
4 Improving Soil Fertility through Fertilizer Management in Sub-Saharan Africa

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4.1 INTRODUCTION

Sub-Saharan Africa (SSA) has been identified as a future hotspot for food shortage due to low agricultural yields and high variability in yield, cultivated acreage, and total production. Several African countries are food insecure and have persistently been unable to feed their population (NEPAD 2003). Haggblade et al. (2004) note that, over the past 40 years or so, agriculture production has increased at a rate of 2.5% per year in Africa compared to 2.9% in Latin America

and 3.5% in developing Asia. As a result of this situation, Africa is a net food-importing region. Food imports in Africa rose from USD 15 billion in the 1990s to about USD 40 billion in 2007 (Rakotoarisoa et al. 2011). The number of chronically undernourished people increased from 168 million in 1990–1992 to 224 million in 2016 (FAO 2017). Agricultural productivity in Africa lags all other continents. NEPAD (2014) notes that productivity per agricultural worker has improved by a factor of only 1.6 in Africa over the past 30 years, compared to 2.5 in Asia. While cereal crop yields in Asia have doubled or quadrupled since the 1960s, they have stagnated in Africa (Haggblade et al. 2004), and as populations have increased, food production per capita has been declining in Africa for the past three decades. This leaves African families with ever less opportunity to feed themselves and their children. As a result, malnutrition remains shockingly common in Africa, increasing from 160 million people in 1990 to 205 million in 2015 (FAO 2019).

SSA uses 13 kg per hectare of nitrogen, phosphorus and potassium (NPK), fertilizers on croplands in SSA, and this usage remains low compared to the world average of 100 kg NPK ha⁻¹ with consumption in 2016 in Eastern, Middle, Western, and Southern Africa of 15.8, 4.3, 9.6, and 53.4 kg ha⁻¹, up from 12.3, 2.6, 3.9, and 53.7, respectively, in 2002 (FAO 2019). Despite the increase, the consumption of fertilizer per capita is stagnant – five times lower than Asia (Figure 4.1).

As a consequence of the low use of fertilizers and suboptimal soil fertility management, crop yields have stagnated in the past 50 years, causing food insecurity and encouraging encroachment upon the remnant forests to meet the food needs of an overgrowing population. Meanwhile, Africa has considerable fertilizer resources. Seventy percent of the world's phosphate rock resources (Figure 4.2) and significant deposits of nitrogen and potash resources are found in Africa (Figure 4.3).

Although significant progress has been made in research in developing principles, methodologies, and technologies for combating soil fertility depletion, soil infertility still remains the fundamental biophysical cause for the declining per capita food production in SSA over the last 3–5 decades (Vanlauwe 2004). This is evident from the huge gap between actual and potential crop yields (FAO 1995).

During the period of 30 years from 1960 to 1990, soil fertility depletion has been estimated at an average of 660 kg N ha⁻¹, 75 kg P ha⁻¹, and 450 kg K ha⁻¹ from about 200 million ha of cultivated land in 37 African countries (Vanlauwe 2004). Stoorvogel et al. (1993) estimated annual net

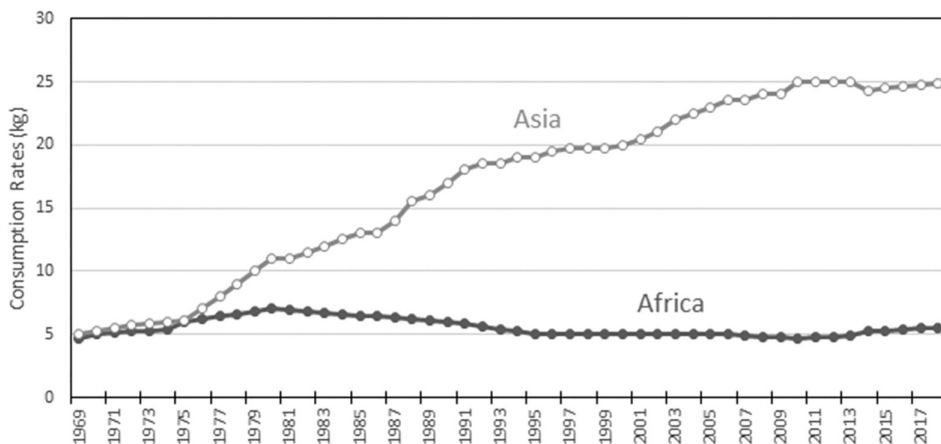


FIGURE 4.1 Evolution of fertilizer consumption per capita (kg) in Africa. Based on FAO (2019) and FAO (2016).



FIGURE 4.2 Phosphate rock deposits in Africa. (Source: IFDC.)



FIGURE 4.3 Nitrogen and potash deposits in Africa. (Source: IFDC.)

TABLE 4.1
Average Nutrient Balance of N, P, and K (k ha⁻¹ yr⁻¹) for
Arable Land for Some Sub-Saharan African Countries
(Average of 1982–1984)

Country	N	P	K
Botswana	0	1	0
Mali	-8	-1	-7
Senegal	-12	-2	-10
Benin	-14	-1	-9
Cameroon	-20	-2	-12
Tanzania	-27	-4	-18
Zimbabwe	-31	-2	-22
Nigeria	-34	-4	-24
Ethiopia	-41	-6	-26
Kenya	-42	-3	-29
Rwanda	-54	-9	-47
Malawi	-68	-10	-44

Source: Stoorvogel, J.J., et al., *Fertil. Res.*, 35, 227–235, 1993.

depletion of nutrients in excess of 30 kg N and 20 kg K ha⁻¹ of arable land per year in Ethiopia, Kenya, Malawi, Nigeria, Rwanda, and Zimbabwe (Table 4.1).

Given the current low levels of fertilizer use, green and animal manures are insufficient to sustain soil health and the nutrient balances remain negative for many cropping systems, indicating that farmers are mining their soils of nutrient reserves of over 50 kg ha⁻¹ year⁻¹ of N, P, and K combined (e.g., Lesschen et al. 2007; Cobo et al. 2010).

The development of the modern fertilizer industry had a tremendous positive impact on agricultural productivity and global food security, and it is widely acknowledged that fertilizers are responsible for at least half of the global food supply (Erismann et al. 2008). The data in Table 4.2 gives the yield of selected crops in farmer's field without the use of fertilizers as compared to the potential yields obtained on station with the use of fertilizers. It is evident from the data that for some crops it is possible to increase the yield up to five times by improving soil nutrients management.

TABLE 4.2
Yield Potential with Fertilizer Use in Africa

Crop	Actual Yields in Farms without Fertilizer (kg/ha)	Potential Yield on station with Fertilizer (kg/ha)	Increase over Control (%)
Irrigated rice West Africa	3,000	8,000	167
Upland rice West Africa	1,000	4,000	500
Cassava West Africa	8,000	47,000	487
Maize West Africa	800	6,000	650
Sorghum West Africa	600	3,000	400
Millet West Africa	300	2,000	567
Maize East Africa	1,500	8,000	433
Maize Southern Africa	1,500	8,000	433

Source: Bationo, A., unpublished data.

4.2 CHANGES IN PARADIGMS FOR SOIL FERTILITY MANAGEMENT IN SUB-SAHARAN AFRICA

Since the 1960s, the paradigms underlying soil fertility management research and development efforts have undergone substantial changes because of experiences gained with specific approaches and changes in the overall social, economic, and political environment faced by various stakeholders. During the 1960s and 1970s, an external input paradigm characterized by increased use of improved germplasm and fertilizer significantly led to a rapid increase in food production, commonly referred to as the “Green Revolution,” especially in Asia and Latin America. This paradigm put little if any significance on the set of organic resources as sources of nutrients for soil health.

The impacts of the Green Revolution strategy resulted only in minor achievements in SSA. The environmental degradation resulting from massive and injudicious applications of fertilizers and pesticides observed in Asia and Latin America between the mid-1980s and early 1990s (Theng 1991) and the abolition of the fertilizer subsidies in SSA (Smaling 1993), imposed by structural adjustment programs, led to a renewed interest in organic resources in the early 1980s. The balance shifted from mineral inputs to low input sustainable agriculture (LISA) where organic resources were believed to enable sustainable agricultural production (Vanlauwe 2004). The adoption of LISA technologies, such as alley cropping or live mulch systems, was constrained by both technical (e.g., lack of sufficient organic resources) and socioeconomic factors (e.g., labor-intensive technologies) (Vanlauwe 2004). This led to the second paradigm, integrated nutrient management (INM), which emphasized the need for the judicious use of both mineral and organic inputs to sustain crop production (Vanlauwe 2004).

A further shift in paradigm in the mid-1980s to the mid-1990s advanced the combined use of organic and mineral inputs accompanied by a shift in approaches toward involvement of the various stakeholders in the research and development process, mainly driven by the “participatory” movement. One of the important lessons learned was that the farmers’ decision-making process was not merely driven by soil and climate but by a whole set of factors cutting across the biophysical, socioeconomic, and political domain. The integrated natural resource management (INRM) research approach was thus formulated, aimed at developing interventions that take all the above aspects into account (Izac 2000).

Past paradigms of soil fertility management focused on fertilizer or “low-input” methods, but rarely on both, and ignored the essential scientific fact that fertilizers are most effective and efficient in the presence of soil organic matter (SOM) and well-conserved soil structure. This dichotomy is resolved by the integrated soil fertility management (ISFM) framework. The framework entails applying locally adapted soil fertility management practices to optimize the agronomic efficiency of fertilizer and organic inputs in crop production. Large-scale adoption of ISFM will promote soil fertility management practices, which include the use of mineral fertilizers, organic inputs, improved germplasm, and knowledge of their local adaptation. Such practices would maximize agronomic use efficiency of applied nutrients and improve crop productivity (Figure 4.4). Widespread adoption of ISFM is crucial in harnessing healthy soils, given that inorganic fertilizer provides most of the nutrients and organic fertilizer increases SOM status, soil structure, and buffering capacity of the soil in general. Moreover, use of both inorganic and organic fertilizers has proven to result in synergy, improving efficiency of both nutrient and water use.

In addition, the ISFM concept also takes into account other socioeconomic factors such as land tenure, input-output markets, access to credit, and institutional support, among others, in a value chain approach. ISFM, therefore, seeks to develop competitive commodity chains by strengthening the technical and managerial competencies of the various actors involved, particularly the farmers and local entrepreneurs (including inputs dealers, processors, stockists, and traders) at the grassroots level. Past paradigms had ignored such a holistic approach to agricultural development.

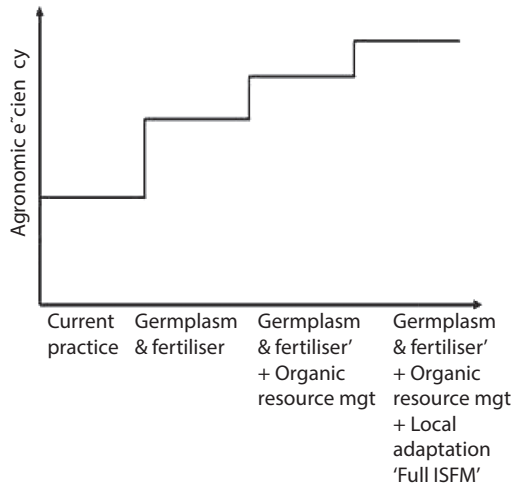


FIGURE 4.4 The ISFM paradigm. (Source: Vanlauwe, B. et al., *Outlook Agr.*, 39, 17–24, 2010.)

4.3 PRODUCTIVITY OF AFRICAN SOILS

Africa covers an area of about 3.01×10^9 hectares, out of which about 230×10^6 hectares represent water bodies. Relative to soil in other parts of the world, African soils have an inherently poor fertility because they are very old and because lack of volcanic rejuvenation has caused the continent to undergo various cycles of weathering, erosion, and leaching, leaving soils poor in nutrients (Smaling 1995). Inappropriate land use, poor soil fertility management, and lack of input have led to a decline in productivity.

