Fertilizer and Soil Health in Africa

THE ROLE OF FERTILIZER IN BUILDING SOIL HEALTH TO SUSTAIN FARMING AND ADDRESS CLIMATE CHANGE

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Fertilizer and Soil Health in Africa: The Role of Fertilizer in Building Soil Health to Sustain Farming and Address Climate Change

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Contents

Acronyms

AE	agronomic efficiency
AfSIS	Africa Soil Information Service
BNF	biological nitrogen fixation
CA	conservation agriculture
CEC	cation exchange capacity
DAP	diammonium phosphate
FAIR	findable, accessible, interoperable, and reusable
FUE	fertilizer use efficiency
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographic information system
IFDC	International Fertilizer Development Center
INS	indigenous nutrient supply
ISFM	integrated soil fertility management
LEISA	low-external-input sustainable agriculture
NGO	non-governmental organization
NUE	nutrient use efficiency
SDG	Sustainable Development Goal
SMNs	secondary and micronutrients
SOC	soil organic carbon
SSA	sub-Saharan Africa
SSNM	site-specific nutrient management
SSP	single superphosphage
TSBF	Tropical Soil Biology and Fertility
TSP	triple superphosphate
WUE	water use efficiency

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Summary

Soil health is commonly defined as the ability to generate sufficient crop yields while maintaining the future productive capacity of soils and the ecosystem services soils regulate and deliver. However, less consensus exists on indicators to assess soil health and its changes over time and space, although soil organic carbon (SOC) is generally acknowledged as a key indicator. In the context of this paper, soil health status is equated with SOC status. Current SOC conditions are influenced by soil properties and climate. Under smallholder farming conditions, SOC is variable and affected by past crop and soil management practices, which are influenced by farmer typology. Although SOC content under cropland is a maximum of 60-70% of that under natural vegetation, there is substantial scope to increase it in smallholder farming conditions.

A conceptual framework relating to fertilizer, crop productivity, and soil health is presented here. While fertilizer application commonly results in a substantial increase in crop yield at various scales, a key indicator of fertilizer use, agronomic efficiency (AE), is often observed to be lower than relatively easily achievable values under well-managed conditions, caused by a diversity of factors. Low AE values do not necessarily result in greater greenhouse gas (GHG) emissions because of the low fertilizer application rates in sub-Saharan Africa (SSA), though increases in GHG emissions are likely with increases in fertilizer use.

Crop response to organic inputs is substantially lower although organic inputs increase SOC content, which usually results in greater AE values relative to sole application of fertilizer. Increases in crop productivity are associated with increases in SOC, though the relationship is weak and efforts besides fertilizer application itself are required. That said, N(PK) fertilizer has had a positive effect on SOC in most parts of the world except SSA, an observation corroborated by an analysis of past and ongoing long-term experiments, likely related to the low and erratic use of fertilizer in the region. While fertilizer use can be an entry point to increasing soil health, this will not likely happen on degraded soils where responses to fertilizer are limited. In such cases, investments to rehabilitate degraded soils should come first.

Several approaches can be followed to determine best fertilizer recommendations, while recognizing nutrients needs by crops and soil-specific properties. Site-specificity commonly requires an assessment of the soil fertility status of a particular field, and analytical tools now allow for the development of locally relevant recommendations at scale with some early successes. While organic inputs do positively impact SOC, attractive options to increase organic inputs in smallholder farming systems are limited and mostly related to in-situ production, with an important emphasis on multi-purpose legumes. Climate adaptation is facilitated by healthy

soils and requires fertilizer to be combined with other crop, soil, and water management practices (Wortmann and Stewart, 2021).

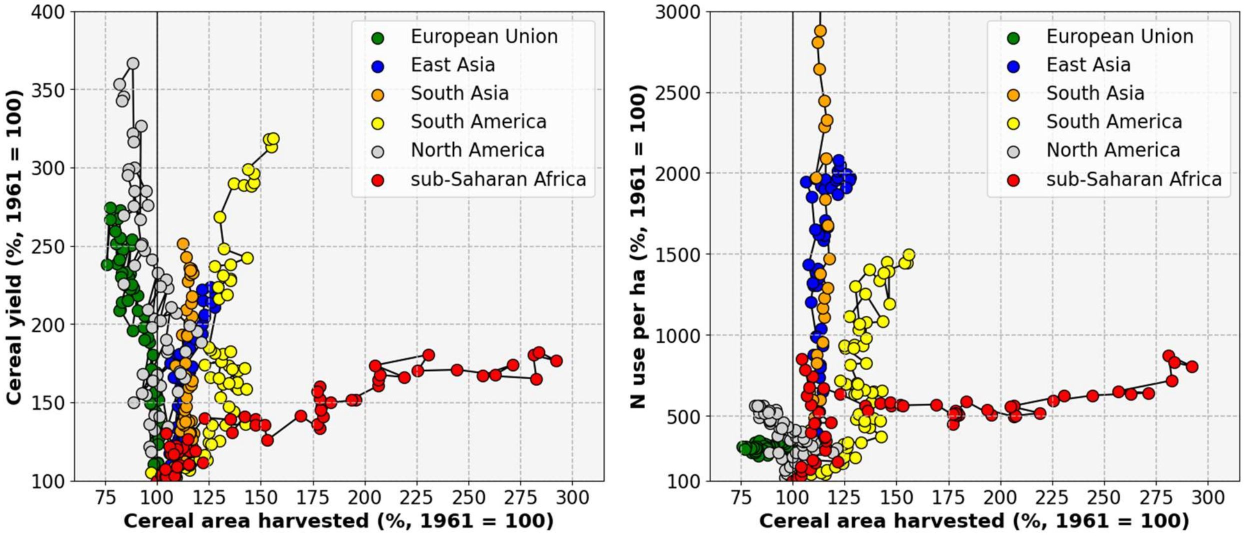
While low yields are linked to the ecological yield gap, whereby the potential productivity of crops is set by biological factors, input and output prices determine the economic yield gap, which is usually quite lower than the former because of unfavorable ratio of fertilizer prices to crop product prices. Even though profitability is a key driver of impact, many other factors affect the adoption of appropriate fertilizer and soil health recommendations, including farmers' production objectives, resource endowment, land tenure, and access to markets.

A main bottleneck in engaging smallholder farmers in soil health-restoring practices is the relatively large amount of time such practices take to deliver benefits that are visible to farmers. In the absence of incentive programs, farmers require short-term benefits, generated within their farming systems. Furthermore, associated advice on complementary practices to fertilizer use increases the complexity of information to be conveyed to farmers. Scaling models have moved toward the delivery of bundled services, often digitally enabled, to address challenges with communicating complex information and the necessary complementary crop and soil management practices. Targeted policy interventions can support the delivery of broad digitally enabled fertilizer management recommendations and the creation of conditions that enable smallholder farmers to implement these recommendations at scale.

A number of recommendations have been generated from the scientific information, covered under the following headings: (1) key elements of a Fertilizer and Soil Health Action Plan; (2) development of quantitative indicators and targets of soil health; (3) addressing climate change requires choices; (4) incentivizing farmers; (5) soil health investments, which require localized actions (think global, act local); and (6) not only fertilizers, but also auxiliary interventions, as defined by the Integrated Soil Fertility Management (ISFM) approach. Action is needed today to reverse the downward spiral of low and inefficient fertilizer use, resulting in low yields and declining soil health.

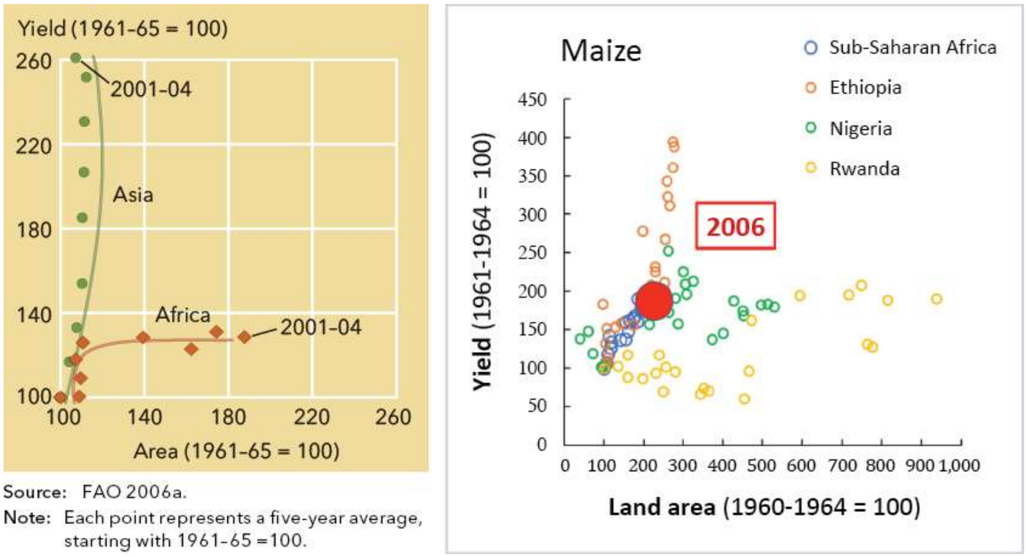
1 Background and Objectives

The urgent need to increase agricultural production in SSA to ensure food and nutrition security of the growing population has been widely acknowledged (van Ittersum et al., 2016). If intensification is not successful and massive cropland expansion is to be avoided, SSA will come to depend much more on imports of cereals than it does today. In 2004, Kofi Annan (UN, 2004) called for a uniquely African Green Revolution to take root within the rich diversity of the continent in terms of history, culture, and agroecological conditions (soils and climate), based on a report by the InterAcademy Council (2004). His ambitious vision was to draw on existing, proven technologies for increasing agricultural production to address hunger, nutrition, poverty, soil health, and infrastructure. In 2006, the African Union, through the *Abuja Declaration on Fertilizer for an African Green Revolution* (AfDB, 2006), recognized the critical need to enhance access to fertilizer to achieve this African Green Revolution, given the poverty trap caused by poor and declining soil fertility. Yet, progress has been slow and the problem remains, often resulting in a per capita yield decline for many countries in SSA. In contrast with other continents, cereal yields in Africa have stagnated and food production has increased largely through an expansion of the area under agriculture (Figure 1a). Increased fertilizer use has undoubtedly been a major factor contributing to the marked increases in cereal yield, as the two have gone hand in hand (Figure 1b). Erisman et al. (2008) estimated that 50% of the current world population is fed thanks to fertilizers. By contrast, the food requirements of the increasing population of Africa as a whole have been largely met through land expansion and grain import. Fertilizer use in Africa increased rapidly in the 1960s and 1970s, albeit from a very small base, but both crop yields and fertilizer use stagnated in the late 1980s (Figure 1b).



Analysis by João Vasco Silva, based on FAOSTAT.

Figure 1. Past intensification and area expansion trajectories of staple cereal production across different regions of the world: (a) cereal yields by percentage of cereal area harvested (Giller et al., 2021); (b) N use per hectare per percentage of cereal area harvested. Data is shown in relation to the base year of 1961 and the lines track the trajectory from year to year.



Source: FAO 2006a.
Note: Each point represents a five-year average, starting with 1961-65 =100.

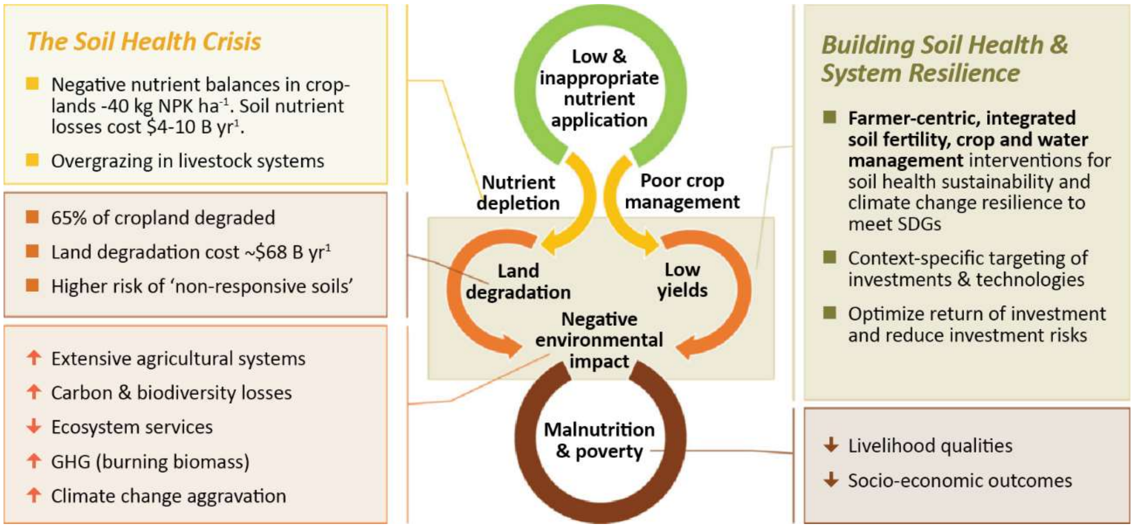
Source: FAOSTAT (https://www.fao.org/faostat/).

Figure 2. Relative changes in grain yield and land area used for growing cereals (rice, wheat, maize, barley, sorghum, and millet) in Asia and Africa (left; World Bank, 2007), and in selected countries of sub-Saharan Africa (right). The red dot in the right graph refers to the 2006 Abuja Fertilizer Summit. Data shown in the right graph are five-year averages for 1961-2015 and the three-year average for the period 2016-2018. The average of 1961-1965 was set as 100.

Notwithstanding disappointing continent-wide figures, some countries in Africa have moved toward a trajectory similar to that of Asia, with increased yields generated mainly on the same acreage of agricultural land, driven by increased fertilizer use. Some countries have approached or actually reached the Abuja target of 50 kg of fertilizer nutrients per hectare (Figure 2).

Soil degradation is a major factor underlying the low crop productivity and high prevalence of malnutrition in SSA (Figure 3). Soil degradation in cropping systems is primarily driven by low application and suboptimal management of nutrients, which leads to nutrient losses and a decline in soil biological, chemical, and physical quality, thereby reducing the capacity to support production and environmental functions (ten Berge et al., 2019).

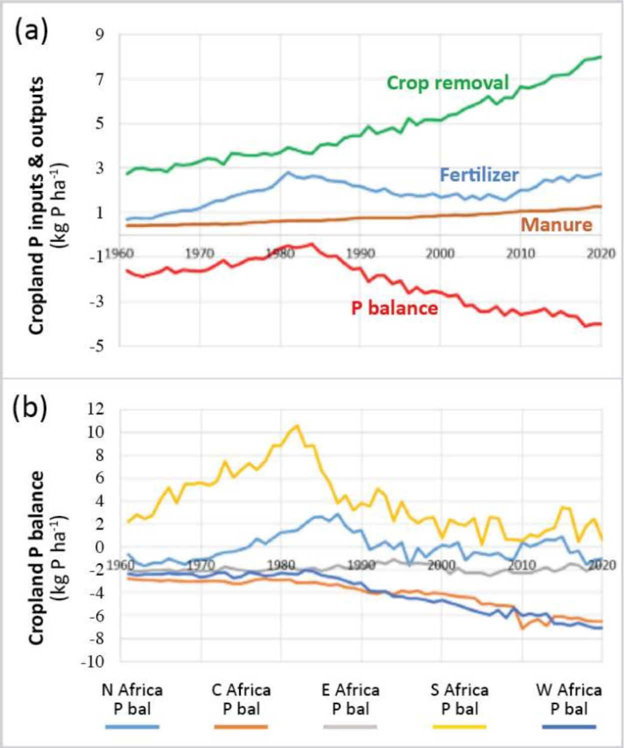
Decades of soil nutrient mining have eroded the productive capacity of large areas of agricultural soils in SSA. The subcontinent loses over U.S. $4 billion worth of soil nutrients each year (AfDB, 2006) and SSA remains the only global region experiencing negative nutrient balances that have continued to increase over time (Zou et al., 2022; Figure 4). Increasing crop productivity to meet current and future food needs will be elusive without increased, effective and efficient use of fertilizer nutrients. The greater nutrient amounts that higher-yielding crops remove means that more nutrient inputs are needed for increased productivity and at risk of loss from the system. In the context of SSA, sustainable intensification to deliver the anticipated economic, social, and environmental benefits will depend on efficient and effective management of nutrients to concurrently increase crop productivity and nutrient use efficiency (NUE) at a higher fertilizer use intensity.



Source: APNI.

Figure 3. The vicious cycle of soil health decline, land degradation, poor crop yields, and ecosystem service loss underpinning the high incidence of malnutrition and poverty triggered by poor management of fertilizers and organic nutrient resources. Locally adapted integrated soil fertility and water management practices are critical for reversing this negative spiral and building soil health and resilience of crop production systems in SSA.

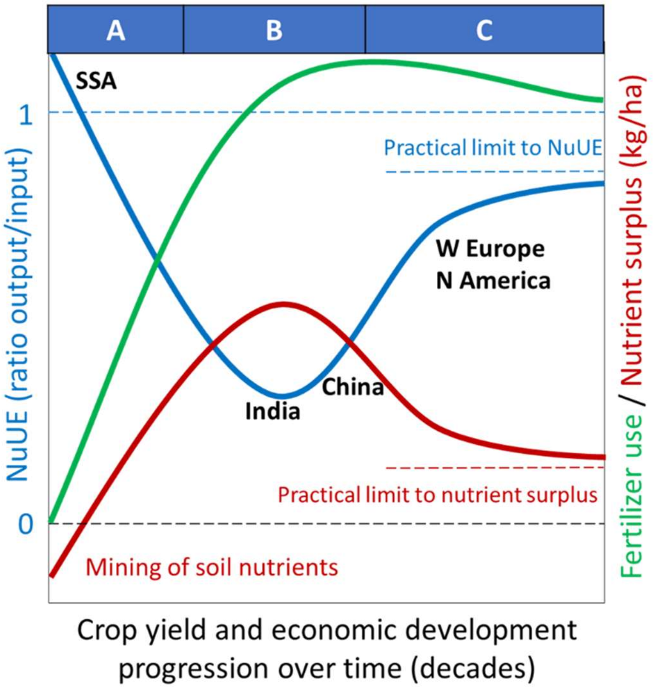
Growth in economic development increases the demand for food, often more diverse food, which increases the intensity of agricultural production and results in more nutrient losses to the environment (ten Berge et al., 2019). Historical crop yields and fertilizer use trends across global regions show a close correlation between economic development and NUE in three distinct phases (Zhang et al., 2015; Figure 5). Typical for very low-income countries, the initial phase is characterized by extremely low fertilizer use, resulting in negative soil nutrient balances, as the small amounts of nutrients applied are insufficient to offset the nutrients removed by crops. Many countries in SSA are in this phase. They face large food deficits and experience major land degradation and nutrient depletion problems linked to low fertilizer use. In the second phase, the greatest emphasis is placed on increasing fertilizer use as the main driver for increasing productivity, which is often achieved with the penalties of reducing NUE and increasing negative environmental



Source: FAO, 2022.

Figure 4. (a) Cropland P inputs and outputs for Africa and (b) cropland P balance for its sub-regions for the period 1960-2020.

consequences. This phase currently characterizes several middle-income countries, such as India and China, and many developed countries have experienced this the past (Lassaletta et al., 2014).



Source: Dobermann et al., 2022. For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.

Figure 5. Generalized development pathway for nutrient use efficiency (NuUE) in crop production. The green line represents the general evolution in fertilizer use over many decades. The blue curve shows the typical progression of NuUE (defined as the nutrient output/nutrient input ratio) in a country, region or farm over time, whereas the red curve illustrates the corresponding nutrient surplus and risk of environmental pollution.

Further along the economic development trajectory, improved access to advanced technologies and increased demand for improved environmental quality leads to a third phase, in which productivity and NUE concurrently increase. The trend toward sustainable intensification in the third phase depends on holistic systems-level best management practices for soil, crops, nutrient, and water that include the use of improved and adapted crop varieties, improved water management, balanced nutrient application, precision crop and fertilizer management, and the use of enhanced-efficiency fertilizers (Ciampitti and Vyn, 2014). Improved nutrient management in this phase is also driven by government regulatory policies or incentives to reduce negative environmental impacts. Accelerating the pathway to sustainable intensification in SSA will largely hinge on balanced fertilizer use to address the nutrient needs of specific crops under site-specific conditions.

The 2006 Africa Fertilizer Summit in Abuja aimed to position fertilizer as a key ingredient to increase crop yields and address the associated challenges of food insecurity and poor incomes faced by smallholder farmers in Africa. The discourse has since changed from a crop productivity and profitability focus to a broader set of goals and targets, with a specific focus on sustainability, climate change mitigation, rehabilitation of degraded land, and restoration of environmental services, including biodiversity, driven by ever-increasing evidence that agricultural systems are operating beyond planetary boundaries on a global scale. That said, one could argue that this is not the case when only considering the African continent. While the original focus on the need to increase the use of fertilizer in Africa more than 15 years ago remains as valid today, consensus that this must not happen at the expense of the environment is growing. There is increasing concern to build soil health to ensure efficient use of added nutrients and for additional co-benefits. Concomitant with this change in discourse, which gives a welcome addition over and above a simple increase in use of fertilizer, has been an increasing polarization in standpoints concerning the use, or exclusion, of external inputs. In this document, we strive to offer a balanced and nuanced discussion of the need for nutrient inputs based on the best evidence available. Where there are faults in our arguments, we welcome suggestions and a productive dialogue.

The main objectives of this document are thus to: (i) conceptualize soil health as a condition that can be subjected to monitoring over the short and the longer term; (ii) assemble evidence on how fertilizer use interacts with soil health; (iii) summarize practical recommendations on how fertilizer use can be enhanced to improve yields, profitability, and soil health; and (iv) present a realistic vision for future investments in fertilizer and soil health.

The paper focuses on upland annual cropping systems, since these are the most common farming systems managed by smallholder farmers in SSA (Table 1). While we recognize that the recommendations derived for upland systems may not apply to irrigated dryland or lowland agriculture or perennial systems, most smallholder farmers in SSA, including those with part of their farm under perennials or lowland rice, do derive a large proportion of their livelihoods from upland annual systems.

Table 1. Acreage of specific farming systems in sub-Saharan Africa. The annual crop farming system was formed by merging root crops, rainfed mixed, maize mixed, and cereal-root crop mixed farming systems (Dixon et al., 2001). Data for dryland agriculture were equated with dryland mixed farming systems (Dixon et al., 2001). Data from Spatially Disaggregated Crop Production Statistics (SPAM, version 2017; IFPRI, 2020) were used to estimate the cultivated acreage of lowland rice and rice-tree systems for Madagascar (Dixon et al., 2001). All pixels of rice from SPAM data within the wetlands and irrigated systems were considered lowland rice. The coffee, cocoa, and oil palm areas were calculated from the SPAM data (IFPRI, 2020).

