growing AFRICA

Volume Two • Issue One - 2023

IMPACTS OF THE GLOBAL FERTILIZER CRISIS

SOIL HEALTH CHALLENGES

BUILDING RESEARCH, DEVELOPMENT AND EXTENSION CAPACITY

MORE INSIDE!

SPECIAL ISSUE

A FOCUS ON THE UPCOMING AFRICAN UNION SUMMIT ON FERTILIZER & SOIL HEALTH

Developing Africa's 10-Year Action Plan

African Union

ACTIONABLE SCIENTIFIC INFORMATION ON PLANT NUTRITION

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CONTENTS

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Inside this Issue

A new concerted focus on the issues surrounding soil health in Africa is about to take center stage. Later this year, the African Union will be holding its highly anticipated Summit on Fertilizer and Soil Health (AFSH), which "*seeks to build a more dynamic African fertilizer market that addresses the primary soil health constraints on the continent… to bring together high-level stakeholders to reach an agreement on a 10-year action plan for sustainable productivity growth in African agriculture*." This forum holds much promise as a new inflection moment of redirection that will be well informed by the impacts felt, and vulnerabilities identified, from the most recent waves of fertilizer and food supply disruption in Africa.

It is our pleasure to able to dedicate this issue of *Growing Africa* to soil health-related issues for Africa through a series of articles authored by leaders in soil fertility and plant nutrition research for development in Africa. In the months leading up to the Summit, our contributors have been guiding the progress within technical and policy workgroups, pre-conference background publications, as well as the defining 10-year action plan and declaration that will ultimately arise from the Summit.

We acknowledge and appreciate our authors contributions during these busy days. They have provided us with a broad range of topics that crisply illustrate the key considerations, recommendations, and strategies needed to build upon the current momentum that is supporting soil health science in Africa.

Thank you for your continued interest in *Growing Africa*. We continue to strive to provide unique and practical information for those with a direct stake in the use and adaptation of agricultural knowledge for Africa. Please also take a moment to participate in one of the publication's forums. Considering a submission? Review our guide for authors available from our website https://growingafrica.pub, and contact us for more details on how you can participate.

Sincerely yours,

Gavin Sulewski

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Welcoming a New Fertilizer and Soil Health Vision for Africa

Dr. Kaushik Majumdar
Director General | k.majumdar@apni.net

Fertilizer and soil health are crucial enablers that work in tandem to help produce the food and other agricultural commodities we consume. Balanced and adequate application of fertilizer provides the plant nutrients required to produce sufficient crop biomass—the building block of soil organic matter and the most important indicator of soil health. In turn, a soil rich in organic matter provides the right physical, chemical, and biological conditions for efficient and effective utilization of applied fertilizer leading to rich crop harvests of adequate quality, and better economic returns from fertilizer investments.

Low fertilizer application has long been a key constraint restricting food and commodity production in Africa. Inadequate nutrient addition on-farm has failed to fulfil the food and nutritional needs of Africa's expanding population and has not generated enough above- and below-ground biomass to build soil organic carbon. Many years of such practice has stripped African soils of their native fertility and organic matter, seriously undermining soil health. This has led to many other negative outcomes, namely widespread hunger and malnutrition, fewer livelihood opportunities, and loss of biodiversity and other non-provisional ecosystem services that we must remedy.

The soon to be organized Fertilizer and Soil Health Summit under the aegis of the African Union Commission has created a lot of interest and enthusiasm within the Continent. We are eagerly looking forward to the 10-year action plan planked on fertilizer and soil health to fundamentally transform African agriculture.

The endorsement of the 10-year action plan by the African Union Commission countries, however, only marks the point where concerted efforts must begin. The African Union Commission has 55 member states at different development trajectories with diverse aspirations and goals. For the 10-year action plan to successfully produce the desired results, the national goals of the member states must align with this continental vision. The many national and regional public organizations dealing with research for development, policy and financing; NGOs; civil societies; international research and development agencies; and input industries, etc. must synergize their actions by leveraging the key strengths of each other. It will also require a robust and long-term financing mechanism to backstop its implementation. This is a complex task, but it should be achievable when a new continental vision of development is guiding us.

The African Plant Nutrition Institute (APNI) has remained steadfast in our effort to support the African Union Commission in preparation for the Summit. We remain committed to an inclusive effort for implementing the 10-year action plan in alliance with our partners and collaborators spread across the continent. This issue of *Growing Africa* is dedicated towards a successful Summit. ■

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The Impact of the Global Fertilizer Crisis in Africa

By Samuel Njoroge, Esther Mugi-Ngenga, Pauline Chivenge, Hakim Boulal, Shamie Zingore, Kaushik Majumdar

The Covid-19 pandemic and recent geo-political conflict has combined to significantly disrupt the global fertilizer supply chains and cause disproportionate fertilizer price hikes and shortages in Africa. This study assessed the effects of the fertilizer crisis on prices and availability, and the macro- and micro-level responses of stakeholders and farmers in Kenya and Ghana. Fertilizer prices doubled since the onset of the crisis with various interventions implemented at the country, continent, and global levels in response to the crisis, while at the local level farmers adopted a wide range of coping strategies.

Farmers in Eastern Kenya receiving fertilizer and seeds as part of the Covid-19 support program implemented by APNI.

Higher fertilizer use is critical to increase crop productivity and attain food security in Africa. Fertilizer nutrient use in sub-Saharan Africa (SSA) is the lowest globally at less than 20 kg ha^{-1} compared to the global average of 135 kg ha^{-1}. This is largely due to high fertilizer cost, limited production and distribution infrastructure, and low availability, among other factors. For example, fertilizer prices in SSA are at least four times higher than in Europe (Intelligence, 2016), while farmers rarely access fertilizers in an adequate and timely manner due to import and local distribution challenges.

In early 2022, the geo-political crisis in Ukraine worsened global supply chain disruptions initially triggered by the Covid-19 pandemic. Many African countries are dependent on fertilizer imports from Russia, Belarus, and Ukraine. The reduced supply from these regions led to shortages and price hikes, with doubling of fertilizer prices between 2020 and 2022 in many countries like Kenya, Uganda, and Tanzania (Hassan, 2023), further constraining fertilizer use in Africa.

Reduced fertilizer use in SSA has worsened the already poor crop yields and high incidence of food insecurity in the region.

For example, the World Food Program (WFP) estimated that cereal production decreased by 16% (year-on-year) in East Africa during the 2022 cropping year, raising the region's food insecure population by nearly 6-7 million people by the end of 2022 (WFP, 2022). However, severity of the fertilizer crisis and the response of stakeholders and farmers is likely to vary by country and location. To what extent have the prices, availability, accessibility, and use of fertilizer in Africa been affected by the current fertilizer crisis? What were the responses to the fertilizer crisis at the macro-level by various stakeholders? What coping strategies have farmers adopted to mitigate the impact of the fertilizer crisis? These are the questions addressed within this recent impact analysis.

Study description

This study was designed to assess the impact of the fertilizer crisis using primary data collected from Kenya and Ghana and available secondary data across Africa. Primary data on effect and responses to the fertilizer crisis was collected in early 2023 and covers the period from 2019 to 2022. Secondary data on international, and national retail fertilizer prices was accessed from Africa Fertilizer (www.africafertilizer.org) for 2021 and 2022.

Trends in international fertilizer prices

Secondary data on international fertilizer prices for diammonium phosphate (DAP) and urea show steep, short-term increases (**Fig. 1a**). Initially, prices gradually increased from January to September 2021 with minimal price differences observed among similar products from different origins. During this period, DAP prices were, as expected, consistently higher than those for urea. A sharp increase in the price of urea occurred from November to December 2021, with peak prices above 800 USD t^{-1}. At this point, international prices for urea matched those for DAP. High urea prices at the end of 2021 were followed by a sharp decline in early 2022, before another notable increase immediately after the onset of the geopolitical crisis. This was followed by a significant decrease in prices, some relative stability, and a gradual decline towards the tail end of 2022. Urea prices at the end of 2022 were, however, still substantially higher than prices at the start of 2021.

For DAP, prices also increased gradually from January to September 2021, which was followed by a period of relative stability up to February 2022 (**Fig. 1a**). The onset of the crisis then caused a sharp rise in the prices of DAP originating from North Africa and the Middle East, reaching peak prices (>1,100 USD t^{-1}) in April 2022 before their gradual decline. On the contrary, DAP prices from the Black Sea region remained stable at about 850 USD t^{-1} from November 2021 to August 2022, and thereafter declined during the later part of the year. The increased urea prices observed during the same period most likely caused DAP price increases in North Africa, which largely depends on ammonia imports for DAP manufacture. Stable prices for DAP from the black sea region are likely related to the trade restrictions that suppressed demand on fertilizer products from this region following the onset of the geo-political crisis. However, these restrictions likely triggered higher prices for DAP from the other regions due to the reduced total supply.

Trends in local fertilizer retail prices

Monthly urea retail prices in six African countries were used to track changes in national retail prices (**Fig. 1b**). Urea costs at the start of 2021 were substantially different among countries, with the lowest price per ton recorded in Ghana at USD 395, and the highest in Mali at USD 572. Higher prices in landlocked Mali are most likely related to the lack of access to seaports compared to the other countries.

Cost of urea in all countries remained relatively stable until May 2021 when prices in Mali rose sharply, while those in Nigeria and Kenya remained steady until September 2021 (**Fig. 1b**). Prices in Senegal, Ghana, and Ivory Coast showed their initial increases in June, August, and September, respectively. Observed price increases in Ghana and Ivory Coast were in line with international trends, while the cost of urea in Senegal were similar to Nigeria, suggesting differences in urea sources between Ghana and Ivory Coast on one hand, and Senegal on the other.

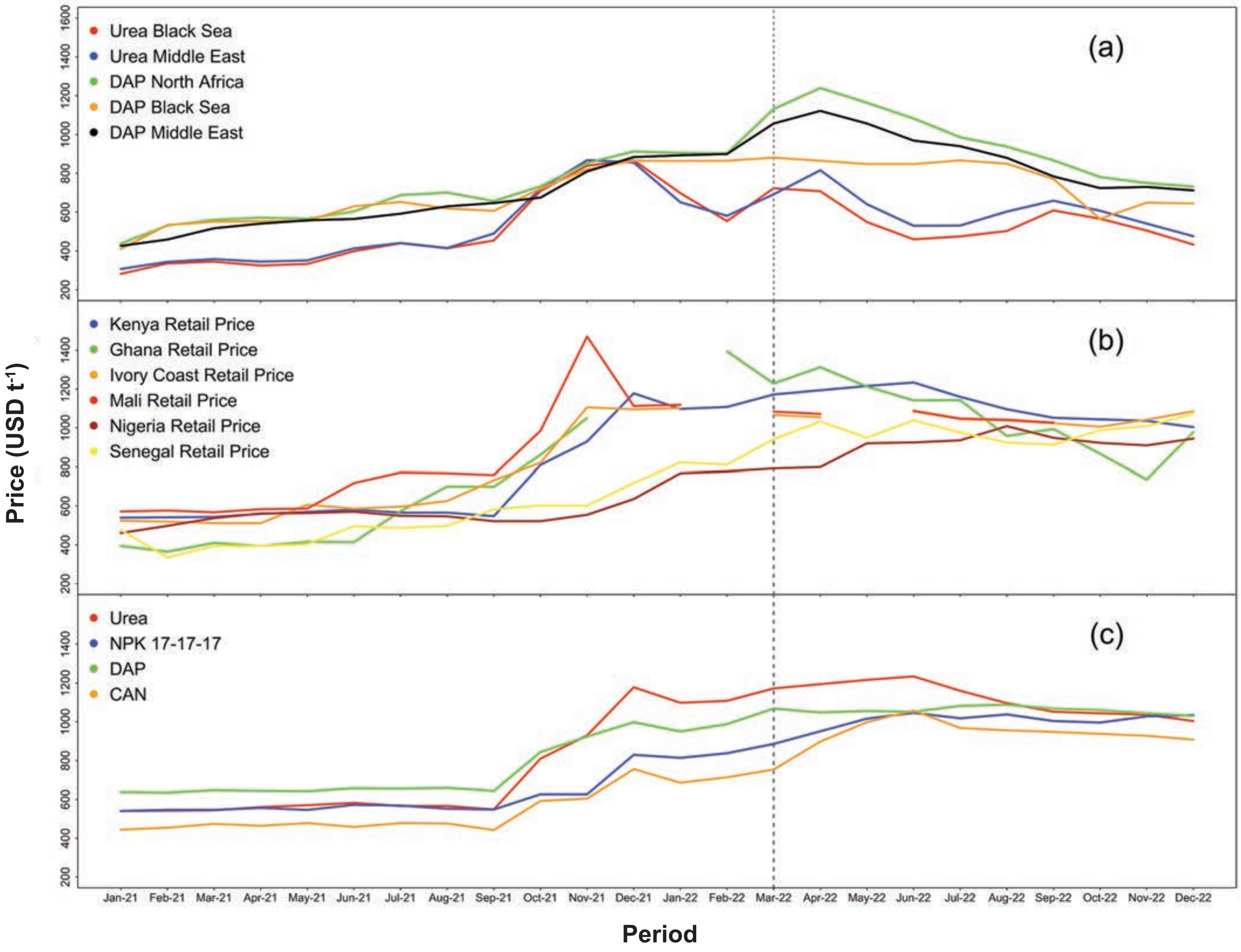

Figure 1. Changes in (a) international market fertilizer prices, (b) selected national retail prices for urea, and (c) retail prices for selected fertilizers in Kenya between January 2021 and December 2022. Broken trend lines indicate missing data. Dotted vertical lines represent the onset of the geo-political crisis. Source (www.africafertilizer.org).

Much like the international trend, urea retail prices increased sharply towards the end of 2021. However, retail prices remained high throughout most of 2022 in contrast to the international trend, indicating a longer time lag in changes in retail prices (**Fig. 1a** and **1b**). Differences in cost of urea between countries were amplified between October 2021 and May 2022, with Ghana, Mali, and Kenya showing markedly higher prices compared to Senegal and Nigeria (**Fig. 1b**). The urea retail prices in Nigeria, and to some extent in Senegal, appeared not to be affected by the international price increase that occurred after November 2021. For Nigeria, this could be linked to the large urea production capacity, illustrating the utility of local production in countering the effects of global price increases.

Monthly retail prices for urea, NPK, DAP, and calcium ammonium nitrate (CAN) in Kenya provide short-interval trends in fertilizer retail prices at the national level between January 2021 and December 2022 (**Fig. 1c**). The cost of all products was stable between January and September 2021 with retail prices ranked as DAP > NPK = Urea > CAN. However, a sharp increase in retail prices was observed from September to December 2021 across all fertilizer types with the highest increase observed for urea, which now had the highest retail price. This period was followed by relative stability from January to June 2022, and by a gradual decline in retail prices towards the end of 2022. However, the cost of all fertilizer products at the end of 2022 was substantially higher than those recorded at the start of 2021. These trends correspond with observations from primary data where cost of

Table 1. Effect of fertilizer crisis on the availability and accessibility of fertilizer.

Reference year	*Availability status in 2022 vs. 2021, 2020 and 2019*			*Accessibility status in 2022 vs. 2021, 2020 and 2019*		
	Decreased (%)	**Remained the same (%)**	**Increased (%)**	**Decreased (%)**	**Remained the same (%)**	**Increased (%)**
Ghana						
2022 vs. 2021	22	78	0	22	78	0
2022 vs. 2020	100	0	0	100	0	0
2022 vs. 2019	100	0	0	100	0	0
Kenya						
2022 vs. 2021	35	49	16	31	52	17
2022 vs. 2020	52	35	13	55	32	13
2022 vs. 2019	55	45	0	59	41	0

fertilizer, on average, doubled between 2019 and 2022 (data not shown). Primary data also showed that higher fertilizer prices were associated with reduced supply of fertilizer, with most farmers reporting that availability and accessibility had decreased in 2022 relative to 2019 (**Table 1**).