At least 485 million Africans are affected by land degradation, making land degradation one of the continent's urgent development issues with significant costs: Africa is burdened with a \$9.3 billion annual cost of desertification. While the cumulative loss of crop productivity from worldwide land degradation between 1945 and 1990 has been estimated at 5%, as much as 6.2% of productivity has been lost in SSA. An estimated \$42 billion in income and 6 million hectares of productive lands are lost every year due to land degradation and declining agricultural productivity (UNDP/GEF 2004). Globally, Africa suffered a net loss of forests exceeding 4 million hectares per year between 2000 and 2005, according to FAO (2006). This was mainly due to conversion of forest lands to agriculture. During a period of 30 years, soil fertility depletion has been estimated at an average of 660 kg N ha^{-1} , 75 kg P ha^{-1} , and 450 kg K ha^{-1} from about 200 million ha of cultivated land in 37 African countries. Africa loses \$4 billion per year due to soil nutrient mining (Smaling 1993). Soil fertility depletion in smallholder farms is a fundamental biophysical root cause of the declining per capita food production; it has largely contributed to poverty and food insecurity. Over 132 million tons of N, 15 million tons of P, and 90 million tons of K have been lost from cultivated land in 37 African countries in 30 years (Smaling 1993). Nutrient loss is estimated to be 4.4 million t N, 0.5 million t P, and 3 million t K every year from cultivated land (Vanlauwe 2004). These rates are higher than Africa's annual fertilizer consumption (excluding South Africa) of 2.4 million tons N, 0.40 million tons P, and 0.5 million tons K (FAO, 2016). The loss is equivalent to 1400 kg ha^{-1} urea, 375 kg ha^{-1} Triple Super-phosphate (TSP), and 896 kg ha^{-1} KCl during the period of three decades.

N and P are the most deficient macronutrients in SSA, but the crop responses to these two nutrients is quite variable due to the high heterogeneity of the soils in their initial nutrient status, crop nutrient uptake, and response to applied fertilizer vary with soil type, as indicated in Table 4.3. Whereas P was limiting nutrient in the Nitisol, N was the most limiting nutrient in the Vertisol. These results point to the need to effectively tailor fertilizer to soil fertilizer status to ensure use efficiency of use by crops on the different soil types.

TABLE 4.3
Yields and NPK Uptake of Maize on Three Kenyan Soils as a Function of Soil Type and Fertilizer Treatment (Long Rainy Season, 1990)

Soil	Treatment	Yield (ton/ha)	Nutrient Uptake		
			N	P	K
Nitisol (red, clayey)	N ₀ P ₀	2.1	42	5	30
	N ₅₀ P ₀	2.3	50	6	36
	N ₀ P ₂₂	4.9	79	12	58
Vertisol (black, clayey)	N ₀ P ₀	4.5	63	24	95
	N ₅₀ P ₀	6.3	109	35	126
	N ₀ P ₂₂	4.7	70	23	106

Source: Smaling, E.M.A., et al., *Ambio*, 25, 492–496, 1996.

Note: N – kg/ha as CAN; P – kg/ha as TSP.

A major issue preventing effective utilization of fertilizers by crop has been the “pan-territorial/blanket” nature of the recommendations that fail to take into account differences in farmers’ resource endowment (soil type, labor capacity, climate risk, etc.). Past fertilizer recommendations have been based on single major cash crops such as maize, tea, and cotton and did not take into account complex farming systems involving crop rotations, intercropping, and conservation agriculture that are characteristic of most smallholder farming systems in Africa. Different fertilizer responses have been observed in different parts of the same field due to the existing within-farm soil fertility gradients. Research has shown that the use of high-yielding cereal varieties, along with the increasing use of fertilizers containing major nutrients (N, P, K), but without micronutrients through inorganic or organic fertilizers, dramatically increases food production under intensified systems. However, in the long run as a result of depletion of micronutrient reserves in the soil, this practice results in a number of nutrient disorders and associated nutrient imbalances. Micronutrients are required by plants in small quantities, but they limit plant growth and substantially lower yields when deficient. In SSA, only a few studies (Schutte 1954; Sillanpaa 1982; Kang and Osiname 1985) have documented the micronutrient status of soils in the region, as compared to the enormous amount of literature available on macronutrients. The study by Sillanpaa (1982) showed that copper, zinc, and molybdenum deficiencies are common in many coarse-textured acid soils of Ethiopia, Ghana, Malawi, Nigeria, Sierra Leone, Tanzania, and Zambia. Recently, Kihara et al. (2017), using a meta-analysis of published articles on crop response to secondary and micronutrients in Africa, concluded that S, Zn, Cu, and Fe induced positive and significant crop response following their addition to the major NPK fertilizers. In many SSA countries, replenishment of micronutrients through fertilizers or other amendments is still in its infancy. Additions of soil micronutrients can improve the yield response to macronutrients (N and P) on deficient soils. Nutrients such as Zn, B, S, and Mg can often be included relatively cheaply in existing fertilizer blends; when targeted to deficient soils, these nutrients can dramatically improve fertilizer use efficiency and crop yield. During the 1950s, 1960s, and 1970s, S, Mg, and (less commonly) Zn and B deficiencies were detected for maize on sandy soils in Zimbabwe (Grant 1981). Enhanced yields were obtained by including selected micronutrients in fertilizer blends (Grant 1981). Recent experience in Malawi provides a striking example of how N fertilizer efficiency for maize can be raised by providing appropriate micronutrients on a location-specific basis.

Soil organic carbon is an exhaustible natural resource capital, and, like the negative nutrient balances, its decline threatens soil productivity. The concentration of organic carbon in the top soil is reported to average 12 mg kg⁻¹ for the humid zone, 7 mg kg⁻¹ for the subhumid zone, 4 mg kg⁻¹

in the semiarid zone, and 2 mg kg⁻¹ for the drier semiarid zone (Windmeijer and Andriessse 1993). Most African soils are inherently low in organic carbon (<20 to 30 mg kg⁻¹). This is due to the low root growth of crops and natural vegetation, but also to the rapid turnover rates of organic materials with high soil temperature, persistent bush burning, and intense faunal activity, particularly termites (Bationo et al. 2003). There is much evidence for rapid decline of soil organic C levels with continuous cultivation of crops in Africa (Bationo and Buerkert 2001). Results from long-term soil fertility trials indicate that losses of up to 0.69 tons carbon ha⁻¹ yr⁻¹ in the soil surface layers is common in Africa even with high levels of organic inputs (Nandwa 2003). There is much evidence for a rapid decline of Corg levels with continuous cultivation of crops (Bationo et al. 1995). For the sandy soils, average annual losses in Corg, often expressed by the k-value (calculated as the percentage of organic carbon lost per year), may be as high as 4.7%, whereas for sandy loam soils, reported losses seem much lower, with an average of 2% (Pieri 1989; Table 4). Topsoil erosion may lead to significant increases in annual Corg losses, such as from 2% to 6.3% at the Centre de Formation des Jeunes Agriculteurs (CFJA) in Burkina Faso (Table 4.4). However, such declines

TABLE 4.4
Annual Loss Rates of Soil Organic Carbon Measured at Selected Research Stations in the Sub-Saharan West Africa

Place and Source	Dominant Cultural Succession	Observations	Clay + Silt (%) (0–0.2 m)	Annual Loss Rates of Soil Organic Carbon (k)	
				Number of Years of Measurement	k (%)
Burkina Faso					
With tillage					
Saria, INERA-IRAT	Sorghum monoculture	Without fertilizer	12	10	1.5
	Sorghum monoculture	Low fertilizer (lf)	12	10	1.9
	Sorghum monoculture	High fertilizer (hf)	12	10	2.6
	Sorghum monoculture	lf + crop residues	12	10	2.2
CFJA, INERA-IRCT	Cotton–cereals	Eroded watershed	19	15	6.3
Senegal					
With tillage					
Bambey, ISRA-IRAT	Millet–groundnut	Without fertilizer	3	5	7.0
	Millet–groundnut	With fertilizer	3	5	4.3
	Millet–groundnut	Fertilizer + straw	3	5	6.0
Bambey, ISRA-IRAT	Millet monoculture	with PK fertilizer + tillage	4	3	4.6
Nioro-du-Rip, IRAT-ISRA	Cereal–leguminous	F0T0	11	17	3.8
	Cereal–leguminous	F0T2	11	17	5.2
	Cereal–leguminous	F2T0	11	17	3.2
	Cereal–leguminous	F2T2	11	17	3.9
	Cereal–leguminous	F1T1	11	17	4.7
Chad					
With tillage, high fertility soil					
Bebedjia, IRCT-IRA	Cotton monoculture		11	20	2.8
	Cotton – cereals			20	2.4
	+ 2 years fallow			20	1.2
	+ 4 years fallow			20	0.5

Source: Pieri, C., *Fertilité des terres de savane. Bilan de trente ans de recherche et de développement agricoles au sud du Sahara*. Ministère de la Coopération, CIRAD, Paris, France, 1989.

F0 = No fertilizer, F1 = 200 kg ha⁻¹ of NPK fertilizer, F2 = 400 kg ha⁻¹ of NPK fertilizer + Taiba phosphate rock, T0 = manual tillage, T1 = light tillage, T2 = heavy tillage.

are site specific and heavily depend on management practices such as the choice of the cropping system, soil tillage, and the application of mineral and organic soil amendments. Data from Chad show that crop rotation and fallow management can minimize Corg losses. Thus k-values in cotton–cereal rotations were 2.4%, compared to 2.8% in a continuous cotton system. Also, four years of fallow after 16 years of cultivation led to large increases in Corg and a reduction of annual Corg losses to 0.5%.

The soil patterns in the five major agroecological zones of Africa are determined by differences in age, parent material, physiography, and present and past climatic conditions. In the humid zones, dominant soils are Ferralsols and the Acrisols. Less important in this zone are Arenosols, Nitosols, and Lixisols. The subhumid zone is characterized by the dominance of Ferralsols and Lixisols and, to a lesser extent, Acrisols, Arenosols, and Nitosols. In the semiarid zone Lixisols have the larger share followed by sandy Arenosols and Vertisols (Deckers 1993). A map showing the distribution of major soils in Africa is shown in [Figure 4.5](#), and [Table 4.5](#) gives the constraints of the main soils and countries covered.

[Table 4.5](#) summarizes the extent of the main soil types, constraints, and countries covered (Bationo et al. 2007a).

Land can be classified as prime, high, medium, and low potential, and unsuitable. [Figure 4.6](#) gives the agricultural potential of African soils. Prime land comprises those soils with deep, permeable layers and with an adequate supply of nutrients, and these soils generally do not have significant periods of moisture stress. The soils are without impermeable layers, textures are loamy to clayey with good tilth characteristics, and the land is generally level to gently undulating. They occupy about 9.6% of Africa, and they occupy significant areas in West Africa south of the Sahel, in East Africa mainly in Tanzania, and in Southern African countries of Zambia, Zimbabwe, South Africa, and Mozambique.

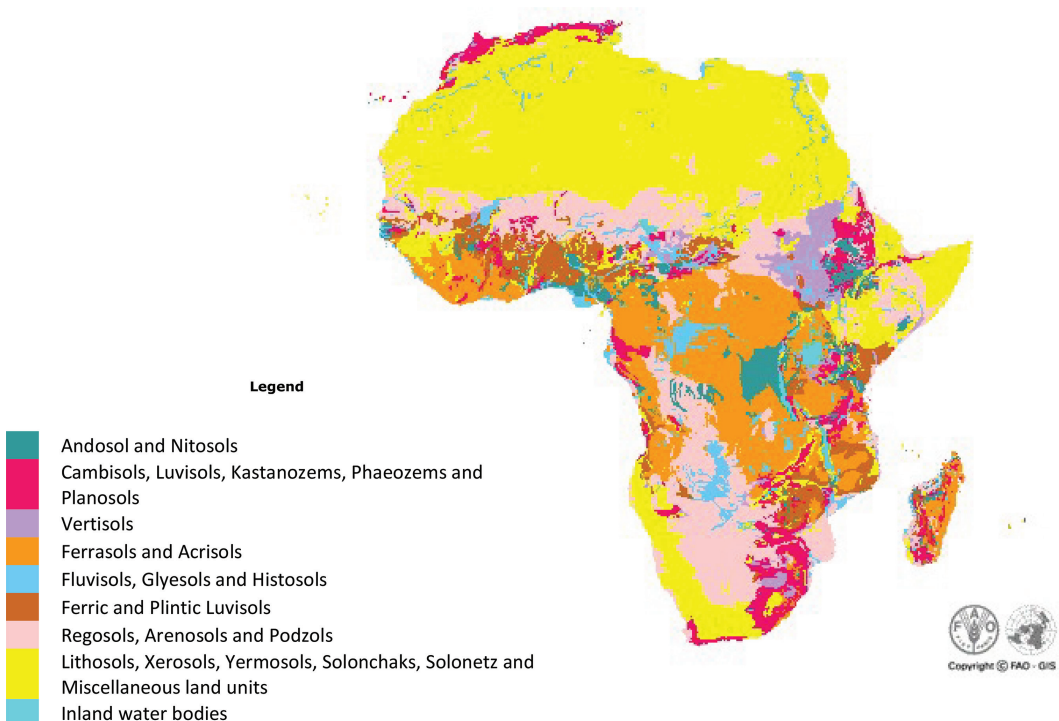


FIGURE 4.5 Major soil types in Africa.