System	Acreage (million ha)
Upland annual cropping systems	1,215
Lowland irrigated rice and rice-tree systems in Madagascar	34
Dryland agriculture	65
Cocoa, coffee, and oil palm	15

2 The Changing Context of Smallholder Agriculture in Sub-Saharan Africa

The central role of enhanced fertilizer use in boosting agricultural productivity in the face of poor and declining soil fertility was recognized at the time of the Abuja Declaration in 2006. So what makes the problem of soil fertility so important on the African continent? Why is Africa different from other parts of the World? And how has the agricultural context changed since 2006? These questions will be addressed in this section.

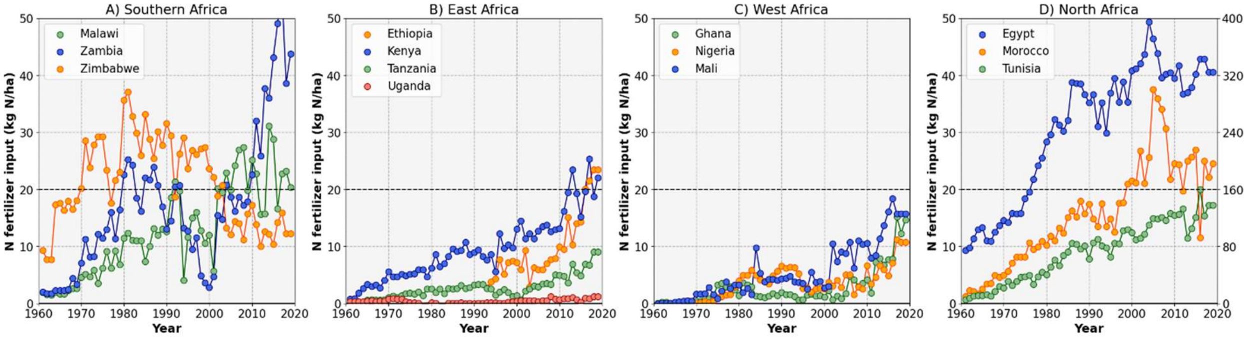
2.1 Soil Fertility, Fertilizer Use, and Crop Yields

Africa is a huge, diverse continent of over 30 million square kilometers – large enough to encompass the USA, China, and the whole of Europe (Desjardins, 2020; https://www.isda-africa.com/isdasoil/). Some of the oldest geological land surfaces in the world cover much of the continent, which results in heavily weathered and inherently infertile soils; yet, volcanic activity where two tectonic plates meet at the East African Rift results in much younger soils. These differences in age and weathering, together with deposition of more fertile alluvium across flood plains and deltas, means that generalizations concerning soil fertility are dangerous and often misleading (Lal and Sanchez, 1992). Nevertheless, some 40% of the cropland surface area is covered by coarse-textured sandy soils with little ability to store nutrients, which are rapidly depleted under continuous cropping. The issue of soil fertility decline under continuous cropping and the need for long periods of fallow to restore productivity were recognized in the 1950s in landmark publications on shifting cultivation (Quillemin, 1956; Nye, 1960). Such declines had already been observed when human population densities were sparse, and the time to rely on natural fallows to regenerate soil productivity has long passed.

Population growth has gathered pace since the 1960s, going hand-in-hand with an expansion of cropland area (Figure 1a). The critical importance of soil fertility emerged during the 1980s as a major issue due to the convergence of two factors. First, the land came under increasingly intense use as populations grew, leading to a lack of fallow periods. Second, structural adjustment policies were introduced in the 1980s, which had a number of drastic impacts on agricultural production, including the removal of subsidies on inputs such as fertilizer, dismantling of parastatal input supply mechanisms, and abandonment of government control on the prices farmers received for their staple grains. Wiig et al. (2001) estimated that structural adjustment in the 1990s led to soil degradation equivalent to a cost of 5% of gross domestic product (GDP) of Tanzania as a direct result of decreases in input use.

As clearly demonstrated in Figure 6, there is considerable diversity among regions and countries in the amounts of fertilizer used, as well as in the trends over time. The trends at national level obscure differences in widely diverse agroecological regions among different crops and between smallholder and large-scale farms where these sectors are prominent. Clearly, fertilizer use developed much earlier and more rapidly in southern Africa and north Africa than in east or west Africa. Across all regions, increases in fertilizer use stalled in the 1980s; while the rates of use were maintained in North Africa, they declined in many countries until picking up again after the turn of the millennium.

Many authors have questioned why the Green Revolution took off in Asia but not in Africa (Breman and Debrah, 2003). This is not a simple question to answer, as countries on both continents followed diverse trajectories. One factor often highlighted is the abundance of irrigated land in many countries of Asia and its dependence on rice. Indeed, gains in productivity in uplands of Asia have been less marked than in the lowlands. Major factors that supported the Green Revolution in Asia were the strong commitment by governments to investment in small-scale farming in terms of price support, input subsidies, infrastructure, and extension services (Djurfeldt et al., 2005; van Donge et al., 2012). The rise in agricultural productivity in Asia predated the general economic development of countries (Henley and Nordholt, 2015), which has led to the firm belief that increases in agricultural productivity in African countries can drive development in the same way (CAADP, NEPAD). Yet, the cost of labor in Africa remains relatively high, suggesting that the same development pathway may not be possible. Agricultural development, on the other hand, can result in cheaper food and reduced labor costs (World Bank, 2007).



Analysis by João Vasco Silva and Gatien Falconnier, based on FAOSTAT.

Figure 6. Changes in N use (kg ha^{-1}) since 1961 for selected African countries. The righthand axis of panel D applies only to Egypt.

2.2 Paradigm Shifts in Approaches to Managing Soil Fertility

From the 1960s to the 1980s, what has been coined as the First Soil Management Paradigm involved meeting the nutrient demands of new high-yielding crop varieties through additions of fertilizers. Central to the Freedom from Hunger campaign launched by FAO in 1960, this is often described as the Green Revolution approach, which included investment in large farms and irrigation systems across the continent. Such Green Revolution technologies were not available to smallholder farmers due to cost constraints, remoteness, and low priority of governments. During this time, little attention was given to the need to maintain soil health. For example, Sanchez (1976, p. 180), in his seminal text on tropical soils, wrote: “When mechanization is feasible and fertilizers are available at reasonable cost, there is no reason to consider the maintenance of organic matter as a major management goal.”

In the 1980s and 1990s, increasing attention was directed to these small-scale farms, and the critical role of soil fertility was highlighted through work on nutrient mining in Africa by Stoorvogel and Smaling (1990) and the ensuing nutrient depletion maps generated by IFDC

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(Henao and Banaante, 1999). Many smallholder farming areas were established on marginal lands, in terms of both biophysical constraints (inherently low fertility, acidity, slopes, climate) and socio-economic factors. Even in high-potential areas, continuous cropping without the use of inputs led to increasingly degraded soils due to years of nutrient mining. Out of this need to address smallholder farms and low-fertility soil, the Second Soil Management Paradigm was articulated (Sanchez, 1994). This second paradigm highlighted the need to "rely more on biological processes to optimize nutrient cycling, minimize external inputs and maximize the efficiency of their use." The initial focus was on using crop varieties that were adapted to adverse soil conditions, such as soil acidity and poor nutrient availability, and increasing the availability of organic inputs to complement fertilizer, with a strong emphasis on improved (leguminous) fallows. This paradigm was strengthened and refined through the efforts of the Tropical Soil Biology and Fertility (TSBF) Programme and the International Fertilizer Development Center (IFDC), emphasizing the combined use of mineral fertilizers and organic inputs and the importance of soil organic matter as means of increasing efficiencies of nutrient use. The TSBF Programme developed protocols and network trials to investigate the interactions of mineral fertilizer and organic inputs on nutrient availability, particularly nitrogen (N) and phosphorus (P), and crop yields. Research on organic input resource quality also distinguished the types of inputs that were better for quick nutrient mineralization and their N fertilizer equivalency values and organic inputs that were better for mulching and soil physical properties (Palm et al., 2001; Singh et al., 2007). The other consideration focused on the effects of the quantity and quality of organic inputs on soil organic matter, total nutrient contents, and different nutrient fractions and their functions (Woomer and Swift, 1994; Cadisch and Giller, 1997).

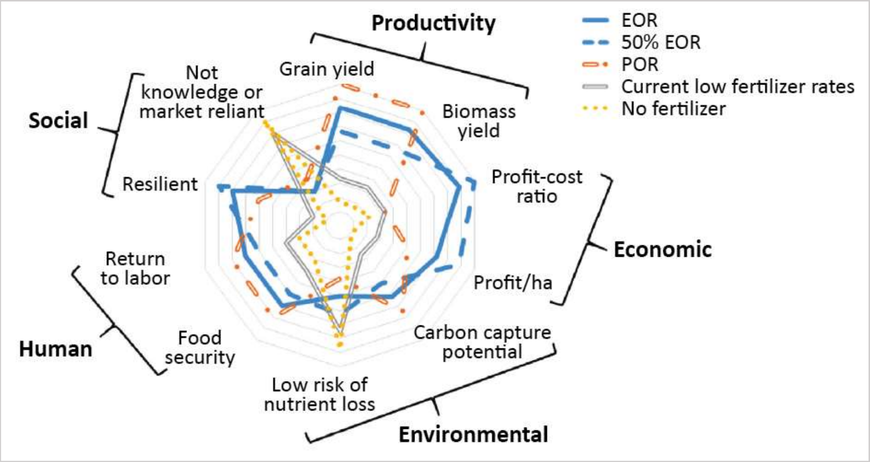
Concurrently during the 1980s and 1990s, low-external-input sustainable agriculture (LEISA; was given much attention (Reijntjes et al., 1992). Increasing concern that the low yields achieved with the LEISA approach without nutrient inputs could not address the critical issues of poverty and food security led to a focus on replenishing soil fertility (Buresh et al., 1997). Biological nitrogen fixation (BNF) by legumes was found to be strongly limited by a lack of other nutrients, particularly P (Koné et al., 1998; Giller, 2001). Nitrogen-fixing legumes – green manures or improved legume fallows of legume shrubs – were promoted widely by non-governmental organizations (NGOs) and research organizations but did not take hold. Once projects ended, few farmers continued to use them, often citing the labor costs and the lack of immediate food or cash benefits as the main reasons. Because of this, subsequent initiatives to boost nutrient input from N fixation have focused on grain legumes (Ojiem et al., 2006). Participatory research led to the realization that there was a critical shortage of animal manures and other organic resources when considering farm and farming system level (Connor, 2022; Giller et al., 2022). Smallholders cultivating nutrient-depleted and degraded soils have few organic resources available for soil improvement due to low crop yields and competition for crop residues (Rufino et al., 2011). Thus, although research on organic inputs and soil organic matter and its fractions have provided a better understanding of the implications for crop growth and soil rehabilitation, such information will not be put to use on smallholder farms until nutrients are replenished through mineral fertilizers to jump-start farm productivity, including that of residues and other organic resources.

The Integrated Soil Fertility Management (ISFM) paradigm (Vanlauwe et al., 2010) emerged from the Second Paradigm, based on the previous decades of soil and crop research in Africa. ISFM recognizes the critical need to use all organic and mineral nutrient resources efficiently and focuses on the use of fertilizer as an entry point toward the intensification of smallholder agriculture (in contrast to the Second Paradigm). ISFM is a stepwise approach that begins with rehabilitating degraded soils and improving marginal soils, first by using mineral fertilizers and improved germplasm. Fertilizers are considered a necessity to begin rebuilding the fertility base of the soils. The next step is incorporating organic resources into the soil management, which is necessary to rebuild the soil organic matter that is 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. 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.

Over the past two decades, major investment has been made in the promotion of conservation agriculture (CA), largely driven by concerns of soil erosion and loss. Smallholder farmers face a number of challenges to implement the three pillars of CA, which are: (i) minimizing soil disturbance through tillage; (ii) maintaining a continuous soil cover; and (iii) diversifying crops (FAO, 2006). These challenges include the increased labor burden for weed control if soils are not tilled when herbicides are not available. Further, maintaining a mulch cover on the soil surface is difficult, particularly under drier climates or given widespread shortages of feed for livestock. To ensure sufficient crop production, a fourth principle for CA was proposed – using mineral fertilizer appropriately (Vanlauwe et al., 2014). Undoubtedly, the CA principles are positively related to soil health. Yet, despite the huge amount investment in promotion of CA across the African continent, its use remains largely confined to larger-scale mechanized farms and uptake by smallholders remains limited (Andersson and D'Souza, 2014; Bouwman et al., 2021; Giller et al., 2015).

More recently, other approaches to agricultural development receiving increased attention include agroecology and regenerative agriculture. One could refer to a Third Paradigm in which other ecosystem services besides crop productivity are considered equally important products of farming systems. In this context, soil health is a key indicator for the delivery of those other services. The term agroecology has been defined in various ways over the past decades. FAO (2018) recognizes 10 elements of agroecology: diversity, co-creation of knowledge, synergies, efficiency, recycling, resilience, human and social values, culture and food traditions, responsible governance, and circular and solidarity economy. Rather confusingly, the High Level Panel of Experts on Food Security and Nutrition (HLPE, 2019) presents 13 agroecological principles: recycling, input reduction, soil health, animal health, biodiversity, synergy, economic diversification, co-creation of knowledge, social values and diets, fairness, connectivity, land and natural resource governance, and participation. Regenerative agriculture is a somewhat nebulous concept that has gained substantial support among a wide range of organizations in recent years and is increasingly promoted in Africa (Giller, 2022). Most descriptions of regenerative agriculture indicate that it is based on a set of principles that includes: (i) activities that encourage infiltration and percolation of water and prevent soil erosion, such as minimizing tillage and maintaining soil cover; (ii) practices that build soil carbon (C) and greater reliance on biological nutrient cycling; (iii) practices that foster plant diversity, such as diverse rotations; (iv) integration of livestock; and (v) reduced reliance on external inputs. Although many of these principles can be argued to lie at the heart of good agricultural practice, some appear contradictory, such as minimizing tillage while reducing the use of herbicides. Essentially, regenerative agriculture emphasizes moving from approaches to prevent harm to those that ensure agricultural production has a positive impact on the environment. Although none of the above explicitly refer to minimizing or avoiding the use of external inputs, including fertilizers, as with LEISA, both agroecology and regenerative agriculture are often interpreted as emphasizing minimal use of inputs, including fertilizers, which is perhaps unhelpful where nutrients are scarce and soil stocks need to be replenished. Agroecology and regenerative agriculture do not need to be redefined but should be correctly interpreted and applied, without trying to tweak these toward a personal worldview or belief set.

Independent of the paradigms or approaches presented, it is now understood that the evaluation of alternative practices must consider more dimensions than just crop yield or profitability, including environmental, human, and social dimensions (Figure 7). Trade-offs between these dimensions need to be evaluated and monitored over time to ensure that any change in practice does not generate unintended negative consequences for farmers, farming communities, or society as a whole.



EOR and 50% EOR, 100% or 50% of economically optimum rate of nutrient application; POR, productivity optimum rate of nutrient application; Current low fertilizer rates, current rates of fertilizer application at suboptimum, low levels; No fertilizer, zero fertilizer applied to the cropping system, as is common in SSA (Wortmann and Stewart, 2021).

Figure 7. Systems assessment comparing fertilizer use at economic- and production-optimized rates with the status quo of low and no fertilizer use, as displayed in a radar chart (Stewart et al., 2018). Application at <EOR is appropriate for financially constrained fertilizer use.

Approaches that advocate minimizing or eliminating external nutrient inputs fail to recognize the removal of nutrients from the farm in the harvest and sale of crops. Unless the soil has very high inherent fertility or positive nutrient balances due to long-term fertilization, whether mineral fertilizers, animal manures, or other organic inputs brought in from outside the field or farm, crop production will decline, even with recycling of crop residues within the field. Only N can be (partly) addressed through on-site use of legumes and BNF. Phosphorus and potassium (K) are necessary for the growth of N-fixing plants and require external inputs in the medium to longer term

The importance of the biological processes promoted in all of these approaches cannot be overemphasized. These biological processes depend on organic inputs, either recycled or brought in, which then rebuild soil organic matter and all the associated chemical, biological, and physical soil health properties – the beginning of a virtuous cycle and sustained soil health that begins with the use of fertilizers on degraded soils. Therefore, a more refined definition or, better yet, quantification of the amount of external nutrient inputs that is required to increase crop productivity and rebuild soil health is needed, including macro, secondary, and micronutrients

(Kihara et al., 2020). The amounts needed will depend on the soil status, including soil organic matter levels and partial nutrient budgets, crop requirements, and so on.

In summary, contrary to doomsday forecasts, the Green Revolution has allowed food production increase to exceed global population growth over the past decades, except on the African continent. Yet, the increasing awareness about adverse environmental and societal challenges has focused attention on the sustainability of food systems and their resilience in the face of climate change. In relation specifically to the role of soils and crop nutrition, this has changed the focus from one solely on crop nutrients and nutrient recycling to one that highlights soil health and contribution to future sustainability of agriculture as a key outcome. Section 3 goes into further detail, providing a conceptual framework on the interlinkages between fertilizer and soil health.

2.3 Lessons Learned since the 2006 Africa Fertilizer Summit Concerning Enabling Conditions

The central resolution of the 2006 Africa Fertilizer Summit was to increase fertilizer consumption from 8 kg NPK ha^{-1} to 50 kg NPK ha^{-1} by 2015. To enable this, countries were encouraged to implement targeted fertilizer subsidies to improve farmers' access to fertilizer. The rationale behind introducing subsidies was that smallholder farmers cannot afford the high cost of fertilizer. By 2019, two-thirds of the countries were implementing some form of fertilizer subsidy program (both targeted and non-targeted), accounting for approximately 40% of the fertilizer consumption in SSA (Wanzala-Mlobela et al., 2013). In 2017, 88% of fertilizer use (0.8 million metric tons [mt]) in Mali was subsidized by the government, while 35% of fertilizer use (1.6 million mt) in Nigeria was subsidized by the government (IFDC and AFAP, 2019). These subsidy programs have been heavily criticized for not delivering the expected benefits in food production. A comprehensive analysis indicates that the overall costs of subsidies outweighed their benefits (Jayne and Rashid, 2013). Surely, using a narrow economic definition of cost:benefit does not consider the positive impacts of such programs on increased food availability and lives saved. Yet, without the accompanying investments in the infrastructure needed for timely supply of fertilizer, such as agro-dealer networks or road access, and the lack of concurrent investment in more precise fertilizer recommendations beyond the national level aiming at increasing fertilizer use efficiency, it is not surprising that impacts are not always delivered as planned. That situation is changing rapidly, given the urgent need to increase productivity and the interest from the fertilizer sector in the growing market in Africa.

While subsidies have proven to be effective in raising national production quickly in one season, most studies show that the crop yield response to fertilizer on smallholders' fields is far less than would be expected based on research trials. The underlying reasons for the poor efficiency of fertilizer use are complex but include: (i) suboptimal crop management in terms of sowing time, crop density, timely weeding, etc.; (ii) late application of fertilizer, often caused by issues of timely access to inputs; (iii) inappropriate fertilizer formulations for the local conditions; (iv) lack of training in fertilizer management; and (v) poor soil health, a topic that will be discussed in detail in Section 3.

Furthermore, most fertilizer recommendations were provided in the form of blanket national recommendations that ignored variation in soils, past nutrient use, and the type of farming system. Crops do not respond well to fertilizers with poor soil health. As poor farmers often have poor soils due to their lack of access to animal manure, this represents a double poverty trap (Franke et al., 2019). Chamberlin et al. (2021) showed that 30% of farms in their sample had nonresponsive soils. Nziguheba et al. (2021) concluded that nonresponse, defined here as zero agronomic response to fertilizer in a given year, was relatively rare, affecting 0-1% and 7-16% of fields on average for cereals and legumes, respectively. The most commonly used fertilizers in SSA contain N and P, and less frequently K, and the lack of response to fertilizer can be associated with deficiencies of other secondary nutrients, such as sulfur (S), calcium (Ca), and magnesium (Mg), or micronutrients. Nonresponsiveness to fertilizer can also be due to local physical constraints, such as shallow depth, compaction, plow layers, and surface crusting, which all lead to poor soil moisture availability for crop growth. All the above said, a major pending question is whether the attention given to nonresponsive soils is driven by curiosity from scientists rather than by the widespread prevalence of such situations, especially since limited or no response to fertilizer can be the result of a plethora of non-soil fertility-related factors.

Fertilizer subsidy programs influenced smallholder farming practices in varying ways. Harou et al. (2022) illustrated the joint importance of knowledge about the correct fertilizers for their fields and subsidies to overcome cash constraints to buy fertilizers. Farmers in Tanzania who received information on the specific fertilizer needed for their field along with a 50% subsidy for that fertilizer used more fertilizer than those farmers who only received the fertilizer information or the subsidy. Evidence from Zambia suggests that subsidies reduce fallowing and intercropping of maize with other crops while encouraging monocropping of maize over time (Levine and Mason, 2014). Komarek et al. (2017) found that subsidizing fertilizer prices increased fertilizer use, maize yield, and household income, but it also had a disincentivizing effect on the use of organic materials and methods in maintaining on-farm soil fertility. Specifically, lowering fertilizer prices reduced the area of legumes under cultivation – an important source of BNF (Pieri, 1989).

It can be argued that previous fertilizer subsidies missed an opportunity to use fertilizer as a vehicle to promote complementary practices, such as ISFM, that aim to maximize the use efficiency of fertilizer, covered in Section 3. Policies to support increased investment in strategies that restore and enhance soil health are needed to render the fertilizer subsidies "future-smart." Another strategic consideration includes the availability of improved seeds to encourage cereal-legume systems for boosting BNF, household nutrition, and income. Further, policies designed to enhance fertilizer use must be linked to policies that support output market development (infrastructure, post-harvest, commodity prices, import and export) to ensure that increased crop yields translate into higher incomes for farmers. Measures should be in place to link farmers to profitable markets to encourage farmers to reinvest in fertilizers and soil health practices.

3 Fertilizer and Soil Health – Theory and Evidence

Interest in soil and its health has recently increased among various stakeholder groups, partly driven by emerging interest in sustainability and claims made in relation to the climate change mitigation potential of soils, as illustrated by the Sustainable Development Goals (SDGs). In this section, we discuss the concept of soil health and its nemesis, soil degradation, and present a conceptual framework linking fertilizer use to soil health. Various interactions between fertilizer use, soil health, and crop production are evaluated, and the current status of soil health and its drivers, as well as the potential for soils to accumulate SOC, is presented.