Micro-level responses to fertilizer crisis

Primary data revealed that farmers adopted various coping strategies to mitigate the impact of the fertilizer crisis (**Fig. 2**). Strategies common to Kenya and Ghana included use of organic fertilizer sources (9-28%), reduction in fertilized area (7-23%), growing low fertilizer demanding crops (9-18%), omitting fertilizer application (5-14%), and increased crop diversification (5%). In Ghana, the most popular on-farm strategy (23%) was to reduce the area receiving fertilizer; while in

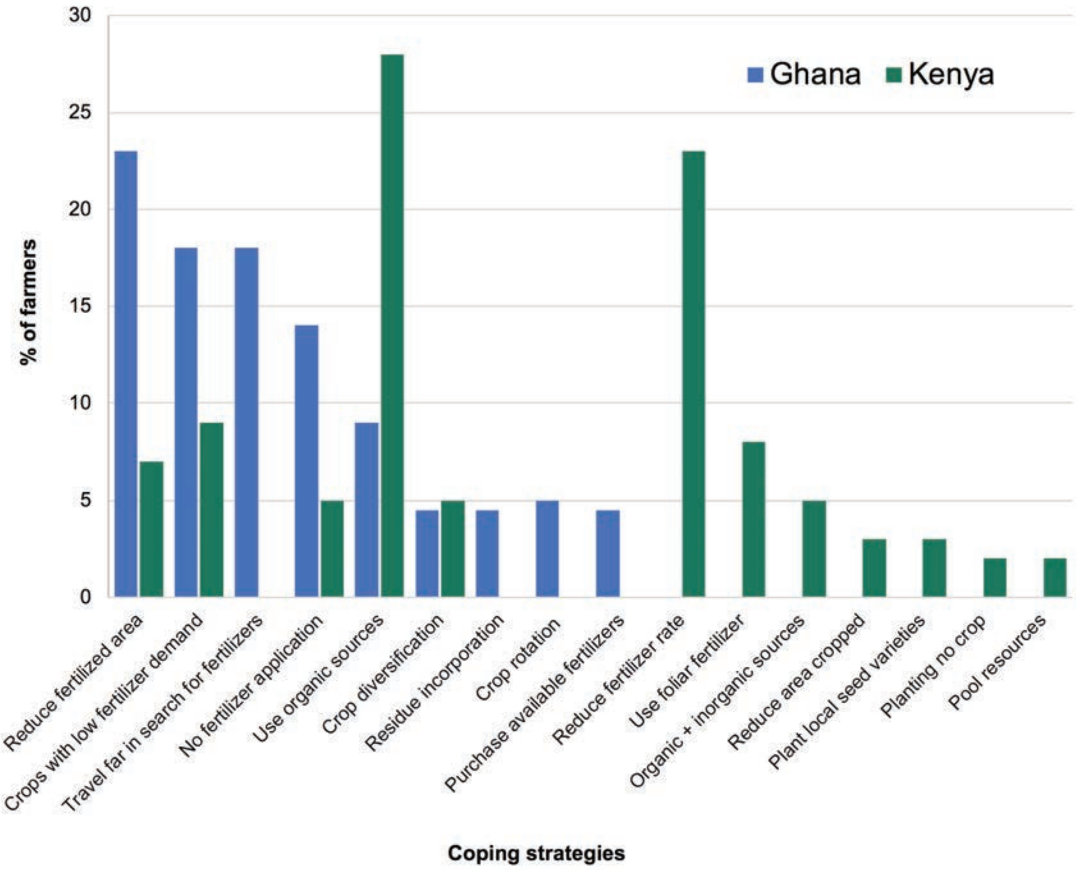

Figure 2. Summary of coping strategies adopted by farmers to mitigate the impact of the fertilizer crisis.

Kenya 28% of farmers increased their reliance on organic nutrient sources.

Macro level responses to fertilizer crisis

At the macro level, governments, the fertilizer industry, and non-governmental organizations (NGOs) used various interventions to support farmers. These included fertilizer subsidies, promoting the use of organic fertilizer, and joint efforts by government and NGOs to supply fertilizer and seed to farmers (**Table 2**). Notably, some fertilizer producers (e.g., Sanergy in Kenya), doubled organic fertilizer production in 2022 with the support of USAID.

Looking Ahead

Africa was severely affected by the fertilizer crisis, with sharp increases in prices and short supply because of the heavy reliance on imports. There has been some support in mitigating the crisis. However, the micro and macro level interventions to mitigate the effects of the fertilizer crisis were largely short-term. Subsidies and reduction of fertilizer application rates are likely not sustainable in the long run. There is, therefore, a need for Africa to develop long-term and sustainable solutions to address such disruptions in the future. These include, but are not limited to, increasing Africa's capacity for fertilizer production which is low and limited to a few countries (www.africafertilizermap.com). However, even the countries with capacity to manufacture fertilizers often source part of the essential raw materials from outside Africa and may therefore not be fully immune from global disruptions. For example, DAP production from Morocco relies on imported ammonia. Investments aimed at enhancing the fertilizer manufacturing capacity of African countries using internal resources

Table 2. Summary of responses to fertilizer crisis at the macro-level by various stakeholders.

Ghana		
Government	**Fertilizer industry**	**Non-governmental organizations**
• Increased regulatory functions to prevent entry of inferior products into the country • Input support (improved seeds) • Extension service provisioning • Fertilizer subsidies • Checking the artificial shortages and unnecessary hikes in prices of fertilizer in the market • Collaboration with NGOs to support farmers' access to inputs • Motivating the fertilizer dealers to import more fertilizer • Taking steps to stop smuggling of the available fertilizer to neighbouring countries • Delegation of fertilizer coupon system to private sector to ensure efficiency • Encouraging production and use of local organic fertilizer	• Fertilizer marketing promotions • Establishment of on-farm demos on best fertilizer use practices • Supporting soil analysis to guide fertilizer blending	• Liaising with fertilizer sellers to supply fertilizer to members on credit • Encouraging farmers to utilize government subsidies • Providing fertilizer to farmers at a more affordable price • Producing organic fertilizer that is cheaper than mineral fertilizer
Kenya		
Government	**Fertilizer industry**	**Non-governmental organizations**
• Fertilizer subsidies • Promoting use of organic fertilizers • Promoting use of foliar fertilizers • Promoting intercropping of cereals and legumes • Promoting crop diversification and crop change • Input support through a world bank project • Supporting fertilizer distribution for enhanced access	• Fertilizer marketing promotions • Organizing farmers into fertilizer purchasing groups • Discounts to distributors • Increased blending of locally suitable fertilizers • Ensuring fertilizer is available at the market price	• Provision of inputs on credit • Training farmers on efficient fertilizer use • Training on alternative nutrient sources • Promoting organic fertilizers through training • Input support

can therefore potentially shield local farmers from global supply chain disruptions as we have seen recently. For example, in Nigeria, the lower impact of fertilizer crisis on retail prices of urea as reported in this study can be directly linked to the capacity for local production of urea.

At the continental level, the fertilizer industry has stepped up efforts to make fertilizers more widely available and improve agricultural production on the continent. There are many noteworthy examples including the multi-institutional "Sustain Africa" initiative, a crisis response and resilience initiative aimed at increasing access of fertilizers to smallholder farmers in sub-Saharan Africa (https://sustainafrica-initiative.org), with the ultimate aim of improving the availability, affordability, and effective and sustainable use of fertilizers. The fertilizer industry is also extending immediate support to help farmers tide over the current crisis by making fertilizer available either free of cost or at a greatly reduced cost (https://newafricanmagazine.com/28344; Latrech, 2022). Major international financial and development institutions and governments are also providing support to strengthen and revitalize the fertilizer supply chains in Africa to avoid the fertilizer crisis spiralling into a major humanitarian crisis. In countries like Ivory Coast, Malawi, and Zambia, with limited raw materials, investments are focusing on developing fertilizer blending and granulation facilities. Financial support from global and regional financing institutions such as the World Bank and the African Development Bank is therefore critical for enhancing the capacity for fertilizer production.

Between countries in Africa, access to, and cost of, imported fertilizers are usually further affected by high inland transportation costs, distance from seaports, access to seaports, inefficiencies linked to poor infrastructure, limited access to finance, local regulations on entry in fertilizer markets and fertilizer distribution, among other factors. Policy changes that reduce barriers to entry into fertilizer markets and fertilizer distribution can also help in improving the access to and affordability of fertilizers. The implementation of intracontinental policies, such as the African Continental Free Trade Area (AfCFTA) is expected to improve cross-border trade efficiency and is likely to enhance movement of fertilizers and other goods making them easily available and reducing prices currently caused by cross-border tariffs.

With Africa having more than 65% of the world's uncultivated arable land, there is potential for the region to become a breadbasket with agricultural transformation. Yet, Africa remains the largest food importer with low crop productivity. Improving fertilizer access and availability can potentially enable Africa to withstand shocks such as those experienced during the fertilizer crisis and become self-sufficient in food production. ■

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Discover Our 2022 Annual Report: Towards Transformation

Defined as a marked change in form, nature, or appearance for better, “transformation” aptly articulates the modus operandi of the African Plant Nutrition Institute since its inception. Transformation is key for any organization to be relevant. Especially when changes in its operating environment are so abrupt and encompassing. Early 2022 brought a surge in geo-political conflict capable of short-circuiting the plant nutrition and food production sectors globally, but particularly for Africa, where fertilizer became even more scarce and costly within the lowest fertilizer using continent.

While fertilizer is unquestionably the central pivot for improving crop productivity in Africa, high prices and low access continue to make it a difficult choice for farmers. This intensifies the downward spiral towards lower crop productivity, extensive land degradation, and subsistence livelihoods within African communities. Millions of Africans became more food insecure as input and output markets ceased to function adequately due to the recent disruptions.

Our 2022 Annual Report is not only a celebration of our activities this past year, but also our partnerships and collaborations across the African continent and beyond. The national agricultural research and extension systems (NARES) of several countries, the CGIAR institutions, and many other public and private organizations contributed to our understanding of the nuances of crop nutrition in diverse African agro-ecologies and how to manage them for greater public good. They help us do credible science, stay contextually relevant and legitimate, and act nimbly for impact.

Sincerely,

Dr. Kaushik Majumdar
APNI Director General

View and download your copy of our report here:

https://apni.net/annual-reports

Building Research, Development, and Extension Capacity for Sustainable Fertilizer Use and Soil Health in Africa

By Thomas S. Jayne, Shamie Zingore, Amadou Ibra Niang, Cheryl Palm, and Pedro Sanchez

Key findings are summarized from a study detailing how international donors and research organizations can more effectively strengthen the capacities of African national agricultural research and extension systems (NARES). International efforts are more successful in building the capacities of individuals than in strengthening the NARES institutions. Successful implementation of the Africa Fertilizer and Soil Health Summit and similar initiatives will require stronger national, regional and continental agricultural research systems that can lead and drive these initiatives. The authors identify actions required to strengthen these African systems and effectively implement African-led agricultural initiatives.

Sustainable soil health and fertilizer use in Africa – as well as many other important goals of Africa's governments and people - depend on building dedicated local scientific expertise to support its agricultural sectors. The challenge is essentially how to build the research, development, and extension (R&D&E) capacity to generate a continuous stream of productivity- and resilience-enhancing technical innovation that can be scaled-out to millions of farm households facing highly varied agro-ecologies and resource constraints.

National capacity boils down to the skills of its people and the performance of its institutions. While there are many national institutions responsible for generating sustainable farm technical innovation, the national agricultural research and extension systems (NARES) are the centerpiece. Without strong NARES, African countries cannot provide technical guidance to their farmers and therefore become dependent on international agricultural research systems (IARS) for achieving national goals related to fertilizer and soil health sustainability. IARS are crucial allies for supporting African agriculture, but they are generally not well-suited to scale-out technical innovations on their own, nor do they have the resources to do so, hence strong NARES on the ground are required to adapt technologies and policies in collaboration with millions of African farmers. Countries that were once relatively poor, but which were able to build strong NARES (e.g., Brazil and many Asian countries), generally achieved impressive agricultural productivity growth, broader agri-food systems development, and rapid increases in living standards (Fuglie et al., 2020; Goyal and Nash, 2016; Pardey et al., 2016).


J. MUTHAMIA/APNI

Field day extension and outreach program gathers the community of farmers in Njumbiri village, Embu county, Kenya.

Table 1. Comparison of public agricultural research and development expenditures by region.

	Agricultural R&D Expenditures		*Agricultural Research Intensity, 2011 PPP$*			
	1981	**2011**	**R&D / Ag GDP**		**R&D / cropland**	**R&D / ag worker**
	2011 PPP*$, millions		**%**	**Trend**	**($ / hectare)**	**$ / worker**
Latin American and Caribbean	2,820	4,689	1.06	↑	25.0	107.7
West Asia and North Africa	978	2,253	0.49	↑	26.5	79.6
East and South Asia	2,709	13,572	0.46	↑	27.1	22.3
Sub-Saharan Africa	1,179	1,893	0.38	↓	9.3	10.1

Source: Fuglie et al. (2020)
Note: Public sector allocations to NARES; PPP = Purchase Power Parity

Table 1 presents the levels and trends in agricultural R&D expenditures over time for sub-Saharan Africa (SSA) and other developing regions. Trends are reported for R&D expenditures in relation to agricultural gross domestic product (GDP), hectares of cropland, and the number of agricultural laborers in the country. For all the metrics, funding for agricultural R&D in SSA has been lower than in other regions for many decades. This is consistent with Goyal and Nash (2019), Fuglie et al. (2020), and Stads et al. (2021).

The slow rate of crop yield growth in Africa over the past four decades attests to the need to better understand the actions that African governments and development partners can take to enable their NARES to perform better and contribute to the achievement of resilient, inclusive, and productive agri-food systems. This article takes the premise that strong NARES are at the heart of Africa's efforts to achieve sustainable agricultural systems, which include soil health and much greater and more efficient use of fertilizers.

This article also addresses how African countries can build the capacity of their NARES to achieve these goals, summarizing key findings and conclusions from a forthcoming study on African NARES (Jayne et al., 2023). The objectives of the report were to pinpoint the reasons for the slow development of African NARES and highlight actions that African governments can take to build the capacity and performance of their NARES.

What exactly are NARES and what do they do that leads to improved soil health and agricultural productivity?

NARES are the system of national institutions that generate and adapt farm technical innovation to be taken up by millions of African farmers. They include the national agricultural research institutions that undertake crop and animal science research, and the national extension systems that work with farmers to adapt and adopt new technologies and practices that lead to improved yields, resilience, and sustainable agricultural intensification. They also include national agricultural universities that ideally create a steady stream of trained professionals to take up positions in the NARES and in the private sector to achieve bi-directional learning between farmers and scientists in support of more resilient, sustainable, and inclusive agricultural performance. NARES include the national policy analysis institutes that guide African governments in identifying broader systemic change necessary to promote sustainable, inclusive, and resilient agricultural growth. Currently, few African NARES conform to this idealized definition. The challenge is how to enhance the effectiveness of NARES.

Main Findings

Four main findings can be highlighted from the study.

First, building strong NARES will require a regional approach at first for many countries. Today, only a few African countries have viable NARES; at least 25 African countries have historically devoted a small fraction of their limited public expenditure to agriculture and their NARES. As a result, they lack a viable national agricultural R&D program or university system required to develop the in-country professionals needed for effective operation of a NARES. Hence delivering soil heath and fertilizer sustainability to farmers in many African countries will require starting with a regional approach. Stads et al. (2021) propose organizing agricultural R&D investment by agro-ecological zones rather than political boundaries, at least for relatively small African countries. Integration of agricultural R&D at the subregional and regional level, through joint research programs and regional centers of excellence, may be the most effective way to allow countries with lagging agricultural research systems to benefit from the gains made in countries with similar agro-ecological conditions that have more advanced systems. Better coordination and a clear articulation of mandates and responsibilities among national, subregional, regional, and global R&D players are essential to ensuring that scarce financial, human, and infrastructure resources are optimized, duplications minimized, and synergies and complementarities enhanced. This is not just a policy consideration for African governments but for continental and regional African development organizations as well.

> " Better coordination and a clear articulation of mandates and responsibilities among national, subregional, regional, and global R&D players are essential to ensuring that scarce financial, human, and infrastructure resources are optimized, duplications minimized, and synergies and complementarities enhanced.

Second, sustained commitment and funding from African governments is a precondition for building strong NARES and regional and continental agricultural R&D&E systems. Through their Maputo Declaration commitments, African leaders recognize that agriculture is a critical engine for economic development, job creation, and poverty reduction. Yet by most metrics, SSA governments spend very little on agricultural R&D (Stads et al., 2021). African leaders must become convinced that greater commitment to their NARES organizations will help them achieve many of their most valued national policy objectives. Sustained political commitment could be galvanized by respected champions of African agriculture who compellingly demonstrate to political leaders how the performance of their NARES affects, in various direct and indirect ways, many of their most cherished policy goals. Leaders would then need to be guided regarding what greater commitment means in practice: sustained funding at greater levels, serious performance monitoring, and accountability. The national and international research community may also do more to demonstrate to African leaders how and why most of their national policy goals, including sustainable soil heath and fertilizer use, depend on improving the capabilities of African tertiary education systems to generate a continuous stream of well-trained agricultural scientists needed to sustainably operate African NARES. Effective NARES require skilled people.

Third, international donors and research organizations can and must do more to build the capacity of African NARES and regional R&D organizations. A serious stocktaking by international partners, including donors, the CGIAR, and international universities, is warranted to develop a greater appreciation of how their own effectiveness (i.e., impact generated per dollar of donor funds allocated to international research systems) depends on the performance of NARES, and that, by extension, efforts to build the capacities of these partners should be prioritized more seriously. The fact that much improved genetic materials developed by international research fail to be commercially distributed and adopted by farmers demonstrates how impact of the CGIAR and other international partners is constrained by severe weaknesses and challenges faced by NARES. System performance is constrained by its weakest link in the system. Support for building strong NARES needs to be pursued with much greater commitment by international donor organizations; impacts from their own grants and projects in fact depends upon it.

