diamonds), N leaching (bar chart), and estimated grain nitrogen use efficiency (dashed line, squares) (*Adapted from Hawkesford (2014)*.

Innovation advances

In addition to good agronomic practices like integrated soil fertility management to improve nitrogen agronomic use efficiency, exploration of innovations that are cost-effective to maximize the return on investment would be critical. One of the innovations that have proven cost effective in smallholder farming systems is the 'urea briquette' mainly in rice production, and similar results have been reported for maize and selected vegetables (Table 5). The potential has not only been shown in Africa, but also in Asian countries like Bangladesh. Although the innovation is labour-intense, the improved canopy reduces the labour for weeding. While other slow N release innovations (e.g. inhibitors, N coating) may also represent a comparative advantage, their costs would generally represent a challenge for resource-constrained smallholder famers in Africa.

Table 5 Comparative advantage of urea briquette versus conventional urea granules under smallholder famer conditions in selected African and Asian countries

Country	Crops	Yield Increment (t ha^{-1})	Gross margin (USD ha^{-1})
Burkina Faso	Rice	1.7	
Ethiopia	Maize	1.3	
Madagascar	Rice	2.0	
Mali	Rice	1.6	
Niger	Rice	1.5	
Nigeria	Rice	2.5	
Rwanda	Rice	1.1	
	Maize	1.1	
Senegal	Rice	1.6	
Togo	Rice	1.0	
Bangladesh	Cabbage		960
	Tomato		1622

Adapted from Wendt (2014); personal communication

Another innovation that is gaining momentum in sub-Saharan Africa is the incorporation of bio-fertilizers like rhizobia inoculants in integrated soil fertility management. This does not only benefit the legume crops, but also subsequent crops in the rotation. Under conducive conditions, legume crops can fix as much nitrogen as they required, and therefore leave behind residual N (Table 6; Figure 11). However, the performance of biological nitrogen fixation (BNF) depends on the legume genotype, rhizobium strain, environmental conditions like soil fertility, and crop management like planting dates (Woomer et al. 2014). Poor 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 bio-fertilizers in sub-Saharan Africa will therefore depend on the proper diagnosis of BNF limiting factors for local adaptation. This would require enabling policies to support smallholder farmers.

Table 6 Potential N fixation through effective symbiotic associations of rhizobia and legume crops

Legume crop	Range of N fixed (kg ha^{-1} yr^{-1})
Faba bean	54-200
Sesbania	45-552
Alfalfa	290-299
Lentil	165-189
Pea	52-77
Vicia	80-102
Common bean	40-70

Adapted from Sifi (2014), personal communication

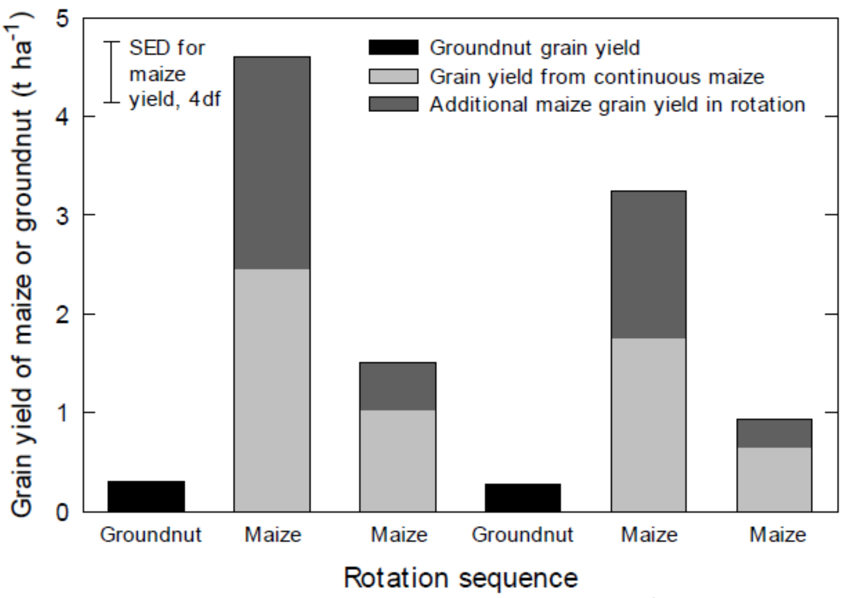

Figure 11 Grain yields of groundnut and maize (t ha^{-1}) in two cycles of a groundnut-maize-maize-groundnut rotation without fertilizer at Domboshava station, Harare, Zimbabwe, 1994-2001 *(Adapted from Waddington et al. 2004)*

Policies and innovation platforms to improve N agronomic use efficiency

In sub-Saharan Africa, farming is mainly practiced by resource-constrained smallholder farmers. Enabling policies would therefore be critical to address the barriers to adoption of good agricultural practices to increase the nitrogen agronomic use efficiency. Most of the constraints are of an agronomic or socio-economic or nature. Agronomic policies must address for instance:

- poor extension services to ensure good agronomic practices are understood and adopted by farmers (Akpan et al. 2012a,b; Kiptot et al. 2016)
- poor quality of agricultural inputs not only for enhancing efficiency but also for ensuring that farmers get confidence in the products (Bold et al. 2015; Masso et al. 2013), and
- blanket fertilizer recommendations by investing in site and crop-specific researches to generate specific recommendations (Mutegi and Zingore 2014).