3.1 Soil Health and Soil Degradation

Soil can be defined as the uppermost layer of the Earth's surface that consists of sand, silt, clay, and other mineral particles, mixed with decayed organic matter, which together have the capability of retaining water and nutrients to support the lives of (micro)organisms and growth of plants for the production of food for humans and animals. Soils therefore determine the productive capacity of the land and, consequently, the amount and quality of food. Here, soil health is defined as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and (micro)organisms, and deliver nutrients to promote plant and animal health (Doran and Zeiss, 2000; Powlson, 2020; Coyne et al., 2022). The functional benefits of healthy soils are multiple; they serve as a habitat for (micro)organisms, act a sponge for holding water, release a variety of nutrients needed for plant yield and nutritional value, serve as a foundation for farm productivity and income, and improve environmental health, such as through mitigation of greenhouse gas and water pollution (runoff and leaching) and sequestration of carbon.

From an agronomic viewpoint, healthy soils increase yields through the release of a variety of nutrients, support water holding, facilitate root growth through appropriate physical conditions, and control pests and diseases, which in turn reduces fertilizer (Kuyah et al., 2021) and irrigation needs and sets the resilient foundation for farm productivity and income. On the environmental side, healthy soils prevent erosion, control flooding, increase biodiversity, clean water, and sequester carbon, among other benefits (Moebius-Clune, 2017).

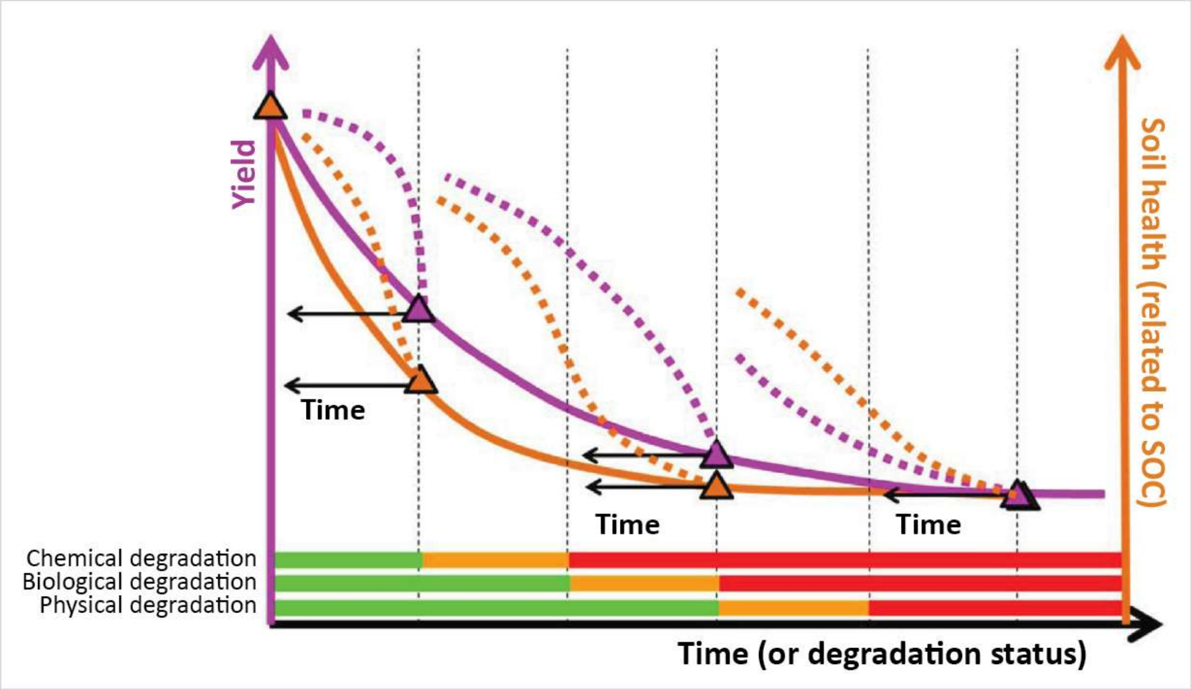
Identification of indicators to quantify soil health have not reached the stage of universal quantitative assessments, and this may indeed remain unlikely to be achieved (Baveye, 2021). Healthy soils comprise interacting physical, chemical, and (micro)biological properties. Soil organic matter is key to a healthy soil, as it favorably affects all these properties. Soil pH can also be considered a "master variable" that influences nutrient availability and microbial populations, with a direct impact on crop growth (Wood and Litterick, 2017). While it would be important to quantify or assess their impact on soil health, current microbial measurements are not easy to interpret and may not necessarily provide credible inferences about soil health status (Fierer et al., 2021). The timely and sufficient availability of the required nutrients for uptake by the plant is critical. Depending on the type of soil, availability of P particularly is hampered due to complex edaphic processes that immobilize it in the soil (Bindraban et al., 2020), making P management an essential component of soil health. Soil acidity is another key indicator, with acidity-induced limitations to crop growth commonly occurring at pH values below 5. Physical indicators of soil health are commonly related to the ease of root growth through the top- and subsoil and the regulation of water infiltration and storage. Surface crusting and the formation of hardpans are common features hindering crop establishment and growth and soil moisture dynamics, so in their absence, these processes are not restricted.

In addition to the need for specific indicators to assess soil health, three other aspects must be considered: (i) spatial heterogeneity of some soil properties and the need to integrate this into protocols aiming to measure change in specific indicators; (ii) the rate of change of some indicators, which can be relatively fast (e.g., changes in available P as affected by P fertilizer application) or slow, especially when these are measured against a relatively large background (e.g., changes in soil organic matter); and (iii) the cost of measuring indicators over large areas of land. Alternatively, instead of measuring soil health indicators directly, one could assess the change in crop and soil management practices as related to expected changes in the status of key indicators through empirical or mechanistic modeling.

In this report, we do not aim to arrive at a universal quantitative assessment of soil health but present a framework to address the specific situation of African soils in view of their productivity. This should allow us to reflect on soil health and its outcomes through measurable and deployable indicators. In view of the above, we will use soil organic carbon (SOC) as the main indicator of soil health. Later, some of the limitations of using SOC as the principal indicator of soil health will be highlighted. For the remaining text, we will consistently refer to SOC rather than soil organic matter, noting that both soil properties are very closely related in most instances. While sufficient available P and lack of soil acidity-induced constraints to crop growth are also important elements of a healthy soil, technical implements to address low P and acid soils are well known and not the focus of this paper.

Conversion of natural vegetation or long-term fallow land into low-input agricultural production leads to considerable losses of SOC over relatively short time periods as well as rapidly declining crop yields (Figure 8; Tilman et al., 2002). The rate of the decline depends on soil properties (texture, inherent fertility), management (degree of soil disturbance during production), and the fate (residues) of the crop (West and Six, 2007). The soil degradation processes underlying SOC losses consist of varying dimensions, including biological (e.g., biodiversity losses), physical (e.g., structure losses), and/or chemical degradation (e.g., nutrient losses) and depend on the inherent properties of specific soil types. For instance, while physical degradation is unlikely to be a major short-term issue for deep soils such as Nitisols and Ferralsols, it can occur quickly in soils with shallow topsoil (e.g., Lixisols).

Trajectories to restore soil health status and associated crop productivity are unlikely similar to the degradation trajectories (de Ridder et al., 2004; Tittonell et al., 2005). For instance, while crop yields can decline rapidly, where the soil degradation processes have not crossed important thresholds, management practices such as addition of simple soil amendments (e.g., NPK fertilizer) could result in immediate increases in crop yields, close to those observed immediately after land conversion. The additional crop residues produced, in this case, if used appropriately (e.g., either as surface mulch or returned after conversion to manure) could gradually regenerate



Source: Chivenge et al. (2022a).

Note that (i) the relative importance of the degradation processes is dependent upon soil type – the various colors used in the above graph are only indicative, (ii) the relative yield and soil health status decline kinetics may vary with soil type, and (iii) the rehabilitation trajectories may end up at or below the original yield and soil health level but not necessarily within a timeframe similar to that followed by the degradation trajectories.

Figure 8. Conceptual descriptions of soil health (solid brown lines) and crop yield (solid purple lines) decline under low-input agricultural practices, the relative importance of the associated degradation processes in time (red = high, green = low), and the hypothesized rehabilitation trajectories (dotted lines) through intensification methods.

soil health (Tejada et al., 2009; Bationo et al., 2007). Where degradation has been severe, substantial soil health rehabilitation efforts may be required for many years to regain critical thresholds before crop yields can be expected to rise to acceptable levels. In such cases, high amounts of external inputs, mineral fertilizers with either organic inputs, lime, or conservation tillage practices, may be required as part of the rehabilitation process, whereas technologies that include mineral fertilizer only are ineffective (Vanlauwe et al., 2010).

Soil degradation is continuing and often worsening, with soil nutrient depletion being especially problematic on the African continent. Worldwide, over 10 million hectares per year are prone to soil degradation, representing a loss worth billions of U.S. dollars. Dozens of initiatives, ranging from international development programs and national fertilizer subsidy programs to local fertilizer demonstration trials, have been implemented over the past decades but have been unable to revert this downward spiral of resource degradation and poverty into a sustainable upward spiral of prosperity. The rate of crop productivity growth, for instance, has declined from approximately 2% per year during the Green Revolution to about 1% per year currently, with even lower and negative rates for several crops in some African countries. Soil degradation is being considered one of the main causes of stagnating productivity growth (Bindraban et al., 2012) and also in increasing soil constraints.

3.2 Conceptual Framework Relating Fertilizer and Soil Health

The conceptual framework relating fertilizer use to soil health contains the main components for agricultural systems and their connectivity, along with management interventions and environmental implications (Figure 9).

3.2.1 Key Elements of the Conceptual Framework

The production of crop yield and biomass, or food for humans and feed for animals (top left box in Figure 9), is driven by sufficient availability of nutrients for structural growth and water to effectively capture radiation for conversion of atmospheric carbon dioxide (CO_2) into organic matter (Brown et al., 2022). Large amounts of plant nutrients are removed from farmers' fields with the export and consumption of the crop produce. For instance, in its aboveground biomass, each metric ton of maize contains about 23 kg N, 4 kg P, and 13 kg K, as well as 2 kg Mg and S, and micronutrients, such as 175 g of iron (Fe) and 25 g of zinc (Zn). It is estimated that soils in SSA are depleted by about 30-50 kg N, P, and K per hectare per year combined in current cropping systems (e.g., Lesschen et al., 2007; Cobo et al., 2010), which cannot be replenished without the use of fertilizer. More diverse cropping and crop-livestock systems could reduce the need for fertilizer nutrients through recycled manure or BNF by legumes (Edreira et al., 2018; Ludemann et al., 2022; Stagnari et al., 2017).

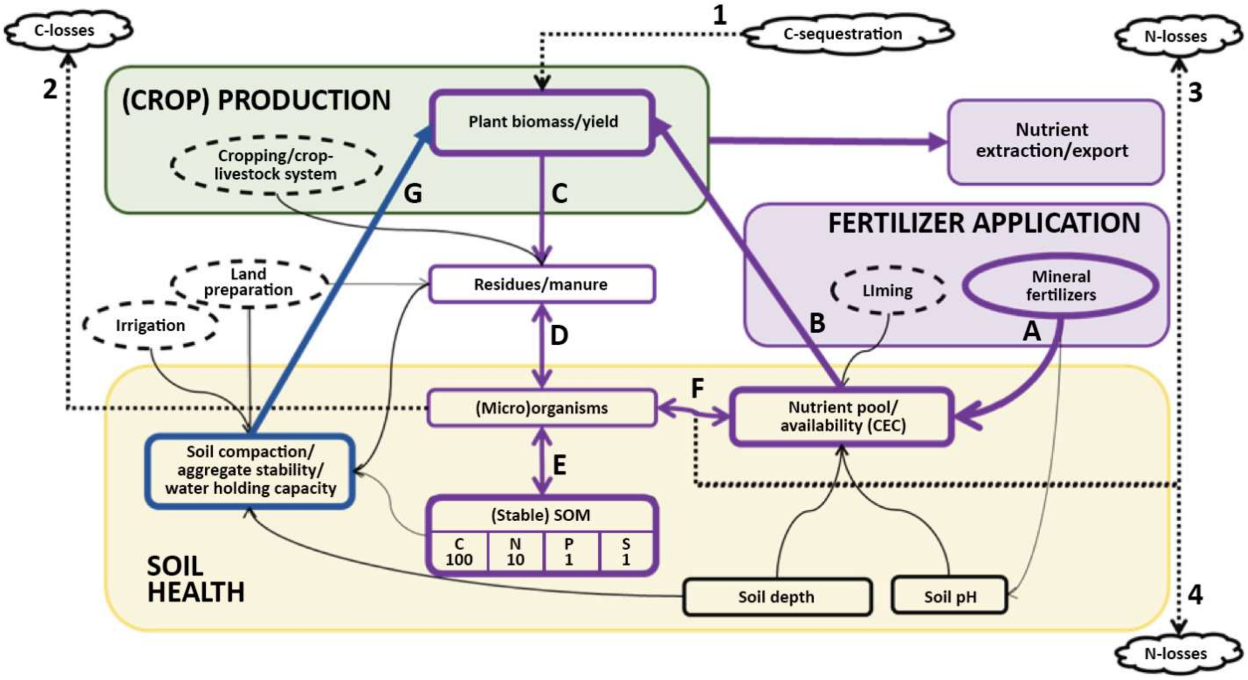


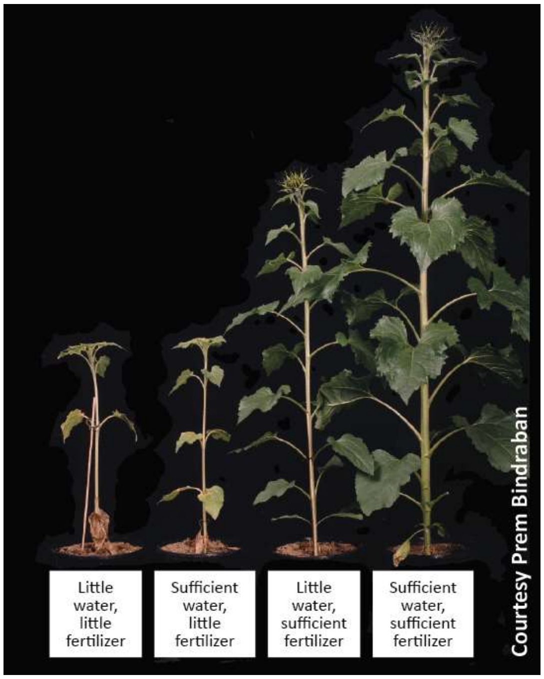
Figure 9. Visualization of the Soil Health framework used in this report (Pulleman et al., 2022, Baveye et al., 2021, Coyne et al., 2022) Rectangles are systems components, with healthy soils comprising favorable physical, chemical and biological properties. Ovals present management interventions. Emissions and sequestration are presented as clouds. Arrows present processes connecting the components. The blue line relates to water availability and the purple lines indicate most direct impact of mineral fertilizers on biomass/yield and soil organic carbon.

Healthy soils (bottom box in Figure 9) comprise favorable physical, chemical, and (micro)biological properties with multiple interacting processes. Soil organic carbon is key to a healthy soil, as it favorably affects all these properties. It is especially critical for soil structure and fertility and water-holding capacity. SOC consists of plant and animal residues at various stages of decomposition as energy and a nutrient source for (micro)organisms. These convert organically bound elements to inorganic or mineral forms, and vice versa, through mineralization and immobilization processes. Use of mineral fertilizers may alter ratios between soil microbial communities, but the high diversity and functional redundancy of microbial communities do not result in loss of generalist soil functions for plant growth, with the exception of a few keystone species (Pulleman et al., 2022).

The discovery by Justus von Liebig in the mid-19th century that plants need nutrients has been fundamental for understanding plant growth and development. Mineral fertilizers (top right box in Figure 9) boost biological growth by continuous injection of reactive nutrients, extracted from inert forms of nutrients from the atmosphere and lithosphere, into the biosphere. Since the discovery of the need for nutrients by plants for their growth and development, the use of mineral fertilizers has undeniably been one of the greatest human innovations and a driving force for societal development (Hijbeek et al., 2017). Over half of the world's current population has been estimated to be fed from food produced by the use of mineral fertilizers (Erisman et al., 2008). Decades of continuous cropping using only NPK fertilizers has depleted soil micronutrients, as reported in India and the United Kingdom (Jones et al., 2013; Shukla et al., 2015). Treating visible micronutrient deficiency symptoms may result in the buildup of hidden or subclinical deficiencies that can further depress yield and the nutritional quality of the produce (Bindraban et al., 2020).

3.2.2 Interactions Between the Key Elements and Other Factors

Fertilizer application interacts with water availability, and crop growth in areas commonly associated with drought, such as the Sahel, are often more limited by a lack of nutrients than a lack of water. Combined water-nutrient application allows the plant to develop properly and grow to its genetic potential (Figure 10). Agriculture in SSA is predominantly rainfed, where productivity is more strongly related to the variability of rainfall in the growing season than the total annual precipitation, with less than 15% of the terrestrial precipitation taking the form of productive "green" transpiration. In-situ rainwater harvesting raises soil water content of the rooting zone by up to 30%, with substantial increases in crop yields in the presence of fertilizer application (Biazin et al., 2012; Dile et al., 2013). Water conservation measures and land preparation practices, such as plowing and minimum tillage, affect the soil water-holding capacity through their impact on soil compaction and aggregate stability, with ridges, hills, and other structures enhancing the volume of soil that can be penetrated by roots.



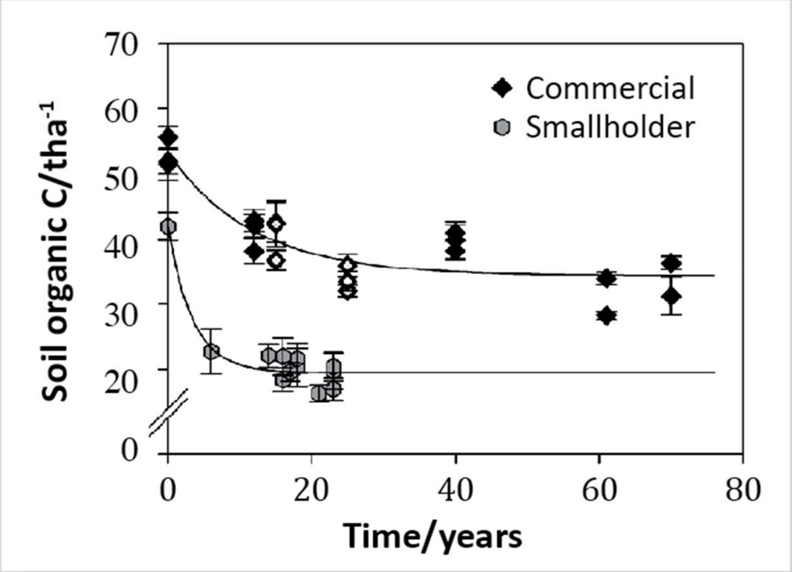
Source: Prem Bindraban.

Figure 10. Demonstration of interaction between water and nutrients on growth.

Crop residues and manure can be left on the land surface or incorporated and serve as substrate for (micro)organisms (Turmel et al., 2015), thus raising SOC in the long term (Bationo and Buerkert, 2001). Integration of N-fixing legumes and forages (Bekunda et al., 2010) or grasses with dense and deep rooting systems into specific crop rotations can further enhance organic resource availability. Recycling of organic amendments (manure, residues) is internal to the system, relocating nutrients from one place to the other, but does not increase total amounts of organic inputs or nutrients in the system and is therefore unable to raise the total amount of C sequestered.

Plants obtain their nutrients from the available pool of nutrients, influenced by the cation exchange capacity (CEC) of soils. Minerals primarily determine CEC, with clay soils having a greater capacity to hold nutrients than sandy soils. In soils with low CEC, SOC is a key supplier of cation exchange. Also, soil acidity, soil water content for nutrient dissolution and diffusion, and mineral and organic fertilizer application affect nutrient pool size and availability. The nutrient pool and its dynamics vary for different nutrients and can be affected by agronomic practices and edaphic processes. For instance, while the most important aim of liming in the tropics is mitigation of aluminum (Al) toxicity under low pH, liming may also support yield increase through the immediate increase of soil pH (in the range of 4.0 to 5.5) and associated availability of nutrients (Hijbeek et al., 2021). The effect of liming decreases rapidly at higher pH values. Also, the addition of organic matter or increasing SOC can mitigate Al toxicity through complexation and enhance P availability from decomposition (Haynes and Mokolobate, 2001). Nitrogen fertilizers can induce soil acidity, based on their content of ammonium, which releases protons as it is converted to nitrate. Soil acidification may be caused by various other sources as well, including precipitation (with rainfall pH of about 5.7), nutrient transformation and uptake, and leaching.

It is well known that large amounts of CO_2 are released through the decomposition of SOC, such as after land clearing, and SOC continues to decline under continuous cultivation with limited to no mineral or organic inputs. That said, even soils under commercial agricultural practices do not accumulate SOC at the levels of natural fallow land that has been cleared (Figure 11). Whether this is a major issue or not depends on the amount of SOC that is required to maintain critical ecosystem services, as affected by soil properties and climatic conditions, a question that is still awaiting a conclusive answer.



Source: Zingore et al. (2005).

Sampling depth 20 cm; lines represent fitted exponential functions. The dotted symbols represent commercial fields from the Chikwaka site where irrigated wheat had been grown during the winter seasons.

Figure 11. Changes in soil organic C in the soil with period of cultivation in the Chikwaka smallholder and commercial farming sites.

Generally, the extent of N leaching depends on rainfall intensity and amount, evaporation rate, soil structure, texture, tillage, cropping practices, and the amount and form of N fertilizer applied, but the overall influence of management practices on nitrate-N leaching is still unclear. However, the serious problems with nitrate pollution observed in regions of the world where N fertilizer rates are high are almost certainly not relevant in most African situations, where the likely increases in use are still well below the rates causing problems elsewhere. This is no call for complacency, but to ensure that N fertilizer management recommendations focus on maximizing N use efficiency, thus avoiding the negative consequences of fertilizer misuse generated elsewhere.