TABLE 4.5
Main Soil Types, Extent, Constraints, and Countries Covered

Soil Type	Hectare (ha)	Percentage of Total Land (%)	Main Constraints	Main Countries Covered
Andosol and Nitisols	117,123,121	3.8	Fertile (volcanic ash), high P-fixation, Mn toxicity, medium water and nutrient retention	Rift valley (Ethiopia, Kenya, Tanzania, Zaire)
Cambisols, Luvisols, Kastanozems, Phaeozems, and Planosols	211,348,146	6.8	Low to moderate nutrients content	Mediterranean countries
Vertisols	98,985,811	3.2	Heavy soils, medium mineral reserves, erodibility and flooding	Sudan, Ethiopia, South Africa, Lesotho
Ferrasols and Acrisols	500,910,947	16.2	Low nutrients content, weathered, Al and Mn toxicity, high P-fixation, low nutrient and water retention, susceptible to erosion	DRC, Angola, Zambia, Rwanda, Burundi, Uganda, Sudan, Central Afr. Rep., Cameroon, Liberia, Sierra Leone and Madagascar, subhumid zone of West Africa
Fluvisols, Gleysols and Histosols	132,037,611	4.3	Poor to moderate drainage	West, Central, and southern Africa
Ferric and Plintic Luvisols	179,786,479	5.8	Low nutrients content	Western and Southern Africa
Regosols, Arenosols and Podzols	579101963	18.7	Mainly quartz, low water and nutrient holding capacity, wind erosion, poor soils with nutrients leaching	West Africa/Sahel, Sudan, Botswana, Angola and DRC, north Africa
Lithosols, Xerosols, Yermosols, Solonchaks, Solonetz, and miscellaneous land units	1,244,513,150	40.3	Shallow soils, soils subject to drought, presence of salt	North African countries, South Africa, Namibia, Somalia, Sahel
Inland water bodies	27,230,091	0.9	Flood zones	
TOTAL	3,091,037,319	100		

High-potential soils are similar to prime soils but have some minor limitations such as extended periods of moisture stress, sandy or gravelly materials, or root-restricting layers in the soil. The high-potential lands occupy an area of about 6.7%.

Medium- and low-potential lands, which occupy 28.3% of the surface, have major constraints for low-input agriculture. These lands have a major soil constraint and one or more minor constraints that can be corrected. Constraints include adverse soil physical properties including surface soil crusting; impermeable layers; soil acidity and specifically subsoil acidity, salinity, and alkalinity; and high risks of wind and water erosion. The large contiguous areas of Central and West Africa are considered as medium potential, due to the presence of acid soils and soils that fix high amounts of P. With an inherently low soil quality, low-input agriculture can be equated to potential soil degradation. These are some of the priority areas for technical assistance and the implementation of appropriate soil management technologies.

The unsustainable class of lands are those that are considered to be fragile, easily degraded through inappropriate management, and in general are not productive or do not respond well to management. These occupy about 55% of the African continent. They are generally erodible and require high investments.

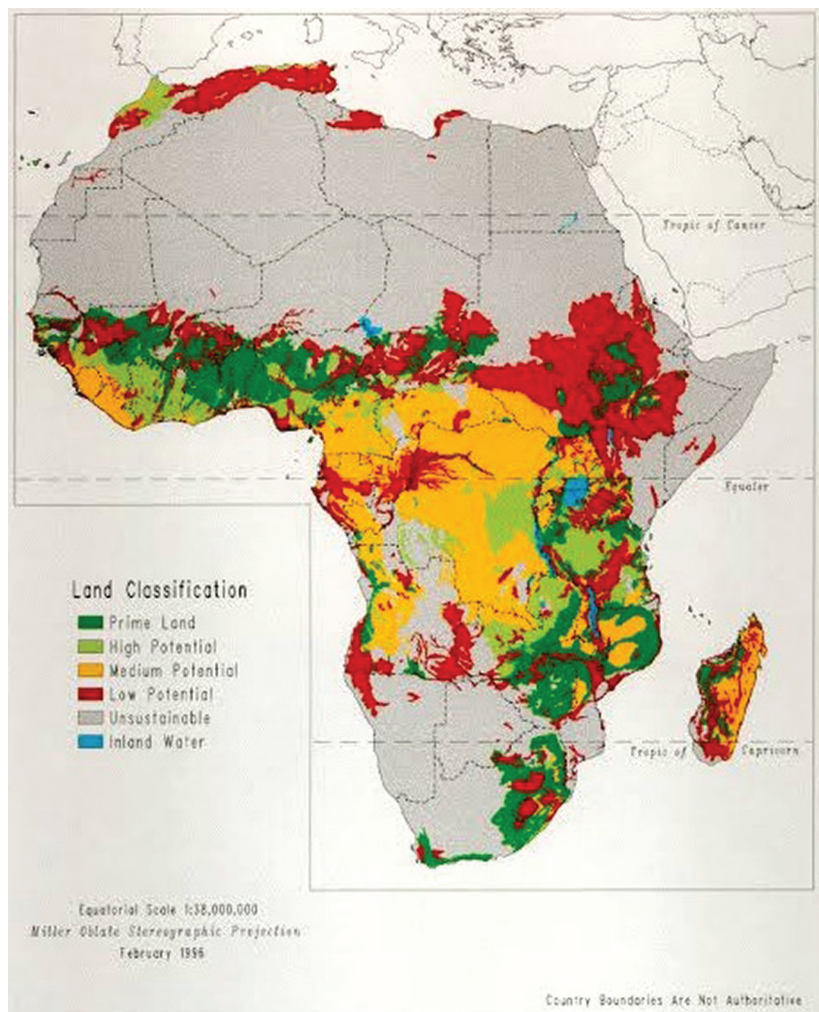


FIGURE 4.6 Land classification of African soils.

4.4 OVERVIEW OF FERTILIZER MANAGEMENT

The regional reviews by Okalebo et al. (2006), Mafongoya et al. (2006), and Schlecht et al. (2006) highlight the potential of soil fertility management technologies in Eastern, Southern, and Western Africa. These technologies include the use of mineral (soluble) fertilizers, mineral soil amendments, organic inputs, improved land use systems, and soil and water conservation.

Fertilizer was as important as seed in the Green Revolution, contributing as much as 50% of the yield growth in Asia (Hopper 1993). Several studies have found that one-third of the cereal production worldwide is due to the use of fertilizer and related factors of production (Bumb 1995, citing FAO). Van Keulen and Breman (1990) and Breman (1990) stated that the only real cure against land hunger in the West African Sahel lay in increased productivity of the arable land through the use of external inputs, mainly inorganic fertilizers. Pieri (1989), reporting on fertilizer research conducted from 1960 to 1985, confirmed that inorganic fertilizers in combination with other intensification practices had tripled cotton yields in West Africa from 310 to 970 kg ha⁻¹. There are numerous cases of strong fertilizer response for maize in East and Southern Africa (Byerlee and Eicher 1997).

TABLE 4.6
Maize Response to Organic and Inorganic Fertilizer Application in Selected Sites in East, West, and Southern Africa

Site	Treatment	Yield (t/ha)	% Yield Increase
West Africa ¹ (multisites 3–6 year average)	Control	1.51	–
	TSP + N + K	3.172	110
	N + K	2.319	54
	P + K	2.426	61
	P + N + K	3.765	149
	P + N + K + lime (500 kg ha ⁻¹ every 3 years)	3.794	151
	Crop residue (CR)	1.999	32
	Manure (10t ha ⁻¹ every 3 years)	2.497	65
	P + N + K + Mg + Zn	3.880	157
	P + N + K + Mg + Zn + Lime	4.006	165
	P + N + K + Mg + Zn + CR	4.083	170
East Africa ² (1981–1985)	P + N + K + Mg + Zn + Manure + Lime	4.289	184
	Control	1.9	–
	Crop residues	2.5	32
	Manure (5 t)	3.5	84
	Fertilizer 60 kg N, 25 kg P)	4.1	116
	Manure (10 t)	4	111
	Fertilizer 120 kg N, 50 kg P)	4.6	142
	Manure 5 t + Fertilizer 60 kg N, 25 kg P)	5.2	174
Southern Africa ³	Control	0.729	–
	N + P + K	2.194	201
	Termitaria + N + P	2.229	206
	Cattle manure + N + P	2.644	262
	Maize stover + N + P	1.575	116
	Fresh litter + N + P	2.553	250
	<i>Crotalaria juncea</i> + N + P	2.496	242

¹ Mokwunye et al. (1996) – Results from 6 different AEZ in Togo.

² Qureish (1987) – Results from Kabete, Kenya.

³ Mtambanengwe and Mapfumo (2005) – Results from Chinyika Zimbabwe.

The data in [Table 4.6](#) summarizes the multisite response to soil fertility improvement and clearly demonstrates the importance of fertilizers in maize yield improvement in different agro-ecological zone (AEZ) and soil types in Africa. Maize yield increase over the control due to NPK fertilizer application from six AEZ and averaged over four years was 149%, but when the soil was amended with lime and manure yield response over the control increased to 184% (Mokwunye et al. 1996). Similarly higher-yield improvements have been observed in Eastern (Qureish 1987) and Southern African countries (Mtambanengwe and Mapfumo 2005).

One lesson we learned from IFDC work in West Africa is the importance of adopting good agronomic practices before using fertilizers. In farmers' managed trials it was found that using good agronomic practices will result in higher yields in plots not using fertilizers than using fertilizers with poor agronomic practices such as planting late with poor crop density ([Figure 4.7](#)). There is a growing body

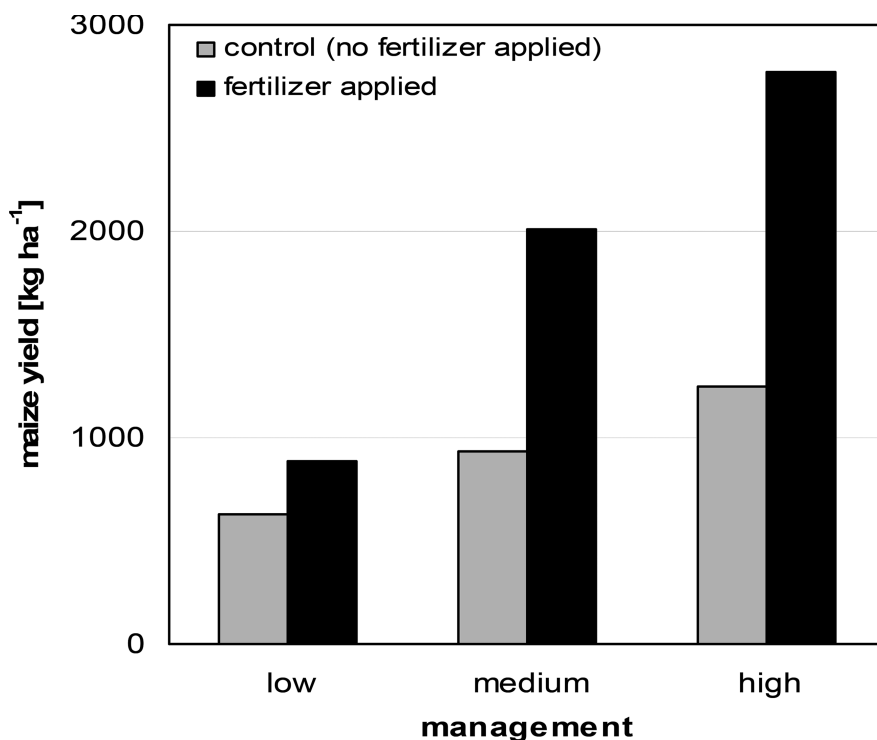


FIGURE 4.7 The effect of management intensity (planting date, crop density, and time of phosphorus application) on maize grain yield at Tinfouga, Mali. (From Bationo, A. et al., *Nutr. Cycl. Agroecosys.*, 48, 179–189, 1997).

of literature that shows fertilizers to be an essential component for sustainable yield increase in cropping systems and to be profitable in much of SSA (e.g., Droppelmann et al. 2017; Jama et al. 2017).