Donor commitment to supporting African agriculture requires direct engagement with the NARES. After the African governments, international and African funding organizations hold the key to strengthening African R&D&E systems by the grants that they make. We encourage donors to consider ensuring that grants related to African agricultural technical innovation require including organizations in the NARES at the design stage, supporting nationally led priority setting agendas, and ensuring that NARES interests and priorities are reflected in proposal and budget development. Grants with co-directors from NARES organizations would enable these organizations to feel greater ownership and commitment to achieving the objectives of the grant. Donor and development bank funding should be consistent with priorities set by national stakeholder processes, which can draw upon the expertise of international, African continental, and regional partners.

In many cases, these proposals for consideration may entail (a) putting host-country institutions in the lead, supported by international expertise; (b) the priority agenda being defined by national governments to build local ownership; and (c) taking a systems approach to NARES development, which requires socio-economic/policy analysis units to be integrated into the NARES.

Fourth, confront the issue of "work-arounds": Some donor organizations are reluctant to directly partner with public sector entities and often create parallel structures to the NARES that carry out activities that duplicate the mandates of the NARES. While donors may ensure greater accountability for their funding by creating their own partners working on the ground, the long-term impacts are unclear, as they may weaken or marginalize organizations in the NARES that African governments rely upon to carry out the public goods role of agricultural R&D&E in their countries. Resentment, lack of cooperation, missed opportunities, and limited long-term impact are common outcomes when donors create and fund new organizations to carry out tasks that overlap with the mandate of existing national entities. ■

Summary: Who needs to do what?

Actions by African governments

The most crucial step to improving the performance of NARES is for national governments to increase their funding and commitment to supporting their own NARES, to monitoring performance, and to demand greater accountability for results.

- Increase overall public disbursements to agriculture and raise the share of public agricultural expenditures going to organizations in the NARES. Rather than relying too much on donor contributions and development bank loans to fund critical areas of research, governments need to determine their own long-term national priorities and design relevant, focused, and coherent agricultural R&D&E programs accordingly.
- Incentivize the private sector to collaborate more with African NARES. Governments' calls for the private sector to step up and support African farmers often fall on deaf ears unless governments provide the necessary incentives. Many private agribusiness firms are already heavily involved in supporting farm technical innovation in Africa, including soil health and fertilizer use. But African governments could leverage much greater support from the private sector by making it attractive for the private sector to invest in, and collaborate with, African NARES, by providing a favorable policy and

enabling environment, effective accountability frameworks, and by stepping up to support their own NARES.

- Ensure that budget lines to organizations in the NARES are fully disbursed each year. Stads et al. (2021) found that in many cases, governments did not fully disburse approved budgets to their NARES.

Actions by African university leadership

- Prioritize improving post-graduate training in faculties of agriculture, including sandwich programs at qualified universities. The University of Pretoria Collaborative Masters in Agricultural Economics and Extension provides a useful model for consideration. This program allowed MSc students to take courses both at their home university and at the University of Pretoria for a year, where international faculty and UP faculty taught and mentored them, guided their thesis work, and supported their efforts to be placed in suitable organizations on the African continent after graduation. External reviews considered the program highly effective in raising the supply of well-trained MSc agricultural economists and could be considered to build African capacity in other agricultural disciplines.
- The senior management of many African universities tend to regard their resources and budget limits as being exogenously determined by budget allocations from their central governments. But African universities could potentially expand their budgets by proactively competing for international donor resources. They could form partnerships with CGIAR organizations, international universities, and/or relevant organizations in the global south to prepare proposals for funding new activities or expanding the funding for existing activities.

Actions by international donors and research systems

- Encourage donor grants targeted to CGIAR or international universities to include organizations in the NARES at the design stage, ensuring that NARES interests and priorities are reflected in proposal and budget development. Donors could do more to ensure that their grants are co-led by organizations in the CGIAR and the NARES, starting from project design, so that NARES or regional R&D&E systems are brought in from the beginning.
- Explore opportunities to leverage the formidable R&D&E systems of the private sector. The private sector is currently the least developed source of sustainable financing for agricultural R&D&E in Africa.
- Donor and development bank grants in support of sustainable fertilizer use and soil health should be consistent with priorities set by national governments.
- Donors that can afford to take a long-term time horizon for impact, should see the necessity of long-term support to the NARES, extension, and agricultural universities with long-term commitments, moving away from grants that focus on low-hanging fruit with short-term impact.

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Photo Contest Update

Join our photographic challenge by contributing to the contest! Your contributions will help build a valuable forum and educational resource …plus winners are eligible for a cash prize of US$250!

Our contest is **accepting entries till August 30, 2023.**

Category 1: Nutrient Deficiency Symptoms in Crops

We are looking for examples of nutrient deficiency symptoms in African crops that can provide our readers with a teachable moment. Ideally your images would be supported by a short description of the location and what you saw. If you have any background on how the crop was managed, or any results from the lab, please include that in your description for the benefit of others, and to help our evaluation. Full credit is given to the photographer. If you need help distinguishing the symptoms, you may consult the general reference diagram provided on the contest website.

Category 2: Plant Nutrition Research in Action

Our contest's second category is looking to gather your examples of plant nutrition in action for Africa. We are especially looking for images that depict or describe either: 1) Climate & Weather Smart Plant Nutrition, 2) Soil Health & Improved Livelihoods, or 3) Precision Nutrient Management. Who knows? You may be featured on the next cover of Growing Africa!

For more details about the contest and how to submit your entry visit https://apni.net/photo-contest.

Soil Health Challenges in Sub-Saharan Africa: Status and Solutions

By Job Kihara, Mordecai Mkiza, Dominic Mutambu, Michael Kinyua, Obadiah Mwangi, Peter Bolo, Feyera Liben, and Wuletawu Abera

Soil health is an essential foundation for providing the food requirements of a growing population. Technologies for improving soil health are available, but many are only practiced to a limited extent. Partnerships involving governments, the private sector, and research and development initiatives promise to accelerate the packaging of the available data and information; and develop and deliver tailored recommendations that support sustainable soil health management.

Soil health, the capacity of soil to function and provide ecosystem services, is important for sustained food and nutritional security in sub-Saharan Africa (SSA). Agriculture contributes about 23% of the region's GDP and employs about 60% of its population. With Africa's population expected to increase 2.5 times and cereal demand to triple by 2050 (Van Ittersum et al., 2016), soil health is critical. An estimated 65% of the arable land in SSA is degraded, with annual losses of soil nutrients worth approximately US$4 billion. The degradation of the soil's physical, chemical, and biological properties is due to unsustainable land use practices. The main forms of degradation include nutrient depletion, erosion, organic matter loss, biodiversity loss, contamination, acidification, salinization, sodification, waterlogging, compaction, and crusting (**Table 1**; Bado and Bationo, 2018). For example, decline in soil organic carbon (SOC) has been reported from long-term (over 10 years) trials in Kenya, Nigeria, and Togo (Kihara et al., 2020).

Soil health contributes not only to increased crop productivity but also to other ecosystem services, including climate change regulation through greenhouse gas emission controls and C sequestration, water quality provisioning through controlled water and nutrient movements, supporting the functioning of soil organisms and their roles in nutrient cycling, and even cultural services through aesthetic landscapes (Kihara et al., 2020). A healthy soil also supports pest regulation and disease suppression. Soil health is also linked to human nutritional security through improved produce quality. Human nutritional deficiencies have been correlated with poor soils and micronutrients such as iron and zinc. The health and productivity of populations in SSA can be affected by soil health (Joy et al., 2015).

Table 1. Prevalence of selected soil health problems in sub-Saharan Africa.

Degradation form	Status
Soil erosion	77% of Africa is affected by erosion[†]. For example, Malawi loses 30 t ha^{-1} of soil year^{-1} (Omuto and Vargas, 2018).
Nutrient depletion	Almost all countries have a negative soil nutrient balance ranging from -2 to -60 kg N ha^{-1} yr^{-1}, from 0 to -11 kg P ha^{-1} yr^{-1}, and from -2 to -61 kg K ha^{-1} yr^{-1} due to low fertilizer application (average of 12 to 17 kg ha^{-1}) [†].
SOC	Below 1.5% yet declines annually of 2.8 to 13.0 t C ha^{-1} (Namirembe et al., 2020)
Soil biodiversity loss	Soil organisms constitute >25% of the earth's biodiversity. Croplands have lower biodiversity compared to undisturbed or less disturbed soils. Main threats include deforestation, burning of above-ground cover, loss of soil organic carbon, compaction, erosion, landslides, invasive species, and over-grazing (FAO et al. 2020).
Soil acidity	~30% of the SSA have pH < 5.5, mainly in sub-humid areas [†]
Salinization	Over 80 million ha of soils with pH >8.5 commonly in arid and semi-arid areas[†]

[†] from FAO and ITPS, (2015)

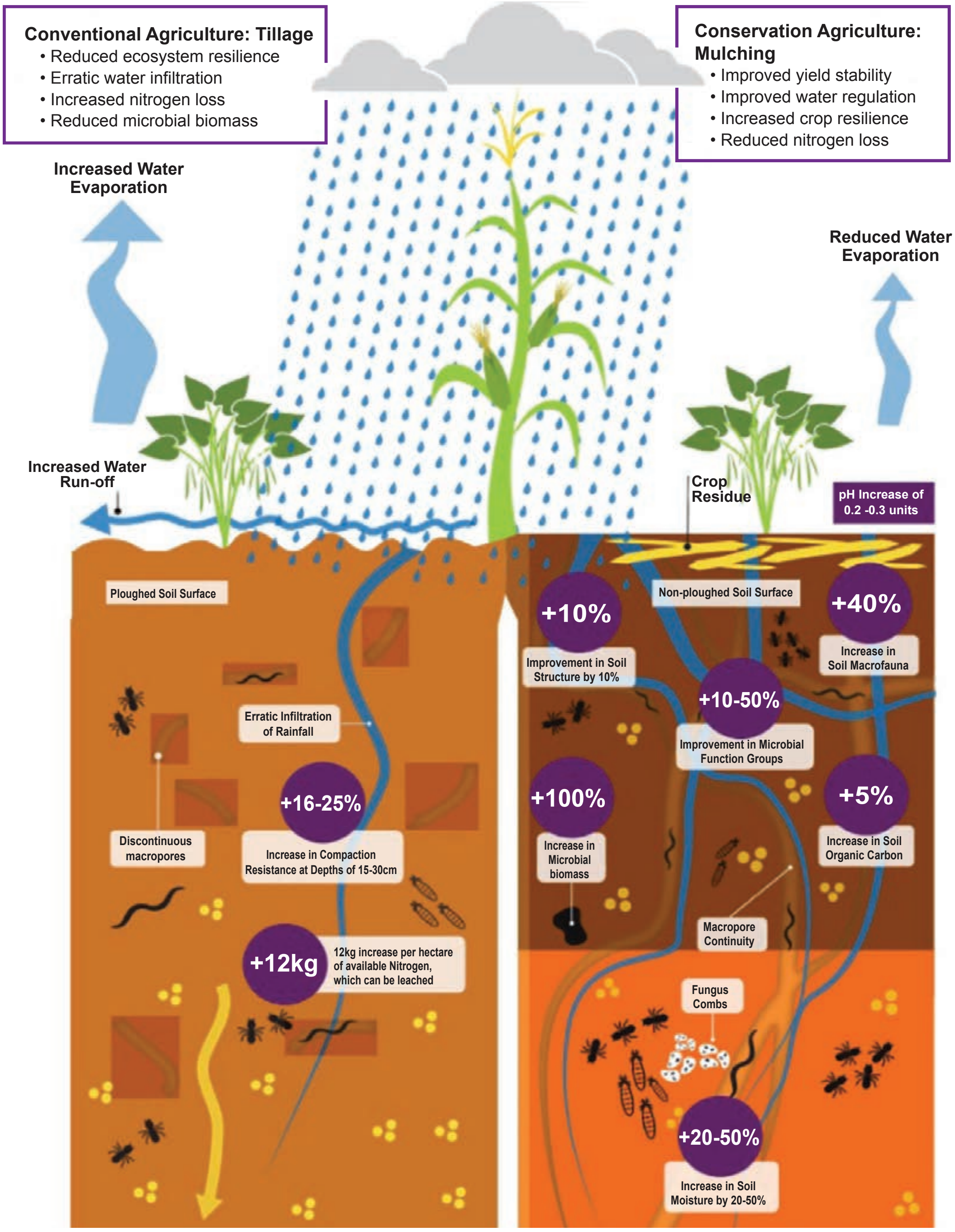

Figure 1. Soil health benefits from CA systems compared to conventional tillage. **Source:** Kihara et al. (2020).

The common strategies and practices for enhancing soil health in Africa include conservation agriculture, Integrated Soil Fertility Management (ISFM), agroforestry, crop associations (strip/intercropping, crop rotation), green manure cover crops (GMCC), and pit cultivation technologies. Recently, regenerative agriculture and agroecology approaches have gained interest. Here, the extent of use for the above soil health-promoting strategies is assessed, and some challenges and opportunities discussed.

Managing soil health in sub-Saharan Africa

Conservation agriculture

Conservation agriculture (CA), a practice integrating minimum soil disturbance, permanent soil cover, and crop rotation/associations, is important for soil health and the associated ecosystem services (**Fig. 1**). Scientists have demonstrated more SOC under CA relative to conventional tillage (Sommer et al., 2018; Chivenge et al., 2007), improved soil structure, enhanced soil biodiversity and biological activity (Bolo et al., 2021), soil water infiltration and retention. Despite reduced yields in the initial years of converting to CA in some cases, increased yields are expected in the long term (Kihara et al., 2020; Thierfelder et al., 2013).

Despite evidence of increased CA adoption (**Fig. 2**), hurdles to its adoption include inadequate equipment and machinery to mechanize operations, low supply/availability of crop residues for mulching, and competing needs for residue use as animal feed. Yet, 50% of the farmers are willing to pay for mechanized minimum tillage (Ngoma et al., 2023). Thus, with adequate equipment and machinery there is potential for widespread adoption of CA and participatory CA technology testing can support information diffusion as farmers become agents of change.

Integrated soil fertility management

ISFM consists of four critical components: (i) improved crop varieties; (ii) fertilizer; (iii) organic resources; and (iv) local adaptation, which includes soil and water conservation practices. ISFM is effective for sustainable soil health management and increases

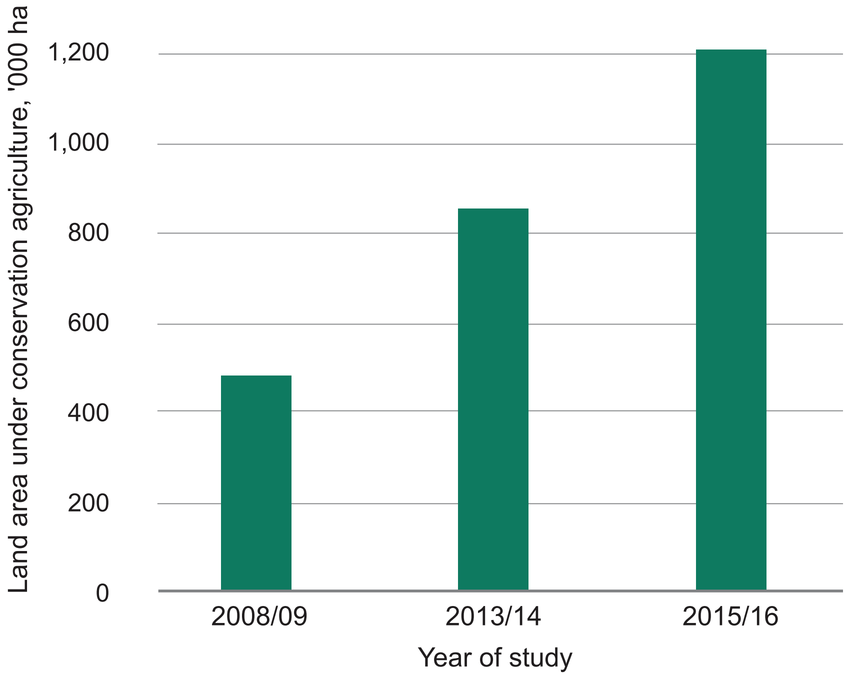

Figure 2. Extent of CA adoption ('000 ha) and expansion in selected countries in Africa (South Africa, Zambia, Kenya, Zimbabwe, Sudan, Mozambique, Tunisia, Morocco, and Lesotho) between 2008 and 2016. Adapted from Kassam et al. (2019).

productivity in smallholder farms reaching up to 300% in some cases, depending on the level of ISFM implementation. But many farmers only have a selected set of ISFM components, even though yields (**Fig. 3**) and economic returns increase with the number of components (Kihara et al., 2022). Employing an increasing number of ISFM components is associated with increased labor costs, but these are often offset by the economic gains. Unlocking limitations that lead farmers to partial ISFM adoption is important.