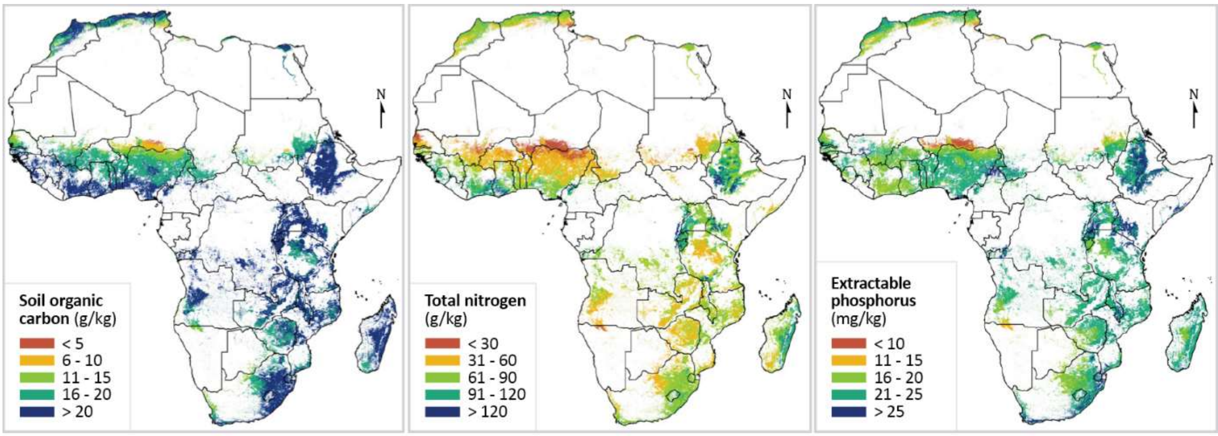
3.3 Soil Health Status in Smallholder Farming Systems

3.3.1 Smallholder Farmer Effects on Soil Health Status and Diversity

Soil properties vary widely across the continent and are related to climate, soil type, land-use systems, and land-use management (Figure 12). Before discussing the soil health status in smallholder farming systems, it is important to highlight that comparing soil health between a sandy and clayey soil does not hold, since clayey soils will almost always have a higher SOC content. One could argue that the search for a threshold value for specific indicators, separating "good" from "poor" soils across soil types, is irrelevant. For instance, while Sahelian Arenosols rarely have an SOC content above 10 g kg^{-1}, it is unusual to have an SOC content below 10 g kg^{-1} on clayey Nitosols in Central Kenya. Comparing soil health indicators between fields and farms on similar soil types is relevant and such information, combined with information on soil management practices, provides insights on current soil health conditions and potential measures for its improvement.

Current soil health status on smallholder farms is determined, in large part, by soil type (clayey vs. sandy) and climate (sub-humid vs. semi-arid). These biophysical factors, coupled with socio-economic factors, influence the farming system and crop and soil management practices. Farming system and management practices determine crop yields, amounts of biomass produced on farm and the surrounding landscape, and how the crop residues are used. Partial nutrient and organic matter balances can serve as a rapid proxy measure to indicate whether the soil health is degrading or improving. If the balance of nutrients and organic inputs compared to the nutrients exported through the harvested produce or removal of residues is negative, more nutrients are being removed than added, resulting in declining soil health. The impacts of long-term soil mining (negative nutrient and carbon balances) are likely the overall drivers of soil health status on smallholder farms in SSA.

Soil health differs between types of farms, between fields within a farm, and even within fields on a farm. This heterogeneity results from differences in farmers' access to resources and a higher amount of inputs and better management on fields closer to homesteads, on better soils, planted to preferred crops and locations within a farm (Zingore et al., 2007; Giller et al., 2011;



Data source: iSDA soil: Open Soil Data for Africa. Hengl, T., MacMillan, R.A., (2019)

Figure 12. Soil organic carbon, total nitrogen, and extractable phosphorus (mg kg^{-1}) in African soils.

Tittonell and Giller, 2013). The inputs for these preferred fields come from the crop residues and animal manures produced from other fields on the farm, biomass from the outlying fields, and household refuse and composts. These practices result in positive nutrient balances and higher fertility and SOC, and thus soil health, on a few fields compared to net negative nutrient balances and lower fertility, SOC, and soil health on other fields. SOC decreased by 15% to over 50% and available P was 60-70% lower on fields farther from homesteads (Zingore et al., 2007). These soil health differences correlate with differences in crop yields, with yields decreasing as the fields are farther from the homestead. A study in Zambia comparing adoption of soil management practices by wealth category indicated fertilizers were used by just over 60% of farmers in the lowest income category but were used by more than 80% of farmers in the three other wealth categories (Keil, 2001). The poorest farmers also had lowest use of organic inputs, such as animal manure, and improved fallows. The wealthiest group had far higher adoption rates of all soil management practices, except for improved fallows.

Van den Bosch et al. (1998) compared nutrient balances between cash crops, such as tea, coffee, and livestock, and staple crops, such as maize and bean, in Kenya. Partial nutrient balances for N and P in coffee and tea were positive, while those for maize or maize/beans were negative and much more negative for Napier grass cut-and-carry systems and grazed pastures. These differences reflect the low quantity of nutrients in and added to the maize and grass systems compared to tea and coffee. The total nutrient balances were negative for all systems when losses from erosion and GHG emissions were included. Wortman and Kaizzi (1998) found negative partial and total nutrient balances in Uganda for several crops, including banana, sweet potato, and maize, among others, all of which received very low nutrient inputs. Akoyi and Maertens (2018) investigated the welfare and productivity implications of private sustainability standards in the coffee sector in Uganda. It appeared that triple UTZ-Rainforest Alliance-4C certification increased income and land and labor productivity and reduced poverty. However, without use of fertilizer, double Fair Trade-Organic certification was found to be associated with higher producer prices but resulted in lower land and labor productivity, thereby failing to increase producer income or contribute to poverty reduction.

Most comparisons of soil health and nutrient budgets have been from cereal-based farming systems. Some examples from other farming systems can also be found. Agropastoral systems in the Sahelian region and agrosilvocultural systems (*Faidherbida*) in southern Africa also exhibit farm heterogeneity in soil health parameters. In both of these regions, the tree *Faidherbida albida* is left (or planted) within crop fields. The tree provides shade for cattle, where manure is deposited, and captures nutrients from the subsoil and from leaf fall and litter, recycles nutrients to the soil surface, and provides an environment conducive to macrobiota, such as termites, that maintain soil structure, porosity, and infiltration. In addition, the microclimate provided by the trees also benefits crops in the hot Sahelian environment. All these factors lead to higher soil fertility, SOC and, under certain conditions, even crop yields under trees within farm fields compared to the open areas of the fields (Breman and Kessler, 1995; Sileshi, 2016). The soils in the open areas also exhibit severe compaction and plow pans due to long-term tillage and trampling by cattle during the dry season.

3.3.2 Potential Soil Organic Carbon Content for Different Soil Types and Agroecosystems

Soil organic carbon under natural vegetation can be seen as a proxy of potential SOC sequestration, assuming that this pool has reached an equilibrium under such conditions. Comparing SOC under cropland and natural vegetation for a given soil and climate combination could then provide a proxy of SOC sequestration potential (Breman et al., 2004). That said, while pristine SOC provides a guide for the C sequestration potential of soils, SOC values in pristine soils cannot be seen as a realistic goal for SOC restoration under agriculture since natural ecosystems are not meant to produce and export much biomass, but are dominated by plant species that allocate much of their carbon to roots, which are a primary source for forming stable soil organic matter. As such, attainable SOC restoration under agriculture may reach only 60-70% of that natural potential (Powlson et al., 2022).

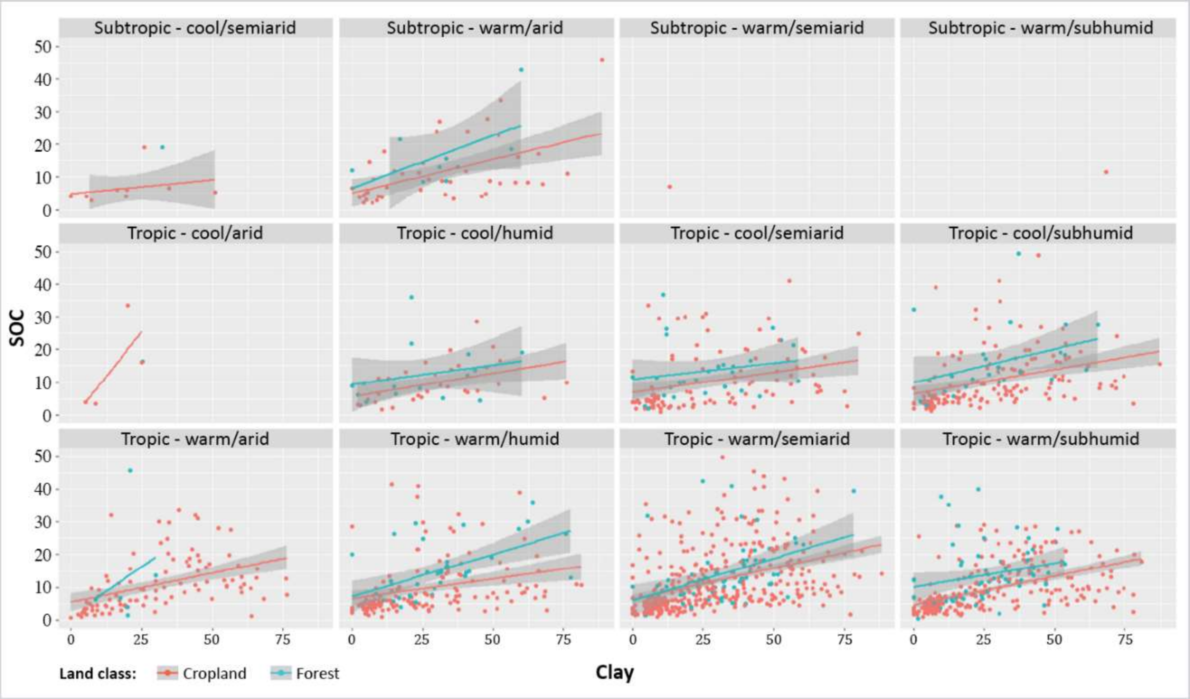


Figure 13. Soil organic carbon content (0-30 cm) as function of soil clay content under cropland versus native vegetation for different agroecologies.

We used the soil profile database over SSA from the Africa Soil Information Service (AfSIS) to compare SOC under croplands and natural vegetation (natural forest and/or savannah). Forests (n=300 profiles) were found to have 66% more SOC in 0-30 cm compared to croplands (n=1,250 profiles), meaning that, theoretically, 66% more C could potentially be stored in croplands. The largest SOC differences between croplands and natural vegetation were for warm humid and sub-humid tropical climates, where SOC contents under forests were 2.3 and 2.1 times higher, respectively, than in croplands (Figure 13; Breman et al., 2004). Surely, these are theoretical figures since agricultural soils are not meant to reach the SOC levels of pristine soils, as discussed above. Probably due to a lack of observations, some climates, such as tropical cool humid and tropical warm arid climates, have similar SOC levels under forest and cropland, indicating that SOC sequestration potential has no margin to increase under those climates. The difference in SOC between forests and croplands is soil type dependent and tends to increase with clay content, especially in warm humid climates (Figure 14; Powlson et al., 2022). Also, in volcanic soils, there is evidence that clearance of natural vegetation does not necessarily lead to much SOC decline (Powlson et al., 2022).

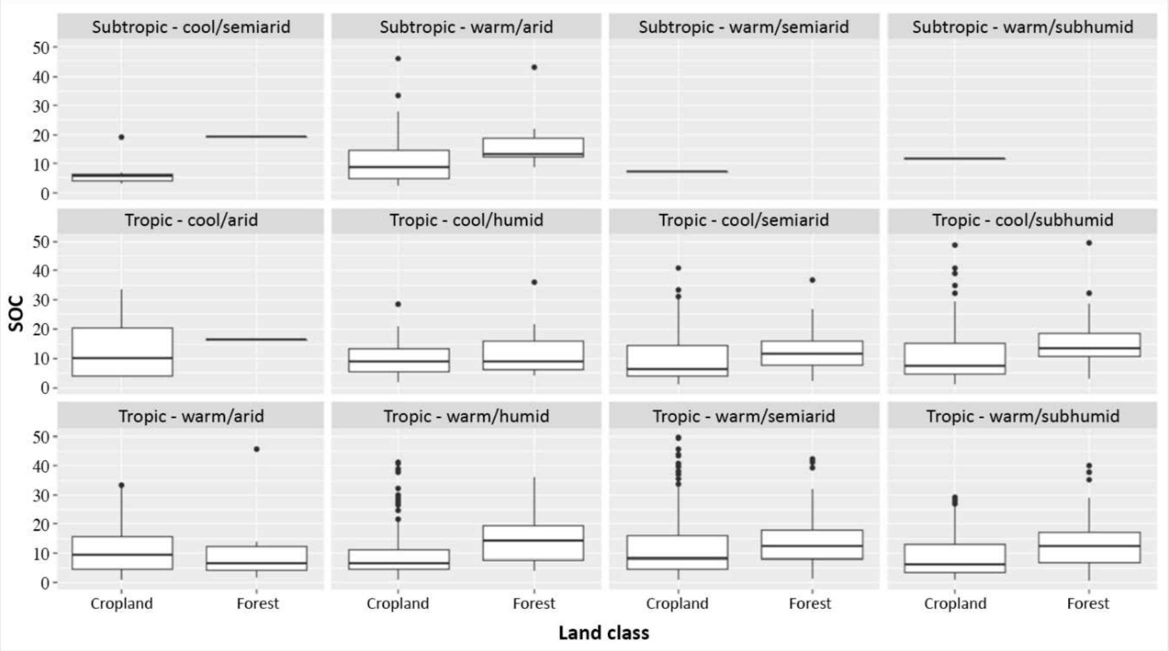


Figure 14. Soil organic carbon content (0-30 cm) under cropland versus native vegetation for different agroecologies.

Overall, we found that differences in SOC between natural vegetation and croplands are in accordance with SOC loss when soil is cleared for cropland (Cardinael et al., 2022; Powlson et al., 2022; Zingore et al., 2005). Powlson et al. (2022) and Duval et al. (2013) showed that levels of SOC under arable cropping were in the range 38-67% and 16-44%, respectively, of pre-clearance values. In Ethiopia, Amanuel et al. (2018) found that SOC stock was 36% higher in natural vs. cultivated soils. Powlson et al. (2022) concluded that, in the vast majority of situations, it is unrealistic to expect to maintain pre-clearance SOC values, meaning that SOC sequestration potential in SSA would remain below 66% (van Ittersum et al., 2013; van Loon et al., 2019).

3.4 Fertilizer Use in Africa and Its Impacts on Yield and Soil Health

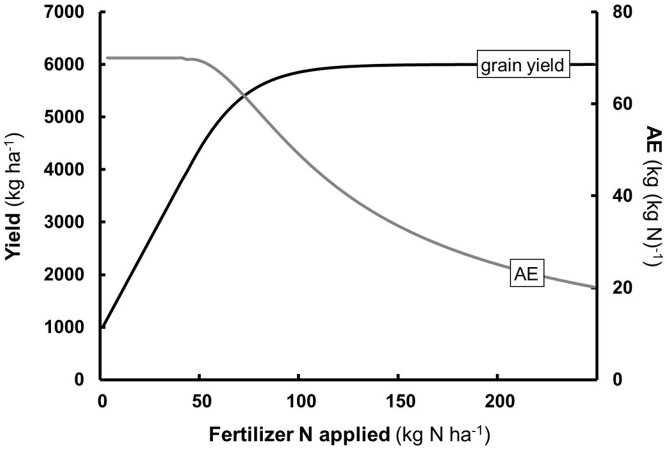
3.4.1 Reflections on Fertilizer Use Efficiency

Fertilizer use efficiency (FUE) is a commonly used indicator to evaluate the effectiveness of fertilizer application. This indicator is generally suboptimal in SSA, resulting in relatively poor yields and economic returns and disincentivizing the use of mineral fertilizers by smallholder farmers. A major driving force for the use of fertilizers is, therefore, their effectiveness to increase crop yield.

Various methods have been used to assess FUE, with agronomic efficiency being one of the most common since it is relatively easy to measure. For instance, the agronomic efficiency of N (AE-N) is defined as:

AE-N = [Yield with Fertilizers – Control Yield (Without Fertilizers)] / kg N Applied

Theoretically, AE is high at relatively low application rates and constant until the response curve starts leveling off; it then declines as rates increase (Figure 15). Also, high AE-N values, exceeding 50-60 kg grains kg^{-1} N, suggest depletion of soil N, with more N taken up by the plant than supplied as fertilizer (Pasley et al., 2020; van Grinsven et al., 2022).



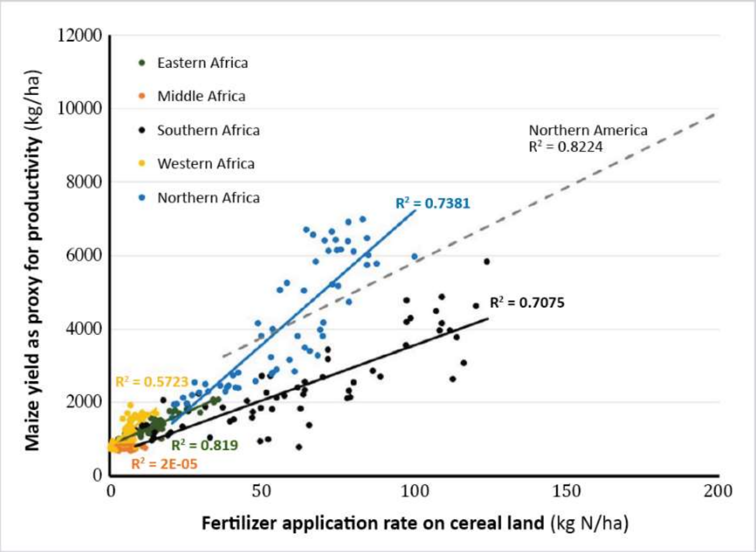
Source: Vanlauwe et al. (2011).

Figure 15. Conceptual diagram depicting the theoretical relationship between crop yield and the derived relationship between N fertilizer agronomic efficiency (AE-N) with fertilizer N application rate for a single field.

While AE values are presented based on a single cropping season, some inputs have substantial residual effects and single season AE values can substantially underestimate the actual value of applied fertilizers (Vonk et al., 2022; ten Berge et al., 2019). This is especially the case for organic inputs and for fertilizer P. Moreover, in systems with intercropping or rotational systems, AE should be calculated based on the nutrients recovered in all crops of a particular cropping system. Nutrients not recovered by growing crops are not necessarily lost but can be immobilized in the soil organic matter pool, since the C:N ratio of most soils is around 10. Nutrients thus retained in the soil organic matter pool can benefit future crops or maintain essential SOC functions and should not be ignored when assessing use efficiencies (Vanlauwe et al., 1998; Dourado-Neto et al., 2010). Besides the need to consider multiple seasons, it is also important to consider preceding crops and the fertilizer these received. A preceding legume crop with high proportions of N derived from N fixation and high biomass accumulation can increase the use efficiency of fertilizer applied to a subsequent crop while reducing the required N application rate (Vanlauwe et al., 2019). In short, a complete evaluation of FUE requires evaluations across multiple seasons and an understanding of the contributions of specific crops to nutrient availability and use in specific cropping sequences.

While the assessment of AE requires information on crop performance in the absence of fertilizer (control treatments), such control plots are often missing from surveys, national statistical calculations, and farmer adaptation trials. Partial AE values are then estimated as yield:fertilizer nutrients used, thus including soil-derived nutrients. Other approaches are also available to estimate FUE; however, these often require a direct measurement of the actual amounts of nutrients taken up by the crop and crop biomass and their use is most often limited to experimental work.

3.4.2 Fertilizer Use, Soil Organic Carbon, and Crop Yields



Source: FAOSTAT (accessed June 2022).

Figure 16. Estimated nitrogen application rate per hectare vs. maize yield as a proxy for soil productivity from 1990 to 2019. In the absence of data for fertilizer application per crop, application rates on maize were estimated by (i) assuming all N fertilizer to be applied to cereals, (ii) quantifying the proportion of cereal land planted to maize, and (iii) assuming that most N fertilizer is applied to maize. The dotted line presents data for North America.

National-level data shows convincing evidence that total increase in fertilizer use per hectare relates to higher crop yields; the data presented use proxy values since data on fertilizer use by crop are not available (Figure 16). While fertilizer use has been increasing in SSA, FUE is often suboptimal, as described above. The source of fertilizer, the application method, and the integration of legumes or forages, soil mulch, and balanced plant nutrition can improve FUE values, especially when combined with water conservation and harvesting measures in drought-prone areas.

African farmers generally obtain highly variable and relatively low AE-N values, resulting in marginally profitable or unprofitable use of fertilizer for a large proportion of farmers (Jayne et al., 2019; Adzawla et al., 2021), while experimental farms commonly obtain AE values that are two to six times higher. Ichami et al. (2019) found that the main factors affecting AE-N for Kenya were deficiency of P as shown by low Olsen-P test values, silt content, soil pH, clay, and rainfall, with only a small proportion (33%) of the AE variation explained. They pointed to the need for systematic studies at high spatial resolution to identify yield-limiting factors. Drivers for the low FUE values beyond soil properties should be found. Over 60% of the yield variability of maize in Ghana was found to depend on variety, altitude, weather variables, soil physical and chemical properties, and fertilizers (Kouame et al., accepted). This suggests that attention should also be given to factors such as variety, temperature, and root zone depth, in addition to soil chemical properties. Indeed, Burke et al. (2022) found that complementary good agronomic practices, including effective weed

Table 2. Water use (WU), grain yield (Y), and water use efficiency (WUE) for millet at Sadore and Dasso (Niger).

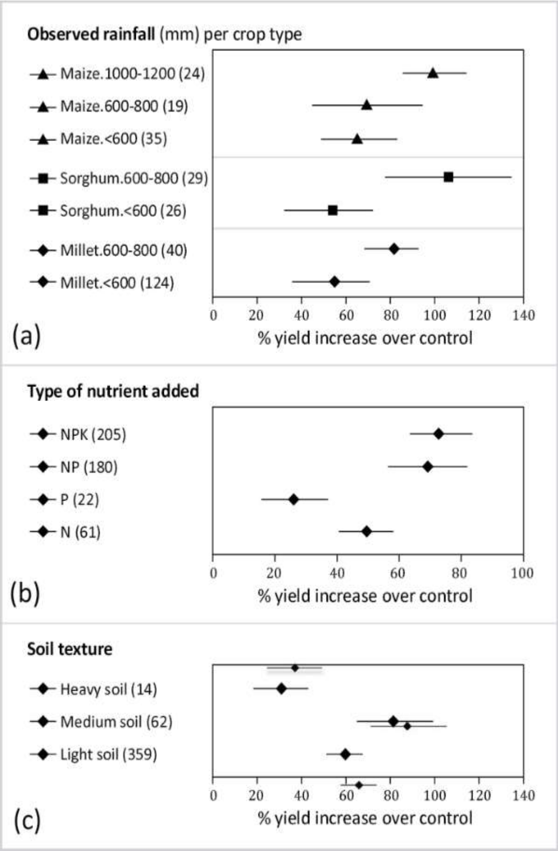
Treatment	Sadore			Dosso		
	WU (mm)	Y (kg ha^{-1})	WUE	WU (mm)	Y (kg ha^{-1})	WUE
Fertilizer	382	1,570	4.14	400	1,700	4.25
Without fertilizer	373	460	1.24	381	780	2.04

Source: ICRISAT (1985).

management, crop rotation, and organic inputs, had positive influences on the response of maize to fertilizer.