4.4.1 SOURCES AND MANAGEMENT OF NITROGEN AND PHOSPHORUS FERTILIZERS

The use of ¹⁵N in order to construct N balances and to determine fertilizer N uptake and losses provides an important tool for nitrogen management. IFDC undertook a systematic N balances study on nitrogen sources (urea versus calcium ammonium nitrate), time of application, and methods of application in the humid, subhumid, and semiarid zones of SSA (Mughogo et al. 1986; Bationo and Vlek 1998). One of the main findings was the high loss associated with nitrogen application in the semiarid zone (Table 4.7). The mechanism of N loss is believed to be ammonia volatilization. For all the years, losses of calcium ammonium nitrate (CAN) were less than urea because one-half of the N in CAN was in the nonvolatile nitrate form. The high losses through volatilization associated with urea N can be explained by the low cation exchange capacity of the soils and because significant rainfall does not occur shortly after N application. Although CAN has a lower N content than urea, it is attractive as an N source because of its low potential for N loss via volatilization, and its point placement will improve its special availability. At Gobery, CAN point placed outperformed urea point placed or broadcast (Figure 4.8). Nitrogen-15 data from a similar trial at Sadore illustrates the strong effect of N source and placement (Table 4.7). Plant uptake by ¹⁵N-N from point-placed CAN was almost three times that of urea applied in the same manner. A 57% reduction in fertilizer N uptake by the plant was found when the CAN was broadcast rather than point placed.

TABLE 4.7
Recovery of ^{15}N Fertilizer by Pearl Millet Applied at Sadore, Niger, 1985

N Source	Application Method	^{15}N Recovery			
		Grain (%)	Stover	Soil	Total
CAN	Point incorporated	21.3	16.8	30.0	68.1
CAN	Broadcast incorporated	10.9	10.9	42.9	64.7
Urea	Point incorporated	5.0	6.5	22.0	33.5
Urea	Broadcast incorporated	8.9	6.8	33.2	48.9
Urea	Point surface	5.3	8.6	18.0	31.9
SE		1.2	2.0	1.9	2.4

Source: Christianson, C.B., and Vlek, P.L.G., Alleviating soil fertility constraints to food production in West Africa: Efficiency of nitrogen fertilizers applied to food crops, in Mokwunye, A.U. (Ed.), *Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa*, Kluwer Academic Publishers, Dordrecht, the Netherlands, 1991.

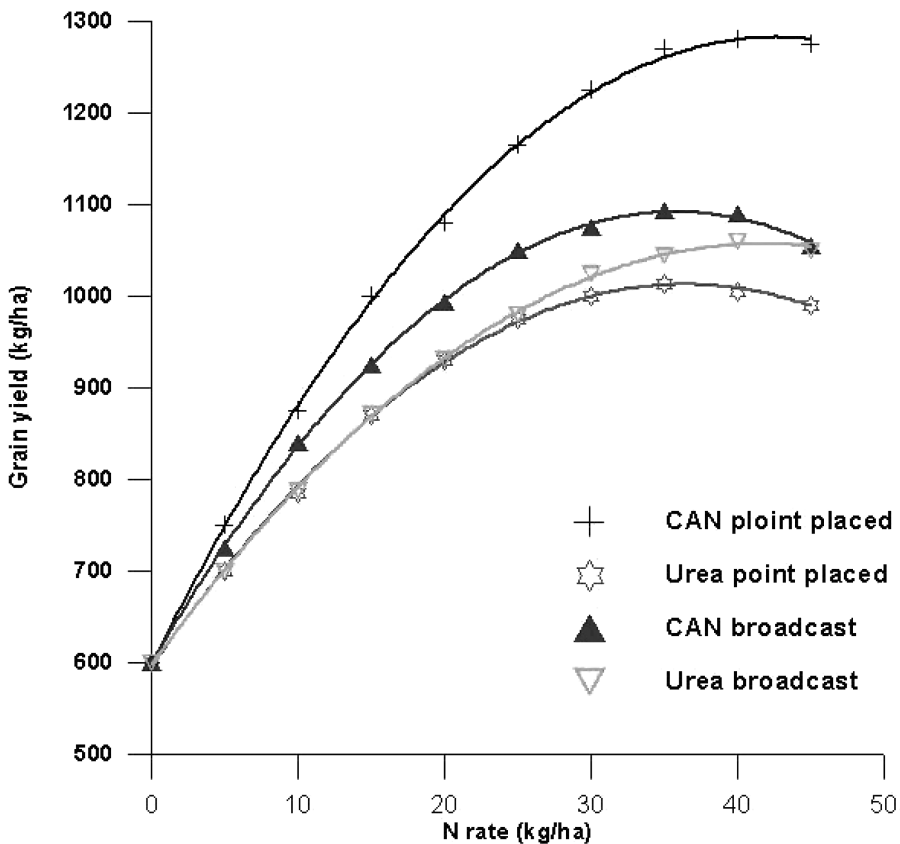


FIGURE 4.8 Effect of broadcast and point application methods for urea and CAN on grain yield of pearl millet.

4.4.2 MAINTENANCE OF SOIL ORGANIC MATTER PLAYS A KEY ROLE IN FERTILIZERS' USE EFFICIENCY AND RECOVERY

In a study in West Africa, Fofana et al. (2008) observed that grain yields across years and fertilizer treatment averaged 0.8 t ha⁻¹ on outfields and 1.36 t ha⁻¹ on infields (home gardens). Recovery of fertilizer N (RFN) applied varied considerably among the treatments and ranged from 17% to 23% on outfields and 34% to 37% on infields. Similarly, average recovery of fertilizer P applied (RFP) across treatments over the three-year period was 31% in the infields compared to 18% in the outfields. These results indicate higher inherent soil fertility and nutrient use efficiency in the infields (fertile fields) compared to the outfields (infertile fields) and underlines the importance of soil organic carbon and micro and secondary nutrients in improving fertilizer use efficiency. Once soils are degraded and poor in organic matter, the response to fertilizer is less and the recovery of applied fertilizers is reduced.

4.4.3 INCREASING THE LEGUME COMPONENT IN THE CROPPING SYSTEM CAN AFFECT THE EFFICIENCY OF MINERAL FERTILIZERS

Rotation of cereals and legumes can be used as means of improving soil fertility and productivity. Several researchers (Stoop and Staveren 1981; Klaij and Ntare 1995; Bagayoko et al. 1996; Bationo et al. 1998a; Bationo and Ntare 1999) have reported cereal/legume rotation effects on cereal yields. A rotation of pearl millet with groundnut and cowpea resulted in significantly higher pearl millet grain yields than in the monoculture cropping of pearl millet on average over a four-year period (Figure 4.9). With no application of N fertilizer, millet grain yield after cowpea increased by 57% at Sadore, 18% at Bengou, and 87% at Tara. Even at higher levels of N, continuous cropping of millet produced the lowest yields of millet grain. One of the reasons for the improvement of the efficiency of fertilizers in the rotation system was due to the increase of soil organic carbon in this system due

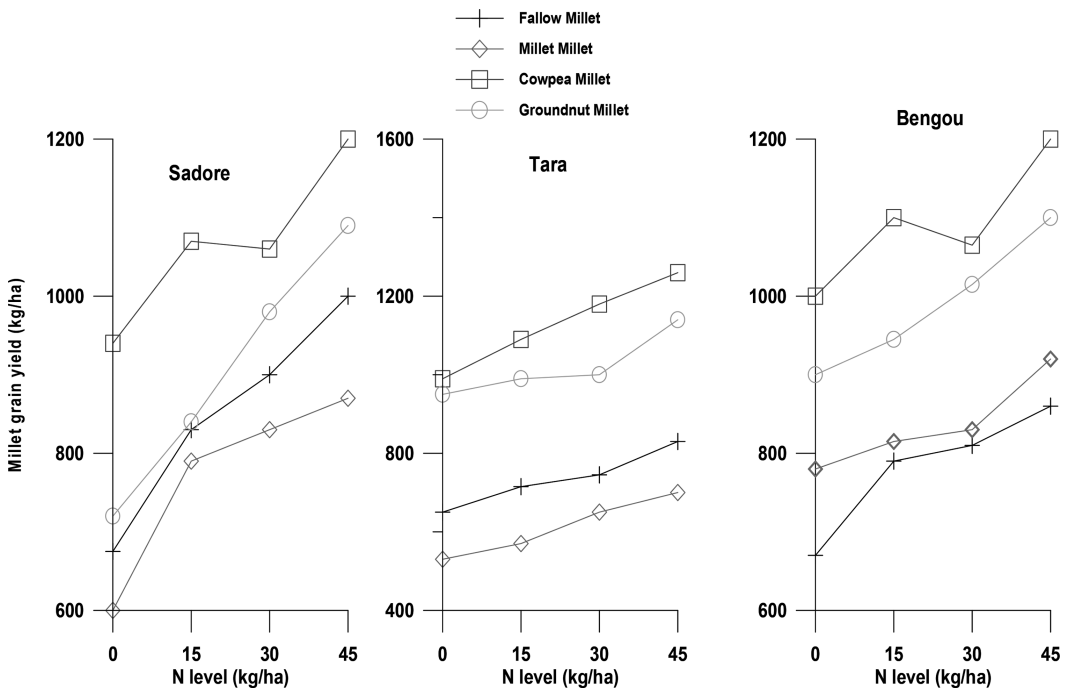


FIGURE 4.9 Effects of nitrogen and rotation on pearl millet grain yield (kg ha⁻¹ average of four years) at Sadore, Tara, and Bengou.

to the dropping of legume leaves (Bationo and Ntare 1995). It has been assumed by many workers that the positive effect of rotations arises from the added N from legume in the cropping system. Some workers, however, have attributed the positive effects of rotations to the improvement of soil biological and physical properties and the solubilization of occluded P and highly insoluble calcium-bounded phosphorus by root exudates (Gardner et al. 1981; Arhara and Ohwaki 1989). Other advantages of crop rotations include soil conservation (Stoop and Staveren 1981), organic matter restoration (Spurgeon and Grissom 1965), and pest and disease control (Sunnadurai 1973).

In N15 balances trials including rotation, N use efficiency increased from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea. Nitrogen derived from the soil is better used in rotation systems than with continuous millet (Bationo and Vlek 1998). Nitrogen derived from the soil increased from 39 kg N ha⁻¹ in continuous pearl millet cultivation to 62 kg N ha⁻¹ when pearl millet was rotated with groundnut.

4.4.4 UREA DEEP PLACEMENT INCREASES RICE PRODUCTIVITY AND NITROGEN USE EFFICIENCY

The main constraint to achieving high rice productivity in Africa is the chronic deficiency of major nutrients and particularly nitrogen. N is the most difficult nutrient to manage efficiently as it is very mobile in soil ecosystems and therefore is easily lost by leaching, runoff, denitrification, and volatilization. In Africa, prilled urea (PU) conventionally broadcast applied by rice farmers is inefficient in irrigated rice, largely because of serious losses (up to 60% of applied N) via ammonia volatilization and denitrification. And this calls for the development of new ergonomically efficient, economically attractive, and environmentally sound technologies aiming at improving the efficiency of input use, including improved seeds and particularly N source. Bandaogo et al. (2015) showed that through urea deep placement (UDP), the avenues for N losses in rice production system are reduced and improved N uptake by the plant is possible. In field trials conducted in Burkina Faso, the authors reported that UDP is a highly efficient soil nutrient management technology, enabling farmers to achieve higher crop yields (15%–20% higher than with broadcast application) with lower use of high-cost fertilizer (20%–30% lower than urea broadcast).