The practice of ISFM among farmers varies within and across regions. According to Kihara et al. (2022), farmers practiced 1 to 4 ISFM components in sub-humid agroecological zones (AEZs) of Tanzania relative to 0 to 3 components in semi-arid AEZs. There is often high variability in the mix of ISFM components, even within a region, reflecting the complex socioeconomic and biophysical variability that characterizes smallholder farms (Giller et al., 2006; Hörner and Wollni, 2021). Tailored and site-specific management recommendations, and the availability of the inputs required, can support adoption. Sustained scaling out through various strategies is required, especially through national efforts.

Fertilizer use in the ISFM framework can double crop yields. Yet, application rates remain low (Chianu et al., 2012), because of high costs and low returns due to low nutrient use efficiencies under suboptimal recommendations and management conditions. New tailored fertilizer recommendations, for example, in Ethiopia, increased wheat yields (24 to 38%) and profits (**Fig. 4**; Liben et al., 2022). Modest rice

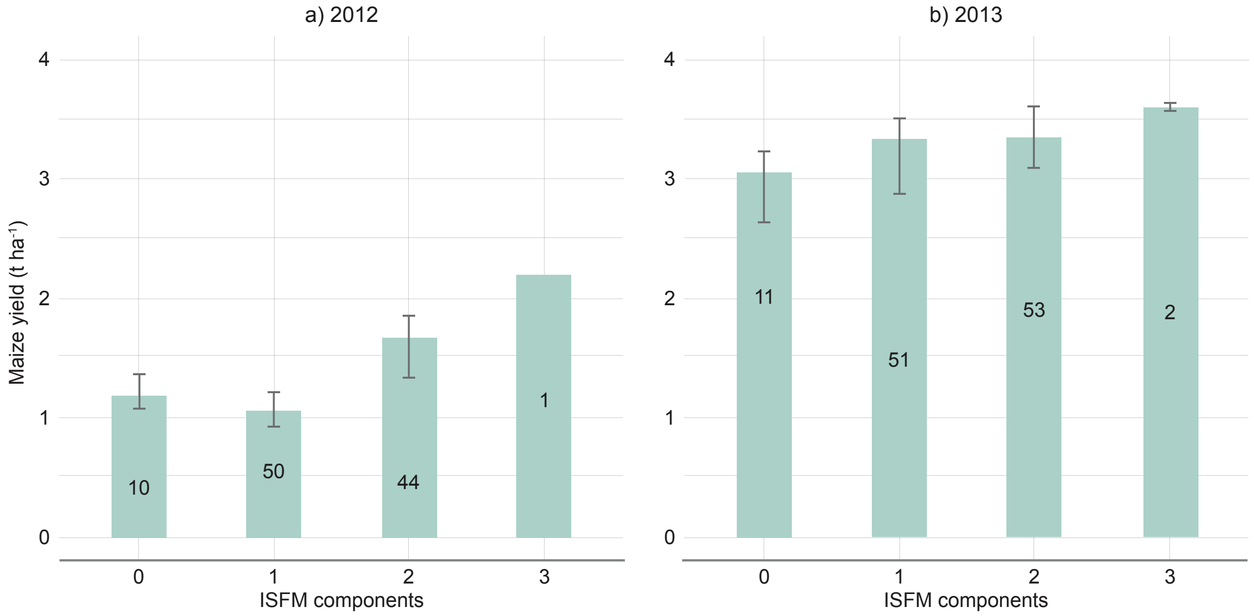

Figure 3. The rate of ISFM component use and yield gains in two separate seasons in 2012 and 2013. The numbers within each column represent the number of fields. Source: Kihara et al. (2022).

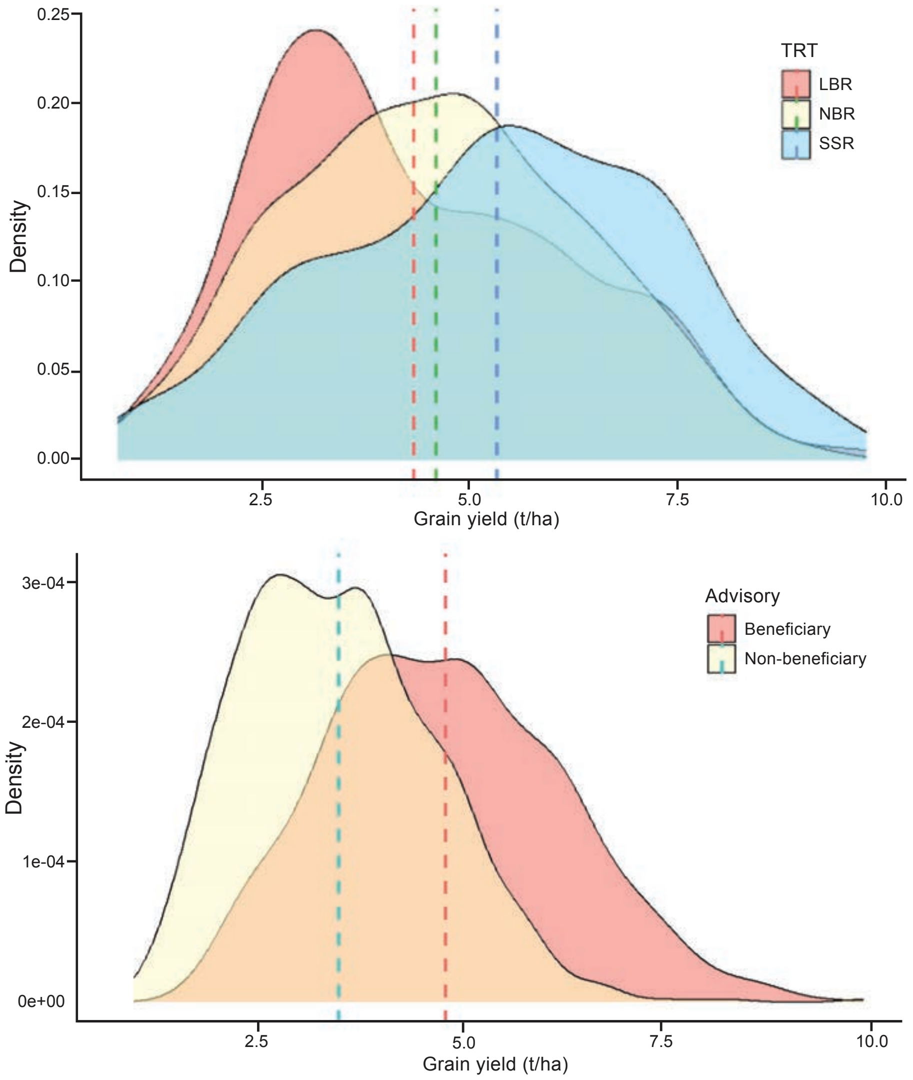

Figure 4. Wheat grain yield observed under local (LBR) and national (NBR) blanket fertilizer recommendations and location-specific rate (SSR) treatments (TRT) across 277 farms in Ethiopia (top) and under new agronomic advisories across 4,000 farms as observed in Ethiopia in 2022 (bottom). The vertical dash lines indicate mean grain yields (Liben et al., 2022). The density values on the y-axis indicate the probability per unit of value shown on the x-axis.

and maize yield increases of 11% and 4%, respectively, were also observed elsewhere compared to blanket recommendations (Chivenge et al., 2022). Upscaling these efforts can result in large changes in the African agricultural landscape. Low rates of fertilizer application in SSA contribute small amounts to greenhouse gases (e.g., N_2O-N emissions from cropland in SSA range from 0.4 to 3.9 kg N_2O-N ha^{-1} year^{-1}; Kihara et al., 2020). However, groundwater contamination and eutrophication of water bodies, linked to uncurbed runoff is widespread. Thus, upscaling of fertilizer recommendations should be accompanied with sustainable land management practices.

Combined application of organic resources and mineral fertilizers is associated with greater nutrient use efficiency and yields than with either organics or mineral fertilizers alone. The manure applied on croplands across Africa can cover just about 10% of croplands (FAOSTAT; **Table 2**). When combined with fertilizers, the area applied with manure can extend.

Crop associations

Intercropping is widespread in SSA and is associated with increased land equivalent ratios relative to monocrops. Cereal-legume intercrops improve soil biophysical and chemical conditions (Chikowo et al., 2020) and fix N (e.g., 53 to 84 kg N ha^{-1}; Mugi-Ngenga et al., 2022). Unfortunately, intercropping systems are often characterized by low yields of the legume intercrops.

Strip cropping innovations increase legume yields, for instance by 101%, 52%, and 15% for groundnuts, soybean, and beans, respectively (Woomer et al., 2004). A triple crop, strip-cropping innovation, Mbili-Mbili, recently developed in Tanzania and now introduced to Malawi and Zimbabwe, improved smallholder food and nutritional security

Table 2. Organic manure use in the main regions of Africa.

Region	Cropland area (Million ha)	Manure (Million t)	Potential area (%)†
Eastern Africa	78	54.8	14.1
Middle Africa	37	16.4	8.9
Northern Africa	50	15.7	6.3
Southern Africa	14	4.9	6.8
Western Africa	102	37.5	7.4
Total	**281**	**129.4**	**9.2**

Source: https://www.fao.org/faostat/en/#data/ESB. †assuming manure to supply 60 kg N ha^{-1} based on an N concentration of 1.25%

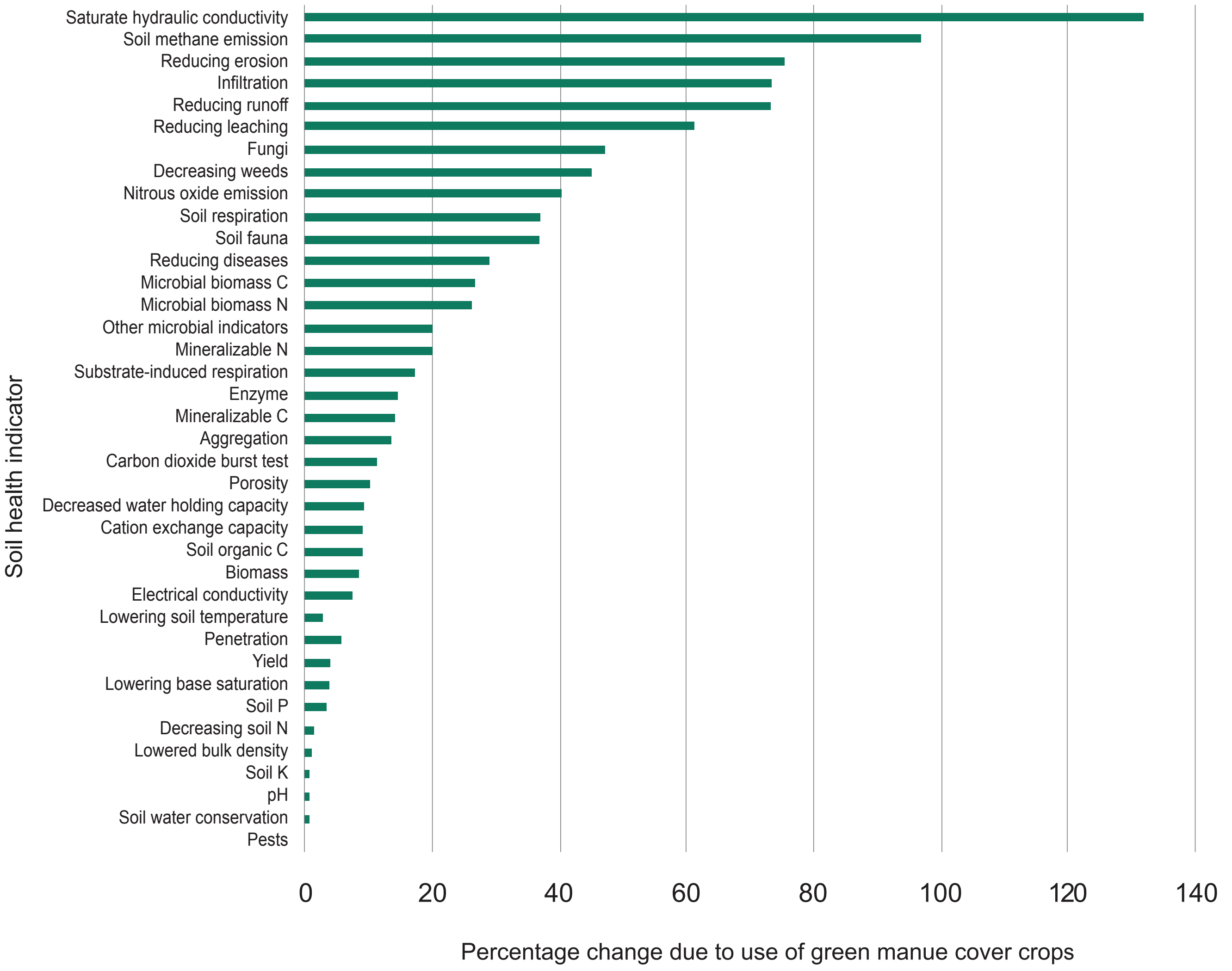

Figure 6. Improvement of soil health as influenced by cover crops relative to no cover crop. Data used in the plot was obtained from Jian et al. (2020).

through increased and seasonally distributed harvests and increased revenues (by $150 ha^{-1} season^{-1}) and their stability (Kinyua et al., 2023). Scaling uptake of these innovations is important to improve soil health and the livelihoods of smallholder farmers.

Legume cover crops provide positive changes of 1 to 133% across various soil health indicators (**Fig. 6**; Jian et al. 2020). Despite the benefits, adoption of cover crops in Africa is still below 50% (Autio et al. 2021), attributed to limited cultivation knowledge, access to seeds, increased labor during cultivation and incorporation, and loss of crop season when rotated with food crops.

Under mixed crop-livestock systems, ley rotation of annual crops with managed perennial/annual grass or grass–legume mixtures (ley) improve crop productivity (5-135%) as well as soil properties (e.g., pH 4%, SOC 12%, pore space 4%, percolation 12%, and infiltration 22%; **Fig. 7**; Wortmann et al., 2021). Alternate ley with annual crop strips of 5-20 m width and rotation cycles of 6-10 yr is recommended (Wortmann et al., 2021). Push-pull is a specific ley cropping technology that integrates N-fixing crops (e.g., Desmodium) and Napier grass strips to increase crop productivity (e.g., 100 to 200% more cereal grain yields in western Kenya; Khan et al., 2011).

Agroecology

Agroecology encompasses all the practices presented here and others (i.e., agroforestry, regenerative agriculture) and is considered as a concept guided by specific principles. In Africa, agroecology can vary greatly across farms with 1 to 5 practices commonly implemented (**Fig. 8**). Approximately 40% of cropland in Africa is under agroforestry, with >45% in humid regions of West Africa, 30% in sub-humid Africa, and <10% in Sahara regions (Zomer et al., 2016; Miller, et

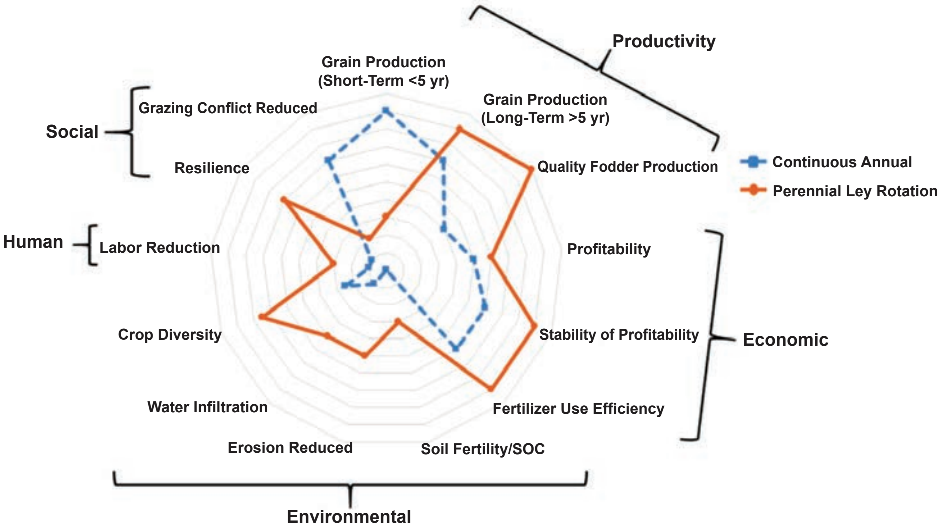

Figure 7. Comparison of continuous annual cropping and ley perennial grass rotated with annual crop (Wortmann et al., 2021).

al., 2017; Kuyah et al., 2021). In Kenya, 56% of the farmers were inadequately informed and 80% required training in regenerative agriculture (Otara et al., 2023). Inadequate knowledge and skills among farmers, and unsupportive policies are barriers to the success of regenerative agriculture. Further scaling of agroecological practices in Africa is important to restore soil health.