The interactive effect of fertilizer and water use efficiency (WUE) has been demonstrated (Table 2), with WUE increasing under crop management practices resulting in higher yields (Fofana et al., 2008; Rockström, 2003, Molden et al., 2010). Fertilizers are as key to improving WUE as water harvesting is to improving FUE. Soil and water conservation measures have been shown to reduce runoff by up to 60% and soil loss by up to 80%, as demonstrated by the Zai and stone bund systems that are widely used in West Africa.

Fertilizer microdosing is being promoted in Africa on smallholder farms to increase land and labor productivity, as the farmers may not be able to afford larger quantities of fertilizers. A meta-analysis reveals that microdosing increased yield of maize, sorghum, and millet by 68%, 70%, and 63%, respectively, with its impact depending on rainfall amount and water conservation, soil texture, and fertilizer composition (Figure 17). Yet, while microdosing at rates of 10-20 kg ha^{-1} appears unable to sustain those yield levels over longer periods of time (Adams et al., 2016), these authors find higher yields at recommended rates of around 40-50 kg fertilizers ha^{-1} to decline over time as well on sandy soils in Niger. Therefore, a longer-term strategy should be devised to turn this kick-start into sustainable practice over time to gradually build up biomass for improving soil health.

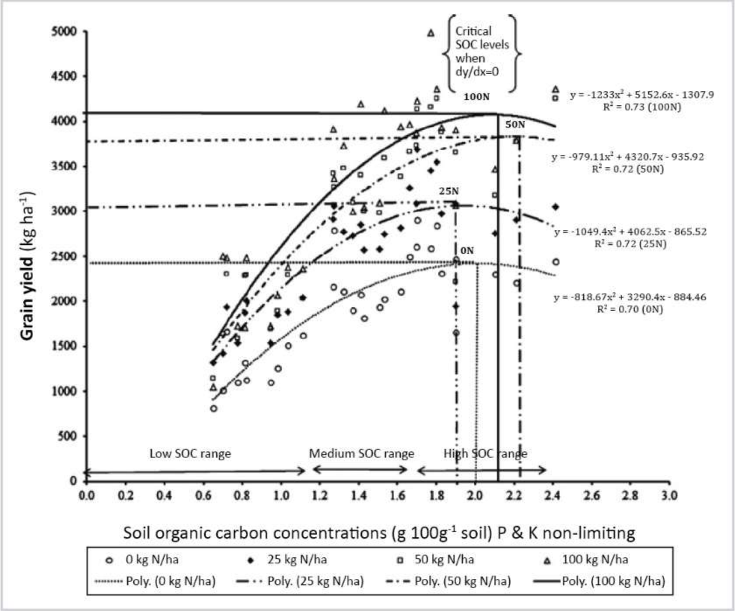


Source: Ouedraogo et al. (2020).

Numbers in brackets represent the number of data pairs that contributed to the calculation of the averages. The error bars represent the 95% confidence intervals obtained by bootstrap.

Figure 17. Yield increase following microdosing fertilization relative to the control (a) by crop type and observed rainfall class, (b) as a function of the type of nutrients supplied, and (c) as a function of soil texture for all data.

There is ample evidence that maintaining and improving SOC will lead to higher FUE (Figure 18; Hijbeek et al., 2017) when soils are not severely degraded (or nonresponsive) or have relatively high SOC content that supports high crop yields, even in the absence of fertilizer. A nice illustration is presented by a three-year study of the FUE in millet grown close to a homestead and far away from it. The FUE appeared to be significantly higher on the field near the homestead than on the field further away in all three years, in spite of low rainfall (Fofana et al., 2008). That said, very fertile homestead plots can result in reduced FUE values since the soil is able to supply most of the nutrients required by growing crops. In the same context, the co-application of fertilizer and organic inputs, as part of the ISFM principles, has also been demonstrated to sometimes result in improved FUE values, mainly caused by the alleviation of a key constraint to increased nutrient uptake by the applied organic resources. In other cases, the effects of co-applied fertilizer and organic inputs are additive with reasonable application rates; negative interactions between both inputs are exceptional.

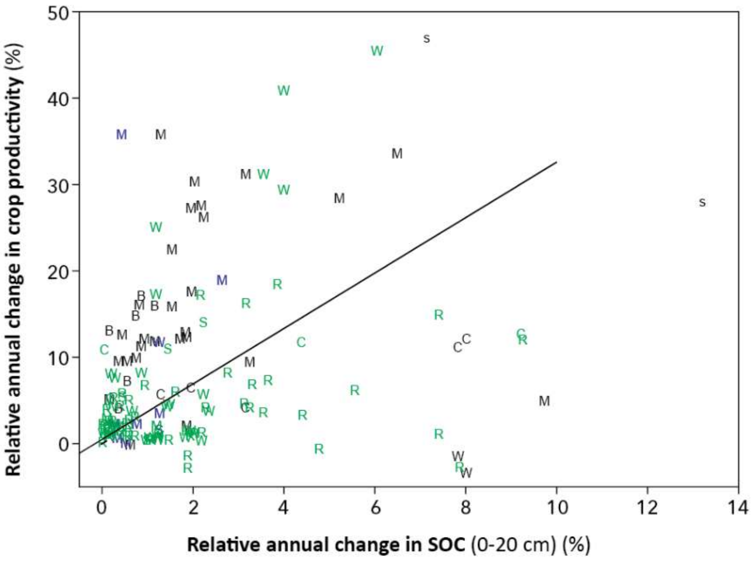


Source: Musinguzi et al. (2016).

Figure 18. Non-linear model fitting of maize grain yield response to added nitrogen fertilizer under soils of different SOC ranges in a Ferrosol in Uganda.

Crop yields increase after application of organic inputs, but this increase is usually much lower than the increase obtained with fertilizer because of limited availability of organic inputs and their slow decomposition. A meta-analysis of 57 studies across SSA involving addition of organic input and/or mineral fertilizer found that maize yield response over the control was 84% on average following the addition of mineral fertilizer and only 60% following the addition of organic inputs (Chivenge et al., 2011). However, availability of organic materials for surface mulching are scarce due to the low overall production levels of biomass and their multiple competitive uses as fodder, construction materials, and cooking fuel. While up to about 1,000-1,500 kg of stover can be produced per hectare at the end of a season, far less than 500 kg remains for mulching due to the competing uses.

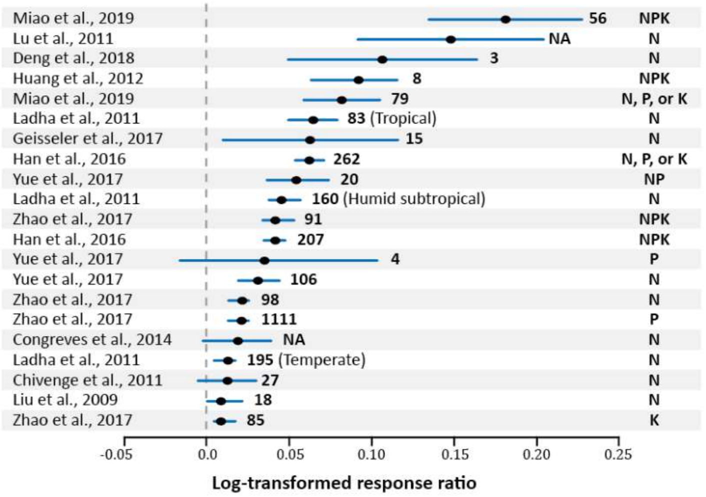
Animal manure has a comparable role as residue mulching for the maintenance of soil productivity (Bationo and Buerkert, 2001; Bationo et al., 2007). Depending on the rangeland productivity, between 10 ha and 40 ha of dry season grazing land and between 3 ha and 10 ha of rangeland of wet season grazing will be required to maintain yields on 1 ha of cropland (Fernandez-Rivera et al., 1995). The availability of manure for sustainable crop production is limited, with a potential annual transfer of nutrients from manure of 2.5 kg N ha^{-1} and 0.6 kg P ha^{-1} on cropland in West Africa (de Leeuw et al., 1995; Bayu et al., 2005). Quantities



Source: Soussana et al., 2019.

Crop species: B, beans; C, cassava; M, maize; P, sweet potatoes; R, rice; S, soybean; s, sorghum; W, wheat. Field experiment regions: Africa (black); Asia (green); and Latin America (blue). The solid line is the standard major axis regression for all data points (n=151, Spearman's rank correlation: y=0.495+3.21x; r=0.205, P<0.012).

Figure 19. Relative annual changes in crop productivity and in soil organic carbon stock (over 0-20 cm) (%) after changes in land management improving SOC.



Points represent the mean effect size, and error bars represent the confidence interval. Numbers represent paired data used in a given meta-analysis. N: nitrogen; P: phosphorus; and K: potassium. Data from the evidence map of Beillouin et al. (2022).

Figure 20. Synthesis of several meta-analyses evaluating the effect of fertilizer on soil organic carbon.

used by farmers range from 1,300 kg ha^{-1} to 3,800 kg ha^{-1}, while on-station experiments are carried out with manure application rates of between 5 mt ha^{-1} and 20 mt ha^{-1} (Williams et al., 1995).

The use of fertilizers is essential to kick-start a process of accumulating residues to increase SOC that comes with the sequestration of N, P, and S. Despite scatter, on average, a 1.3% annual increase in crop grain yields was associated with a 0.4% annual increase in SOC stock across studies in Africa, Asia, and Latin America (Figure 19). The large scatter indicates that there are many other factors besides increased crop yields affecting changes in SOC and points to the need for additional practices to ensure that increased crop yields and biomass production have a positive effect on soil health.

Whereas long-term application of fertilizer in temperate climates increased SOC (Haynes and Naidu, 1998), this relation is not obvious in SSA. Research on the impact of fertilizer use on SOC in different cropping systems is scant, with general indications that soil health-promoting practices are not increasing SOC (Kihara et al., 2020). From a review of published meta-analyses on the effect of fertilizer on SOC, Beillouin et al. (2022) found only one meta-analysis covering experiments in SSA (Chivenge et al., 2011), which showed no significant effects of fertilizer on SOC (Figure 20). There are indications, however, that the inclusion of soybean can improve SOC content and land productivity (Naab et al., 2017; Muzangwa et al., 2021).

In line with the findings of Chivenge et al. (2011), a review of 25 long-term experiments conducted in SSA with contrasting climate, soils, and mineral fertilizer inputs revealed no clear evidence that SOC decreased less strongly over time in the treatment with mineral fertilizer compared with the control (Figure 21). Probably, lower yield levels (and thus C inputs) in SSA explain the different trends observed in croplands globally. That said, even in long-term experiments in temperate regions with fairly high rates of fertilizer use, the impact on SOC is modest – but almost always positive (e.g., Ladha et al., 2011).

It is also important to note that biomass transfer systems can have an impact on soil health but at the cost of depleting the soil health status of the land on which this biomass was produced. One could argue that the net benefit at the overall system level is not enhanced by transferring biomass from one location in the system to another, though the impact of root vs. aboveground biomass needs to be considered in this equation before final conclusions can be drawn, since root-derived C is often observed to be sequestered in larger proportions compared with aboveground-derived C.

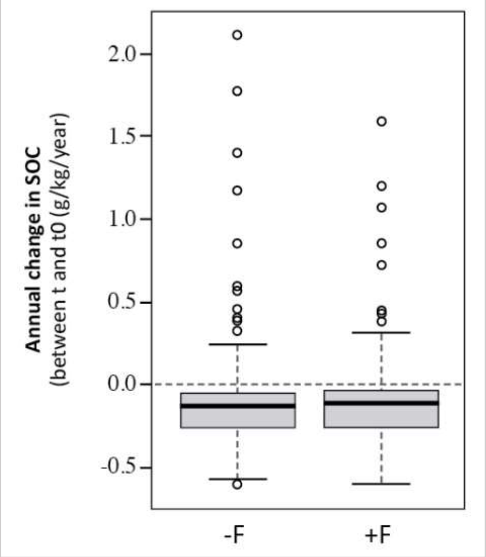


Figure 21. Boxplot of annual change in SOC between the end (t) and the start (t0) of the long-term experiment for the treatment with mineral fertilizer (+F) and the control (-F) for 25 long-term experiments in sub-Saharan Africa.

3.4.3 Reflections on Fertilizer Products

For decades, research efforts have focused on improving the efficiency of fertilizer use through the development of nitrification inhibitors, slow-release fertilizer (N fertilizer coated with S, micronutrients, and inert material), and controlled-release fertilizer (polymers, including natural and biodegradable). In recent years, efforts have also focused on reducing the environmental footprint of fertilizer production. While it is not the intention of this document to cover all major developments aiming to increase the availability of fertilizer while reducing its environmental footprint, some of these are worth highlighting.

A game-changing industrial green ammonia (NH_3) production technology is currently under development and expected to be operational in only a few years. Industrial NH_3 production mainly relies on the Haber-Bosch process, which is energy-intensive and heavily dependent on fossil fuels with massive GHG emission. As the production of green ammonia will no longer depend on the availability of natural gas, the production of N fertilizers will potentially have major geopolitical consequences, driven by major investments by fertilizer companies (Noussan et al., 2020). Green ammonia technology may provide an opportunity for African nations to reduce their dependence on fertilizers imports for the production of food, especially with the increasingly important hydro, thermal, and wind energy taking off in the next decade.

Sufficient P resources are available on the African continent, primarily in Morocco, but also in smaller pockets scattered throughout the continent (Van Kauwenbergh, 2010). Exploration and conventional deep mining of potash salts is a major capital investment, where the exploitation of soluble K fertilizers in the soils of the northern hemisphere is more effective than in deep-leached soils such as those on the African continent. High investment costs and innovative technologies may be needed to propel the development of K mines in the Global South (Ciceri et al., 2015), though the private sector is investing in local exploitation of P and K, which is expected to increase substantially in the coming decade. Alternatives to conventional P fertilizer could allow smaller non-commercial phosphate rock deposits to economically produce P fertilizers, although quality control would be critical in such situations.

While increasing production capacities in Africa is often proposed to reduce prices, most fertilizer currently produced in SSA is exported due to low demand on the continent. Local production is needed, but this must go hand in hand with greater demand and profitable use on the continent by smallholder farmers.

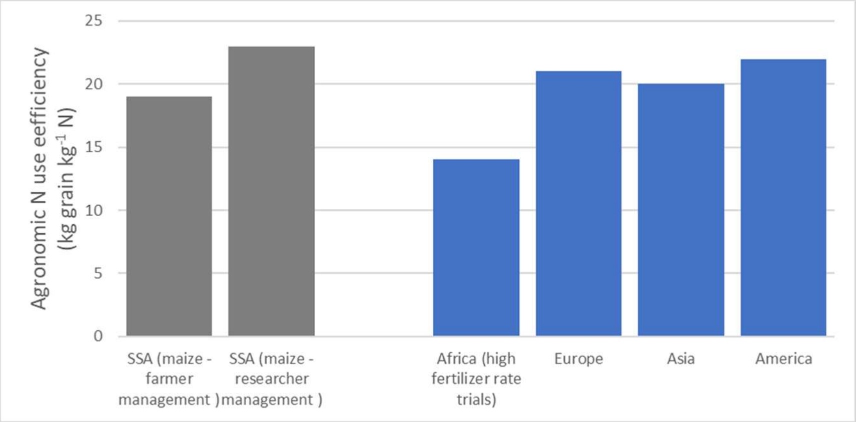
4 Fertilizer and Soil Health – The Practice

The preceding sections provide critical perspectives on the status of soil fertility in SSA and the context of fertilizer and organic resource management for increasing crop productivity while maintaining soil health in the long term. The pervasive crop production and land degradation challenges in SSA are underpinned by complex biophysical and socio-economic constraints, which cannot be adequately addressed through simple and quick-fix solutions. Sustainable crop production intensification and soil health management under the prevailing conditions will require innovative, relevant, economically viable, and locally adapted nutrient management technologies and practices. While the principles that govern sustainable soil fertility management are universal, their application must be context-specific and aligned with the needs and demands of the farmers and stakeholders supporting them. This section tackles the practical considerations for improving fertilizer and organic resource management in SSA, recognizing the need for optimizing resource use under highly diverse and often adverse growing conditions (van Grinsven et al., 2022; van Ittersum et al., 2013).

4.1 Getting the Most Out of Fertilizer

4.1.1 Which Rates for Which Purposes?

Effective and efficient management of fertilizer nutrients is imperative for achieving sustainable increases in crop productivity in SSA. The social, economic, and environmental sustainability outcomes of fertilizer use in crop production systems are dictated by a delicate balance between increasing productivity, optimizing economic returns, minimizing adverse environmental effects, and maintaining soil health and ecosystem services (Petersen and Snapp, 2015). The main target of fertilizer recommendations is to ensure an adequate supply of nutrients to meet yield targets in specific locations based on agroecological and soil conditions and farmers' objectives. An ideal fertilizer recommendation enables farmers to achieve potential yields, maximum fertilizer use efficiency, and optimum economic returns while maintaining soil health in the long term. Effective nutrient use emphasizes increasing productivity and NUE, which sets the foundation for maximizing economic returns and improving soil health through higher biomass production while avoiding the negative environmental consequences of oversupply or undersupply of nutrients. This section presents the critical nutrient management principles and practices that underpin nutrient management sustainability in the context of crop production systems in SSA.



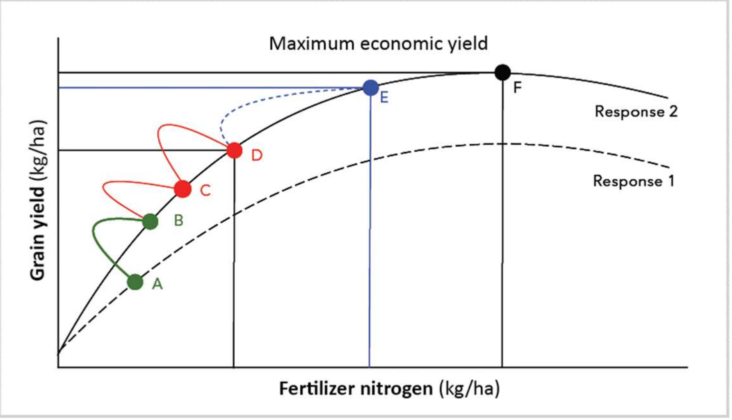
Source: Vanlauwe et al. (2011); Fixen et al. (2015); Lahda et al. (2005).

Figure 22. Agronomic N use efficiency in maize production in sub-Saharan Africa under farmer and research management compared, AE-N for major cereal crops (maize, rice, wheat) high fertilizer rate trials (>100 kg N ha^{-1}) for Africa and other world regions.

AE-N values for maize under farmer and researcher management practices in SSA are comparable the values for other global regions. This is likely due to higher AE-N achieved at lower N application rates. However, for high fertilizer rate trial, agronomic N use efficiencies for major cereal crops in Africa of 14 kg/kg are much lower that other regions (see Section 3; Figure 22; Dobermann, 2005; Lahda et al., 2005; Wortmann et al., 2010; Fixen et al., 2015; Tenorio et al., 2020). The lower agronomic N use efficiency in Africa for comparable crops and high fertilizer rates reflects suboptimal growing environments and management practices. Cereal crops are predominantly produced under unfavorable rainfed conditions that often limit yield response to fertilizer application. Poor soil fertility conditions compound lower responses. In addition, limited resources and a lack of extension services inhibit the adoption of improved seed varieties and appropriate agronomic and fertilizer management practices, including planting densities, timely planting and weeding, and practices that support high AE-N.

Despite the wide variability in crops and heterogeneity of soil fertility at various spatial scales, fertilizer recommendations in SSA are mainly blanket over large regions within countries and based on attainable yields, as defined by rainfall, for example. This overlooks the benefits of adapting fertilizer recommendations to the needs of a specific crop, soil, and climatic conditions and setting relevant target yields in line with farmers' production objectives and the socio-economic environment. The need to change the thrust of research from classical randomized on-station trials or average on-farm conditions that served as the basis for traditional nutrient recommendations to systematic processes that embrace and address this variability is well recognized (Vanlauwe et al., 2016).

Targeting the appropriate nutrient application rates is a critical factor for optimizing productivity, nutrient use efficiency, and economic returns. Applying nutrients amplifies yield, but the yield gain per unit of nutrient applied declines with increasing nutrient application rate, following the typical nutrient response curve. At first, yield increases at the highest efficiency as the fertilizer application rate increases. As the rate of nutrient application further increases, yields increase at a lower rate in the phase of diminishing returns. A point is reached when yield reaches a maximum. From this point on, any addition of extra fertilizer does not increase the yield. When fertilizer application rates are too high, yields may decline due to nutrient toxicities.



Source: Fairhurst (2012).

Figure 23. Model representing the relationship between nitrogen application rate and grain yield.

A model can be used to explain an example of the relationship between N application rate, grain yield response, and profitability in farmers' fields (Figure 23).

- Response 1 and Response 2 represent the grain yield response to added nitrogen fertilizer in a farmer's field.
- Response 2 is greater than Response 1 because of the effect of other ISFM components on the response to N fertilizer (e.g., splitting and timing of fertilizer application and use of germplasm that is more responsive to fertilizer).
- The farmer can move from point A to point B by adopting practices that improve response to fertilizer N (e.g., splitting and timing of application, use of more responsive germplasm, and improved plant population).
- The farmer can increase grain yields and profits (i.e., move from point B to point C) by increasing the N fertilizer application rate in addition to implementing improved splitting and timing of N fertilizer application.
- Point E is the maximum *economic* yield, which is determined by the ratio of N fertilizer price to grain price and the shape of the response curve. Point F is the maximum *agronomic* yield.
- The farmer can increase grain yields and profits (i.e., move from point C to point D) by further increasing N fertilizer application rates up to the point of maximum economic yield, but with each incremental application of fertilizer, the return in kilograms of output per kilogram of fertilizer used decreases. Thus, moving to the maximum economic yield may be viewed by some farmers as too risky.
- There is a range of fertilizer use in which agronomic efficiency is declining but still acceptable and economic returns are positive (i.e., between points B and D). The best position for the farmer between these points depends on a range of farm-specific factors.
- Moving from point E to point F is not economical because the additional income from increased crop yield is not greater than the cost of the extra increment of fertilizer use.

The 4R Nutrient Stewardship framework provides simple, practical, and actionable guidelines to develop effective nutrient management recommendations that match crop nutrient requirements and fertilizer additions (IPNI, 2012). The set of 4R practices is based on global scientific principles that guide effective nutrient management practices at the local level by applying the right source of nutrients, at the right rate, at the right time, and in the right place. Effective application of 4R practices should be supported by other best agronomic practices the local socio-economic and policy context. A core consideration for the right source and rate is to provide specific crops under specific growing conditions with the correct balance of various nutrients in the form and amount in which they are required. Beyond the appropriate rate of application, crop nutrient requirements depend on several interacting genotypes, as well as environmental and management factors, including crop and variety types, soil and climate conditions, and agronomic and nutrient management practices.