UDP is a science-based technology developed by the IFDC Research and Development Program to improve N use efficiency. It is a simple and low-cost technology, well suited to small-scale rice production. The technology is comprised of production of urea super granules (USG), compacted urea, and hand placement of USG in the puddled soil between each set of four hills of rice at a depth of 7–10 cm seven days after transplanting. It's a single basal deep placement of USG that matches more favorably the N requirement of the plant throughout the duration cycle. It significantly reduces N loss through volatilization and increases N use efficiency and paddy yield. Introduced in Asia in the 1980s, UDP's wide adoption in irrigated rice production systems in Asian countries (Bangladesh, Vietnam, Afghanistan, Cambodia, India, and Nepal) has brought about rice yield increases ranging from 23% to 70% and reduced requirement for urea fertilizer by 32% to 44%. UDP technology has proven to be highly effective in improving crop uptake of applied nitrogen fertilizers in irrigated rice and therefore merits to be experimented in similar production systems in Africa. More than 3500 demonstration plots were developed in 30 irrigation schemes located in the above-mentioned eight participating African countries. The demonstration scheme compares UDP with farmer practice (FP) – that is, the broadcast application of prilled urea.

Yield performance with UDP was higher than broadcast prilled urea (PU) (Figure 4.10). Mean yield advantage of USG over PU across all pilot countries was about 1,200 kg ha⁻¹. But it significantly varied among pilot countries, and the highest mean yield advantage was observed in Niger (1,880 kg ha⁻¹), followed by Nigeria (1,691 kg ha⁻¹) and Madagascar (1,498 kg ha⁻¹), with the lowest in Togo (390 kg ha⁻¹).

In order to study the effect of UDP on urea agronomic and economic efficiency, nitrogen agronomic efficiency (NAE) and value–cost ratio (VCR) were used. NAE was calculated as the additional grain yield (GY) produced by kg of fertilizer urea applied at constant NPK rates. It expresses

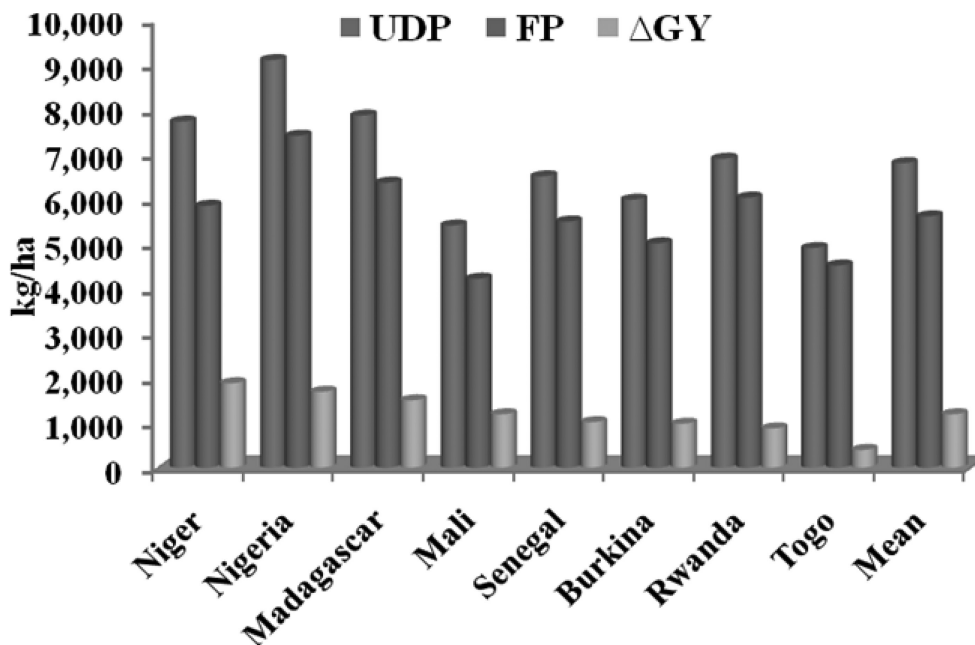


FIGURE 4.10 Efficiency of urea deep placement (UDP) and farmer practice (FP) in irrigated rice systems in the Intervention African Countries (Fofana, unpublished data).

the quantity (kg) of harvested product per kg fertilizer applied. VCR is a simple and effective indicator of nutrient effectiveness from an economic point of view. VCR was expressed as a ratio of economic yield value (with and without fertilizer application) and the total costs of fertilizer applied.

Results of NAE and VCR calculations are given in Table 4.8. The mean values of NAE and VCR varied among countries. The highest NAE (70) and VCR (8) using UDP were observed in Nigeria and Madagascar, respectively. Mean values of NAE across all target countries were 39 for PU and 56 for UDP, indicating that UDP induced an increase of NAE by 28%. Similarly, mean VCR with UDP was higher (6) than with PU (3.7), showing again an increase of 62%. These results clearly show the economic superiority of UDP over PU and suggest that under African conditions, the economics of UDP – instead of broadcast application of PU – offer an attractive N management technology that merits to be scaled up. Even under adverse conditions such as submergence-prone areas in northern Ghana, microdosing, deep placement of prilled urea, and urea briquette were more economical than farmer's practice and locally recommended practice (Table 4.9). UDP technology can be considered as a climate-smart technology because it (1) sustainably increases agricultural productivity and incomes; (2) adapts and builds resilience to climate change; and (3) reduces and/or removes greenhouse gas (GHG) emissions (Gaihare et al., 2015).

Eighty percent of the soils in Africa are P deficient, but Africa has 4,457 million tons of rock phosphate reserves representing about 75% of total world reserves of phosphate rock, and 42% of the phosphate rock used by industry to produce P fertilizers in the world is produced in six countries in Africa. SSA uses 1.6 kg P ha⁻¹ of cultivated land compared to 7.9 and 14.9 kg P ha⁻¹, respectively, for Latin America and Asia.

Despite the fact that the deficiency of P is acute on the soils of Africa, local farmers use very little P fertilizers because of high costs and problems with availability. The use of locally available phosphate rock (PR) could be an alternative to imported P fertilizers. For example, Bationo et al. (1986) showed that direct application of local PR may be more economical than imported water-soluble P fertilizers. Bationo et al. (1990) showed that Tahoua PR from Niger is suitable for direct application, but Parc-W

TABLE 4.8
Nitrogen Agronomic Efficiency and Value–Cost Ratio
for Prilled Urea and Urea Deep Placement Applied to
Irrigated Rice in 2009 in Eight African Countries

Country	Technology			
	Farmer Practice – FP		Urea Deep Placement – UDP	
	PU – NAE	VCR	UDP – NAE	VCR
Niger	36	3.5	59	5.9
Nigeria	49	4.8	70	7.0
Madagascar	44	5.5	63	8.0
Mali	41	3.3	64	6.7
Senegal	50	3.5	69	7.3
Burkina	31	3.1	44	4.3
Rwanda	35	3.5	46	4.6
Togo	28	2.7	33	3.2
Mean	39	3.7	56	6.0

PU, Prilled Urea; NAE, Nitrogen Agronomic Efficiency; UDP, Urea Deep Placement; VCR, Value–Cost Ratio.

TABLE 4.9
Rice Economic Benefits under Submergence Prone Conditions in Northern Ghana with
Various Nutrient Management Technologies

Treatment	Grain Yield (ton/ha)	Total Revenue (GH¢/ha)	Total Production Cost (GH¢/ha)	Gross Profit (GH¢/ha)	Additional Revenue for Applied N (GH¢/ha)	Additional Revenue/kg of Applied N (GH¢)
Farmer's practice – Basal NPK	1.07	1,592	1,560	32	–	–
Recommended (with urea broadcast)	2.12	3,155	1,953	1,202	1,170	7.80
Modified recommended (deep placement of prilled urea)	4.84	6,667	2,021	4,646	4,614	30.76
Microdosing	3.89	5,789	2,005	3,784	3,752	39.08
UDP (urea briquette deep placement)	5.26	7,515	2,044	5,471	5,439	48.13

from Burkina Faso has less potential for direct application. The effectiveness of local PR depends on its chemical and mineralogical composition (Chien and Hammond 1978). Phosphate rocks can be used as a soil amendment and the use of water-soluble P can be more profitable. Under certain soil conditions, the direct application of PR, especially where available locally, has proved to be an agronomically and economically sound alternative to the more expensive imported superphosphates. Kodjari PR in Burkina Faso, Tahoua PR in Niger, and Tilemsi PR in Mali are mined and used for

soil P replenishment and crop production in the three countries. The effectiveness of PR depends on its chemical and mineral composition, soil and climatic factors, and the crops to be grown. The solubility of the three PRs in neutral Ammonium Citrate is 6.1%, 8.3%, and 10.4% for Kodjari, Tahoua, and Tilemsi, respectively. While evaluating Parc-W and Tahoua PR indigenous to Niger using field experiments, Parc-W was 48% as effective as Single Super Phosphate (SSP), whereas the effectiveness of the more reactive Tahoua rock was as high as 76% compared to that of SSP for pearl millet production (Bationo et al. 1990). In an on-station experiment in Burkina Faso, the relative effectiveness of Kodjari was found to be 68% and 39% for millet and sorghum, respectively, whereas in an on-farm experiment, the values were 54% and 50% (Lompo et al. 2018). A phosphate rock decision support system (PRDSS) has been developed by IFDC to quantify the effectiveness of various PR sources for direct application as influenced by the abovementioned factors.

The agricultural sector in Mali involves 80% of the population. However, less than 10% of the 2.7 m ha of cultivated land receives fertilizers. The 70,000 tonnes of fertilizer imported per year is applied on cash crops such as cotton, rice, and groundnuts. This amount is less than 15% of the nutrients exported by the crops. The Tilemsi reserves of PR are estimated to be 20 m tonnes, and the production in 1991 used 18,560 tonnes of PR. For many years, Tilemsi PR was evaluated in different agroecological zones in Mali. Henao and Baanante (1999a, 1999b) made a comprehensive analysis of the results, including an economic evaluation, and concluded that Tilemsi PR is practically equivalent to TSP per unit of P_2O_5 .

Various ways are used to improve the agronomic effectiveness of phosphates to make the products more economically attractive. The biological means include (1) phosphocomposts, (2) inoculation of seedlings with endomycorrhizae, (3) use of phosphate-solubilizing microorganisms, and (4) use of plant genotypes. Chemical means include the partial acidulation of PR. Physical means include (1) compacted PR with water-soluble phosphate products, (2) dry mixtures of PR with water-soluble phosphate fertilizers and phosphate rock elemental sulfur assemblages. In Burkina Faso, Niger, and Mali, partial acidulation of phosphate rock (PAPR) have been tested quite extensively, but very little work has been done on other ways to improve the effectiveness of PR. PAPRs are prepared by reacting PRs, usually with H_2SO_4 , in amounts less than that needed to make SSP or TSP. PARs may offer an economic means of enhancing the agronomic effectiveness of indigenous PR sources that may otherwise be unsuitable for direct application. In Burkina Faso, Lompo et al. (1994) found that the agronomic effectiveness of Kodjari PR improved from 68% to 88% for pearl millet and from 39% to 81% for sorghum when partially acidulated. In Niger, the partial acidulation of PARC-W PR increased its agronomic effectiveness from 48% to 80% for pearl millet production (Bationo et al. 1990). Recent IFDC studies have shown relatively low reactive PRs when compacted with 20% P from DAP or MAP on a wide range of soils (pH 5.0–7.9) and were 75%–100% as effective as water-soluble P.

4.4.5 STRATEGIC APPLICATION OF FERTILIZER: THE MICRODOSE TECHNOLOGY

The strategic application of fertilizers, commonly called microdose technology, was developed for the Sahelian countries as an effective technique to increase fertilizer use efficiency and reduce investment costs for resource-poor small-scale farmers, thereby increasing crop growth and productivity (Bationo et al. 1998b; Buerkert and Hiernaux 1998). This strategic application of fertilizer is based on applying small doses of fertilizer in the hill of the target crop at planting rather than broadcasting it all over the field. The microdosing technology is affordable to the poor because of the reduced investment cost, and it gives a quick start, thus avoiding early season drought, and an earlier finish, avoiding end-of season drought while increasing crop yields (Tabo et al. 2006, 2007).

More recently, Vandamme et al. (2018) found microdosing of 3 kg P ha⁻¹ in the planting hole or beneath the dry-seeded drilled rice to consistently increase early vigor and almost tripled grain yield to 3 t ha⁻¹ compared to broadcast of 6 kg P ha⁻¹. A similar yield increase was obtained with microdosing of NPK compared to basal NPK application.