Integrated soil fertility and water management

ISFM and in-situ water harvesting in practices involving variable pit cultivation such as Matengo pits (Tanzania), Pfumvudza (Zimbabwe), Mambwe (Zambia), Dagomba (Ghana), Zai pits (Mali and Burkina Faso), Tassa (Niger), and Teras (Sudan) with soil organic matter input into planting pits to build soil organic C (Nyamadzawo et al., 2013), control soil erosion and have the potential to improve soil health. While in specific places the uptake of these practices is appreciable, for example, 50% of smallholder farmers use Matengo in Mbinga district of southern Tanzania (Malekela and Lusiru, 2022), and 52% use Zai Pits in northern Ghana (Danquah et al., 2019), adoption in other places is low and constrained by limited labor and insufficient extension services.

Conclusions

Many soil health-promoting practices are available in SSA, but their adoption remains limited across SSA. Evaluation of the relevance of technologies for specific sites and targeted dissemination is necessary to accelerate adoption and impact. Participatory co-design and implementation processes and farmer training can support farmers to adapt innovations to meet the productivity and soil health targets at the farm and community levels.

Advances in data science and digital technologies offer opportunities for the consolidation and analysis of agronomic data to promote tailored guidelines that are more relevant to the needs and demands of farmers. Research and development institutions, such as the CGIAR through its Excellence in Agronomy Program, are driving research efforts to organize data and support analytics and tool development to generate site and context-specific advisory services. Building broader alliances with public and private sector partners will be necessary to deliver effective advisory services and create an enabling environment for the adoption of innovation for sustainable soil health management. ■

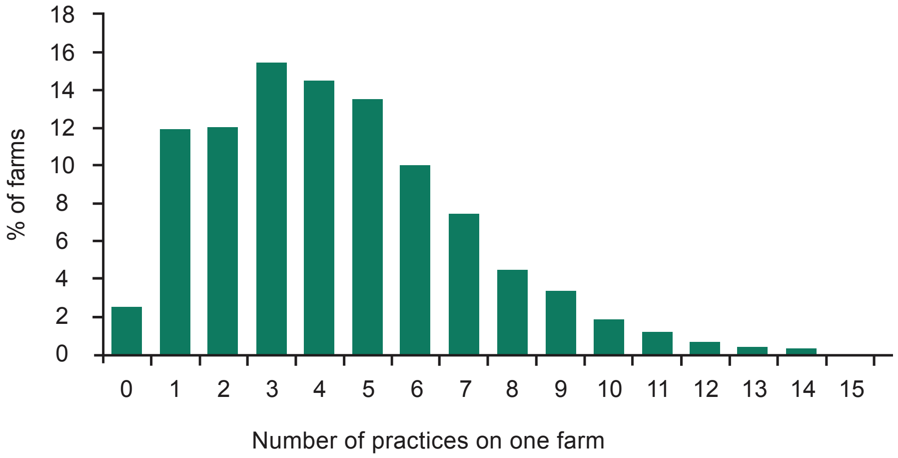

Figure 8. Number of agroecology practices implemented in 5,025 farms across Burkina Faso, Ethiopia, Kenya, Madagascar, Malawi, Senegal, Tanzania, and Tunisia in 2022. Adapted from (Viability Project Team, 2023).

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Integrated Soil Fertility Management: Building on Past Experiences to Address Future Challenges

By Bernard Vanlauwe

There remains a critical need in Africa to implement strategies to brace the continent against its triple threat of degrading soils, increased climatic vulnerability, and a surging need for nutritious foods. Through years of adaptive research, Integrated Soil Fertility Management (ISFM) has evolved into a balanced and inclusive agronomic concept well positioned to tackle these challenges. Still, effective implementation at scale is only achievable given innovative, locally adaptable dissemination technologies, and robust agriculture industry and financial support.

Conceptualization of ISFM

The Integrated Soil Fertility Management (ISFM) approach is a logical consequence of earlier failed attempts to increase crops yields in sub-Saharan Africa (SSA), first through Green Revolution-type approaches driven by improved varieties and fertilizers in the 1960s and 70s, followed by attempts to avoid fertilizer altogether in the 1980s and 1990s by seeking biological means for yield improvement (Vanlauwe et al., 2017).

In 1994, the Second Paradigm for Tropical Soil Fertility Management, launched by Sanchez (1994), was phrased as '*the need to rely more on biological processes to optimize nutrient cycling, minimize external inputs and maximize the efficiency of their use*', and thus accepted that both fertilizer and organic inputs are required to boost crop productivity in SSA. While the Second Paradigm triggered substantial efforts to generate organic resources in-situ, thereby recognizing that some fertilizer would be needed, ISFM is built on similar principles but focuses on the use of fertilizer as an entry point toward the intensification of smallholder agriculture.

The Fertilizer Summit, held in Abuja, Nigeria, in 2006, emphasized the need for increased use of fertilizer in Africa from the then 8 to 50 kg fertilizer nutrients ha^{-1} to increase crop production and reduce the importation of food from outside the continent. Soon after in 2009, in the context of the formulation of a soil strategy for the Alliance for the Green Revolution in Africa (AGRA), ISFM was re-conceptualized with a focus on maximizing the use efficiency of fertilizer. This focus was justified by the high costs of fertilizer and the need to avoid losses of nutrients to the environment – a criticism often associated with Green Revolution approaches. Agronomic efficiency (AE) is defined as incremental return to applied inputs or:

$$AE = (Y_F - Y_C)/(F_{appl})$$

where Y_F and Y_C refer to crop yields (kg ha^{-1}) in the treatment with and without nutrients, respectively, and F_{appl} is the amount of fertilizer nutrients applied (kg ha^{-1}). With constant fertilizer application rates, increased AE results in increased crop productivity.

Key principles

ISFM was thus defined as '*a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles.*' This definition entails two key dimensions: (i) a set of generally applicable principles and (ii) the need for local adaptation.

The key principles underlying ISFM were formulated based on many decades of agronomic research in SSA and supported by a vast amount of scientific evidence. **First,** fertilizer needs to be used properly for it to generate best responses. The 4R Nutrient Stewardship (IPNI, 2016), a science-based framework developed by the global fertilizer industry, focuses on applying the right fertilizer source at the right rate, at the right time in the growing season, and in the right place in the soil and provides an essential basis for optimizing the use of nutrients. **Secondly,** improved crop varieties are required to maximize the agronomic benefits from the supply of nutrients. Such germplasm could be resistant to key pests or diseases, tolerate abiotic stresses such as drought, or contain hybrid vigor. **Thirdly,** fertilizer combined with organic inputs is advocated as a sound management principle for smallholder farming in the tropics because (i) neither of the two inputs are usually available in sufficient quantities, (ii) co-application can result in added benefits that each input by itself cannot generate, and (iii) both inputs are needed in the long-term to sustain soil fertility and crop production since organic inputs also supply C to the soil, thus contributing to the build-up of soil health. It is important to note that organic inputs refer to all available resources, either produced in-situ (e.g., crop residues) or transferred from elsewhere within or outside the farm (e.g., farmyard manure). **Fourthly,** good agronomic practices refer to crop and soil management practices that allow crops to grow and yield optimally, including appropriate land preparation, planting times, plant populations, intercrops, weed and pest and disease management, and harvest procedures. Many studies have confirmed that sub-optimal agronomic practices are main contributors to the current yield gaps in SSA (Pradhan et al., 2015; ten Berge et al., 2019). **Lastly,** local adaptation refers to the need to address locally relevant constraints to crop growth (i.e., the application of lime in areas with soil acidity-related constraints).

ISFM is a stepwise approach that begins with rehabilitating degraded soils and improving marginal soils, first by using mineral fertilizers and improved germplasm (**Fig. 1**). Due to the widespread extent of low soil nutrient availability and a paucity of organic resources, fertilizers are considered a necessity to begin rebuilding the fertility base of the vast majority of soils. The next step is incorporating organic resources into soil management, which is necessary to rebuild the soil organic matter key to soil health and integral to multiple soil functions. This second step, however, can only happen once there is sufficient biomass in the farming system. A final step refers to the need for additional amendments where fertilizer and organic inputs cannot address specific constraints such

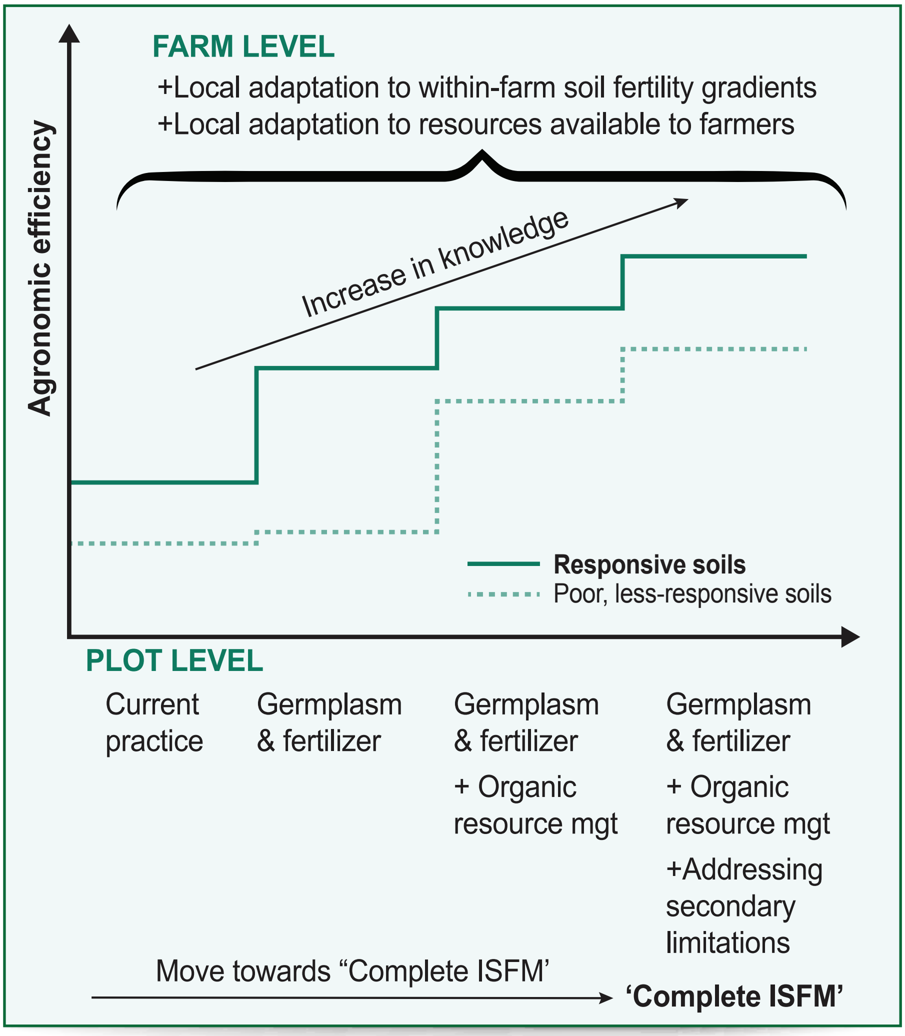

Figure 1. The conceptual relationship between the agronomic efficiency of fertilizers (y-axis) and organic resource and the implementation of various components of Integrated Soil Fertility Management (ISFM), culminating in complete ISFM towards the right side of the graph (x-axis). Moving to the right requires increasing levels of knowledge, based on appropriate diagnostics and farmers' resource endowment. Soils that are responsive to commonly used fertilizer (bold line) and those that are poor and less responsive (dashed line) are distinguished. The 'current practice' step assumes the use of the current average fertilizer application rate in SSA of 8 kg fertilizer nutrients ha^{-1}. A distinction is made between plot- and farm-level 'local adaptation'.

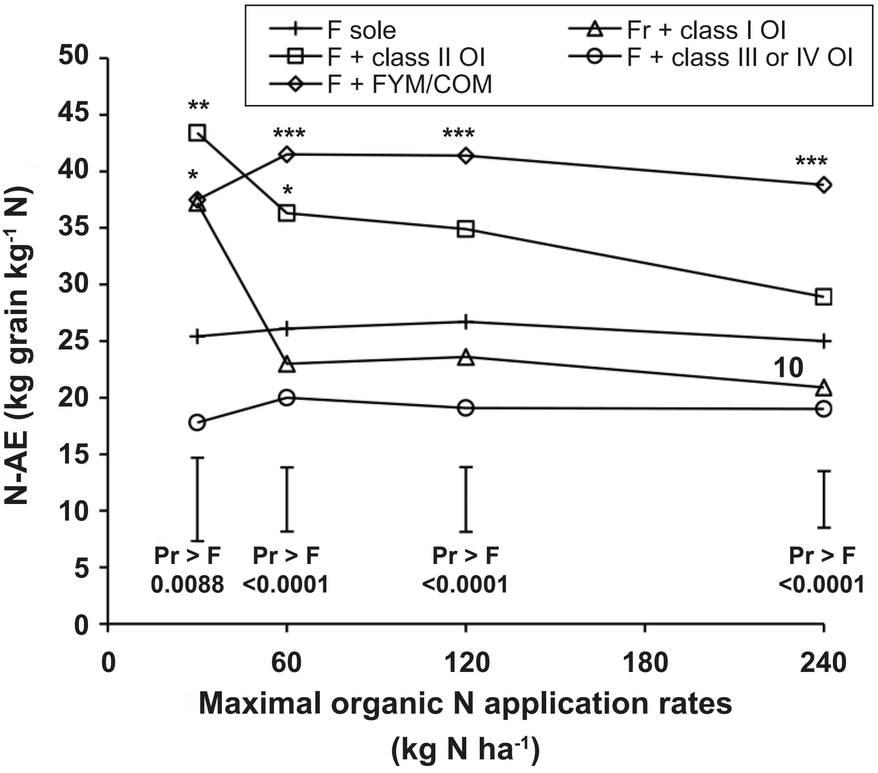

Figure 2. Agronomic efficiency of fertilizer N (N-AE) as affected by combination with different classes of organic inputs (Classes I, II, III+IV, and manure+compost) for organic N application rates ≤ 30 kg N ha^{-1}, ≤ 60 kg N ha^{-1}, ≤ 120 kg N ha^{-1}, or ≤ 240 kg N ha^{-1}. Error bars are average Standard Errors of the Difference. The symbols '*', '**', and '***' indicate a significant difference with the sole fertilizer treatment at the 0.1, 1, and 5% level. In the legend, 'F', 'OI', 'FYM', and 'COM' refer to fertilizer, organic inputs, manure, and compost, respectively. Source: Vanlauwe et al., 2011.

as those that are related to soil acidity, for example. The steps involved in ISFM vary with the local conditions and constraints to improving crop productivity and rehabilitating soils. The entry point for farmers to invest in ISFM depends on the initial soil conditions and the resources available.

The quality of the organic resources and the amount of N applied as fertilizer affect increases in AE values when combining fertilizer with organic inputs. Organic resource quality is related to the speed with which these decompose. High quality Class I residues (with N contents above 2.5%, lignin contents below 15%, and polyphenol contents below 4%) decompose relatively fast and their N availability behaves much like commercial fertilizer. As such, Vanlauwe et al. (2011) show that their impact on AE is mainly observed at very low levels of N application (**Fig. 2**). Intermediate quality organic inputs belonging to Class II (N > 2.5%; lignin < 15%, polyphenols > 4%) and manure/compost had significantly higher N-AE values than the sole fertilizer treatment or the Classes I and III (N > 2.5%; lignin < 15%, polyphenols > 4%), or low-quality Class IV organic inputs (**Fig. 2**). At higher organic N application rates, only the treatment with manure/compost gave significantly higher N-AE values than the sole fertilizer treatment (**Fig. 2**).

Heterogeneity and local adaptation

One element not yet covered concerns local adaptation to heterogeneity in smallholder farming systems. I grew up in a village in Belgium, surrounded by maize cultivation at particular times of the year. When I rode around those fields on my bicycle as a young boy, all the maize crops looked exactly the same in relation to height and color and they were anticipated to produce excellent yields – something I did not know yet at that time. The same can be said for other agricultural areas like the Cerrado of Brazil (**Fig. 3a**). However, the situation in areas of SSA, with relatively dense rural populations, is totally different with maize showing all possible heights and colors over very short distances, often within the same smallholder farm commonly less than 2 ha in size (**Fig. 3b**).

