
Integrated Soil Fertility Management in Sub-Saharan Africa: Evolving Paradigms Toward Integration



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Definition

Integrated soil fertility management is defined as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity (Vanlauwe et al. 2010; Sanginga and Woome 2009). Notably, before the inception of ISFM, there were shortfalls associated with sole mineral fertilizers use such as environmental and health concerns, high cost, and unavailability.

Introduction

The world is experiencing a population rise that calls for food production intensification.

Sub-Saharan Africa (SSA) alone could have a projected 2.7 billion people by the year 2060 (Canning et al. 2015). By the year 2013, the region had 23% of its population being food insecure, while 40% of the children demonstrated stunted growth (UNICEF 2013). Currently, approximately 815 million out of over 7 billion people globally endure chronic malnutrition (FAO 2017). This projection translates to increased demand for food to feed the increasing population. The concern then is that, while crop productivity has increased elsewhere in the world, staple food production in Africa has not kept pace (FAO 2015, World Bank 2015).

Cereal yields in Africa average less than 1.5 MT/ha compared to an average yield in Asia and Latin America of 5 and 8 MT/ha, respectively (FAOSTAT 2015). One of the main explanations for this difference is the relatively poor soil fertility on the smallholder farms. This problem of low soil fertility has plagued Africa's soils for the last 40 years and is currently considered a crisis (AGRA 2016). The low soil fertility is due to several decades of nutrient mining as a result of continuous cultivation with little or no fertilizer (organic and inorganic) application. Consequently, the soils in Africa farmlands are often deficient in nutrients, with low or no organic matter, and have limited ability to hold water. The use of fertilizers to address the crisis has remained low compared to the rest of the world because of unaffordability of fertilizers by the farmers due to high prices of mineral fertilizer

and lack of credit facilities; lack of availability of mineral fertilizer in the market when the farmers need them due to either poor transport and infrastructure or market dynamics-related factors; lack of know-how on effective combinations and application for optimal returns; and counterproductive policies, government regulations, and laws that have corrupted the fertilizer market.

As farmers continue to experience these challenges, soil fertility decline continues, causing low crop production and making the attempts to attain sustainable food security to remain elusive. The low use of fertilizer, below the recommended rates for sustaining soil fertility coupled with nutrient losses, is not only threat to agricultural productivity but also raises pertinent sociopolitical and environmental concerns (Canning et al. 2015). Hence, securing present and future food security depends on how effectively and sustainably soil fertility and sociopolitical and environmental concerns are addressed.

Over the years, soil scientists have developed new approaches and technologies for increasing yields in the smallholder farms. Integrated soil fertility management (ISFM) approaches, developed in the 1970s, offer great potential for tackling soil fertility and sociopolitical and environmental concerns. During the early years (the 1970s and 1980s), the focus in soil fertility management approaches in SSA was in using mineral fertilizer. In the 1990s there was a significant paradigm shift to a more encompassing approach involving a combination of inorganic and organic fertilizers (Fairhurst 2012). The adoption of ISFM in the 2000s was promoted to increase crop productivity by combining improved germplasm, mineral, and organic fertilizers (Fairhurst 2012). Currently, attention is shifting toward ensuring that ISFM technologies are adaptable to farmers' local conditions. The emphasis is on the right combination of agronomic practices with mineral and organic inputs and other amendments that are tailored for different cropping systems and socioeconomic profiles (Vanlauwe et al. 2015).

In the year 2002, Sanchez and Jama (2002) stated that soil fertility depletion in smallholder farms is the fundamental biophysical cause of declining per capita food production in Africa.

They further affirmed that, no matter how effectively other conditions are remedied, per capita, food production would continue to decrease unless soil fertility depletion is adequately addressed. Several years after this exposé, soil fertility decline and declining per capita food production are still a disturbing situation. This is despite efforts made in promoting ISFM interventions to address soil fertility decline. The pertinent question thus emerges; why is the adoption of ISFM technologies still low in SSA? There is a need for researchers and policy-makers to seek answers to this disturbing situation. This paper explores various aspects of ISFM that may be important in providing future direction of ISFM work concerning evolving paradigms of ISFM, results of ISFM interventions, adoption of ISFM technologies, the role of ISFM in climate-smart agriculture, and role of legumes in ISFM.