For many years, the microdose technology has been tested, and many countries are adopting this technology. [Table 4.10](#) reports the most recent results of scientists from INERA achieved by

TABLE 4.10
Productivity of the Microdose Technology as Compared with the Actual Recommendation (Taonda, Unpublished Data)

Crop	Nutrient Applied with Present Recommendation (kg/ha)	Nutrient Applied with the Microdose (kg/ha)	Grain Yield in Farmers Field without Fertilizer (kg/ha)	Grain Yield with Present Recommendation (kg/ha)	Grain Yield with Microdose (kg/ha)	NUE for Microdose (kg/kg)	NUE for Present Recommendation (kg/kg)	Yield Increase over the Control (%)
Maize	110N, 69 P ₂ O ₅ , 42 K ₂ O	41N, 29P ₂ O ₅ , 17 K ₂ O	1,600	2,500	3,200	18	4	100
	Total = 221	Total = 87						
	40N, 23 P ₂ O ₅ , 14 K ₂ O	8.7N, 14 P ₂ O ₅ , 8.7 K ₂ O	620	1,700	900	35	4	174
Sorghum	Total = 77	Total = 31						
	40N, 23 P ₂ O ₅ , 14 K ₂ O	8.7N, 14 P ₂ O ₅ , 8.7 K ₂ O	600	1,200	650	19	3	100
	Total = 77	Total = 31						
Cowpea	14N, 23 P ₂ O ₅ , 14 K ₂ O	8.7N, 14 P ₂ O ₅ , 8.7 K ₂ O	600	1,200	850	19	4	100
	Total = 51	Total = 31						
	14N, 23 P ₂ O ₅ , 14 K ₂ O	8.7N, 14 P ₂ O ₅ , 8.7 K ₂ O	650	1,200	1,200	18	11	85
Groundnut	Total = 51	Total = 31						

the microdose technology in Burkina Faso compared to the recommendation by the extension services. Whereas the mode of application of the recommended rate by the extension is broadcasting, the microdose technology consisted in applying the reduced rate of fertilizer in the hill of the crop.

The following conclusions can be made from [Table 4.9](#):

1. The rate of the fertilizer applied with the microdose technology is reduced by more than half with the microdose technology. For example, for maize, while a total of 221 kg ha⁻¹ is used as per the present rate recommended by the extension services, the microdose technology will apply only 87 kg ha⁻¹ of nutrient.
2. In most of the cases, the strategic application of nutrient with the microdose resulted in higher grain yield as compared with the broadcasting of larger rates of nutrients. As an example, for pearl millet the microdose used resulted in a grain yield production of 1,700 kg ha⁻¹ as compared to 900 kg ha⁻¹ with the broadcasting method.
3. The yield increase over the control due to the microdose ranged from 85% to 174%. Most farmers can double their production with the adoption of the microdose technology.

4.4.6 CROP RESIDUE AND MANURE MANAGEMENT

Crop residue (CR) management can play an important role in improving crop productivity in SSA. Numerous research reports show large crop yield increases as a consequence of organic amendments in the Sahelian zone of West Africa (Abdullahi and Lombin 1978; Pieri 1986, 1989; Bationo et al. 1993, 1998a; Evéquoq et al. 1998). Bationo et al. (1995, 2007b) reported from an experiment carried out in 1985 on a sandy soil at Sadoré, Niger, that grain yield of pearl millet (*Pennisetum glaucum* L.) after a number of years had declined to only 160 kg ha⁻¹ in unmulched and unfertilized control plots. However, grain yields could be increased to 770 kg ha⁻¹ with a mulch application of 2 tons CR ha⁻¹ and to 1,030 kg ha⁻¹ with 13 kg P as SSP plus 30 kg N ha⁻¹. The combination of CR and mineral fertilizers resulted in a grain yield of 1,940 kg ha⁻¹.

In different parts of SSA, crop or organic residues applications have been shown to increase soil P availability (Kretschmar et al. 1991), enhance PR availability (Sahrawat et al. 2001), cause better root growth (Hafner et al. 1993), improve potassium (K) nutrition (Rebafka et al. 1994), protect young seedlings against soil coverage during sand storms (Michels et al. 1995), increase water availability (Buerkert et al. 2000), and reduce soil surface resistance by 65% (Buerkert and Stern 1995) and topsoil temperature by over 4°C (Buerkert et al. 2000). These effects are especially stronger in the Sahelian zone, but weaker in other areas with lower temperatures, higher rainfall, and heavier soils (Buerkert et al. 2000). From incubation studies under controlled conditions, Kretschmar et al. (1991) concluded that increases in P availability after crop residue (CR) application were due to a complexation of iron and aluminum by organic acids. The organic amendments have also been reported to reduce the capacity of the soil to fix P, thereby increasing P availability for uptake and hence higher P use efficiency (Buresh et al. 1997; Sahrawat et al. 2001). Availability of organic inputs in sufficient quantities and quality is one of the main challenges facing farmers and researchers today.

Manure, another farm-available soil amendment, is an important organic input in African agroecosystems. One of the earliest reported manure application studies in SSA was by Hartley (1937) in the Nigerian Savannah. He observed that application of 2 t ha⁻¹ FYM increased seed cotton yield by 100%, equivalent to fertilizers applied at the rate of 60 kg N and 20 kg P ha⁻¹. Palm (1995) has concluded that for a modest yield of 2 t ha⁻¹ of maize the application of 5 t ha⁻¹ of high-quality manure can meet the N requirement, but that this cannot meet the P requirements in areas where P is deficient. Bationo and Mokwunye (1991) found no difference between applying 5 t ha⁻¹ of FYM as compared to the application of 8.7 kg P ha⁻¹ as Single Superphosphate, pointing to the role of manure to availability of P through complexation of iron and aluminum (Kretschmar et al. 1991).

Other reports have shown that crop yields from the nutrient-poor West African soils can be substantially enhanced through the use of manure (McIntire et al. 1992; Sedogo 1993; Bationo and Buerkert 2001).

Several scientists have addressed the availability of manure for sustainable crop production. De Leeuw et al. (1995) reported that with the present livestock systems in West Africa the potential annual transfer of nutrients from manure is 2.5 kg N and 0.6 kg P per hectare of cropland. Although the manure rates are between 5 and 20 t ha⁻¹ in most of the on-station experiments, quantities used by farmers are very low and ranged from 1,300 to 3,800 kg ha⁻¹ (Williams et al. 1995). This is due to insufficient number of animals to provide the manure needed, and the problem becomes more pronounced in post-drought years (Williams et al. 1995). The amount of livestock feed and land resources available are also limited. Depending on rangeland productivity, it will require between 10 and 40 hectares of dry-season grazing land and 3–10 hectares of rangeland of wet-season grazing to maintain yields on one hectare of cropland using animal manure (Fernandez et al. 1995).

4.4.7 MANAGING OTHER NUTRIENTS SUCH AS SECONDARY NUTRIENTS AND MICRONUTRIENTS

IFDC investigated whether secondary nutrients (calcium, magnesium, and sulfur) and micronutrients (zinc, boron, copper, manganese, iron, chlorine, molybdenum, nickel, and cobalt) could be limiting crop response to NPK fertilizers. Field work has been conducted in Burundi, Rwanda, Uganda, Ethiopia, Kenya, Zambia, and Mozambique to develop a “next generation” of balanced fertilizers. Over 3,000 georeferenced soil samples taken in Rwanda, Burundi, and parts of Uganda and Zambia were analyzed to map the extent of nutrient deficiencies and soil acidity constraints. These nutrient maps show large areas of S, Zn, B, and Cu deficiencies, as well as considerable regions of Ca and Mg deficiencies and soil acidity constraints. Based on this information, “best-bet” formulae were developed. Results from IFDC trials in several countries show consistently large significant yield increases on several crops due to secondary and micronutrient (SMN) additions. Yield increase over NPK fertilizers due to the addition of SMN range from 1 to 2 t ha⁻¹ for cereal crops, 0.5 to 1.0 t ha⁻¹ for legumes, and 5 to 10 t ha⁻¹ for roots and tubers. Sometimes, yield increases due to SMNs equal yield increases due to NPK fertilizers alone (Figure 4.11). As SMNs cost less than NPKs, this represents an increased return on fertilizer investment.

With large increases in crop productivity due to the addition of SMNs, the use of fertilizers is more profitable and therefore more attractive to farmers. Fertilizer manufacturers and blenders are also keen to provide farmers with more profitable products. The data in Figure 4.4 clearly indicate that the addition of secondary and micronutrients will result in higher productivity.

In addition to increasing yield, the nutritional quality of food items is likely to simultaneously increase, with the aim to contribute to human nutrition and fight hidden hunger. The potential of “agronomic fortification,” that is, the application of mineral SMN-containing NPK fertilizers to soils and/or plants’ leaves, is to increase the nutrient content of edible plant parts.

Supplementation by S, Zn, B, and K have frequently been reported to increase cereal yields by 40% or more over the standard N-P recommendation alone (Wendt et al. 1994; Wendt and Rijpma 1997; Kihara and Njoroge 2013; Kihara et al. 2017).

4.4.8 WATER AND NUTRIENT USE EFFICIENCY

Variability of rainfall is a critical factor in efficiency of fertilizers and in determining risk-aversion strategies of farmers in Africa. The variability in cultivated acreage and yield for various staple cereals is significantly related to rainfall variability.¹ Acreage and yield differences between years can reach up to 50%, and total cereal production may vary over 25% and has not declined during

¹ Based on unpublished data from the FAO, obtained by the author in 2019.

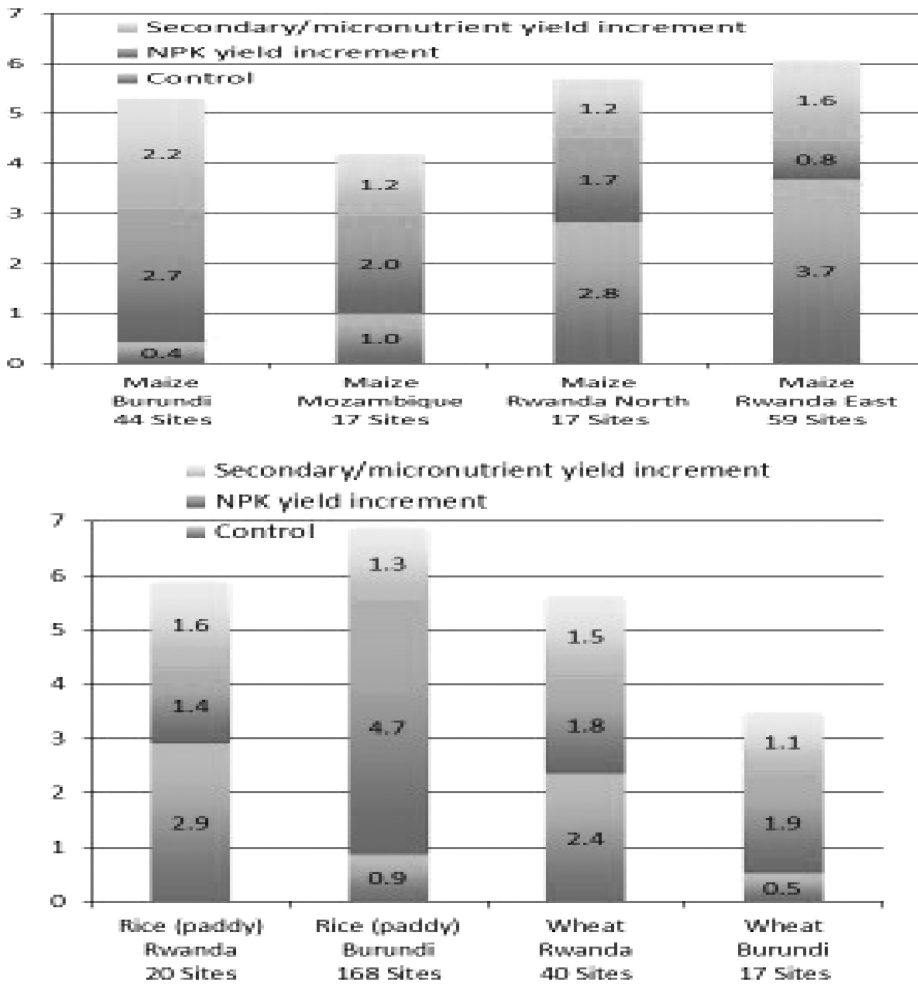


FIGURE 4.11 Impacts of secondary and micronutrients relative to NPK for maize rice and wheat in selected SSA countries (Wendt, unpublished data).

the past decades, jeopardizing food security. The tendency of African rainfall to be both spatially and temporally concentrated has important implications for fertilizer use. A survey of available data found Africa levels of available water from rainfall at 12.7 cm year⁻¹ compared to North America at 25.8, South America at 64.8, and the world average at 24.9 (Brady 1990). Fertilizer is commonly thought to increase risk in dryland farming, but in some situations it may be risk neutral or even risk reducing. Phosphorus and shorter-duration millet varieties in Niger, for example, cause crops to grow hardier and mature earlier, reducing damage from and exposure to drought (ICRISAT 1985–88; Shapiro and Sanders 1998). A key constraint, though, is the availability of fertilizer and the incentive for adopting fertility-enhancing crop rotations in these zones (Thomas et al. 2004).