Similarly, socio-economic policies are needed to improve:

- the market opportunities by controlling input costs and output prices to increase profitability of agricultural technologies and reduce the volatility of produce prices to minimize risks, and consequently trigger adoption (Dittoh et al. 2012; Kelly 2006)
- (ii) the supply chain of inputs and outputs to improve the market systems and reduce transport costs to/from farm-gate (Akpan et al. 2012a; Bumb et al. 2011)
- the financial capacity or access to credit for smallholder farmers (Akudugu et al. 2012), and
- land tenure systems for farmers to ensure ownership and thus to create incentive for farmers to move towards sustainable intensification (TerrAfrica 2009).

Currently, some of these policies have been developed in selected sub-Saharan countries, but operationalization remains a critical issue (Kargbo 2010; TerrAfrica 2009). Future interventions should ensure that novel and existing policies are strengthened and effectively implemented. Hence, innovation platforms would be crucial to inform policy decisions in 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.

Food safety

As mentioned earlier, food security has been considered as accessibility to sufficient, safe, and nutritious food to meet dietary needs (White et al. 2012). World widely, instances of excessive N use for food production have been reported, which is characterized by high nitrogen positive balances (Goulding et al. 2007). In its efforts to improve food security, sub-Saharan Africa would benefit from lessons learned elsewhere to produce sufficient food to meet the demand of the fast increasing population, while minimizing environmental pollution and improving food quality. The scientific community has reported negative and positive impacts of the presence of nitrate and/or nitrite in food crops such as leafy vegetables as well as drinking/cooking water (Hord et al. 2009; Sindelar and Milkowski. 2012). However precautions would be crucial to minimize health risks associated with consumption of food or drinking water containing high levels of nitrates and/or nitrites. Variable limits of nitrate levels (e.g., 200-7000 mg NO_3^--N kg^{-1}) in various food crops particularly vegetables have been developed by the European Union (Weightman and Hudson 2013). Some authors reported that nitrate and nitrite represent significant health risks (Gao et al. 2012), related to the formation of nitrosamines considered as cancer-promoting moieties or conversion of hemoglobin to methemoglobin leading to methemoglobinemia or anoxia (Lairon 2010). Conversely, others referred to positive benefits in human diets including prevention of various types of cardiovascular diseases such as hypertension, atherosclerosis, and stroke (Hord et al. 2009; Sindelar and Milkowski 2012). Weightman and Hudson (2013) reported that nitrate consumption represent more risk for animal than humans, except for babies and young children. There is certainly a need to determine the threshold value that delineates the positive and negative impacts of nitrate and nitrite on human health. In the meantime, FAO has recommended maximum daily intakes of 3.7 mg nitrates kg^{-1} body weight, 0.07 mg nitrite kg^{-1} body weight, and maximum nitrate level of 50 mg L^{-1} in drinking water (Lairon 2010); however, Hord et al. (2009) did question these threshold values in plant foods and called for their reevaluation given the potential health benefits of nitrate and nitrite. Additional scientific evidence would be required to inform the update of norms for nitrate and nitrite in plants food and drinking water.

Research capacity and future perspectives

In sub-Saharan Africa, there is a paucity of information on the full N cycle as consequence of limited research capacity and the research priorities of most national and international research organizations. In general, the human choices in terms of food consumption drive nitrogen use particularly for food and feed production (Sutton et al., 2013). Selected investigations in sub-Saharan Africa have been made to improve the nitrogen agronomic use efficiency in food production; however, quantification of N flows in the whole food supply chain has been too scarce to be representative, which has resulted in excessive uncertainties in N budgets (Rufino et al., 2014; Zhou et al., 2014). Consequently, key intervention areas to optimize the N agronomic use efficiency and minimize the N losses to the environment are often not well-understood particularly at regional and continental levels. Based on current challenges and opportunities related to N management in Africa, priorities to improve food security could among others include the following:

- Use a participatory approach to determine segments of the whole food supply chain with low N efficiency and develop solutions to address the underlying causes to optimize food production

- Develop crop-specific N application rates in the context of integrated soil fertility management to improve food production and quality, while minimizing food contamination by nitrate and nitrite beyond the tolerable levels
- Develop smart subsidies for N inputs that promote the N use, conducive to the public private partnership, and minimize dependence on public support overtime
- Advocate for market policies conducive to increased profitability of nitrogen use for food production
- Conduct comprehensive regional and continental N budgets to determine (i) the sources, (ii) the efficiency of each, (iii) the types of losses, and (iv) effective mitigation approaches for each type of loss to optimize food production, while minimizing environmental pollution
- Assess the quality of emerging N inputs (i.e. bio-fertilizers) 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' losses to the environment. Proper interventions are required to reverse the trend so as to meet the food demand of the region with the highest 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-constrained 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 integrated soil fertility management so as to produce enough nutritious food, and diversify the production systems to meet the dietary needs.

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