Changing Paradigms of ISFM

Over the years, as research and development practitioners continue to address the problem of soil fertility, there have been shifts in thinking and conceptualization of ISFM approaches in the last 50 years. In the 1960s and 1970s, the primary emphasis in managing soil fertility was on the use of external inputs (mineral fertilizers) to increase crop production. The use of external inputs in the form of fertilizer, lime, and irrigation water was thought to be the only essential components to boost production (Bationo and Waswa 2011). This was mainly based and driven by the results of the Green Revolution that had taken place in Asia and Latin America. However, there was a limited success due to shortfalls in infrastructure, policy, and farming systems.

In the 1980s, there was a shift of emphasis to organic inputs which resulted in limited adoption because organic matter production requires livestock ownership and excessive land and labor. In 1990s, the use of both organic matter and mineral fertilizers was emphasized with the organic matter as the entry point but also taking into consideration other aspects (Sanchez et al.

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Table 1 Evolution and changes in integrated soil fertility management approach

Period	Approach	Role of fertilizer	Role of organic inputs	Experience
1960s to 1970s	External input use	Use of fertilizer alone is thought sufficient to improve and sustain yields	Organic resources play a minimal role	Limited success due to shortfalls in infrastructure, policy, and farming systems
1980s	Organic input use	Fertilizer plays a minimal role	Organic resources are the main source of nutrients	Limited adoption organic matter production required livestock ownership, excessive land, and labor
1990s	The combined use of fertilizer and organic residues	Fertilizer use is essential to alleviate the main nutrient constraints	Organic resources are the primary “entry point”	Localized adoption around specific crops
2000s	Integrated soil fertility management	Fertilizer is a major entry point to increase yields combined with organic resources	Organic resources can improve the use and efficiency of fertilizers	The goal is to achieve wide-scale adoption Importance of input and output markets
2010 and beyond	Integrated soil fertility management with intensification	Fertilizer combined with an organic resource	Organic resource management at plot and farm level	The new emphasis on intensification and local adaptation

Sources: ASHC 2012; Vanlauwe et al. 2010, 2015

1997). Later on, a definition of ISFM was given as holistic approach to soil fertility management, inclusive of a full scope of causing factors and consequences including biological, physical, chemical, social, economic, and political facets of soil degradation. This resulted in localized adoption around specific crops and a significant emphasis on integrated nutrient management. Recently, much of the work is focusing on research combining the use of mineral fertilizers and organic resources in ways that are adaptable to local conditions to achieve satisfactory crop yields and efficient fertilizer use efficiency (Table 1; ASHC 2012).

The processes of nutrient depletion and soil degradation that limit the productivity of smallholder African farms are spatially heterogeneous (Bunde 2017). Both biophysical and socioeconomic factors cause the heterogeneity. Vanlauwe et al. (2015) mention four main constraints: soil acidity, secondary nutrient and micronutrient deficiencies, physical conditions, and drought spells. According to these authors, these constraints limit crop productivity and reduce agronomic

efficiency and therefore the need for targeted application of agro-inputs and management practices to enhance the benefits of ISFM. Heterogeneity within and among farms is documented by several authors (Annan 2008; Lambercht et al. 2015), and this negatively affects the optimization of ISFM benefits. Nonetheless, there is a current feeling that ISFM interventions should be adaptable to local conditions (Vanlauwe et al. 2015). Therefore, in the face of changing ISFM paradigms, incorporation of these aspects is endorsed (Table 1; ASHC 2012).

Over the years the definitions of ISFM by Sanginga and Woomer (2009) and Vanlauwe et al. (2014) suggest a more encompassing approach. Whereas the components of ISFM allude to seed, mineral fertilizer, organic inputs, and knowledge, there is a need for an approach that adds more localized variables within the soil fertility gradients and revises conceptual framework developed by Vanlauwe et al. (2015) as presented in Table 2 to emphasize these components.

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Table 2 Important components integrating local adaptation and intensification in integrated soil fertility management incorporating the approach

Component	Explanation
Good seed	High yielding varieties Free from pests and diseases Drought-tolerant varieties
Mineral fertilizer	To conduct soil analysis to know soil pH, nutrients available, what is limiting and specific crop requirement To apply right amounts of mineral fertilizer To apply mineral fertilizer at the right time To place mineral fertilizer where plant roots will access nutrients
Organic inputs	Farmyard manure Green manure Legumes (crops + trees) to fix nitrogen, trees will also recycle leached nutrients Compost manure Crop residue (recycle, don't burn)
Knowledge	Appropriate spacing (to maximize yields) Crop rotation and intercropping Scouting, prevention, and control of pests and diseases Efficient water management Control soil erosion and maintain good soil cover Timely weed control
Local adaptation	Adaptation at plot and farm level Less resource use
Intensification	Intensification Integrated systems High production

What Has ISFM Delivered?