In the dry land of the Sahel, several scientists have reported that where the rainfall is more than 300 mm, the most limiting factor to crop production is nutrient and not water. Quantification of the attainable yields under rainfed conditions with and without fertilization using crop growth simulation models (Bindraban et al. 2000) with actual yield levels reveal great potential for productivity increase (Conijn et al. 2011) through fertilization, presuming effective water harvesting (Figure 4.12).

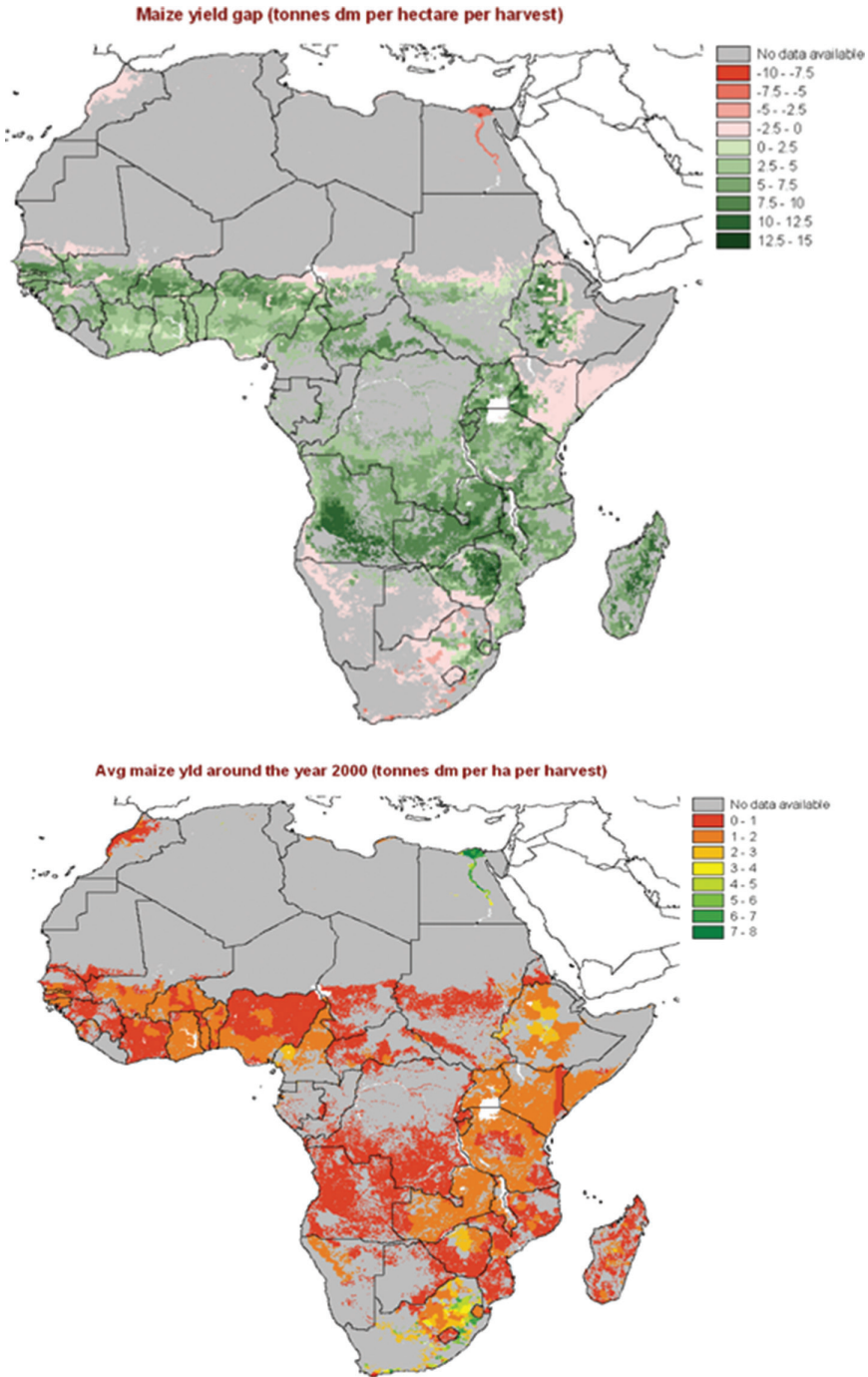


FIGURE 4.12 Average maize yield (left) around the year 2000 in tonnes dry matter per hectare harvest (Monfreda et al. 2008) and calculated yield gap with maize yield potentials under rainfed and fertilized conditions (right). (From Conijn, J.G., et al., *Agricultural Resource Scarcity and Distribution: A Case Study of Crop Production in Africa*, Plant Research International, Wageningen, the Netherlands, 2011.)

TABLE 4.11
Water Use (WU), Grain Yield (Y) and Water Use Efficiency (WUE) for Millet at Sadore and Dasso (Niger)

Treatment	Sadore			Dosso		
	WU (mm)	Y (kg ha ⁻¹)	WUE	WU (mm)	Y (kg ha ⁻¹)	WUE
Fertilizer	382	1570	4.14	400	1700	4.25
Without fertilizer	373	460	1.24	381	780	2.04

These principles have been substantiated by numerous fields studies. At Sadore, where the annual average rainfall is 560 mm, the nonuse of fertilizers resulted in a harvest of 1.24 kg of pearl millet grain per mm of water, but the use of fertilizers resulted in the harvest of 4.14 kg of millet grain per mm of water (Table 4.11).

Many development projects have invested billions of dollars in soil and water conservation. These projects mostly did not include soil fertility improvement, and the water harvested in this manner did not fulfill its full potential for productivity improvement. It is well known that fertilizers are a key to improved water use efficiency, as water harvesting can also improve fertilizer use efficiency. The Zai system is widely used in West Africa for water harvesting and soil conservation. The data in Table 4.6 indicates that the use of Zai alone will not significantly improve the productivity (only 200 kg ha⁻¹ of sorghum grain), but when the Zai is associated with manure and fertilizer, large crop yield increases can be obtained (1,700 kg ha⁻¹ of sorghum grain) (Table 4.12).

The mineral fertilizer microdosing (MD) technique was disseminated in the North Sudanian zone of Burkina Faso for three years using various extension tools. This study aims to analyze the economic efficiency as well as farmers' perception of the use of MD technique. Quantitative and qualitative data were collected from 60 demonstration plots conducted by innovative farmers and from 300 households using an interview guide during the focus groups. The results of the demonstration trials show that this innovation significantly increases sorghum productivity compared to farmer's practice. It even triples sorghum yields when combined with soil and water conservation (SWC) techniques and the use of improved seed varieties. The efficiency of mineral fertilizers by microdose in association with SWC techniques was assessed through the evaluation of yields and incomes from the different treatments on the demonstration plots.

Microdose fertilization resulted in significant increases in sorghum grain yields of 100% and 186% with the local seed variety and the improved seed variety, respectively, compared to the

TABLE 4.12
Effect of "Zai" on Sorghum Yields

Technology	Sorghum Yield (kg ha ⁻¹)	Yield Increase (%)
Only planting pits (Zai)	200	–
Zai + Cattle manure	700	250
Zai + Mineral fertilizers	1400	600
Zai + Cattle manure and fertilizers	1700	750

Source: Reij, C., et al., *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa*, Earthscan, London, 1996.

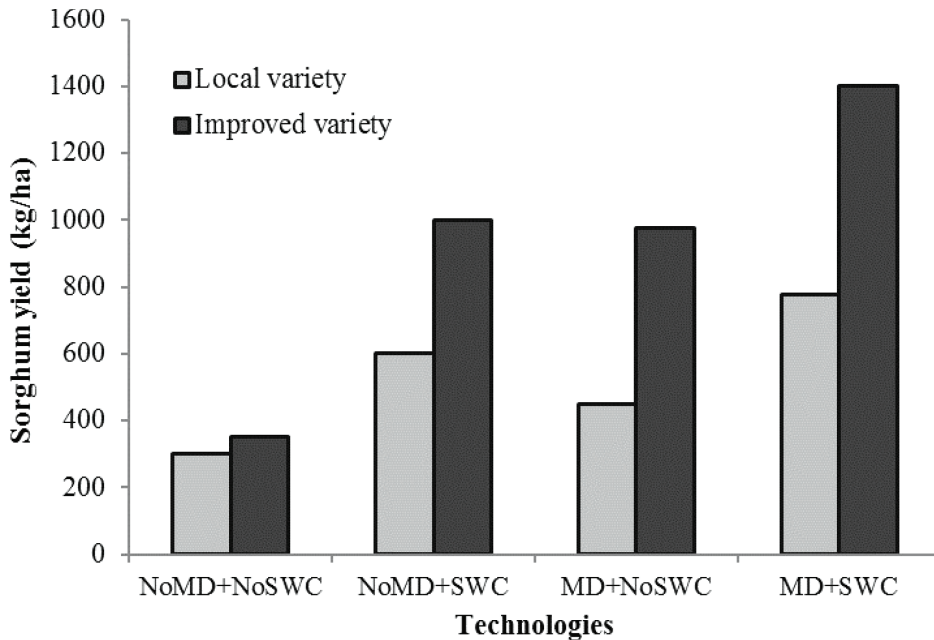


FIGURE 4.13 Response of sorghum to MD combined with SWC techniques. NoMD + NoSWC = without Microdose and without SWC techniques; NoMD+SWC = without Microdose with SWC techniques; MD+NoSWC = Microdose without SWC techniques; MD+SWC = Microdose with SWC techniques. (Source: Ouattara, B. et al., Improving agronomic efficiency of mineral fertilizers through microdose on sorghum in the sub-arid zone of Burkina Faso, in Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., and Fening, J.O. (Eds.), Volume 1, *Improving the Profitability, Sustainability and Efficiency of Nutrients through Site Specific Fertilizer Recommendations in West Africa Agro-Ecosystems*, Springer, the Netherlands, 2018.)

control (Figure 4.13). Its effects are even greater when combined with SWC techniques. This combined use of techniques on the local and improved varieties yielded increases of 158% and 300%, respectively, compared to the absolute control. The yields obtained with the SWC techniques alone were higher than those of the control, but lower compared to those with the microdose alone.

4.4.9 LESSONS LEARNED FROM LONG-TERM EXPERIMENTS

Long-term experiments (LTEs) offer the best practical means of studying the effects of management or global change on soil fertility, sustainability of yield, or wider environmental issues. LTEs are used for biophysical aspects of sustainability, the impact of agriculture on environments, the impact of environment on agriculture, and the development and testing of crop models.

Most trials were designed to determine the effects of inorganic fertilizers and organic inputs on crop yields and soil properties, including other parameters such as rotations of cereal with legumes.

LTEs serve as living laboratories, providing opportunities for experimentation in which the effects of manipulation may be separated from other variables. This is clearly essential in understanding processes of soil fertility change.

The data from Figure 4.14 of the LTEs established since 1960 in Burkina Faso clearly show that the application of mineral fertilizers alone will result in crop yield decline, but when mineral fertilizers are combined with manure, sustainable higher yields can be obtained.