The following factors provide the basis for determining nutrient needs:

- Although all crops need 17 essential nutrients for proper growth and development to complete their life cycle, the relative nutrient requirements vary for specific crops.
- Nutrient uptake requirements for specific crops are a function of nutrient concentrations in products and residues and total biomass production (e.g., https://www.fao.org/food-agriculture-statistics/data-release/data-release-detail/en/c/1618651/).
- In the case of macronutrient needs for major food crops, cassava, banana and, to a lesser extent, and yams and sweet potato, are high-carbohydrate producers. They require a large amount of K, which has a special role in carbohydrate synthesis and translocation. Although the K concentrations are relatively lower than in cereal crops, the greater demands for K are due to higher biomass production.
- Legumes contain a high N content in grain and residues relative to cereal crops. A large proportion of the N is derived from BNF, and while low or no N application is required for most grain legumes, effective fixation does require available P.
- The actual nutrient application should take into consideration the uptake by specific crops, yield targets, and soil nutrient supply capacity, which is governed by site-specific soil fertility conditions.
- Fertilizer formulations tailored for specific crops are essential for enhancing fertilizer use efficiencies.

4.1.2 Balanced Nutrition and Its Role in Increasing NUE

Smallholder farming systems in SSA are characterized by profound variability in soil fertility due to inherent soil fertility differences (Niang et al., 2017), landscape position, and differences induced by management practices (Zingore et al., 2007; Tittonell et al., 2008; Amede et al., 2020). While in some instances, distinct landscape positions are clearly differentiated by different and often contrasting soil types (e.g., in the Ethiopian highlands), resulting in landscape position explaining most of the variation in crop response to fertilizer, in other situations, management-induced variation overrides the variation in response to fertilizer. Consequently, with blanket fertilizer recommendations, nutrients can be applied in excess or inadequately for different crops and locations, reducing the efficient utilization of applied nutrients.

Fertilizer management practices tailored to spatial variation in soil fertility are imperative for optimizing crop productivity and nutrient use efficiency. Efforts to refine fertilizer recommendations have followed two main approaches:

1. The crop-based site-specific nutrient management (SSNM) approach (Chivenge et al., 2022b) is based on calculating fertilizer nutrient requirements for a specific crop and field from the difference between the total amount of nutrients required by the crop to achieve a given

target yield and the indigenous nutrient supply (INS) in the soil, which reflects the amount of a particular nutrient (N, P, or K) available from the soil, crop residues, or biological N fixation during one crop cycle. In SSNM, the INS values are estimated from plant nutrient uptake or grain yield in nutrient omission trials, which involve growing a crop with an adequate supply of nutrients except the one whose supplying capacity is being determined. Typical nutrient omission trials comprise a set of five treatments that include (i) control (no nutrients added), (ii) PK (N omitted), (iii) NK (P omitted), (iv) NP (K omitted), and (v) NPK. Estimating INS in SSNM is fundamentally different from soil testing approaches for deriving fertilizer needs, predominant in many other world regions, particularly those with established commercial farms and support services. It provides a direct, quantitative estimate of nutrient supply and thus allows the calculation of the specific amounts of additional nutrients needed to obtain a certain crop yield. The advantage of correctly implemented (following the 4R approach) nutrient omission trials is the simple treatment structure, the contribution of large volumes of data that support big data analytics and crop modeling, and the ability to utilize weather forecasts for weather-sensitive nutrient management decision support.

2. Soil test-based recommendations are well established – established in the sense of general acceptance and the default approach for generating recommendations, but often with limited scientific basis – and widely used in other global regions. Soil testing is not widely available in smallholder farming systems and has general limitations in assessing the effective nutrient supplying capacity (Dobermann et al., 2003; Schut and Giller, 2020). Challenges that limit soil testing in smallholder farming systems in SSA include the high cost of soil sampling and analysis, the difficulty in collecting representative soil samples, ill-equipped laboratories, and the time required to produce results. There are also limitations associated with standardization and interpretation of soil test results (Njoroge et al., 2017). Innovations in infrared spectrometry scanners provide a potential soil testing alternative that could be more accessible and affordable to smallholder farmers. On-the-spot soil testing could support the diagnosis of soil constraints and serve as the basis for field-specific recommendations. The effectiveness of scanners is currently limited by the poor reliability of in-field assessment analysis and the limitations of the models for translating the results into appropriate nutrient recommendations. The raw results of the tests are sent by cell phone to a central website. Then, calculations are made, and recommendations are delivered back to the extension agent. Recent soil information initiatives have generated soil information at a scale that can support the diagnosis of soil constraints and provide guidelines that reduce the uncertainty in fertilizer nutrient responses at specific locations.

Hybrid approaches that deploy components from both of these approaches may actually overcome some of their respective limitations. For example, the Virtual Agronomist application (https://www.isda-africa.com/virtual-agronomist/) presents high-resolution digital soil information (30 m) and uses Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS)-style algorithms to calculate site-specific fertilizer rates while providing advice on important cropping practices.

Local soil fertility indicators are based on farmers' knowledge of the soil fertility, management practices, and characteristic nutrient deficiency symptoms and have been demonstrated to be useful in determining site-specific nutrient requirements. Key indicators that correspond well with laboratory soil testing results include management history, soil color, plant height, deficiency symptoms observed in crops, crop yield, stoniness, and type and abundance of weeds. Nutrient deficiency symptoms provide a direct indicator for detecting deficiencies of specific nutrients. Descriptions of characteristic nutrient deficiency symptoms for various crops, as well as guidelines with color photos, are available for supporting field diagnosis. Photographs of different cassava root sizes have recently been used to engage cassava farmers in assessing the current fertility status of their fields (https://acai-project.org/).

There is increasing recognition of the critical need for secondary and micronutrients (SMNs), including Ca, Mg, S, Zn, Cu, manganese (Mn), Fe, boron (B,) and molybdenum (Mo), that often limit crop yields, especially in sandy soils that are continuously cropped. Several studies point to a significant occurrence of so-called “nonresponsive soils,” in which crop yields showed no or even negative responses to NPK fertilizer (Shehu et al., 2018). In many of these cases, the problem derives from a lack of one or several of the SMNs. Most of the commonly applied fertilizers in SSA contains mainly N, P, and/or K, which accelerates the depletion of SMNs. The application of SMNs can significantly affect crop yields in SSA and increase the use efficiency of macronutrients. A meta-analysis of data from SMN response trials across SSA showed that application of S and micronutrients increased maize yield by 0.84 mt ha^{-1} (25%) over macronutrient-only treatment, with a probability of response ratio exceeding 1 for S of 0.77, for Zn of 0.83, for Cu of 0.95, and for Fe of 0.92 (Kihara et al., 2016). Secondary and micronutrient responses are closely associated with soil type, providing a simple criterion for identifying areas for targeting their application. Because SMNs are required in small quantities, fertilizers with micronutrients could offer a cost-effective and economically viable solution for addressing soil micronutrient deficiencies.

The responsiveness of soils to NPK application is highly variable at the field level, which presents a challenge in diagnosing constraints and developing nutrient management recommendations. A major obstacle in optimizing the agronomic and economic benefits of fertilizer is the prevalence of degraded soils that respond poorly to NPK fertilizers (Breman, 1992). Nonresponsive degraded soils are associated with complex chemical, physical, and biological constraints that severely inhibit NPK fertilizer response. The main soil characteristics that underlie poor crop nutrient response include low soil organic matter, clay content, acidity, nutrient deficiencies and imbalances, moisture deficits, and compaction (Ichami et al., 2019; Kihara et al., 2016; Njoroge et al., 2018; Roobroeck et al., 2021). Urgent attention is required to support diagnostics, and long-term soil fertility investments are necessary to address the challenge of nonresponsive soils in order to maximize the agronomic and economic returns on fertilizer. Section 3.1 addresses the processes underlying soil degradation and judicious fertilizer management in combination with other management practices and soil amelioration and conservation practices that are critical for rehabilitating degraded soils.

While there is much uncertainty in the estimate of the proportion of nonresponsive soils, the occurrence is variable across different areas, on the order of 0-68% for maize production systems in SSA (Kihara et al., 2016; Shehu et al., 2018; Ichami et al., 2019; Nziguheba et al., 2021; Roobroeck et al., 2021). Nonresponsiveness is mostly generated by inappropriate management practices, including poor agronomy, soil acidifying- or erosion-generating practices, a lack of SMN application, or even a shift from single superphosphate (SSP) to triple superphosphate (TSP), resulting in S deficiencies, or from TSP to diammonium phosphate (DAP), resulting in Ca deficiencies. The susceptibility to degradation and poor response is closely related to soil type. A recent analysis showed the highest risk for nonresponse involve Fe-rich Plinthosols, followed by the Al-rich Alisols and the erosion-prone Lixisols and Leptosols (Sileshi et al., 2022). Cambisols, Fluvisols, Luvisols, and Nitisols, on the other hand, were observed to be highly responsive to NPK fertilizer. Investment to rehabilitate nonresponsive soil should target the main constraints limiting yield response. These include organic resource application to increase soil organic matter and improve soil physical, chemical, and biological properties; application of SMNs in deficient nonresponsive soils; liming of acidic soils; and deep tillage of soils affected by a hardpan.

All the above said, despite the wide occurrence of nonresponsive soil, overall positive and agronomically viable crop responses to fertilizer are observed at scale with good fertilizer and agronomic practices under most circumstances. Best nutrient management practices should acknowledge that the use of (some) fertilizers, cultivation, and weathering lead to soil acidification, and therefore, liming should be a component of the prescribed package (Crawford et al., 2008). While nonresponsive soils should not be ignored, especially in areas with high population densities and lack of fallows, their presence should not be used as an argument against the use of fertilizer.

4.1.3 New Science and Data Supporting Locally Relevant Agronomy at Scale

There is a growing research and development shift from uniform and blanket fertilizer recommendations to more specific recommendations fine-tuned to local conditions but designed to reach and benefit large numbers of farmers at scale. Such conditions that drive local adaptation of fertilizer recommendations include soil fertility status, cropping calendars, available fertilizer blends, planting practices (tillage, weed control, density, timing), common nutrient deficiencies, intercropping options, market demands and opportunities, and the availability of labor. A combination of database management, geographic information systems (GIS), remote sensing, modeling, and widespread internet coverage has led to significant progress in agronomy research in the pursuit of providing this information at relevant scales to smallholder farmers. The advisory service AKILIMO, developed by the African Cassava Agronomy Initiative (ACAI), is exemplary in this respect. Specific recommendations became available to farmers at scale, allowing them to choose the best agronomic options to maximize returns on their investment.

Conventional research processes have encountered major limitations in addressing complex variability at local field and farm scales while responding to the demand for agronomic solutions that can be quickly and cost-effectively delivered to millions of smallholder farmers. Rapid technological advancement offers an opportunity to overcome this limitation and enables innovation for developing agronomy-at-scale approaches that remain relevant for local applications. A framework for operationalizing agronomy-at-scale to enable the reliable transfer of effective agronomy recommendations is commonly based on the following components:

- GIS-supported sampling frames: a geospatial information base that provides appropriate biophysical and socio-economic information, such as climate, soil, terrain, crop area distribution, input, and output market access for guiding spatiality to take advantage of agronomic recommendations linked to market opportunities.

- Field trials with effective experimental designs: a network of standardized agronomic trials designed to effectively diagnose nutrient and agronomic constraints and validate the performance of recommendations under representative locations and conditions.
- Fast and accurate (although often less precise) measurements: a shift from precise data collection from limited sites to rapid and reliable measurements that support the collection of large volumes of data that provide insights into trends and uncertainty of the performance of agronomic practices at scale.
- Statistics and geospatial analyses: a data analytics framework and tools that allow credible analysis and interpretation of data for improving investment decisions at various scales; integration of statistical and geospatial analyses, remote-sensing unmanned aerial vehicles (UAVs), field sensors, and crowd-sourced techniques to generate large-scale data for scale-sensitive recommendations.
- Surveys to learn about inherent variation: standardized survey for capturing management decisions and practices and their influence on soil fertility and crop performance.
- Crop modeling to accelerate field testing: development, calibration, and validation of a modeling tool, coupled with geospatial tools that can support assessment of multiple and complex agronomic management scenarios and guide simple solutions for field testing (Franke et al., 2018).
- Efficient data management system: a consolidated, interoperable data management system comprising data collection tools, data storage infrastructure, and data exchange procedures that adhere to findable, accessible, interoperable, and reusable (FAIR) principles and ensure open access to high-quality data.
- Decision support tools and validation exercises: a suite of decision support tools that deliver agronomy information to end users and validation of the performance of such information, supported by training and promotional materials.
- Education curriculum for agriculture students, which should include quantitative methodology and a systems approach.

For the above agronomy-at-scale approaches to be enabled and to support many other data-driven decisions regarding fertilizer use and soil health management, the availability of open and standardized data is critical. A lack of high-quality, high-density, and real-time data in relation to crop production, soil fertility conditions, and input use is hampering the development of agronomic practices that support improved fertilizer use efficiencies and management of soil health. While tools are now available to collect, manage, and assemble “big data” using rapid and efficient methodologies, including remote-sensing information, data are often not compliant with FAIR principles, georeferenced, or standardized, thus resulting in many missed opportunities to address important agronomy-related challenges in smallholder farming systems.

4.2 Niches for Organic Matter Production

Organic resource management is a core component of practices for maintaining soil health due to its strong influence on soil biological, chemical, and physical properties and functions. The combined application of organic and inorganic resources is crucial for sustainable crop production intensification in smallholder farming systems in SSA because of the positive and synergic interactions of their co-application (Vanlauwe et al., 2011). The ISFM framework centers on the complementarity of both organic and mineral nutrient inputs to meet crop nutrient requirements in the short term and sustain soil health in the long term. The type, availability, quality, and effectiveness of various organic resources vary profoundly in SSA in view of the wide diversity of farming systems and are strongly influenced by agroecological conditions, market access, and population density. At the local level, farmers' decisions on the management of organic resources are influenced by a wide array of socio-economic factors, including availability and opportunity costs of land and labor, degree of crop-livestock integration, and the cost of acquiring organic resources.

4.2.1 Availability of Organic Inputs in Smallholder Farming Systems

Among the considerable organic resource options, the technologies that have potential value for wide-scale use in the production of field crops include animal manure, compost, cereal crop residues, natural fallowing, improved fallows, relay or intercropping of grain legumes, perennial ley systems (Place et al., 2003; Wortmann and Stewart, 2021), and biomass transfer systems, with each of those systems having specific characteristics affecting their adoption (Table 3).

Table 3. Potential sources of organic inputs and selected characteristics related to their use and effectiveness.

Source of Organic Input	Key Characteristics	Adoption Potential for Field Crops	Agronomic and Economic Effectiveness	Limitations
Animal manure	Livestock manure collected from stalls and applied to cropland or directly deposited by grazing animals.	High in integrated crop-livestock systems	Short-term nutrient supply potential highly variable and mostly low; effective in long-term soil fertility improvement	High labor demands for management and application of manure; use of manure largely limited to livestock owners
Compost	A range of organic materials collected and incubated before application to croplands	Limited to small areas	Limited due to the small amounts that can be produced	High labor demands for composting and field application
Cereal crop residues	In-situ recycling and utilization of cereal crop residues by surface retention or incorporation	Variable depending on the farming system; limited by competing use of residues for feed and fuel	Limited by low short-term N contribution	High C:N ratio, which can induce N immobilization; poor synchrony between nutrient release and uptake; potential for perpetuating plant pests and diseases
Grain legume residues	In-situ recycling and utilization of grain legume residues by surface retention or incorporation	High due to the added food and income value of grain legumes	Rotational effects on cereal crops variable depending on legume type, production level, and residue management	Low yields achieved due to limited management investments; poor synchrony between nutrient release and nutrient uptake

Source of Organic Input	Key Characteristics	Adoption Potential for Field Crops	Agronomic and Economic Effectiveness	Limitations
Natural fallow	Withdrawal of land from cultivation for a period of time to permit regrowth to regenerate soil fertility	Limited due to increasing demographic pressure	Limited by the long periods required to replenish soil fertility with natural fallows	Reduction of available cropland
Improved fallow	Purposeful planting of a beneficial woody or herbaceous plant to grow for a period of time	Limited due to lack of immediate yield benefits	Impacts equal to natural fallows in a shorter period of time; provides additional benefits, including fuelwood	Limited attractiveness to farmers due to the lack of immediate benefits and limited availability of improved fallow seed; land ownership necessary
Perennial ley systems	Integration of perennial grasses into cropping cycles, rotated with annual crops	High under semi-grazed, intensive livestock systems	Commonly increases the soil organic matter content, with expected benefits on fertilizer use efficiency	Limited applicability in the absence of intense livestock production
Biomass transfer	Transport and application of organic material from its ex-situ site to cropland	Limited due to limited available land	Limited by the small amounts that can be applied to field crops	Need for extra land; high labor demands for the collection and transfer of biomass

While the biomass production potential of the above systems varies widely, in-situ production of organic matter offers the most attractive option for most smallholder farming systems since it does not require movement of large amounts of bulky, often moist matter.

4.2.2 Role of Biological N Fixation

Symbiotic BNF is an option for supplementing N fertilizer due to the supply of organic resources with high N content. Several technologies based on BNF, including agroforestry, green manures, and rotation or intercropping of cereal crops with grain legumes, can provide substantial N and high-quality organic matter and act as a complementary source of N to fertilizers. Grain legumes have the advantage of providing income and protein for human nutrition and potentially supplying N to cereal crops grown in a rotation. Grain legumes are more attractive to smallholder farmers who are concerned about marginal losses in yields when other technologies that do not contribute directly to food security, such as green manures, are used. Legume rotations are essential for maintaining soil fertility for farmers with sufficiently large landholdings. In contrast, grain legumes are predominantly intercropped with cereal crops in densely populated areas. Breman and van Reuler (2001), however, showed that the cost of phosphorus fertilizers for effective BNF is often higher than the cost of using nitrogen fertilizer and presented a decision support system for making a choice. Now, effective high-quality rhizobium inoculants are available in packages that are aligned to smallholder farmers' needs for key legumes, such as soybean, common beans, or groundnut (Vanlauwe et al., 2019).

Net contribution to the N balance of the soil by grain legumes is only possible if the amount of N removed by grain is smaller than the total amount of N fixed, provided that all the stover is retained. Some grain legumes have high N harvest indices and may have a net uptake of N from the soil as they concentrate N in the grain. Other legumes, such as common beans, have low BNF capacity and may require initial supplementary mineral N to boost productivity (Giller, 2001). Important legumes that have shown promising potential in SSA to contribute substantial organic matter and N to the soil include soybean, pigeon pea, and groundnut.

Significant challenges exist in enhancing the productivity of grain legumes and, hence, their impact on maize in rotation under poor soil fertility conditions on farmers' fields where the productivity of grain legumes and BNF are constrained by insufficient availability of nutrients, especially P (Franke et al., 2018). Fertilizer recommendations primarily target sole maize cropping, and application of P fertilizers and organic nutrient resources to grain legumes to increase their productivity is scarcely promoted. Other factors constraining the production of grain legumes are directly linked to farmers' preferences, as they favor the main staple crop of maize over grain legumes to ensure food security instead of income. Farmers also reserve the largest areas on the most fertile plots, often closest to homesteads, for maize and only allocate small portions of outer fields that are poor in fertility to produce grain legumes, usually less than 5% of the cropped area. Intercropping maize with grain legumes offers opportunities to improve the overall productivity of both crops and ensure the legumes benefit from fertilizer targeted to maize.

4.3 Economic Realities

Although fertilizers are a key component of sustainable food systems, their widespread use in Africa is heavily dependent on precarious politics (Gilbert, 2012). Adoption and application rates among smallholder farmers in SSA remain below the requirement, despite substantial initiatives to improve fertilizer use (Sanchez, 2002). Fertilizer use varies greatly between and within countries as a result of differences in both micro- and macroeconomic conditions. At local level, household and farm characteristics, social and human capital, crop type, credit access, off-farm income, regular labor availability, and farmers' perception of the effects of fertilizers on soil fertility influence fertilizer use (Mapila et al., 2012). Moreover, biophysical conditions, such as amount of rainfall and soil type, are important; the risk of crop failure resulting from low rainfall is a strong disincentive to the purchase and use of fertilizers on subsistence crops (Probert et al., 1995). This section focuses on the economic dimensions of fertilizer use.

4.3.1 Ecological vs. Economic Yield Gaps

Across SSA, crop yields are much lower than what is attainable given the environmental conditions (soil and weather) and available technologies, referred to as an ecological yield gap. In fact, yield gaps in smallholder agriculture in SSA are the largest in the world (Tittonell and Giller, 2013). For example, the national average ecological yield gaps for rainfed maize are as high as 4,800 kg ha^{-1} for Tanzania and Burkina Faso and more than 9,000 kg ha^{-1} for Nigeria and Ethiopia (Bonilla-Cedrez et al., 2021). Closing this ecological yield gap is important for food security and the well-being of rural households. Low use of fertilizers combined with low fertilizer use efficiency is an important barrier to closing the yield gap (ten Berge et al., 2019).

Crop response to N fertilizer varies across SSA, within countries, even within farms, according to agroecological and soil conditions (Tittonell et al., 2005; Vanlauwe and Giller, 2006; Zingore et al., 2007). Studies show a wide variation in fertilizer response of between 5 kg and 53 kg grain kg^{-1} N applied (Bonilla-Cedrez et al., 2021). Though N is often the main nutrient that is lacking in African soils, deficiency of other nutrients limits crop response to N in some situations. For example, even if legumes are grown as a means of obtaining N input, legume growth is frequently limited by a lack of P (Koné et al., 1998; Vanlauwe et al., 2019). As a general rule, N is more limited than P in the (semi-)arid zones, but with increasing rainfall, P becomes more limiting than N. The contribution of legumes to the natural vegetation is higher in drier areas than in the more humid regions (Breman, 1998). Soil acidity generates inefficiencies in fertilizer use (Pearce and Sumner, 1997; Evans and Kamprath, 1970), and fixation of P also depresses returns to phosphatic fertilizers (Kanyanjua et al., 2002).

There is concurrence that, on average, farmers in SSA need to use much more fertilizer than they currently use in order to close the ecological yield gap. Even though it may be technically feasible to increase crop yields (closing the yield gap) in many regions of SSA, it is not always economically viable for farmers to substantially increase crop yields. Increasing fertilizer rates is economically illogical or irrational from the farmers’ perspective in some instances (Bonilla-Cedrez et al., 2021). Sheahan (2011) showed that farmers in major maize-producing areas of Kenya may already have surpassed the optimum level of fertilizer application. This suggests that an increase in fertilizer use cannot be encouraged without addressing other constraints besides the nutrients contained in such fertilizer.