Within SSA farming communities, a wide diversity of farmer wealth classes and production objectives may be distinguished. In western Kenya, Tittonell et al. (2005a) identified that some small farms were owned by wealthy households that had external income from pensions or remittances and for whom farming is not their primary income. Such households are not expected to consider agricultural investments a priority. In contrast, well-resource endowed farmers with large areas of land make a relatively good living from farming. Poor households with very small farms have limited access to resources, often selling their labour to other households,

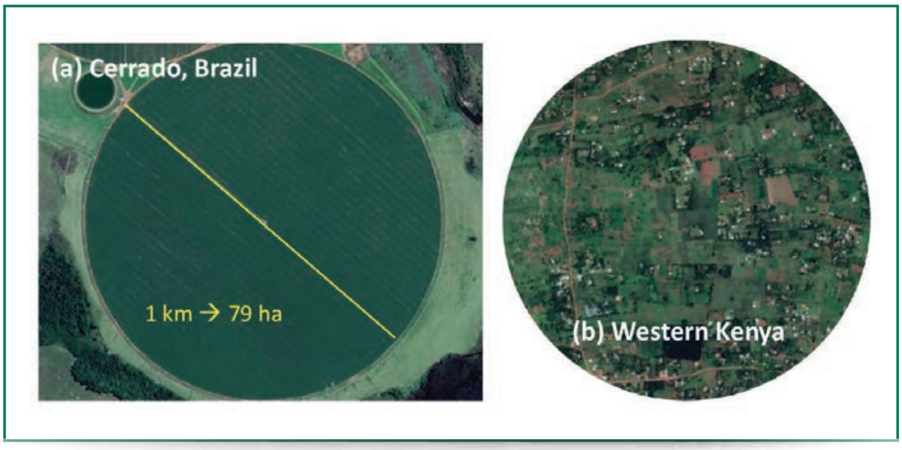

Figure 3. Google Earth scenes from (a) the Cerrado region of Brazil, showing a pivot irrigation circle grown with maize with a diameter of 1 km – the yellow line and (b) from smallholder farms in Western Kenya during the growing season, covering the same area as the pivot circle and containing over 50 individual farms, noting that the white spots are roofs from farmhouses.

and are thus expected to use fewer agro-inputs.

At the individual farm level, the variability between the soil fertility status of individual fields can be high, resulting, for example, in yield ranges between 900 and 2,400 kg maize grain ha^{-1} for different fields within the same farm (Tittonell et al., 2005b). These within-farm soil fertility gradients are created by the position of specific fields within a soilscape, by the selective allocation of available nutrient inputs to specific crops and fields, and by improved management of plots with higher fertility (Tittonell et al., 2005b). As a result, fertile home fields need only maintenance fertilization to sustain good crop yields, and crop response to fertilizer in strongly depleted soils is often weak due to a suite of nutrient deficiencies.

Conventional research processes have encountered major limitations in addressing this complex variability at farm and community scales while responding to the demand of millions of smallholder farmers. Rapid technological advancements have offered an opportunity to overcome this limitation through a combination of data management processes, geographic information systems, diagnostic tools and sensors, remote sensing, modelling, and widespread internet coverage that has led to significant progress in the pursuit of providing locally relevant information at scale. One could argue that in earlier days, an agronomy R&D activity had to choose between (i) working at scale but giving in on detail – which resulted in the development of so-called blanket recommendations – and (ii) focusing on individual fields or farms but working in a limited geographical area. Nowadays, new technology allows us to work at scale while remaining locally relevant while noting that it remains important to have a human interface between advisory systems and individual farmers, stressing the need for empowered and capacitated extension agents.

ISFM and the challenges of today

While ISFM was originally conceptualized around the use efficiency of fertilizer in support of the ‘uniquely African’ Green Revolution, nowadays, the issue of use efficiency has regained prominence because of the large increases in fertilizer prices caused by the Russia-Ukraine war. Three other issues are equally high on the list of development priorities of today: (i) soil health, (ii) climate change adaptation and mitigation, and (iii) human nutrition.

Regarding soil health, ISFM has been demonstrated to present a viable route towards increasing soil organic carbon, a key indicator of soil health. Other potential dimensions of soil health such as sufficient available phosphorus or absence of soil-acidity induced limitations are also addressed by ISFM.

In terms of climate adaptation, depending on the nature of the hazards generated by climate change, ISFM can provide a solution, especially when it concerns lack of sufficient soil moisture, either through lack of rainfall or within-season drought. While in the former situation, the ‘local adaptation’ component of ISFM advocates the use of water harvesting practices, in the latter case, the co-application of fertilizer and organic inputs can result in deeper rooting, increased infiltration and/or reduced evapotranspiration, all increasing crop access to water.

In terms of climate change mitigation, besides potential increases on soil organic carbon stocks, improving the use efficiency of fertilizer can reduce the losses of fertilizer-derived greenhouse gasses, N_2O being the most important one.

In relation to human nutrition, the nutritional quality of crops and production systems in the context of ISFM can be improved by (i) integration of legumes of which the residues can be used as a source of organic matter to be applied with fertilizer and/or (ii) application of fertilizer or organic inputs with a relatively high concentration of human nutrition-related micronutrients.

Scaling of ISFM

Application of 'complete ISFM', including the general principles and local adaptation requires substantial knowledge. The abundance of agricultural technology solutions and the huge investments in information and communication technology being made into the agriculture sector suggest that there is recognition that such knowledge will eventually be transmitted via more effective and low-cost digital channels. However, there is still a relatively high level of asymmetry between the availability of tools and their effective use.

Despite all the complexities, clear wins are being made, which bodes well for taking ISFM solutions to scale, as illustrated by the reach and use of the AKILIMO site-specific fertilizer recommendation portal (www.akilimo.org). By the end of 2022, the partnership had grown to 244 organizations, of which 128 organizations actively use AKILIMO in their operations. 10,156 dissemination events had been registered by a total of 120 partners who integrated AKILIMO in their scaling strategies. We had trained a total of 7,289 extension agents of which 38% were female. We reached a total of 447,818 farmers of which 39% were female, and of which 274,584 are registered AKILIMO users. In Nigeria, 92% of registrants continue to actively use the tools versus 78% in Tanzania. In all, 49% fully and 39% partially apply the recommendations in their farms in Nigeria versus 23% and 64% respectively in Tanzania. We estimate that, by the end of 2022, AKILIMO recommendations were applied on over 350,000 ha of land across both countries, with an average yield increase of 21% and over US$55 million additional crop value generated.

Lastly, ISFM will not scale unless the knowledge on how to implement ISFM is accompanied by access to agro-inputs, finances and insurance, produce quality implements, and output markets. After all, ISFM advocates investing in agronomy and soil fertility management and sustaining such investments requires sufficient returns on those. Reference to 'bundled services' is commonly made and 'complete ISFM' will most likely be adopted in situations where such bundled services are provided. ■

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The Use and Impact of Multi-Nutrient Fertilizers in Kenyan Smallholder Cropping Systems

By Gavin Sulewski and Ivan S. Adolwa

Despite the documented advantages to multi-nutrient fertilizer application their use remains low across smallholder cropping systems in Kenya. A better understanding of the key influences that foster (and restrict) their use can chart a path for new ways to encourage innovation on-farm.

A host of important advantages are linked to the use of multi-nutrient fertilizers in Africa. Formulated and applied correctly, they go beyond the supply of nitrogen (N), phosphorus (P), and potassium (K) provided by conventional fertilizers, and they can begin to address the secondary and micronutrient deficiencies that are commonly left unmanaged in Africa's soils and contribute to poor crop productivity. Plus, their sustained use is known to enhance the quality of harvested crop products that help to generate the additional nutrient stocks needed to tackle diet related disorders and diseases, particularly in the most vulnerable, resource-poor rural areas.

However, there have been longstanding barriers to even the use of more conventional NPK fertilizers in Africa. These include those obstacles that shock regional supply chains with product unaffordability and unavailability. A lack of confidence in fertilizer effectiveness is another factor affecting use as farmers struggle with how best to manage nutrients in variable field landscapes and fluctuating climates.

Multi-nutrient fertilizers face greater challenges due to their relative newness in the market, higher costs, general unfamiliarity, and lack of agronomic support.

A research team in Kenya provides a pertinent case study

Experimental field showing a control/no fertilizer treatment (foreground), NP treatment (middle ground) and multi-nutrient (NPKSZn) treatment (background) in Embu, Kenya. Source: Authors

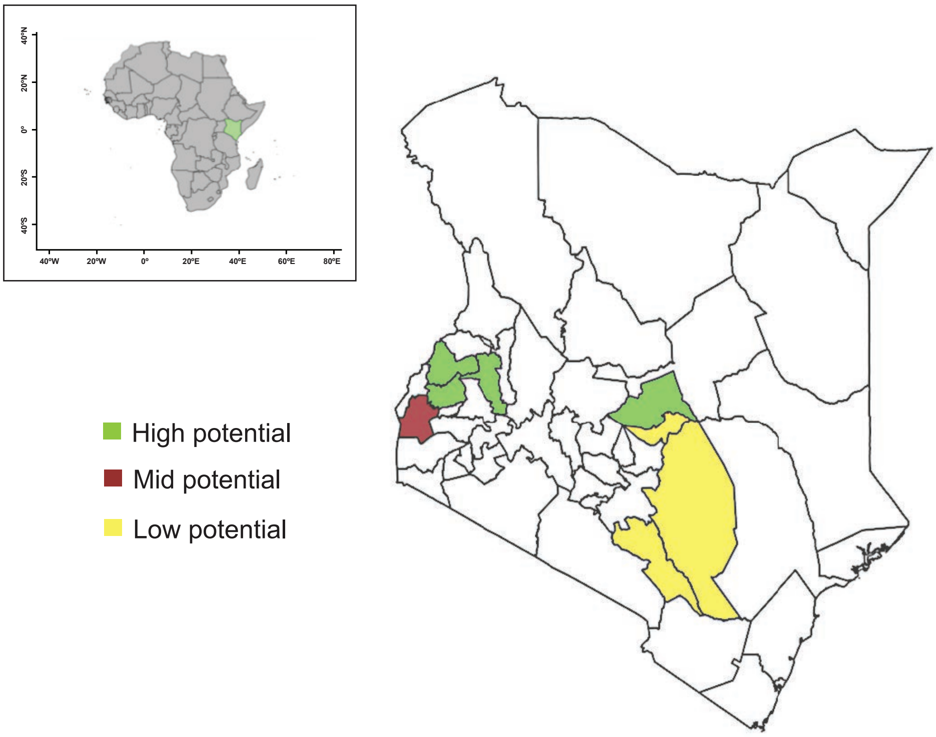

Figure 1. Selected Kenyan counties with agro-ecological zones (AEZs) classified as low, medium, or high potential. Source: Authors.

example on multi-nutrient fertilizer adoption, the subject of this article, through an assessment of the extent of their use in the country, and factors that are influencing their impact. Adolwa et al. (2023) studied the impact of local productive potential, household demographics and resource endowment, and accessibility to extension-based learning on conventional versus multi-nutrient fertilizer use. To gauge effectiveness, the group collected information on crop yields and profitability associated with fertilizer use for maize, potato and bean crops grown across selected counties in agro-ecological zones (AEZs) classified as having low, medium, or high productivity potential (**Fig. 1**). The study included over 1,000 smallholder farmer respondents from 8 counties including those participating (and not participating) within an ongoing on-farm demonstration network designed by the African Plant Nutrition Institute to inform farmers and extension officers about best management practices implemented by a unique system of participatory research and training. Researchers were interested in the range of crop yield responses, as well as the corresponding profitability, to blended multi-nutrient fertilizers in these smallholder farming systems.

Data found that most fields (89%) within high yield potential areas received regular applications of conventional NPK fertilizer types, but only 11% of fields received multi-nutrient fertilizer. By comparison, low potential AEZs were far less fertilized with 45% of fields receiving NPK sources and just over 1% having a history of a multi-nutrient fertilizer application. It was apparent that most fields, regardless of their AEZ, could not be considered as having adequate soil fertility status.

The study also found food security to vary significantly (i.e., 16% to 98% of households considered themselves food secure across the 8 counties surveyed), but food security was lowest amongst low AEZ counties. Regardless, food insecurity was commonplace in spite of AEZ classification since data from 4 out of 8 counties

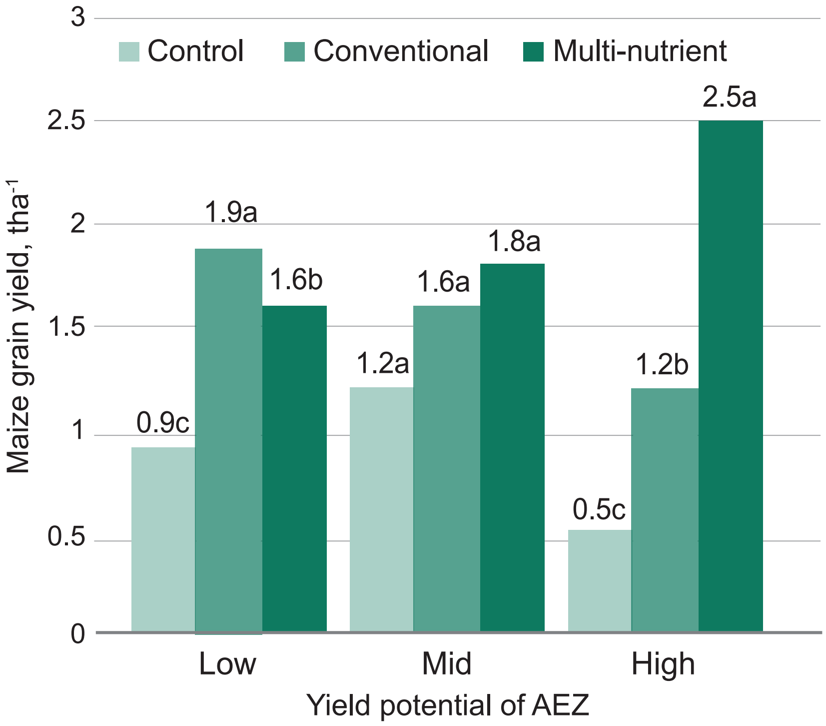

Figure 2. Maize grain yield response (t/ha) to conventional and multi-nutrient fertilizers in different agro-ecological zones (AEZs). Source: Authors.

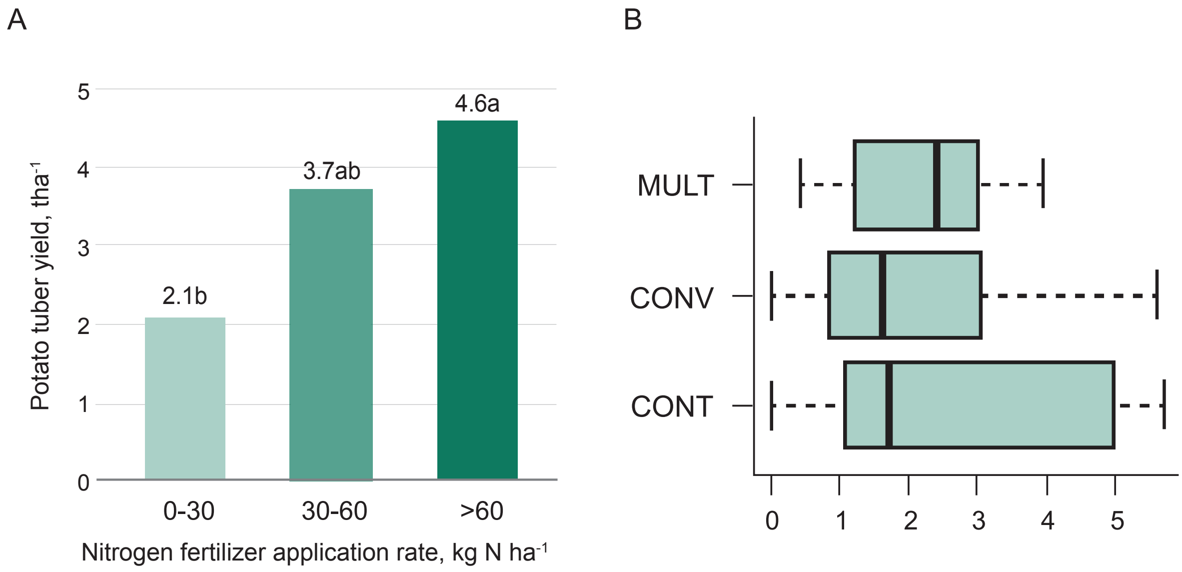

Figure 3 A. Potato yield response (t ha^{-1}) across nitrogen application rates (kg N ha^{-1}). **B.** Benefit Cost Ratio distribution for potato cropping with multi-nutrient (MULT) or conventional (CONV) fertilizers, and where fertilizer is not applied (CONT). Source: Authors

showed that >50% of surveyed households were food insecure.

Where applied in maize, and despite their infrequent use, researchers detected significantly higher grain yield with multi-nutrient fertilizers compared to unfertilized controls (**Fig. 2**). Multi-nutrient fertilizers were particularly effective in AEZs with high yield potential (i.e., 108% greater yields compared to conventional NPK fertilizer).

Profitability for multi-nutrient fertilizers in maize was found to be breakeven at best, however, there is potential for this situation to change given more experience amongst farmers and the right kind of extension interactions and interventions that can encourage success. An example of this is highlighted from the potato cropping data where NPK fertilizer was found most effective in high yielding AEZs compared to crops receiving multi-nutrient sources (**Fig. 3**). However, a closer look revealed that the underperformance of multi-nutrient fertilizers was most likely an artifact of a general lack of understanding by farmers of how best to use these less familiar and under supported products. For example, the authors point out cases where "*responses to multi-nutrient fertilizers may have been masked by the fact that farmers tend to replace conventional fertilizers with multi-nutrient fertilizers on a bag-to-bag basis, when it was evident that the latter had lower basal N content per bag.*" In fact, data showed that in cases where multi-nutrient sources provided potato crops with more N, greater than 30 kg/ha, this yield barrier was lifted, and the comparative advantage of multi-nutrient fertilizers became evident even in terms of profitability. In bean crops, data was characterized as inconclusive for this study; however, yield advantages were found for farmers situated in the low-yielding AEZs.