Past research gives promising evidence of how ISFM has been utilized to solve food and pest challenges currently confronting smallholder farmers. Many studies over the years, including long-term ones, report yield increases and benefits arising from application of ISFM interventions (Kimiti and Odee 2010; Pypers et al. 2011; Manzeke et al. 2014; Guo et al. 2016; Zhang et al. 2016; Hai-cheng et al. 2018; Liu et al. 2018; Negassa and Sileshi 2018). This is mainly attributable to improved nutrient use efficiency than that expected from small additive effects of sole applications (Serafim et al. 2013) of organic or inorganic fertilizers. The higher utilization efficiency (agronomic and/or nutrient recovery efficiency) obtained from ISFM (as compared to sole application) may be attributed to the principles of synergistic effects involving different mechanisms.

Integrated soil fertility management consists of an array of inventions by different researchers to

meet various goals. For instance, combinations of mineral fertilizers and leguminous trees have been used to improve soil fertility in an agroforestry ecosystem (e.g., Mugendi et al. 1997; Palm et al. 2001). The combined use of mineral and organic manure has been used widely in SSA to improve soil fertility and yield of different crops. Other researchers have proposed and used the integration of composts in ISFM systems (e.g., Abiven et al. 2009; Srinivasarao et al. 2012; Aguilera et al. 2013; Zingore et al. 2015). Although most studies utilize ISFM interventions under cereal farming systems (e.g., Agegnehu et al. 2014; Endris and Dawid 2015), legume crop incorporation is often done as an essential component of ISFM. The legumes have been integrated into SSA farming systems through intercropping or rotation (e.g., Zhang et al. 2016; Franke et al. 2017) to explore nutrients available within a given crop rotation cycle.

Documented evidence points to the contributions of ISFM interventions in improving soil

fertility, reducing hunger, and improving livelihoods and economic status of small-scale farmers. The positive synergistic impact is usually observed when mineral fertilizers are combined with organic inputs. For instance, combining inorganic and organic resources dramatically improves soil fertility and crop growth. Integration of mineral and organic fertilizers has been used to improve crop productivity, especially maize, for example, in Kenya, Nigeria, and Ethiopia, to mention a few (Mucheru-Muna et al. 2007; Serafim et al. 2013; Endris and Dawid 2015; Usman et al. 2015). In Malawi, doubled-up legume rotation was shown to sustain soil fertility and crop productivity under maize-based farming systems (Smith et al. 2016). In Kenya, staggering maize-legume intercrop robustly improved economic returns and increased crop yields (Mucheru-Muna et al. 2010). Legumes can fix atmospheric N and reduce the application rate of mineral N in the subsequent cropping season. The use of ISFM in agroforestry has been shown to have several benefits. The benefits include improved household food security (Coulibaly et al. 2017), improved soil fertility, increased maize yield and profitability, and reduced labor inputs (Ajayi et al. 2009). A recent simulation of ISFM interventions (i.e., N-fixing grain and green manure legumes, organic inputs, and inorganic fertilizers) showed that ISFM could not increase maize yield but mitigate against climate risks (Nezomba et al. 2018).

The importance of ISFM in addressing persistent problems faced by smallholder farmers is also reflected in the thoughts of recent researchers. It is thought that appropriate use of ISFM interventions can increase crop yields (Zhang et al. 2018), reduce losses caused by terminates (Negassa and Sileshi 2018), and lessen soil organic C losses (Sommer et al. 2018). Since it has been proved that ISFM inventions could reduce food shortages and meet food, fiber, and fodder requirements while mitigating against climate change risks, researchers have intensified studies on its components. Many studies have shown that inorganic fertilizer is a vital component of ISFM. However, its adoption is low, which is thought to be one of the main factors hindering

the optimal performance of ISFM in smallholder farms.

On the other hand, the quality of organic inputs is thought to be vital in organic inputs improving soil fertility dynamics (Chivenge et al. 2011). Though the emphasis is on adopting the combined use of inorganic and organic resources together with improved seeds, replicating the successes of the outputs of research that used sole mineral fertilizers and improved seed varieties in SSA has been challenging because of the local biophysical and socioeconomic heterogeneities (The Montpellier Panel 2013). For instance, the use of hybrid seeds and mineral fertilizers was constrained by long distances to input markets in Malawi (Chirwa 2005). This is despite the capacity of ISFM interventions to address biophysical heterogeneities at farm level (Kato and Place 2011). In this regard, there is a need to reassess current ISFM interventions to match the practices within the changing farming systems with much focus on knowledge specific-farm characterization to recommend appropriate ISFM interventions. Current statistics shows that small-scale farming systems in SSA are undergoing insightful transformations from subsistence-based agriculture to mixed-enterprise and market-based farming system.