Fertilizer price is an important determinant of farmers’ incentive to adopt or use inorganic fertilizers (Burke et al., 2020). Variable and unfavorable farm-gate prices faced by farmers contribute to making investments in inorganic fertilizers unattractive. There is considerable spatial variation in input and output prices in addition to the variation in crop response to fertilizer (Bonilla-Cedrez et al., 2021). Profitability of fertilizer use, therefore, depends on the effective local price of fertilizer and crop outputs and on the local crop response to fertilizer; thus, fertilizer use is profitable in some regions but not in others (Bonilla-Cedrez et al., 2021). Bonilla-Cedrez et al. (2021) assessed location-specific ecological and economic conditions and how they affect crop response to fertilizer and economic returns on fertilizer investments. The study showed that (i) the average economic yield gap (the difference between current yield and profit-maximizing yield) was about 25% of the ecological yield gap; (ii) though maize yields could be profitably doubled, the economic incentives to do so are weak due to unfavorable input:output prices; and (iii) risk from variable seasonal rainfall makes this worse. In a related study on input and output prices, considerable variation in the profitability of fertilizers was found within countries (Bonilla-Cedrez et al., 2021), which emphasizes the need for tailoring fertilizer recommendations to smaller areas considering localized environmental conditions (Bonilla-Cedrez et al., 2021).

Regardless of how well fertilizer markets work, farmers in areas where yield response to fertilizer is low are unlikely to find investment in fertilizer attractive. Under optimal agronomic response, the expected economic returns on investment in fertilizer are highly variable or uncertain and are conditioned by variable seasonal rainfall. (Chamberlin et al., 2021). Further, sensitivity of fertilizer profitability to yield variability is more acute where there is low soil C (Chamberlin et al., 2021). The dilemma that arises is, where SOC is already low, it is difficult to grow large crops to produce the required residues that can raise SOC. The returns from fertilizer are also dependent on farmers' practices too, with a great effect from late weeding (Burke et al., 2020). Low returns from fertilizer are also attributed to low-quality fertilizers. Low-quality fertilizers, in terms of the nutrient content and weight, are offered to farmers due to the unscrupulousness of traders or suppliers, poor storage conditions, low or inadequate capacity to enforce fertilizer quality regulations and standards, and poor deterrent policies. Several countries, such as Kenya, now have a fertilizer policy that addresses some of these issues; however, enforcement of regulations remains a challenge (Sanabria et al., 2013). Unfortunately, fertilizer blends, such as 15-15-15 and 17-17-17, are often supplied in place of straight fertilizers. This requires farmers to pay for nutrients that often have low profit:cost potential and limits the financing available for full optimization of fertilizer use.

4.3.2 Farmer Segmentation and Other Determinants Affecting Fertilizer Use

Variations in agricultural technology adoption can be attributed to differences between farmers, farms, and the environments in which they operate. These have a significant influence on the attitude, preferences, opportunities, constraints, and incentives regarding fertilizer use and soil health management. Farmers' potential, ability, or willingness to invest in fertilizer and good soil health practices can be understood by examining the determinants of adoption of technology in general, fertilizer, and good soil health practices. Segments of farmers' potential to invest are thus identified by highlighting the factors that have been shown to influence their uptake/adoption.

Profitability is an important determinant of technology use. Profitability of fertilizer use is affected by crop response to fertilizer and by effective input and output prices (prices realized by the farmers). Poor crop response to fertilizer is an important barrier to fertilizer use, and hence, classification of farmer's fields according to probability of responsiveness or nonresponsiveness would be useful. For the latter, it is crucial to identify and, where possible, remediate the constraints. Farm-gate prices (also referred to as the effective prices) of inputs, such as fertilizer and farm produce, differ markedly from market prices, as a result of high transportation and transaction costs. Categorizing farms according to the distance from the fertilizer stockist and produce markets and the related transaction costs would reveal where fertilizer uptake is likely to be high or low. Many smallholder farmers, however, continue to use fertilizers despite being unprofitable (Burke et al., 2020). Unprofitable use of fertilizer is driven by heavy subsidies, which makes fertilizer use profitable even though the returns may be actually lower than farmers would ordinarily accept. It is also associated with smallholder farm households with a strong preference for food self-sufficiency to avoid high food prices.

Farmers are less likely to apply fertilizers where the risk of nonresponse or nonprofitable response is high, real or perceived. Interventions such as insurance, however, are likely to encourage fertilizer use in such environments. The agroecological and institutional environment not only determines the risk farmers are faced with, but also opportunities for profitable technology use, including fertilizer. High risk of crop failure is associated with environments with variable or unpredictable rainfall, so farmers in such areas who rely on rainfed agriculture are less likely to apply inorganic fertilizers. They are, however, likely to invest in good soil health practices as a way of preserving soil moisture – though the availability of organic resources may be a constraint in such environments.

Farmers who grow high-value crops are likely to invest in technologies such as fertilizer and other soil health practices as a way to increase profits, reduce costs, and maximize the moisture available. Although farmers are less likely to invest in traditional food security crops, higher food market prices, often driven by crops becoming raw materials for the processing industry (e.g., cassava for flour), do increase the likelihood that farmers invest in fertilizer and/or soil health management practices.

Land is a key factor of production. Farmers with large farm sizes are likely to invest in fertilizers and soil health practices. They are also likely to have significant or adequate amounts of organic matter resources. Farmers without secure land tenure (access, use, or ownership) are unlikely to invest in technologies (Abdulai et al., 2011; Zeng et al., 2018; Bedeke et al., 2019), while those that have security of land tenure, i.e., where eviction is improbable, have less uncertainty and are likely to invest in soil health practices (Abdulai et al., 2011; Oostendorp and Zaal, 2012) since they are certain to reap the medium- to long-term benefits. Furthermore, farmers who own land are able to access credit, an important enabler for investments in technologies. The converse is also true; farmers are unlikely to invest on land that is rented or land with access insecurity or conflict.

Differences in farm location influence farmers’ access to markets and services. Farmers with a ready market for their produce are likely to invest in fertilizer and soil health. Liquidity constraints prevent farmers from adopting technologies such as fertilizers, and access to credit is likely to positively influence farmers’ willingness to invest in fertilizers and soil health and their willingness to take risks. Similarly, farmers with off-farm income (salary or business) are also likely to adopt technologies because they can absorb shocks, including those generated from failure in agricultural technology. Such farmers who have no liquidity constraints are likely to invest in long-term soil health management interventions. Furthermore, fertilizer subsidies ease liquidity constraints and encourage farmers, including poor farmers, to invest in inputs, such as inorganic fertilizers; however, they are known to abandon fertilizer use once the subsidy is discontinued and fertilizer becomes unprofitable to use.

Farmers’ age, gender, and education level are mediating factors and correspond to farmers’ knowledge, ability, preferences, and risk appetite, with the resultant effect of the above factors on farmers’ uptake of technology. Lower adoption of agricultural technology by women farmers may be attributed to differences in technology preferences, cultural acceptability, and suitability of a particular technology to agricultural tasks performed by women (Quisumbing and Pandolfelli, 2010). Traditionally, women are less likely than men to be aware, to try out or adopt agricultural technologies, as a result of limited land rights, women spending significantly more hours on domestic and reproductive and caregiving roles, and gender norms and power relations which limit the range of decisions women can make (Meinzen-Dick, et al., 2011; Juster and Stafford, 1991; Tufa et al., 2022). Furthermore, women’s adoption of technology is normally constrained by access to and use of agricultural inputs, extension support, and access to credit and markets. They also lack complementary resources, especially land and labor.

5 Fertilizer, Soil Health, and Climate Change

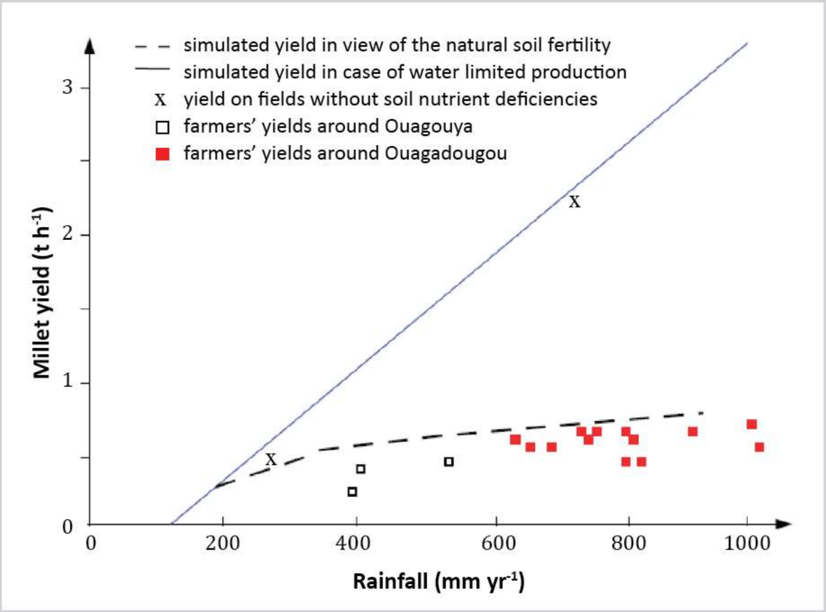
Soil degradation and climate change present two of the most pressing threats to the future sustainability of crop production systems in SSA. They mutually reinforce each other, creating profound implications for food security and livelihoods in Africa. African agriculture is also highly vulnerable to climate change due to rapidly changing climate trends, high reliance on rainfed agriculture, and limited economic incentives and institutional support to buffer farmers against the risks associated with climate change. Climate-smart and sustainable nutrient and soil management interventions are therefore critical for African crop production systems to achieve the targets to increase agricultural productivity while concurrently enhancing soil health, building resilience and adaptation to climate change, and reducing GHG emissions from agriculture. Building on the context of soil health and management practices for optimizing fertilizer use, this section reviews the scope of improved fertilizer and soil health management for climate change adaptation and mitigation in crop production systems in SSA.

5.1 Soil Health and Climate Change Adaptation and Mitigation

Soils play a central role in managing and regulating climate change adaptation and mitigation, and their proper management is critical for ensuring the sustainability and resilience of crop production systems in Africa. The major challenge facing agriculture in Africa is how to increase crop productivity under rapidly increasing demographic pressure and changing climatic conditions while maintaining or enhancing the health of the soil resource base. Climate change and soil degradation are interrelated and together often produce an amplified severity in their impact. The increasing frequency of droughts due to climate change has significant implications for reduced biomass production in natural and agricultural ecosystems, inducing land degradation, particularly in arid and semi-arid zones (Wonkka et al., 2016). On the other hand, land degradation due to agricultural activities contributes to soil GHG emissions. Emissions of GHG from cropping systems in Africa are predominantly caused by increasing demographic pressure and the predominance of low-input systems that drive area expansion and conversion of natural woodlands and forests with higher C stocks to cropping and grazing systems with low C stocks. Agricultural land presents a trade-off because the same land used for providing essential food and other products stores large amounts of C in soils and biomass in its natural state, thus mitigating climate change (Vlek et al., 2017). Therefore, sustainable management of agricultural systems and improved soil health are critical for climate change adaptation and GHG emission mitigation.

Correct and effective fertilizer management plays a vital role in increasing yield and profits and climate change adaptation by enhancing resistance to moisture stress and improving water use efficiency. Tactical fertilizer management systems that are flexible and responsive to intra- and inter-seasonal rainfall variations also provide a crucial adaption and risk management mechanism by matching fertilizer inputs to seasonal crop performance levels determined by the conditions of the season. A balanced supply of N, P, and K to alleviate nutrient deficiencies provides favorable growing conditions that enhance water use efficiency and buffer the effects of moisture stress. Even in less favorable climatic zones, such as the Sahel, significant yield improvements have been observed when fertilizers are judiciously applied. Breman et al. (2001) showed that low soil fertility is a main yield-limiting constraint for millet production in Burkina

Faso despite the low rainfall conditions (Figure 24). Yields observed in farmers' fields were generally lower than the expected yield when no fertilizer is applied, suggesting significant yield limitations associated with low soil nutrient availability. Even at the lower rainfall range of 400-600 mm, opportunities exist to more than double crop productivity with fertilizers.



Source: Breman et al. (2001).

Figure 24. Millet yields in Burkina Faso in relation to rainfall: simulated yield in view of the natural soil fertility and simulated yield in case of water-limited production.

For effective climate change adaptation, fertilizer should be combined with other crop, soil, and water management practices and conservation strategies. Fertilizers on their own seem to have a limited adaptation potential. Yield responses to fertilizer have been predicted to be of the same magnitude as yield reductions caused by changing climatic conditions, indicating that fertilizer application does not buffer yield losses with reduced rainfall (Lobell et al., 2014; Carr et al., 2022).

5.2 Does Fertilizer Application Speed Up the Decomposition of SOC?

Soils that are cleared from natural fallows are known to release substantial amounts of CO_2-C in a relatively short period of time (Figure 11). Arable lands therefore contain less then half the SOC in natural systems and are prone to further degradation as they continue to emit 30-50% more CO_2, with higher soil temperature and lower soil moisture being the main drivers (Anokye et al., 2021). The primary source of African GHG emissions is land clearing equivalent to 1.1-1.5 Pg CO_2-eq annually, which is about double the losses from agricultural practices and somewhat higher than that of fossil fuel use. As agricultural expansion alone accounts for 70-80% of Africa's total forest loss, land use change is by far the largest emitter of GHGs (Olorunfemi et al., 2022). Land-sparing effects, as a result of system intensification aided by increased fertilizer use and soil health, therefore save GHG emissions due to reduced land conversion (van Loon et al., 2019). After all, fertilizer use is essential to intensify farming systems, thus reducing GHG emissions by preventing the need to expand agriculture onto new lands and possibly return agricultural land back to nature.

An important question in this debate is whether fertilizer application speeds up the decomposition of SOC, further increasing the release of CO_2-C. For example, a recent study by Feng et al. (2022) found an increase in microbial C use efficiency after six years of N addition that was primarily driven by increased microbial growth, thus enhancing decomposition. On the other hand, Ladha et al. (2011) showed increased SOC with N application in 135 studies in 114 long-term experiments globally, including only one experiment in Africa but several tropical and subtropical sites in India and elsewhere. They concluded that increased crop growth with N led to increased organic inputs to soil.

N fertilizer can positively or negatively affect SOC decomposition via several direct and indirect pathways. Different mechanisms play a role in the net effect of N fertilizer on soil C dynamics, and N addition has the potential to affect both the processes of C gains from plant growth and turnover as well as C losses through microbial decomposition. Whether N addition increases SOC thus depends on the balance between the response of C inputs and decomposition, the net effect contingent upon pedoclimatic conditions and the cropping context. Moreover, changes in management practices with increased use of fertilizer (e.g., increased crop residue removal) can result in decreasing SOC content, incorrectly ascribed to an effect of N fertilizer.

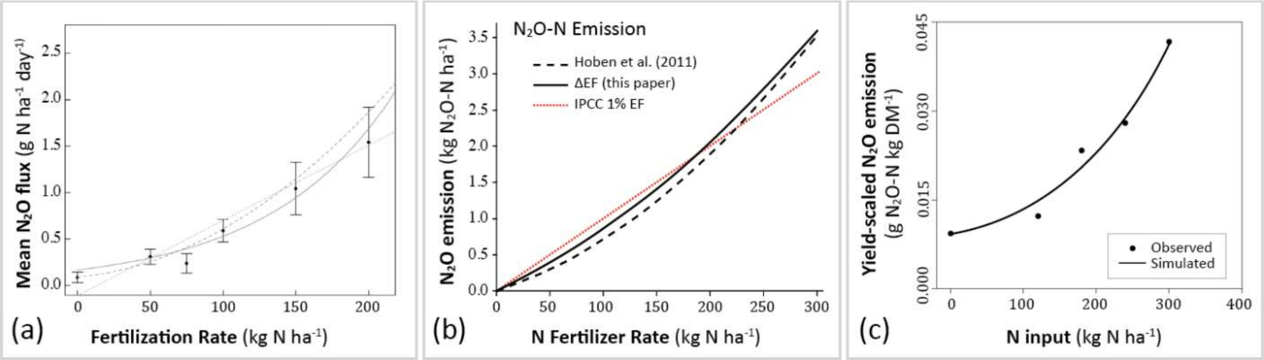
N fertilizer can also have an indirect effect on SOC decomposition via changes in the soil environment, such as changes in the soil pH. However, microbial biomass controls not only decomposition, but also the generation of new SOC through its nutrient requirements. For example, the efficiency of SOC stabilization of cereal straws was increased by two- to eightfold across a range of soils when inorganic nutrients (N, P, S) were added to account for the stoichiometric requirements of soil organic matter (Kirkby et al., 2013). Finally, an important indirect effect of N fertilizer on SOC is that it can stimulate plant growth and thus increase both plant biomass production and C inputs into the soil. Increased production of root biomass and exudates may be crucial here, especially when crop residues are removed from the field (Balesdent and Balabane, 1996).

A recent global meta-analysis showed that N(PK) fertilizer had a positive effect on SOC in most parts of the world except SSA. An analysis of past and ongoing long-term experiments in SSA corroborated these results and showed no significant effects from N fertilizer on SOC (Figure 20; Ladha et al., 2011). While we can only speculate why this would be the case, reasons could include: (i) lower overall crop productivity in SSA compared to rest of the world, resulting in lower C inputs into soil; (ii) removal of crop residues from soils in experiments in SSA, mimicking common smallholder practices; and/or (iii) a faster carbon turnover related to lower protective capacity of silt and clay particles in tropical than in temperate soils, and less tight feedback between aggregation and C content (Six et al., 2002).

5.3 Enhanced Denitrification as a Necessary Evil?

Agricultural soils account for the largest proportion of nitrous oxide (N_2O) emissions, which is the third-largest contributor to radiative forcing, after carbon dioxide (CO_2) and methane (CH_4). Concentration of N_2O in the atmosphere has been increasing and is estimated to contribute 6% of the GHG-related global warming effect (IPCC, 2014).

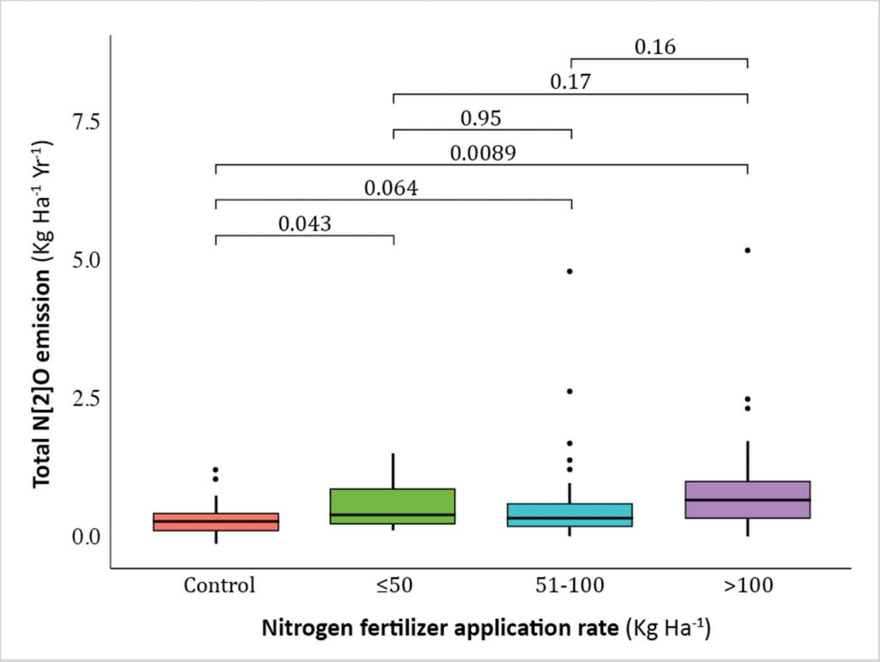
There is ample evidence that NO_x emissions increase exponentially with increasing N fertilizer use. Hence, agricultural intensification, such as in tropical systems in western Kenya (Hickman et al., 2015), may be managed for increasing crop yields without immediate large increases in N_2O emissions if application rates remain at or below 100 kg N ha^{-1}, at which rates N addition exceeds the ability of plants and microbes to immobilize it (Figure 25; Kim et al., 2021). In low-input systems, typical of SSA, modest N additions have little impact on estimated N_2O emissions



Hickman et al., 2015.   Shcherback et al., 2014.   Kima and Giltrap, 2017.

Figure 25. Relationship between nitrogen fertilizer application rate and nitrous oxide emissions from agricultural soils (a, b) and between N application rate and nitrous oxide emission per unit dry matter production (c).

(Lemarpe et al., 2021), whereas equivalent additions (or reductions) in excessively fertilized systems will have a disproportionately major impact (Scherbak et al., 2014). These findings were corroborated by several authors (Kima and Giltrap, 2017). Annual contribution to GHGs for SSA in ISFM systems is reported to be generally low at less than 3 kg N_2O ha^{-1} (Kihara et al., 2020).



Analysis of data from Baggs et al. (2006); Bwana et al. (2021); Dick et al. (2008); Hickman et al. (2014); Mapanda et al. (2011); Mapanda et al. (2012); Masaka et al. (2014); Musuya et al. (2019); Nyamadzawo et al. (2014); Nyamadzawo et al. (2017); and Zheng et al. (2019).

Figure 26. Nitrous oxide emissions from agricultural soils in SSA for four categories of fertilizer N application rates.

Currently, N_2O emissions due to low fertilizer use in SSA are extremely low. Analysis of data from 11 published studies showed that the addition of N fertilizer increased N_2O emissions compared to the no-N control (Figure 26). However, there were no significant differences in emissions with different rates of N application. Moreover, mean N_2O emissions, even with the highest N fertilizer rates, remained below 1 kg N ha^{-1}, although outliers pointed to high emissions generated on low-lying, seasonally flooded areas. The latter soils are mostly used for vegetable production with the addition of high fertilizer rates, and thus, the soils tend to have a high concentrations of available N. Overall, published data under cereal cropping conditions in SSA suggest that fertilizer N addition within moderate rates of 50-100 kg N ha^{-1} will have minimal effects on N_2O emissions.

6 Thoughts on Dissemination

Section 6 focuses on aspects of scaling and dissemination of information related to fertilizer use and soil health. Although technically the relationship between both system components can be reasonably well understood, engaging farming communities with such information that is often complex and communicating how to translate this into specific farming practices is a challenge, especially since the effects of fertilizer can be observed rapidly while changes in soil health require longer periods of time before they accrue visible benefits to farmers. This issue needs to be seen in the context of changing scaling models for agronomy and soil fertility management and the policy context within which these are operationalized.