> " Going forward, similar assessments undergirded by farmer-centric experimentation need to be encouraged for in-depth understanding of the underlying factors behind adoption of multi-nutrient and conventional fertilizers and their contributions towards food and nutrition security in Kenya.

Key characteristics that had a positive influence on multi-nutrient fertilizer adoption reflected dominant gender roles such as male household leadership, household dynamics leading to fewer adult members, and smaller livestock herds generating smaller stockpiles of farmyard manure. Important comparative advantages include location (i.e., being situated within zones of higher productivity potential), higher monthly expenditures with better access to credit, increased access to nutrition-based information, and higher food security status. Interestingly, the influence of past efforts to improve fertilizer use through past methods of technology transfer and extension came across as not being a significant influence amongst the farmers included in the study.

In relation to this last key point, the authors closed their analysis by strongly emphasizing that future efforts for capacity building through identifying and evaluating fertilizer technologies and management innovations, like the inclusion of multi-nutrient fertilizers, need to solidly secure the engagement of farmers to establish an iterative cycle of participatory learning, feedback, and progressively building upon the knowledge gained. ■

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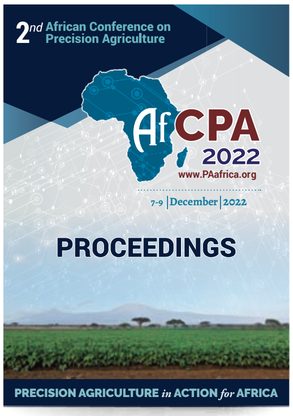

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PRECISION AGRICULTURE in ACTION for AFRICA

The Implication of Soil Acidity and Management Options for Sustainable Crop Production in Africa

By Shamie Zingore, Temesgen Desalegn, Asseta Diallo, Tialhun Amede, Samuel Njoroge, Madani Diallo, Lilian Wanjiru, and Øystein Botillen

Acidic soils are widespread in Africa and present a major crop production challenge in a region faced with multiple climatic and soil constraints. Effective management recommendations in line with the 4Rs of lime management (Right Source, Rate, Time, and Place) are necessary for optimizing the agronomic and economic benefits of lime at the farm-level. In addition, policies and incentives are needed to develop viable lime supply chains.

The soil degradation challenge in sub-Saharan Africa

Soil degradation is recognized as a major underlying factor for both low crop productivity and high prevalence of malnutrition in sub-Saharan Africa (SSA) (Sanchez et al., 2002). It affects the majority of the 60% of Africans who directly depend on agriculture for food and income. Soil degradation in cropping systems is driven by suboptimal management practices that induce declines in soil biological, chemical, and physical quality, and reduce soil's capacity to support production and environmental functions. About 65% of the land area in SSA is classified as degraded (Vlek et al., 2008). Degraded soil accounts for about 350 million (M) ha or 20-25% of the total land area, of which about 100 M ha is estimated to be severely degraded mainly due to agricultural activities. Soil degradation costs SSA approximately \$68 billion (B) yr^{-1} and reduces the regional annual agricultural gross domestic product (GDP) by 3%.

The major constraints associated with degraded soils in SSA include aluminum (Al) toxicity, low cation exchange capacity, soil erosion, shallow soil depth, high phosphorus (P) fixation, vertic properties, salinity, and sodicity (**Fig. 1**). It has long been recognized that soil acidity is one of the most serious challenges to agricultural production worldwide in general. Limitations associated with soil acidity, including Al toxicity and high P-fixation, are pervasive in SSA.

The status of soil acidity in SSA

In SSA, acid soils occupy > 15% of the total land area, and the problem is expanding both in area and severity (Agegnehu et al., 2021). The major drivers of soil acidity are parent material, climate, vegetation, landscape position, atmospheric depositions, nutrient mining, and management. Soil acidity develops on old, stable surfaces exposed to tropical weathering. Acid soils

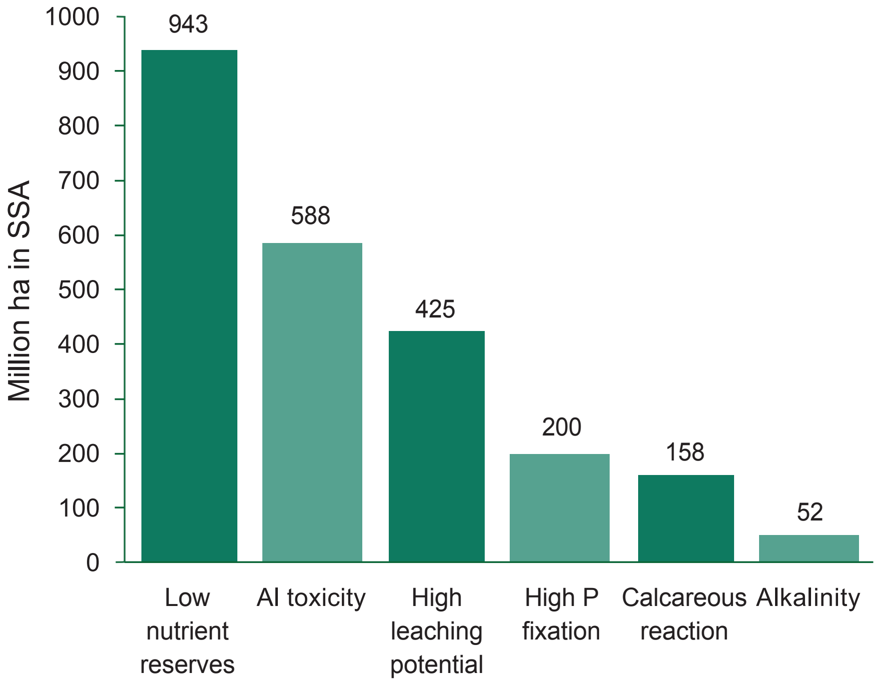


Figure 1. Major soil quality problems in sub-Saharan Africa and their distribution (adapted from Tully et al. 2015).

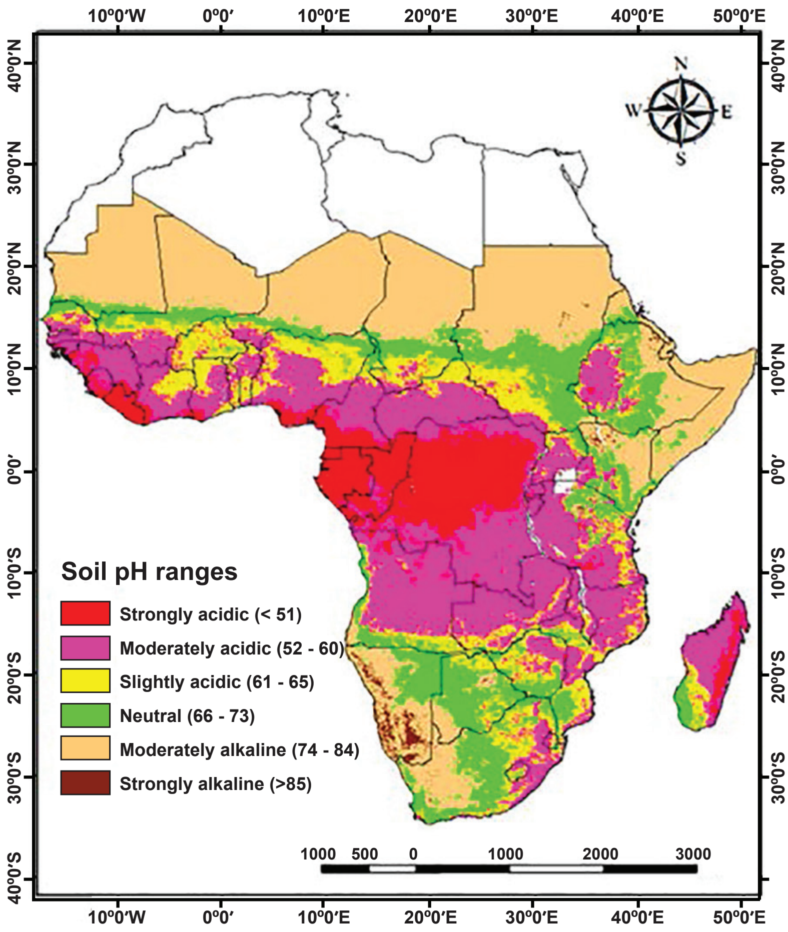


Figure 2. Distribution of acidic soils in sub-Saharan Africa (Leenaars et al. 2014).

predominantly occur in humid and sub-humid regions in SSA (**Fig. 2**). In these regions, frequent heavy rains cause rapid nutrient leaching and soil chemical weathering. The main soil types affected by acidity in SSA are Ferralsols (covering 312 M ha), Acrisols (88 M ha), Alisols (20 M ha), and Nitisols (60 M ha). Management-induced acidity is often caused by unbalanced fertilization (e.g., continuous application of high rates of N fertilizers), continuous cropping without organic inputs, and lack of soil conservation measures resulting in soil erosion. Notably, fertilizer-induced acidity is not widespread in SSA due to low fertilizer application.

Soil acidity is severe in areas where annual precipitation exceeds evapotranspiration and is a leading cause of low agricultural productivity. Crop productivity is constrained in acidic soils due to their poor fertility, P fixation, Al toxicity, and fragile structure. A significant limitation on acidic soils is P fixation caused primarily by a high concentration of Al and Fe oxides and hydroxides, which fix phosphate ions in forms that are unavailable to plants. This causes P deficiency that is difficult to overcome, since added phosphate fertilizers rapidly become fixed in the soil. Over 820 M ha of land area in SSA experiences high P fixation problems. Soil acidity reduces crop yields by about 10% in tropical areas (Sierra et al., 2003), and in Kenya, acidic soils are estimated to reduce yields by 16-28% (Ligeyo, 2007; AGRA, GBD, 2016). Considering the occurrence of acidic soils and potential to increase productivity with liming and other appropriate management practices, acid soils have become a subject of high priority for agricultural research and development in SSA.

The negative spiral of soil acidity and low crop productivity

Although crops vary widely in their tolerances to soil acidity, severe soil acidity has been shown to limit even highly acid-tolerant crops. The following are the specific detrimental effects of soil acidity on crop productivity:

Aluminum and manganese toxicities: Al and manganese (Mn) are toxic to plant roots and result in poor root development. This results in poor water and nutrient uptake. During low rainfall seasons, Al toxicity magnifies the effects of drought. However, the extent of Al toxicity to roots depends on the relative quantities of Al and bases [principally calcium (Ca) and magnesium (Mg)]. For this reason, the soil acid saturation index is a more reliable indicator of the Al toxicity hazard than soil pH.

Deficiencies of calcium and magnesium: Levels of Ca and Mg in acid soils are often very low and may limit plant growth. Adequate supplies of Ca in the soil are particularly critical for root growth. The combination of high Al and deficient Ca concentrations in subsoil is a common yield-limiting factor.

Fixation of phosphorus: Acid soils also have high P fixing capacity. Hence, a large proportion of the P applied as fertilizers in acidic soils are not available for crop uptake. Low P availability to crops is cited as a major factor limiting crop production on acid soils (Desalegn et al., 2016). Phosphorus deficiencies and Al toxicities often occur simultaneously in many acid soils and combine to exacerbate poor yields in acid soils.

Micronutrient deficiencies: Deficiencies of some micronutrients, in particular molybdenum (Mo), frequently limit plant growth on acid soils. In the case of Mo, most soils contain adequate reserves of this nutrient for plant growth, but its availability for plant uptake is severely reduced under acidic conditions.

Soil biological activity: Acidic soil conditions negatively impact soil biological activity. Al toxicity and acidity suppress microbial activity and nutrient cycling (Kunito et al., 2016). Soil acidity also affects other soil organisms, including most earthworm species, resulting in reduced soil biodiversity and bioactivity.

Management of soil acidity

Soil acidification is a natural process that can be amplified by human activity or controlled by appropriate soil management practices. Several agricultural practices have been recommended to overcome the problem of tropical acidic soil infertility worldwide. The main methods include liming, use of organic inputs, planting low pH-tolerant crops, crop rotation, and balanced and effective fertilizer management (**Fig. 3**). An integrated management approach that uses multiple complementary technologies offers the most effective strategy for correcting soil acidity.

Liming

Applying agricultural lime is one of the most effective ways to reduce soil acidity and increase crop productivity (AGRA, GBD, 2016). The main sources of lime material include ground Ca and/or Mg carbonates and hydroxides. Applications of lime at appropriate rates and timings can have an immediately positive effect on soil pH and soil physical, chemical, and biological properties. The most economical and relatively easy to manage liming materials are calcitic or dolomitic agricultural limestone. Calcitic limestone is mostly calcium carbonate ($CaCO_3$), while dolomitic limestone is usually more desirable since it has a mixture of Ca and Mg carbonates ($CaCO_3+MgCO_3$). Other liming materials include burned lime (CaO), hydrated lime ($Ca(OH)_2$), and wood ashes.

The main benefits of liming include: (i) increased available P through precipitation of exchangeable and soluble Al and Fe hydroxides; (ii) increased exchangeable cations and percent base saturation; (iii) increased density and length of root systems and enhanced uptake of nutrients and water; and (iv) stimulation of microbial and biological activities that lead to enhanced N-fixation by legumes and greater N mineralization. These benefits of lime depend on various 4Rs of lime management including the following key considerations:

Right Source: Lime requirements are often expressed in terms of effective calcium carbonate equivalent, which is based upon two criteria: (i) the purity of the lime, determined by the calcium carbonate content in the lime material, and (ii) the fineness of the lime material, determined by how much it is ground (Ritchey et al., 2016).

Right Rate: Liming rates depend on the site-specific conditions including soil pH, desired pH, and soil texture.

Figure 3. Using lime on acidic soils, along with other good agricultural practices, can significantly increase crop productivity (Mbakaya et al., 2010; in AGRA, GBD, 2016).

Right Time: Lime should be applied at least three months before planting season for sufficient reaction time.

Right Place: Reaction of lime is also accelerated when lime in incorporated well mixed in the soil.

Using organic inputs

Increasing soil organic matter (SOM) through application of green manure, farmyard manure, compost, biochar, and crop residues buffer soil pH while also enhancing soil fertility (Agegnehu et al., 2021). A growing body of evidence shows that organic inputs promote microbial activity, improves soil structure, nutrient retention, and water holding capacity. The organic acids from these inputs can form stable complexes with Al and Fe, thereby blocking the P retention sites. Therefore, regular application of organic inputs can reduce soil acidification. Application of lime along with improved SOM has been shown to enhance nutrient use efficiency (NUE) of fertilizer applied to cereal crops in Ethiopia (Amede and Diallo, 2022).

Growing low pH-tolerant crops

The two distinct classes of Al tolerance mechanisms are those that operate to exclude Al from the root apex and those that allow the plant to tolerate Al accumulation in the roots and shoots. Crops with a high soil acidity tolerance include rice, wheat, potatoes, cowpea, and maize among others (Agegnehu et al., 2021). The Ethiopian Institute of Agricultural Research (EIAR) has successfully released acid-tolerant crop varieties for bread wheat, food oats, sweet lupin, and triticale through its intensive breeding program.

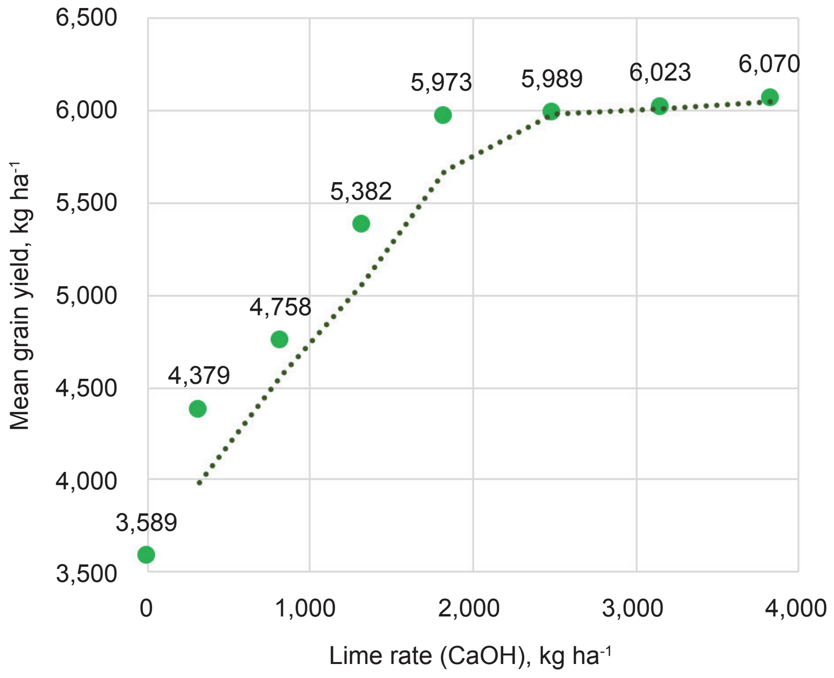


Figure 4. Grain yield increase with increased rate of lime (Desalegn and Dawit, 2022).