Adoption of ISFM

Over the decades, researchers often promote adoption of ISFM to improve soil fertility and consequently increase food productivity. However, ISFM adoption has persistently stagnated over the years. The adoption rate is particularly low among SSA small-scale farmers. A range of socioeconomic and biophysical variations characterizing smallholder farmers could explain the low adoption. Firstly, most smallholder farmers still lack adequate knowledge capital about the benefits of adopting ISFM technologies. Secondly, most farmers require a relatively long time to acclimatize to the economic constraints to minimize potential risks (Morello et al. 2018). Thirdly, coupled with the fact that ISFM is knowledge-intensive (Vanlauwe et al.

Integrated Soil Fertility Management in Sub-Saharan Africa: Evolving Paradigms Toward Integration, Table 3 Important ISFM components in CSA

Management approaches	Details of approaches
Agronomy	Adoption of cover crops Improved fallow and/or crop rotations Improved seed varieties Inclusion of legumes in crop rotations
Integrated nutrient management	Improved N fertilizer efficiency Use of organic fertilization
Tillage and residue management	Integration of crop residues Use of minimum soil disturbance tillage method
Water management	Application of irrigation systems Use of water conservation methods, e.g., bunds, Zai, and tied ridge systems Use of contours and terraces in farms Harvesting of water
Agroforestry	Live barriers, fences Inclusion of crops on tree farms Inclusion of trees on crop fields

Adapted by Branca et al. (2011) from IPCC 2007

that could arise between crop productivity and CSA components such as adaptive capability, mitigation benefits, and food security (Campbell et al. 2014). Soil moisture shortage is a factor affecting crop production in rain-fed agriculture. This has led researchers to propose soil and water conservation methods (Okeyo et al. 2014; Kiboi et al. 2017). Studies have shown that ISFM interventions can be incorporated into the CSA approaches (Table 3; Branca et al. 2011).

Studies have shown that soil and water conservation (SWC) can benefit farmers through economic and environment remedy (Gebremeskel et al. 2018). This is a concept that has been illustrated in Ethiopia by farmers who adopted integrated soil, water, and agronomic approaches. According to the authors, the farmers benefited from improved crop productivity (Erkossa et al. 2018). Soil and water conservation techniques improve soil fertility by reducing soil and nutrient loss. A review by Wolka et al. (2018) showed that SWC technologies reduced runoff, controlling approximately more than 50% soil loss. The authors also showed that crop yields increased in over 80% SSA countries as a result of using SWC techniques. Various ISFM interventions (e.g., reduced tillage, improved seed varieties, etc.) have been used in sustainable weed management within the CA context (Bajwa 2014). Moreover, crop rotation using cover crops could

significantly improve soil organic carbon, N, and water cycles under CA (Camarotto et al. 2018). Although these examples offer interesting insights, there is still a need to understand how various ISFM interventions can be tailored to meeting smallholder farmers' socioeconomic needs.

The Role of Legumes in ISFM

For over a decade, Alliance for a Green Revolution in Africa (AGRA) has funded more than 100 projects on legumes and ISFM through its Soil Health Programme initiated in 2009 (AGRA 2009). Compared to South and East Asia, farmers in SSA produced averagely 1.5–3.5 tons ha⁻¹ of staple grains (Gilbert 2012). This is attributed to low N in the soil that limits crop productivity (SciDev.Net. 2015). This has led to the commercialization of legumes in Africa (ACB 2016) to improve soil fertility and nutrition. Farmers can significantly benefit by adding value to legume crop products.

Farmers practice legume farming using diverse cropping systems. They either practice cereal-legume intercropping or rotate legumes with cereal crops. Apart from being one of the essential food crops (Kunyanga et al. 2013), legume crops have multiple other benefits in smallholder

farming systems. The main benefits include, but are not limited to:

1. Fixation of atmospheric N, therefore providing additional N to plants. This reduces amounts of fertilizer applied
2. Improved microbial diversity and hence improved soil quality
3. Controlled pests and diseases
4. Increased crop diversity in a field

Studies have shown that rotating cereals and legumes could sustain agricultural intensification and increase cereal yields in sub-Saharan Africa (Franke et al. 2018). Legume intercropping enhances the provision of agroecological service in a cropping system (Duchene et al. 2017). This is because leguminous crops facilitate and complement processes within cropping systems. Also, cereal-legume intercrop serves provisional (e.g., yields) and regulatory and maintenance (e.g., pests and weed control) services as documented in the recent literature (Amossé et al. 2013; Bedoussac et al. 2015; Kermah et al. 2017).