6.1 Mismatch Between Farmers' Objectives and the Time Required to Improve Soil Health

For a long time, decisions by local farmers have been informed by indigenous knowledge, which has been established through practice and passed on by word of mouth (Muthee et al., 2019). With increasing population densities and reduction or lack of fallow land in many parts of SSA, indigenous practices have not been able to sustain or intensify crop production. Smallholder farmers are constrained by labor, cash, and organic resources and are known to invest in soil and land management practices where land tenure is secured (Place, 2009), when markets work, when they have access to credit, and when agricultural extension service is strengthened to provide advisory services (Nkonya et al., 2016).

The main deterrent to investment in soil health lies in the mismatch between farmers' time preference and priorities and the length of time it takes to reap benefits from good soil health. The long period before recouping benefits from investment in soil health is a disincentive, particularly on leased or other non-owned land. Land in dispute is also a disincentive for long-term investments, such as use of manure (Muyanga and Gitau, 2014), as compared to investment in other technologies that accrue benefits seasonally, e.g., quality seed or inorganic fertilizer. In many parts of SSA, a substantial proportion of those working on the land have access but do not own it (Langyintou, 2020). Benefits from healthy soils are acquired internally/privately by the farmer. In the absence of farmers' efforts and inputs, the soil health of a piece of land will deteriorate.

Though commonly viewed as a private good, healthy soil fosters positive externalities; it prevents erosion, controls flooding, increases biodiversity, cleans water, and sequesters carbon, among other benefits (Moebius-Clune et al., 2017). Healthy soil is therefore a public good since the environmental benefits it produces are neither excludable nor rival (Ostrom, 2015). Public investment in soil health is thus warranted. Opponents of government intervention, e.g., through a soil health subsidy program, argue that it is inefficient to pay farmers to undertake practices that they would otherwise be willing to perform on their own based on the benefits. The reality, however, is that smallholder farmers heavily discount the long-term or future benefits of investing in soil health. Furthermore, society may value ecological services more than the farmers value the private benefits of soil health. In this case, a policy intervention is warranted. Studies to generate this kind of information are needed, as are behavioral studies to determine incentives that would encourage farmer investment in good soil health practices.

6.2 Complexity of Information

Blanket fertilizer recommendations have not been adequate to drive efficient use of fertilizer. The heterogeneity associated with smallholder farming systems demands a much more targeted approach. Site-specific nutrient management offers an opportunity for transitioning to a potentially more productive system. Transitioning to site-specific (field-level) soil health management recommendations, especially in smallholder farming, is a challenging task. The complexity of the task ahead, however, is not insurmountable, as recent research and development initiatives have proven. Indeed, platforms and solutions for major crops in the region – maize (Nutrient Expert), rice (RiceAdvice), and cassava (AKILIMO), bring us closer to enhanced site specificity (Chivenge et al., 2022b). Such tools are built on the premise that it is possible to provide a recommendation for a specific location by considering innate soil conditions (often derived from long-term farmer-reported yield performance and nutrient omission trials), connecting this information with known water-limited yields, and running crop models to estimate yields at certain proposed fertilizer application rates in certain weather conditions. This information, when combined with economic data, is used to arrive at a recommendation that not only makes technical sense for the particular location in certain conditions, but also is economically feasible/sensible.

Clearly, these are complex decisionmaking processes that require continuous refinement, validation, and rigorous analysis before they are added onto any decision support tool. Capacity development is required across various organizations to ensure that the data required to make these complex and automated decisionmaking processes work is collected through well-designed collection, analysis, and insight-generation protocols (Praveena and Suguna, 2022). A new breed of agronomists with strong data science skills is required in both public and private institutions to initiate, operate, and sustain credible decision support tools and platforms.

Great agronomy/soil science, coupled with equally brilliant data science, is good, but farmers are the ones who make soil health management decisions at the farm or field level. Change in farm- or field-level soil management behavior is only possible when information on soil health management is received, understood, and acted upon. Farmers' uptake and incorporation of soil health information into their decisionmaking process depends on their trust and access to the information and on its usability. Studies show that farmers make choices based on the exposure to and timing of potential risk in their contexts (Spiegel et al., 2021). An understanding of farmers' risk profiles as well as barriers to and opportunities for good soil health decisions are, therefore, prerequisites to successful deployment and uptake of the next generation of soil health advisory services.

A radical paradigm shift from the currently narrow focus on soil fertility management and blanket fertilizer recommendations to more complex decisionmaking processes and specific recommendations for soil health improvement requires buy-in, not only from policy- and decisionmakers, but also investors. Studies to cost the generation and dissemination of increasingly complex soil health management information against the value of such complex information are therefore needed. As noted in Section 6.1, the value of healthy soil far exceeds the private benefits accrued by individual farmers of increased productivity and efficient use of resources (land, fertilizers, and improved seed). Wholesome valuation would therefore include the public good derived from such soils, including soil erosion prevention, flooding control, increased biodiversity, clean water, and carbon sequestration, among other benefits.

6.3 Changing Scaling Models

This paradigm shift hinges upon the successful upscaling of complex information and innovations to a variety of users, public and private, across differing contexts in Africa. The abundance of agricultural technology solutions and the huge investments in information and communication technology (ICT) being made into the agriculture sector suggest that there is recognition that solutions that deliver actionable insights, either directly to farmers, or mediated via extension and advisory networks, will eventually, be transmitted via more effective end 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 soil health management solutions to scale. The AKILIMO site-specific fertilizer recommendation portal (www.akilimo.org) has reached more than 400,000 cassava farmers in Nigeria and Tanzania through a network of over 200 scaling partners, who operate in the fields of aggregation, input supply, and credit and commodity processing. The AKILIMO platform disseminates information through a multichannel approach, making use of traditional SMS, interactive voice recordings, printable guides, and a mobile smartphone app. The system is a good example of responsiveness to different farmer typologies and readiness and use of suitable dissemination formats. The Space to Place approach, which combines georeferenced soil mapping, simulation modeling, and crop responses according to the landscape position of a farmer's field, soil color, texture, soil depth, etc. (Amede et al., 2020) for hyper-localized fertilizer recommendations, has been successfully implemented in Ethiopia by the Sustainable Opportunities for Improving Livelihoods with Soils (SOILS) Consortium.[1] The lessons flowing from soil health management rollouts, such as AKILIMO and SOILS Consortium's Space to Place, provide key building blocks for taking soil health management to scale.

First, there is need for sufficient investment to ensure there is credible and reliable science powering whatever tool is deployed, be it a near infrared (NIR) soil testing scanner or an app-based fertilizer recommendation solution. Adequate experimental data to derive recommendations and rigorous validation of the soil health diagnostics, or efficacy of the fertilizer recommendation, are prerequisites. If science is weak and there is insufficient validation, the proposed solution would be dead on arrival. However, not all available technologies are fit for purpose. Scientists must always do the extra work of assessing whether the technology solution lends itself to ease of use by the target users and that the information generated is usable. So, technologies such as remote sensing, while excellent for informing area-level decisionmaking, might not be the best for field-level insights due to limitations in both

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[1] https://ifdc.org/soils-consortium/

temporal and spatial resolution. Equally, while wet chemistry will generate highly precise soil analysis data, the time and cost might mean a near infrared spectral analysis would be preferred in certain systems for providing accurate (not necessarily precise) information rapidly, for quick action and at a scale that suits smallholder farming systems.

Second, improvement in the quality of soil health advisory services requires that mechanisms be embedded to continuously track use and uptake and provide channels for users and end beneficiaries to provide feedback. In order to improve the efficacy of the decision support tools and the machine-learning algorithms that drive them, the digital architecture must allow for local indicators and their measurements to be continuously fed into the big data and analytical models that inform the decision support tools. This ambition is not always implementable. More work is needed to ensure that, at a minimum, there is interoperability between various data collection tools and that the data elements themselves have common ontologies or, at the very minimum, can be consumed by extract, transfer, and load (ETL) processes or application programming interfaces (APIs) between platforms.

Third, solutions and approaches to disseminate soil health advisories should be informed by context and end user profiles. Often, there is insufficient investment toward human-centered designs and behavioral science aspects, leading to a struggle in scaling up promising technical solutions because not enough attention was given to curating delivery mechanisms that enhance user uptake. Context also matters, especially when it comes to dissemination formats. Solutions would benefit from a multichannel delivery approach that includes printable guides and traditional SMS or chatbots, as well as interactive voice recordings, app-based content, and in-person interfaces. This would ensure that access to information is not restricted and achieves the widest reach. Soil health management happens at farm and field level, and targeted advisories should therefore be aimed at delivering actionable insights at these levels, taking into account heterogeneity between farming households in communities and between fields within a farm.

Last, networks to scale technologies need to be leveraged. Existing and new networks or partnership platforms harness the creativity of multiple partners and provide a large pool for feedback on how to improve the chosen solution and its dissemination. Working with public national agricultural research systems (NARS) and extension providers, private extension, and NGOs compensates for the lack of a discrete distribution network and utilizes partners' goodwill. This model provides a stronger multichannel ecosystem for effective and efficient dissemination in terms of expanded reach and increased penetration at reduced cost. Similarly, a good soil health advisory on its own, without affordable and readily available complementary inputs such as fertilizers and offtake markets that provide assurance of a good return to farmers' investment, would be insufficient for successful adoption. Further, targeted subsidies on the recommended inputs, such as fertilizer, and bundling soil health advisories with these inputs and other services, such as insurance, reduce market friction for farmers and eases decisionmaking. Therefore, a multi-stakeholder approach would create the right platforms for these complex combinations of synergies and nudges.

The scaling readiness approach proposes finding a balance between two dimensions that are complementary and vary according to context, i.e., innovation readiness and innovation use (Sartas et al., 2020). This combination is often missing, resulting in poor scaling performance. Generally, while considerable investments are made toward ensuring the innovation works effectively, insufficient investments are made on increasing their use or usability. In promoting tools that are aimed at empowering farmers to adopt new soil management technologies and innovations, significant investments are needed in understanding the users and their variability and typologies (Hammond et al., 2020), their readiness to use the innovations (McCampbell et al., 2021), the potential impact of gender (Medendorp et al., 2022), and other factors that might affect innovation use. Equally, a good understanding of what complementary innovations might be required to be bundled with the core innovation is essential (Sartas et al., 2020).

6.4 Policy Considerations

The policies driving soil health on the African continent stem from the belief that increasing fertilizer use alone is the panacea to agricultural productivity. Across countries in SSA, the emphasis of government policies has been on increasing crop productivity through the addition of nutrients to the soil, primarily through fertilizer application. Governments in SSA have predominantly invested in programs aimed at promoting fertilizers to increase crop yields, partly driven by the declarations accepted by the African Heads of State during the 2006 Africa Fertilizer Summit in Abuja. This has resulted in the allocation of large proportions of agricultural budgets to input and fertilizer subsidies. For example, in countries like Kenya and Mali, the agricultural budget allocated to fertilizer subsidy has been rising as more crops (and areas) are included in the subsidy basket (Smale and Thériault, 2019). That said, substantial spending on input subsidy programs could crowd out funding for other equally important investments in areas that are critical for adoption of good soil health management, such as access in input supply chains, rural infrastructure, and credit provision.

Earlier programs did not always consider necessary complementary investments, which can be rectified in future programs, including investments in (i) agricultural research and extension; (ii) fertilizer manufacturing and blending plants, aiming at reducing the import bill and cost of fertilizer; (iii) infrastructure, and particularly road networks and information systems, aiming at delivery of fertilizers to farmers at reduced transportation and transaction costs; and (iv) harmonization of regulations and standards, aiming at fertilizer quality assurance and facilitation of trade, particularly within regional economic blocks, noting that thus far, only the Economic Community of West African States (ECOWAS) has harmonized country regulations.

Recent studies, however, show that the use of subsidized fertilizer has either no impact or, in some cases, a negative impact on the adoption of ISFM practices (Smale and Thériault, 2019). Studies have also found that production impacts were lower than expected because a large proportion of smallholder farmers used fertilizers on soils with adverse soil health conditions (Jayne and Rashid, 2013). Subsidies are also based on the assumption that farmers, after using fertilizer at subsidized prices for a given period, are likely to continue using fertilizer at commercial market prices (Dorward et al., 2008). But this assumption needs to be proven and could be wrong in cases where farmers experience lower crop yields and fertilizer response than under experimental conditions (Jayne and Rashid, 2013).

To be effective and relevant, subsidies should be redesigned to make them “smarter,” so they incentivize farmers not only to use fertilizer but also to invest in complementary practices that will improve FUE and gradually restore soil health. Failure by successive governments to design input subsidy programs that are well targeted and deliver improvements in good soil health practices could be because the lessons learned (and improvements in successive subsidy programs) have focused on effectiveness in fertilizer delivery and in ensuring there is no crowding out of the private sector (Jayne and Rashid, 2013). Failure to prioritize soil health or soil degradation promotes inefficient use of scarce resources (land, labor, and capital), ensures the yield gap persists or worsens (Bonilla-Cedrez et al., 2021) and, in extreme cases, relegates farm households to a degraded soil poverty trap (Marenya and Barrett, 2009; Tittonell and Giller, 2013).

Policy interventions are urgently needed to address the systematic soil health decline in SSA (Chamberlin et al., 2021) for Africa to achieve the set development goals, thereby also generating positive externalities:

1. Reversing soil health decline requires an ISFM approach, including fertilizer and other locally adapted soil and fertility management practices that optimize the agronomic efficiency of fertilizer, noting that tools and approaches are now available to develop site-specific recommendations at scale.
2. The focus of policy should be on making information accessible to farmers, including information related to understanding that soil health forms the basis for long-term improvements in productivity with consequent economic and social benefits, the state of their soil health, and how soil health responds to different management techniques and crop yield.
3. Policies that enhance extension services and agricultural advisories that include good soil health management practices, as well as good agronomic practices, water management, weather-crop insurance, and market information, are critical. Since 2009, AfricaFertilizer (https://africafertilizer.org) has been sharing data on fertilizer statistics, such as production, trade, consumption, prices, production capacities, and fertilizer use per crop, and fertilizer market intelligence, including fertilizer policies and regulations, subsidy programs, business and product directories, publications, and news.
4. Subsidies should be made “smarter.” Bundling fertilizer use promotion programs with soil conservation and organic matter management provides better incentives for farmers to use fertilizer (Marenya and Barrett, 2009).
5. Access to data and analytics to monitor the status of and changes in soil health should be facilitated, and medium- to long-term data on the impact of farmer practices on soil health properties should be collected and analyzed.
6. Policymakers also need reliable estimates of soil health benefits on environmental outcomes and ecosystem services, including the benefits of land spared from agriculture through sustainable intensification.

7 Recommendations – A Unified Vision Toward Future Investments in Fertilizer and Soil Health

The 2006 African Fertilizer Summit in Abuja fostered an agreement on the need to increase availability and use of mineral fertilizer in SSA and set the target of 50 kg nutrients ha^{-1}. Since then, fertilizer production capacity has expanded and average nutrient use in SSA has increased from 8 to 20 kg ha^{-1}. Subsidy programs introduced since the Summit made fertilizers more affordable but missed an opportunity to use fertilizer as a vehicle for promoting complementary practices, aiming at enhanced fertilizer use efficiencies and improved soil health with its associated long-term benefits. With current application rates, soil nutrient mining continues, leading to substantial soil degradation and soil health decline, eventually resulting in nonresponsive soils.

Sufficient nutrient and carbon recycling for food security can only be achieved in healthy, fertile, and productive soils. Therefore, agricultural intensification in SSA should be supported by science-based agronomic approaches to improve soil fertility at scale, enhance the affordability and availability of fertilizers, spatially target fertilizer recommendations, and provide incentives for farmers to invest in their soils. The scientific evidence and expert knowledge in this paper proves that mineral fertilizers are essential for higher crop yields per unit area to create and sustain healthy and productive soils and can reverse the expansion of farmland, deforestation, and loss of biodiversity.

To accelerate the role of fertilizer in building soil health to sustain farming and address climate change, we recommend to first and foremost agree on a simple and compelling narrative. To reward investments in soil health, measurable indicators and targets are needed. Soil health plays a role in climate change mitigation and adaptation, and improving soil health through mineral inputs seems an obvious investment with a high return. But farmers will not invest in soil health if there are no short-term incentives to make these investments, since changes in soil health and the services this delivers are only visible in the medium to longer term. While investing in soil health is a long-term process, it is necessary and possible to act now.

1. Key elements of a Fertilizer and Soil Health Action Plan

The 2006 Africa Fertilizer Summit in Abuja will be remembered by its fertilizer target of 50 kg ha^{-1}. Soil health targets are more complex, but a simple, compelling, science-based and generally agreed-upon narrative is imperative for a Soil Health Action Plan:

- There is consensus that agricultural productivity must and can increase, while expansion of arable land, deforestation, and loss of biodiversity must be avoided; consequently, production per unit area must increase.
- Increasing productivity requires fertilizer and organic inputs in combination with additional measures such as good agronomic practices, improved seeds, and other amendments, as summarized in the ISFM approach.

- On healthier soils,[2] both the agronomic efficiency of fertilizer and the efficiency of water use are higher; healthy soils produce "more with less," resulting in higher returns on investments in agro-inputs and labor. The availability of sufficient micronutrients can further increase the agronomic efficiency of fertilizer.
- Building soil health is impossible without fertilizer; organic matter or manure produced elsewhere (biomass transfer) provides only a fraction (10%) of the required nutrients and leads to soil depletion and degradation elsewhere.
- Building soil health or regenerating degraded soils is a long-term process in which C from the atmosphere is sequestered, while destruction of soil organic matter through deforestation, land clearing, or soil nutrient depletion is a rapid process in which C is released into the atmosphere.
- A bottleneck in engaging smallholder farmers in soil health-restoring practices is the large amount of time required by such practices to deliver benefits that are visible to farmers in terms of increased revenue. In the absence of incentive programs, farmers require short-term benefits generated within their farming systems. This requires policies and investments that go beyond support to access and affordability of fertilizers to those that incentivize investments in soil health.

2. Developing quantitative indicators and targets

Soil health is commonly defined in relation to generating sufficient crop yields while maintaining the future productive capacity of soils and the ecosystem services soils regulate and deliver. Less consensus exists, however, on how to assess soil health and its changes over time and space, although SOC is generally acknowledged as a key indicator. In the context of this paper, soil health status is equated with SOC status. Current SOC conditions under smallholder farming conditions are highly variable and affected by past crop and soil management practices, influenced by farmer typology. Although SOC contents under cropland are theoretically a maximum of 60-70% of those under natural vegetation, there is scope to increase SOC contents in specific smallholder farming conditions, mostly related to the texture of the soil and increased inputs of organic matter.

For farmers to be rewarded for investments in soil health, SOC could become a "tradeable entity" (like sequestered aboveground carbon), which is only possible if it can accurately be measure and monitored. That said, SOC is essential for agricultural sustainability, whether or not it is regarded as tradeable.

3. Addressing climate change requires choices

Climate change is affecting the relationship between fertilizer and soil health, and de-risking agriculture will be essential for farmers to engage in fertilizer and soil health management practices while addressing specific hazards created by climate change. Africa's contribution to

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[2] The term "healthier" is used as a reference to the health status of soils in most African smallholder farming systems. Soils that receive an oversupply of organic inputs, e.g., home gardens in the East African highlands, have a health status that actually results in a reduction of fertilizer agronomic efficiency, since the soil can supply all nutrients that a crop needs. That said, the acreage of such soils is very limited and does not reduce the general validity of the current statement.

increasing global CO_2 levels has been small, and the major sources of carbon emissions in Africa are deforestation, land clearing, and soil degradation. Agricultural production through the use of N fertilizers also contributes to NOx emissions, but given the current levels of fertilizer application, this contribution is unlikely a major concern. Investments in climate-smart soil nutrient and soil health interventions and effective fertilizer management by governments, industry, and farmers will increase contributions to mitigation and adaption, with a high return on investment.

4. Incentivizing farmers

A main bottleneck in engaging smallholder farmers in soil health-restoring practices is the relatively large amount of time required by such practices to deliver benefits that are visible to farmers. In the absence of incentive programs, farmers require short-term benefits, generated within their farming systems. Furthermore, associating advice on complementary practices to fertilizer use enhances the complexity of information to be conveyed to farmers. Scaling models have moved toward the delivery of bundled services, often digitally enabled, to address challenges with communicating complex information and required complementary crop and soil management practices. Targeted policy interventions can support the delivery of broadened and digitally enabled fertilizer management recommendations and the creation of conditions that enable smallholder farmers to implement these recommendations at scale.

Policy interventions creating a favorable enabling environment need to be put in place to stimulate the uptake of fertilizer and soil health management recommendations. Redesigning fertilizer subsidies is crucial to make them smarter with respect to soil health management. Soil heath not only is important for smallholder farming systems but also is a public good, and public investment in soil health, informed by actual quantification of these benefits, is thus warranted.

5. Soil health investments require localized actions (think global, act local)

Instead of a blueprint approach, soil health recommendations should always be localized and context based. Several approaches can be followed to determine best fertilizer recommendations while recognizing nutrient needs by crops and soil-specific properties. Site-specificity commonly requires an assessment of the soil fertility status of a particular field, and new data and analytical tools allow for the development of locally relevant recommendations at scale. While organic inputs do positively impact SOC, attractive options to increase organic inputs in smallholder farming systems are limited and mostly related to in-situ production, with important emphasis given to multi-purpose legumes.

While low yields are linked to ecological yield gaps, input and output prices determine the economic yield gap, which is usually much lower than the former because of unfavorable fertilizer:crop product prices. While profitability is a key driver of impact, many other factors affect the uptake of appropriate fertilizer and soil health recommendations, including farmers' production objectives and resource endowment, land tenure, and access to markets, among others.

6. Not just fertilizers but also auxiliary interventions

Farmers are less likely to apply fertilizers where the risk of nonresponse or nonprofitable response is high, real or perceived. Raising the agronomic efficiency values for fertilizer to be profitable, an immediate need that addresses many of the challenges smallholder farmers are facing, would require incentivizing farmers to invest in fertilizer. However, fertilizer application needs to be tailored to specific farming conditions to increase yield, profitability, and nutrient use efficiency because of high heterogeneity across and within smallholder farms.

Healthy soils can enhance fertilizer use efficiency, but auxiliary interventions, e.g., as described by ISFM, maximize the agronomic efficiency of nutrient inputs. Soil health will be mostly a co-benefit of other improved agronomic practices in the absence of incentive programs promoting the uptake of soil health-improving practices. With the broadening of soil fertility management recommendations beyond fertilizer, approaches that translate and deliver complex information are needed, focusing on digitally enabled tools, together with scaling models that can accommodate such tools and bundled services, facilitating access to required agro-inputs and other implements.

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