Using appropriate fertilizers

Applying the right source of fertilizer at the right rate, time, and place is a critical element of managing acid soils. For example, ammonium-based fertilizers can increase soil acidity as they generate H^+ ions when ammonium (NH_4^+) molecules are oxidized. Nitrate and sulphate-based fertilizers can also acidify soils due to nitrate (NO_3^-) and sulphate (SO_4^{2-}) leaching that is accompanied by exchangeable bases. Fertilizers containing Ca and Mg are less acidifying.

Agegnehu et al. (2021) provides examples of yield improvement in barley, beans, faba beans, potato, soybean, teff, and wheat with liming and complementary inputs over experimental control treatments in Ethiopia. Adequate liming increased maize and wheat yields by about 70% compared to recommended NPK fertilizer rates alone. Another study conducted in the central highlands of Ethiopia using different rates of lime and P fertilizer showed that liming at 1.65 t ha^{-1} gave a 133% yield advantage over the control (Desalegn, 2010). Similar experiments conducted in southeastern Ethiopia to validate modeled lime requirements found that yield increases due to liming can be very high with incremental lime rates (**Fig. 4**) if soil nutrients are not limiting and agronomic management is optimized. Similarly, Hijbeek et al. (2021) reported consistent increases in maize yields in Kenya due to liming, but associated profits were only positive if NP fertilizer was included and returns on liming investments were positive only after at least two years.

Achieving impact with lime at scale in SSA

The critical role of liming to mitigate soil acidity and reduce phytotoxic levels of Al and Mn has been well-researched and widely documented. Liming has achieved substantial yield gains in several countries. However, there is a need for identifying areas where lime application brings significant change and benefit in crop yield. For example, about 43% of the cultivated land in Ethiopia is acidic, of which 28% is strongly acidic. About 9 M t of lime is required to amend only the strongly acidic areas in Ethiopia. Accurate information is lacking in most countries on the area requiring liming.

Initiatives such as GAIA (Guiding Acid Soil Management Investments in Africa - https://www.cimmyt.org/projects/gaia), implemented in Ethiopia, Kenya, Rwanda, and Tanzania by CIMMYT in partnership with national research institutions and international organizations, is developing data-driven and spatially explicit recommendations for the rehabilitation of acid soils in smallholder farming systems. GAIA's overall goal is to increase returns on investment for all stakeholders in the lime sector including farmers, private entities, and Government. Initial results show a potential lime requirement of 50-96 M t across the four countries. There are, however, several challenges on the demand side including limited demand from farmers, limited financing, and high costs of production and distribution. Analysis conducted at the regional level show that the ROI for liming at the farm level varies substantially between countries, depending on crop types (**Fig. 5**). Agronomic trials suggest that legumes are currently more responsive to liming than cereal crops, and that the greatest economic returns to lime are achieved with a relatively low (1 t ha^{-1}) lime rate.

To develop viable lime value chains, there is need to stimulate a level of demand within the crop production systems that can support high ROIs in the lime value chain to reduce key logistical costs, such as transport. There is also need to build functional markets and enact supportive policies on taxes, land, investments, and standards among others.

Empowering soil acidity management

The fertilizer industry is working with stakeholders to remove the barriers to expanding soil acidity management. In Tanzania, lime use is still very limited, and it is a challenge to make it available to farmers in an affordable manner. Private-Public partnerships (PPPs) like the one formed in 2016 between Yara, the Southern Agricultural Growth Corridor of Tanzania (SAGCOT), Tanzania

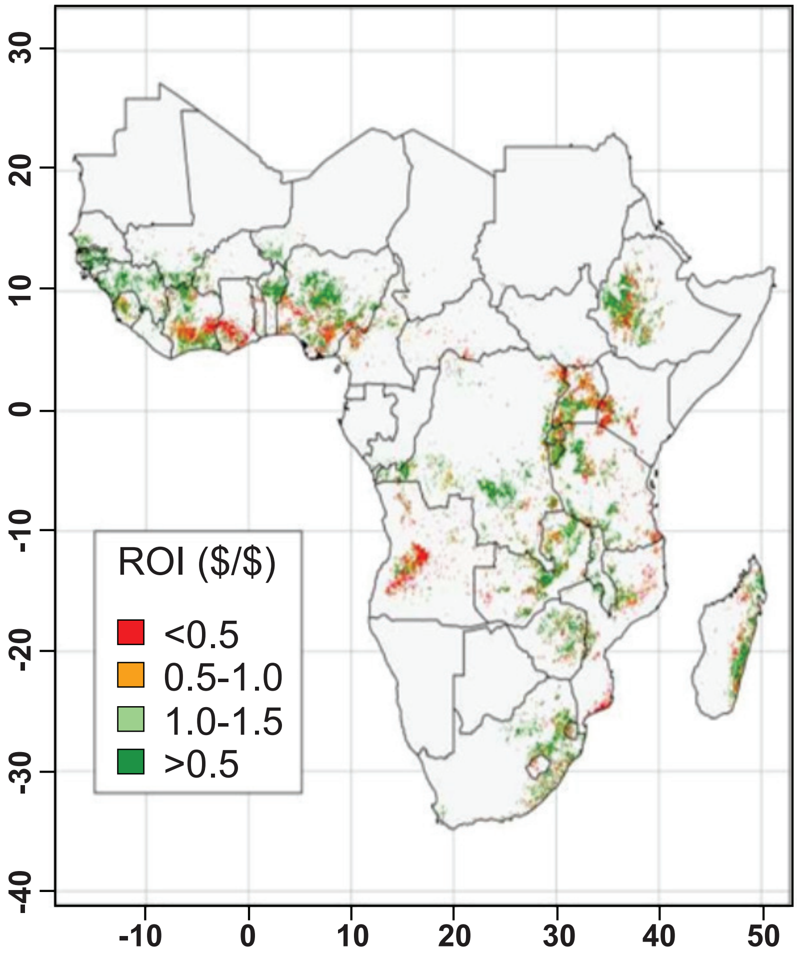
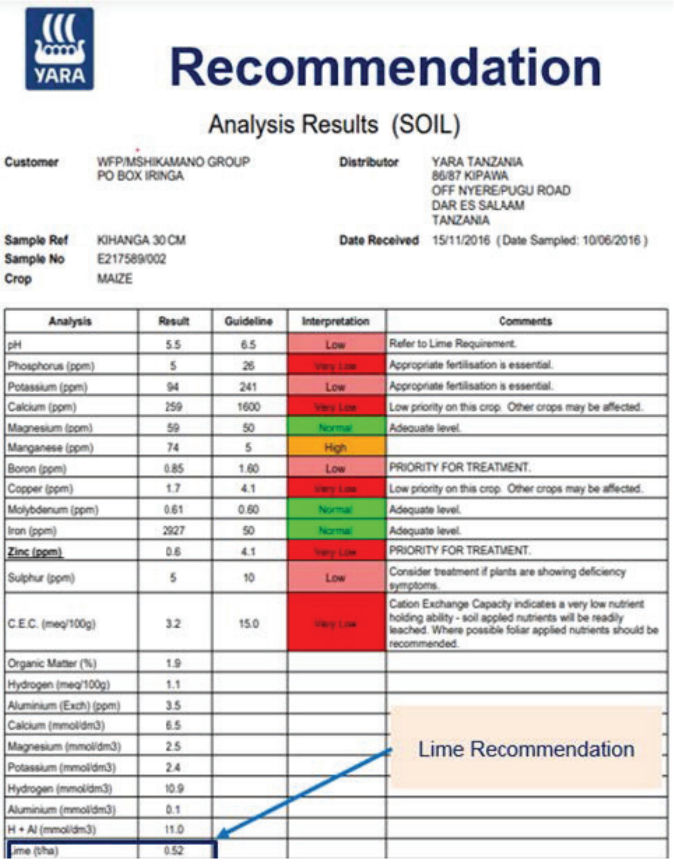


Figure 5. Returns on investments (ROI) to liming in SSA countries (GAIA project). Crop prices were based on average FAO prices across SSA. Lime requirement was based on Kamprath (1970). Lime price = US$100 t ha^{-1}. ROI = sum of returns from extra production of all crops in a pixel divided by the lime requirement in that pixel times the lime price.

Agricultural Development Bank (TADB), and Uyole Agricultural Research Institute brought together the key stakeholders needed to coordinate the implementation of, for example, field demonstrations and trials in Mbozi and Mbeya Districts.

At the farm level, it is important to ensure that a lime recommendation is part of a soil analysis report (**Fig. 6**), and it is further supported by farmer/distributor awareness sessions, digital tools such as *AfricaConnect* and *FarmCare*, dependable access to lime and fertilizer supply chains, and policy lobbying and advocacy for widespread adoption of liming.



Recommendation

Analysis Results (SOIL)

Customer	WFP/MSHIKAMANO GROUP PO BOX IRINGA	**Distributor**	YARA TANZANIA 86/87 KIPAWA OFF NYERE/PUGU ROAD DAR ES SALAAM TANZANIA
Sample Ref	KIHANGA 30 CM	**Date Received**	15/11/2016 (Date Sampled: 10/06/2016)
Sample No	E217589/002		
Crop	MAIZE		

Analysis	Result	Guideline	Interpretation	Comments
pH	5.5	6.5	Low	Refer to Lime Requirement.
Phosphorus (ppm)	5	26	Very Low	Appropriate fertilisation is essential.
Potassium (ppm)	94	241	Low	Appropriate fertilisation is essential.
Calcium (ppm)	259	1600	Very Low	Low priority on this crop. Other crops may be affected.
Magnesium (ppm)	59	50	Normal	Adequate level.
Manganese (ppm)	74	5	High	
Boron (ppm)	0.85	1.60	Low	PRIORITY FOR TREATMENT.
Copper (ppm)	1.7	4.1	Very Low	Low priority on this crop. Other crops may be affected.
Molybdenum (ppm)	0.61	0.60	Normal	Adequate level.
Iron (ppm)	2927	50	Normal	Adequate level.
Zinc (ppm)	0.6	4.1	Very Low	PRIORITY FOR TREATMENT.
Sulphur (ppm)	5	10	Low	Consider treatment if plants are showing deficiency symptoms.
C.E.C. (meq/100g)	3.2	15.0	Very Low	Cation Exchange Capacity indicates a very low nutrient holding ability - soil applied nutrients will be readily leached. Where possible foliar applied nutrients should be recommended.
Organic Matter (%)	1.9			
Hydrogen (meq/100g)	1.1			
Aluminium (Exch) (ppm)	3.5			
Calcium (mmol/dm3)	6.5			
Magnesium (mmol/dm3)	2.5			
Potassium (mmol/dm3)	2.4			
Hydrogen (mmol/dm3)	10.9			
Aluminium (mmol/dm3)	0.1			
H + Al (mmol/dm3)	11.0			
ime (t/ha)	0.52			

Figure 6. Yara fertilizer and lime recommendation in Tanzania based on soil analysis (Megalab, Pocklington).

In Kenya, the private sector and farmers face challenges that restrict lime market development and use including the lack of clear quality regulations guidelines and standards for agricultural lime, lack of a coordinated nationwide lime promotion program and limited incentives to support the production, distribution, and use of agricultural lime, among others. The government of Kenya recently established its liming flagship program with a first phase of four years. However, further support for private sector participation and promotion of liming, including soil analysis, will be needed for long-term sustainability of the liming program.

In Mali, Quarries and Lime of Mali (CCM), established in 2010 to produce and supply dolomitic lime in West Africa, provides a rapid and cost-effective soil acidity testing kit that is used locally by farmers to test for soil pH and site-specific lime requirements. The soil pH test kit uses litmus paper and a cheap container (glass or half plastic bottle) of 100 ml of water. Soil and water are mixed 1:1 and the litmus paper is soaked into the mixture to reveal a color that is compared with a standardized pH scale.

The litmus paper is available in booklets of 40 to 80 strips at a cost of less than $1 per booklet. This cheap and simple method enables farmers to adapt the test method to their region by first defining the pH of test water, and then determining their lime requirement.

Specific recommendations for improved soil acidity management include:

1. Building PPPs for long-term coordinated and harmonized lime market development and demand creation at the farm-level, targeting the regions most affected by soil acidity,
2. Research on liming management options, including source, rate, time, and place to develop innovations for effective lime use on-farm, and
3. Standards for lime quality and labeling of lime products to help farmers make the right choice.

Trials done in the Sikasso region of Mali in the cotton (CMDT) and cereal [Mali Office Haute Vallée du Niger (OHVN)] production areas with the Institut d'Economie Rurale (IER) show yield improvement with liming compared to fields without lime [e.g., in cotton (1,303-1,818 kg ha^{-1}; +39%), sorghum (704-1,139 kg ha^{-1}; +62%), and maize (1,239-1,849 kg ha^{-1}; +49%)].

Policy, incentives, and potential: Lessons from Brazil

The Brazilian experience provides an excellent example of acid soil management and valuable lessons for SSA. Brazil has developed over 60 M ha of

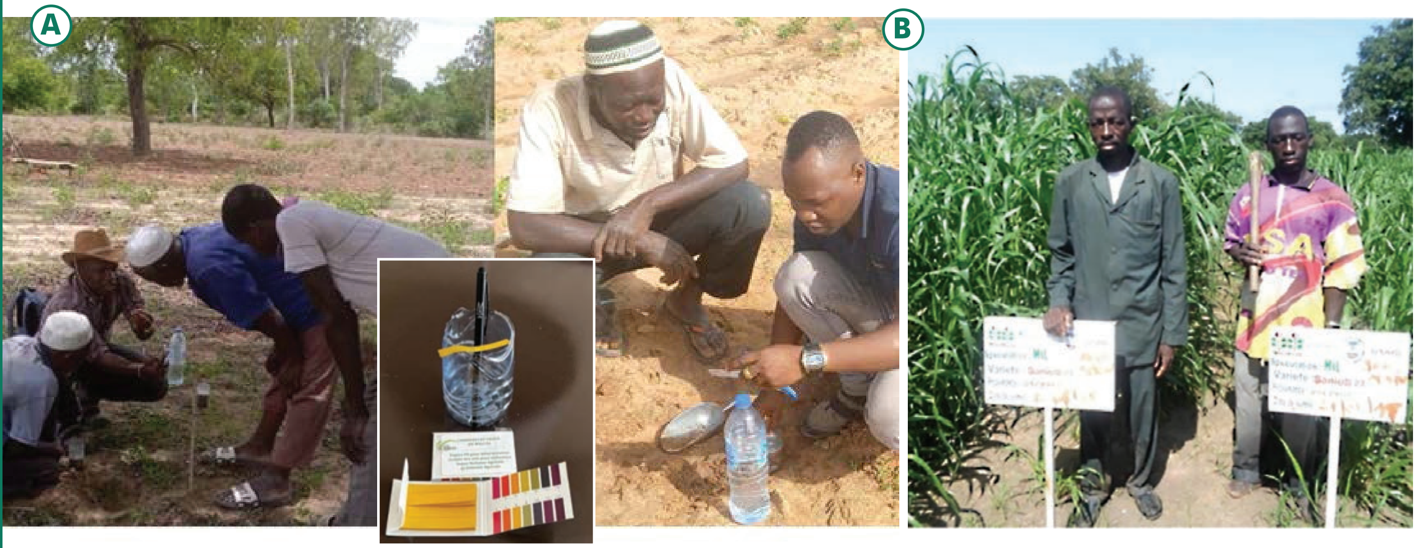


Figure 7. A. Process of defining the soil acidity by farmers in Mali as advised by CCM-SA. Materials include a half plastic bottle + (soil + water @1:1) + stick + litmus paper strip. **B.** Field with liming (left), field without (right) in Sikasso région, Mali.

acid soils (pH of 4.8-5.1) in the Cerrado with the implementation of appropriate technologies and inputs, infrastructure, and policy support. These soils are also deficient in many essential plant nutrients including P, K, Ca, Mg, and sulfur (S). Until the 1970s, the Cerrado was of limited value for agricultural production. Liming for a base saturation of 50% together with corrective and maintenance application of PKS and micronutrients transformed the region into one of the bread baskets of the world today. This was made possible by public investments in agricultural research and development, rural credit, and price support, and land-tenure policies supportive of both large-scale and smallholder farmers.

It is important for countries to continue to formulate appropriate policies including land tenure policies supportive of long-term investment in lime by commercial as well as smallholder farmers. Fiscal incentives (e.g., income tax exemptions, subsidies) should also be formulated to support private investment in acid soil management. Developing national and regional standards and guidelines will ensure the quality and proper use for better returns on investments. ■

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