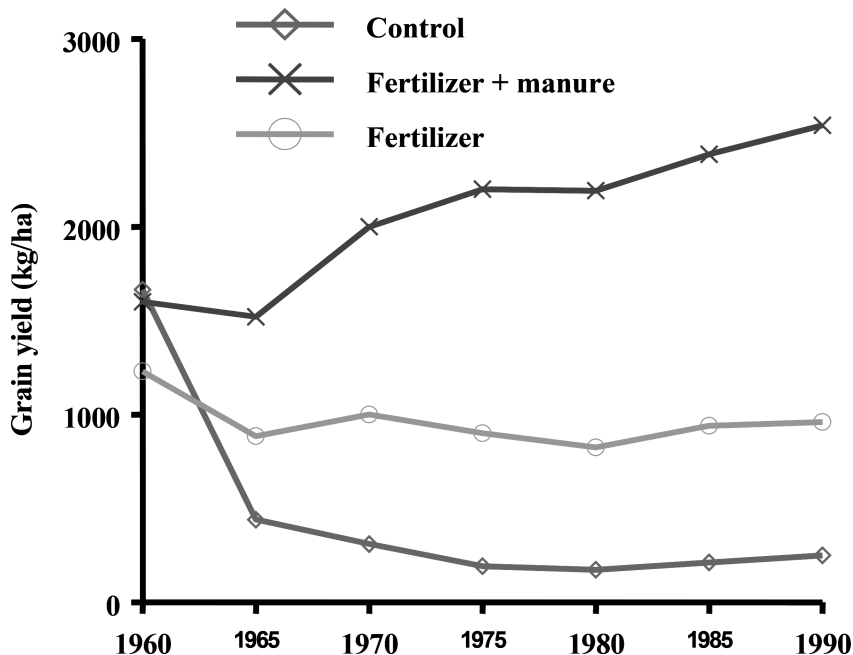


FIGURE 4.14 Sorghum grain yield as affected by mineral and organic fertilizers over time. (Source: Bationo, A. et al., Integrated nutrient management – Concepts and experience from sub-Saharan Africa, in Aulakh, M.S., and Grant, C.A. (Eds.), *Integrated Nutrient Management for Sustainable Crop Production*, CRC Press, New York, 2007a.)

4.5 THE WAY FORWARD

Improving efficiency of fertilizers will remain the center of future research, with the focus on all the different steps, as shown in Figure 4.4. Tailoring fertilizer use for mitigation and adaptation to climate change, the use of crop models, the new SMART approach developed by IFDC, and the use of balanced fertilizers to improve both food and nutritional security are proposed here as the new areas for future research focus in SSA.

4.5.1 TAILORING FERTILIZER USE FOR MITIGATION AND ADAPTATION TO CLIMATE CHANGE

There is a need for more research on the role of fertilizers on climate-smart agriculture. Tilling soils or cutting forests is well known to result in lower SOM levels and thus increase the release of CO₂ into the atmosphere. Crop intensification with the use of fertilizer will allow farmers to use less land for food production and therefore prevent carbon dioxide emission in the atmosphere.

Numerous studies suggest that managing SOM can have a profound impact on the amount of N and C released into the atmosphere, and therefore climate change. Paustian et al. (1998) estimated that atmospheric CO₂ can be reduced by 20 to 30 Pg C over the next 50 to 100 years by better SOM management. Fertilizers maintain yield and increase biomass that can be incorporated into the soil. Incorporated rates of 1–6 tons of biomass per hectare can gradually increase SOM, sequestering 200–1,000 kilograms of carbon per hectare per year.

4.5.2 THE ROLE OF CROP MODELS

Soils and climate are highly variable in Africa, calling for use crop models. Crop models offer the benefit of increasing our understanding of crop responses to management in different soil and

climatic conditions. Such responses are often of a complex and nonlinear nature, given the innumerable interactions among weather, soil, crop, and management factors throughout the growing season. Crop models can also provide insights as to what might happen to productivity under various climate change scenarios, a domain beyond the reach of field experimentation. The outputs can inform key decision makers at local, national, and regional levels in order to put the appropriate measures in place. Although major advances in modeling have been made in the US, Europe, and Asia, SSA lags behind due to the limited number of soil scientists and agronomists with the skills to set up and run crop model simulations. Having a well-trained cadre of African modelers would greatly facilitate the design of best crop management and adaptation measures in the varied environments and boost agricultural productivity in the region. Based on validation trials and simulation experiment outputs, Dzotsi and colleagues (2003) developed leaflets to help farmers in southern Togo choose between varieties as a function of preferred time of sowing and expected yield range. The use of models in decision support is important as field experiments provide empirical data on responses to only a small number of possible combinations of climate, soil, and management situations. Also, existing management systems from other regions, new crops and varieties, and other technologies being developed by scientists may provide useful adaptation options. However, it is impossible to conduct experiments that cover the full range of possible management options and climate conditions to determine production systems that are more resilient to climate variability, potential changes in climate, and farmers' goals. Nix (1984) criticized the predominance of a "trial and error" approach in agricultural research for evaluating management practices. He emphasized the need for a systems approach in which: (1) experiments are conducted over a range of environments, (2) a minimum set of data is collected in each experiment, (3) cropping system models are developed and evaluated, and (4) models are used to simulate production technologies under different weather and soil conditions so as to provide a broad range of potential solutions for farmers. Nix (1984) referred to the high cost of field experiments in addition to their limited extrapolation domain because results are site specific. Yet it should be realized that models are a simplification of the real conditions, unable to simulate a large number of relevant agrotechnical interventions for the African continent. The temporal dimension of crop sequences or interactions in intercropping on water, nutrients, and weed and disease infestation are poorly understood and not or only poorly captured in models. Models accounting for nutrients are limited to N and P, with the exception of K for limited crops (Singh et al. 2007). Descriptive approach models such as QUEFTS (Janssen et al. 1990) and optimizing fertilizer recommendations in Africa (OFRA) (Wortmann and Sones 2017) capture N, P, and K responses and interactions. OFRA fertilizer optimization tools develop and fine-tune fertilizer recommendations within an integrated soil fertility management framework. While SOM dynamics is simulated by DSSAT (Hoogenboom et al. 2017) and APSIM (Keating et al. 2003) models, a better understanding of organic matter dynamics under tropical conditions with very low organic matter content is needed to improve the capability of existing simulation models. Likewise, current models do not simulate micronutrient response. Despite these limitations, crop model use improvements should be encouraged in SSA to help reinforce the existing yield gaps as well as highlight knowledge gaps. Ongoing projects such as AgMIP² are including researchers and policymakers from SSA and other developing regions to promote the use of crop models and model improvements relevant to the developing world.

4.5.3 THE NEED TO UPSCALE IFDC'S NEW APPROACH TO DEVELOP, MANUFACTURE, AND DELIVER BALANCED FERTILIZERS TO FARMERS: THE SMART APPROACH

SMaRT is an acronym for Soil analysis, Mapping, Recommendations development, and Technology Transfer (Wendt and Muthubia, 2017). The concept behind SMaRT is to get better fertilizers to farmers for a given crop and region that substantially and sustainably outperform fertilizers currently

² <http://www.agmip.org/>.

used by farmers. Sustainability is addressed by using “balanced” fertilizers, which have a balance of macro, secondary, and micronutrients that address predominant nutrient deficiencies. Lime Recommendations may be part of a SMaRT recommendation when lime is required.

This approach involves:

1. **Soil sampling.** Assess the extent of nutrient and soil acidity constraints through large-scale country-wide georeferenced soil sampling, followed by chemical soil analysis by certified laboratories.
2. **Soil mapping** of nutrient deficiencies at country level. Maps of all soil nutrients create national recognition of the extent of nutrient deficiencies and soil acidity constraints. Nutrient maps generate the momentum to move away from traditional NPK fertilizers. Soil nutrient maps will guide the research community as to which constraints are most likely, and where they exist. This is the first step toward creating and validating balanced fertilizer formulations. Soil maps are a public good that guides fertilizer policy and assists the fertilizer industry to meet anticipated demand.
3. **Recommendations.** Based on soil maps, “best-bet” crop and soil-specific fertilizers are developed and tested. Best-bet formulations form the basis for evaluating yield gains and economic returns versus current formulations available to farmers, a prerequisite to investing in improved formulations. Further trials (“nutrient omission trials”) are conducted to evaluate the yield and economic contribution of each nutrient in the fertilizer formulation, allowing for fine-tuning of formulations. Farmers’ awareness is created through large numbers (thousands) of farmer-led demonstrations.
4. **Technology Transfer.** Recommendations alone will not deliver technology to farmers, because many private-sector operatives are in the fertilizer value chain and are collectively seen as the “go-to people” for all aspects of fertilizer knowledge, from marketing to technical support.

4.5.4 MULTIPLE FUNCTIONS FROM INNOVATIVE FERTILIZER PRODUCTS AND SECTOR TRANSFORMATION

In addition to increasing yield and resource efficiency, balanced mineral fertilizers can contribute to increasing the nutritional value of crop produce to improve human nutrition and health. They can also improve plant health to reduce biocide use, stimulate plant robustness to enhance tolerance to abiotic stresses, and increase metabolite production to improve taste and shelf life. We refrain from further elaborating these latter benefits that contribute to enhancing the resilience of production systems as they have been described by Bindraban et al. (2018).

The potential contribution of micronutrient-containing fertilizers has yet to be exploited, but initial evidence for some elements, including Zn and Se, are very promising. Micronutrient deficiencies, or “hidden hunger,” affect the lives of approximately 2 billion people around the world. In developing countries, more than 10 million children under the age of five die each year; 60% of these deaths are related to malnutrition. About 1.6 billion people are anemic due to iron deficiency, vitamin A deficiency results in the death of around 1 million children each year, iodine deficiency during pregnancy contributes to the mental impairment of nearly 20 million babies annually, and deficiency in zinc is responsible for about 800,000 deaths annually from diarrhea, pneumonia, and malaria in children under five. Agriculture can play an important role in combating hidden hunger and its consequences.

Traditionally, fertilizers have been used to maintain or restore soil fertility, increase crop yield, and, to a lesser extent, improve crop quality. Their management has been progressively improved to optimize their economic return, while minimizing negative impacts on the environment. More recently, there has been increasing attention to another dimension: managing fertilizers such that they also contribute to healthy and productive lives for all. While fertilizer has been

highly influential in increasing the quantity of food produced, it also holds enormous potential for improving human welfare by improving the quality of food. To eradicate the multifaceted aspects of human suffering, the future food (chain) challenge will be to continue increasing available food quantities at affordable prices, while simultaneously enhancing food quality to address hidden hunger as well.

IFDC proposes to exploit the potentials of “agronomic fortification,” that is, the application of mineral SMN-containing NPK fertilizers to soils and/or plant leaves to increase nutrient contents of edible plant parts. Apart from the nutrient composition, the mode and timing of application also determines in which organ nutrients will accumulate. Based on organ-specific biological needs, foliar application could be suggested for Fe, Cu, Mn, and Zn; root application for Mo and Ni; while B, Cl, Cu, and Zn could be provided through both foliar and soil (Dimkpa and Bindraban 2016).

Protein deficiency in foodstuffs result from a lack of N, and S needed for essential amino acids like methionine and cysteine. Protein content can be increased by postanthesis nitrogen application (Worland et al. 2017). The expression of the genetic potential of biofortified crops could be maximized with adequate availability of micronutrients in the soil or from SMN fertilization (Cakmak 2008). Mandated blending of Se in fertilizers by the Finnish government increased Se levels of 125 indigenous food items including wheat, meat, and dairy products, raising the human intake of Se to sufficient intake levels (Eurola et al. 1991).

Awareness among policymakers, NGOs, and the general public about the multiple goals that fertilizers can deliver could catalyze a process of transformation of the fertilizer sector through public–private initiatives in order to unlock these potentials (Bindraban et al. 2018). More effective and efficient fertilizers that increase the economic volume in the fertilizer value chain may support the last mile delivery of smart balanced fertilizers. Appropriate site-specific fertilizers with a limited spatial reach and consequently small volumes only, and containing multiple macro- and micronutrients, call for adoption of novel business models by the fertilizer industry. The adoption of fertilizers by farmers, even when fully meeting site-specific and farmers’ demand, will have to be accompanied by well-orchestrated actions by fertilizer value chain actors that provide affordable inputs and credits and reliable markets to farmers. Government incentives are imperative to support the creations of these enabling conditions, as are the efforts of knowledgeable development organizations, such as the IFDC, for training and educating chain actors in good agricultural practices and agribusiness.

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