Recent studies have integrated legumes in conservation agriculture (CA) as cover crops. Minimum soil disturbance and maintaining permanent ground cover are among the principles of CA. Legumes not only lessen adverse effects of reduced tillage but also improve soil fertility when used as cover crops (Büchi et al. 2018). Moreover, leguminous crops can modify crop roots to deal with stressful situations. For instance, legume crops can mobilize unavailable or limited soil nutrients (e.g., P) in harsh environmental circumstances (Latati et al. 2016).

Economics of ISFM

Integrated soil fertility management interventions could be profitable to smallholder farmers in SSA. Profitability analysis study conducted in Kenya proves that ISFM approaches could be profitable (Adamtey et al. 2016). The authors observed that local and regional markets influence the profitability of ISFM-produced products. Adamtey et al. (2016) revealed that organically produced crops

earned about twice the crops produced conventionally. Integrated soil fertility management approaches provide farmers with alternatives that increase and economically sustain productivity. For instance, intercropping maize and legumes with an application of N fertilizers has been demonstrated to lead to robust crop yields and increased economic benefits in Kenya (Mucheru-Muna et al. 2010).

ISFM-produced agricultural products (food and feed) are rich in protein (Chianu et al. 2009). Evidence shows that ISFM components (e.g., legume-maize rotation) reduce the cost of N application while increasing yield of one crop without antagonizing performance of the other rotated crop (Ojiem et al. 2014). Judicious use of fertilizers and organic matter together with improved germplasm (components of ISFM) improved crop productivity and revenue earned by farmers practicing cassava-legume intercrop in Congo (Pypers et al. 2011). Thus, farmers can increase their profitability through (1) investing in value addition to fetch better market prices for their prices; (2) reducing the cost of production through the judicious use of inorganic and organic fertilizers; (3) finding appropriate markets beyond their localities; and (4) formulating cooperative groups to increase their bargaining power in the market.

Suggestion for Future Thrusts

Recent work on ISFM suggests for development of ISFM toward more integration while incorporating aspects of heterogeneity. The more recent research proposes local adaptability of ISFM technologies to improve agronomic efficiency (AE) of fertilizer nutrients at both plot- and farm-scale levels. Local adaptation is influenced by the interaction between biophysical, biological, and economic factors. However, gaps still exist in the understanding of these interactions and processes. Therefore, for the optimal inclusion of local adaptation, there is a need for more understanding of these factors. Besides, as small-scale farming tends to shift toward market-oriented production systems, there is a need to research on the

suitability of ISFM technologies on other priority crops.

Small-scale farming intensification is vital to attaining food security in SSA. Pretty et al. (2011) and Vanlauwe et al. (2014) proposed sustainable intensification. However, sustainable intensification still lacks globally conventional definition, which might impact its contextualization in SSA small-scale farming systems. Due to biophysical and socioeconomic heterogeneities demonstrated by smallholder farmers in SSA, researchers should reassess the suitability of the ISFM technologies in the face of the climate change (CC) and mitigation requirements.

Simulation models predicting crop production systems are slowly being introduced to study smallholder agricultural production systems. For instance, the effect of weeding twice was simulated to twice-fold increase nitrogen EA in Malawi (Kamanga et al. 2014). Nonetheless, out-scaling of these simulation models to site- and farm-specific conditions has not been widely explored to assess CC mitigation effects apparent on ISFM technologies.

In the context of improving adoption of ISFM technologies, there is urgency in informing policy-makers about the importance of supporting accessibility to fertilizers and improved seeds by SSA smallholder farmers. Suitable policies underpin accessibility of fertilizers and improved seeds. The policies would include:

- Strengthening access to financial facilities by liberalizing some of the stringent requirements by financial institutions.
- Strengthening access to fertilizers and improved seed subsidies and credit facilities by the government.
- Revitalization of fertilizer markets through improved public and private sector partnerships.
- Increased funding for agricultural research and development at farm-scale level.
- Increasing investment in rural infrastructural development (e.g., markets, roads, and electrification).
- Increased capacity building on gender-related issues.

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