Journal of Experimental Botany, Vol. 71, No. 2 pp. 632–641, 2020
doi:10.1093/jxb/erz446 Advance Access Publication October 5, 2019
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RESEARCH PAPER

Approaches to improve soil fertility in sub-Saharan Africa

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Received 28 April 2019; Editorial decision 16 September 2019; Accepted 26 September 2019

Editor: Om Dhankher, University of Massachusetts, Amherst, USA

Abstract

Soil fertility provides the foundation for nutritious food production and resilient and sustainable livelihoods. A comprehensive survey and summit meeting were conducted with the aims of understanding barriers to enhancing soil fertility in sub-Saharan Africa and providing evidence-based recommendations. The focus regions were West Africa, East Africa, the Great Lakes region, and Ethiopia. Overall recommendations were developed with four emerging themes: (1) strengthening inorganic fertilizer-based systems, (2) access to and use of quality organic inputs, (3) capacity building along the entire knowledge-transfer value chain, and (4) strengthening farming systems research and development across biophysical and socio-economic factors. The evidence-based process and methodology for prioritizing these recommendations makes these findings useful for setting out action plans for future investments and strategies. Access to inorganic fertilizer, its use, and related implementation issues were prominent considerations; nevertheless, biophysical and socio-economic barriers and solutions were identified as equally important to building soil fertility and natural resources. Soil management initiatives should focus on providing holistic solutions covering both biophysical and socio-economic aspects along the entire value chain of actors and creating an enabling environment for adoption. A broader view of soil fertility improvement using all available options including both inorganic and organic sources of nutrients and farming system approaches are highly recommended.

Keywords: Soil fertility, soil health, soil degradation, sub-Saharan Africa, sustainable intensification, resilience, farming systems.

Introduction

The health of our soils provides the foundation for the productivity of our farming systems, the food and nutrition security of our societies, and the improvement of livelihoods and alleviation of poverty in our world (Heger *et al.*, 2018). Soils of sub-Saharan Africa (SSA) are unhealthy, largely due to years of crop nutrient-mining and limited organic or inorganic resupply (Jones, 2013). These soils, in their current state, are not able to provide adequate nutrition for the region's population, with 236.5 million people undernourished in SSA, an increase of 60 million in 10 years and at a prevalence rate of over 23% (FAO, 2017). A lack of food security is also on the rise in SSA, with an increased incidence of nearly 8% from 2014 to 2017 (FAO, 2017). Though SSA has seen increasing agricultural productivity over the last decade, per capita food production has remained stagnant (http://www.fao.org/statistics/en/). The case of poverty as associated to soil fertility and vegetative vigor is analogous to this situation (Heger *et al.*, 2018). Although SSA has seen a decline in poverty from 57%

in 1990 to 43% in 2012, the number living in extreme poverty increased by 100 million over the same time driven by a rapidly growing population (Beegle *et al.*, 2016). By 2050, the global population is expected to increase from 7.3 to 9.7 billion; however, over this same time, Africa will have the greatest growth with a doubling of population from 1.2 to 2.5 billion (UN, 2015), putting growing pressure on the soils of SSA. Approximately 25% of SSA's productive lands are degraded, driven by desertification and erosion but mainly due to the loss of nutrients and soil organic C under continuous cropping (Jones *et al.*, 2013). In 2007, these degraded soils were estimated to affect 485 million Africans and cost the continent nearly US$9.3 billion annually (Thiombiano and Tourino-Soto, 2007). Limited by soil degradation, yield increases from improved crop varieties are estimated at only 28% in Africa as compared to 88% in Asia (IFDC, 2013). Without addressing soil health issues, smallholder farmers cannot equitably benefit from yield gains offered by improved plant genetics and other associated agronomic practices implemented during the 'Green Revolution'.

There has been a renewed focus on soil fertility following the call of UN Secretary-General Kofi Annan for a 'uniquely African Green Revolution' (Annan (2004), and other calls for 'a doubly green revolution', (Conway, 1999) an 'evergreen revolution', (Swaminathan, 2000) and 'sustainable intensification' (Pretty, 1997). Soil fertility has been consistently identified as a primary limiting factor in SSA, preventing the dramatic yield increases seen by the rest of the world over the last half century (Sanchez, 2002, 2015; Pradhan *et al.*, 2015). However, obstacles to overcoming barriers to achieve healthy and fertile soils persist. Over 14 years after Kofi Annan's call, and after numerous activities and investments in the region's soil fertility, cropping systems in SSA still only attain 30% of their potential yield (Mueller *et al.*, 2012). Cereal yields in SSA hover around 1.5 MT ha^{-1} as compared with 3 MT ha^{-1} in Latin America and South Asia, 5 MT ha^{-1} in China, and more than 10 MT ha^{-1} in North America, Europe, and Japan (AGRA, 2016). There is now a renewed need to refocus and prioritize sustainable soil fertility efforts in an inclusive and evidence-driven way that looks holistically at the barriers to improve soil health and productivity in SSA. Soil initiatives that only aim to increase crop productivity will fall into the same trap as the last decade where productivity in SSA has increased but per capita well-being has not (i.e. food and nutrition security and poverty reduction) (Beegle *et al.*, 2016; FAO, 2017; http://www.fao.org/statistics/en/). Future investments in soil fertility improvements must support an 'equitable green revolution' that supports resilient and sustainable livelihoods that both provides the nutrition and economic returns to improve human and social well-being (Musumba *et al.*, 2017; https://sitoolkit.com/).

Soil and plant analysis, paired with agro-ecologically specific fertilizer response functions, is often the first step to producing evidence-based fertilizer recommendations for efficient crop response. Although this model has been attempted across SSA to varying effect, its self-sustaining business model and adoption by smallholder farmers has been limited. In addition, past soil fertility improvement efforts have often focused on inorganic fertilizer use as the primary mechanism for improving soil fertility and improving crop yields (Jayne and Rashid, 2013); however, under SSA conditions where soils are largely degraded [e.g. limited organic matter (OM) and organic nutrient pools], a focus on inorganic fertilizer use alone has had limited success in improving soil fertility. Soil organic C pools, as an indicator for soil health, have been depleted across SSA, resulting in reduced nutrient-use efficiency and water-holding capacity (Lal, 2004). Long-term solutions, such as approaches that build OM and organic nutrient pools, in addition to inorganic fertilizer applications will likely be an essential component to achieving sustainable soil fertility in SSA (Vanlauwe *et al.*, 2010, 2014, 2015). These biophysical pathways will continue to be critical but must also incorporate economic, environmental, social, and human domains to enable the adoption of such practices and to ensure that improvements in soil fertility have the desired outcomes to improve well-being. There have been numerous literature reviews covering soil fertility approaches for SSA; however, these reviews are almost exclusively biophysical in nature (Buresh *et al.*, 1997; Donovan and Casey, 1998; Bationo *et al.*, 2007; Conway, 2012). There is still a need for a more inclusive evaluation of the soil fertility landscape that is aimed at evaluating the entire soil fertility supply chain; one that is inclusive of interdisciplinary approaches (e.g. production, social/human, regulatory/policy, environmental, economic) to understand soil fertility barriers and that establishes evidence-based priorities to overcome these barriers, which we have done in this study.

Materials and methods

A survey and summit meeting of multi-disciplinary actors working in SSA soil fertility were conducted to determine critical soil fertility priorities focused around identifying key barriers (e.g. increasing soil organic matter, nutrient limitations at both the macro and micro scale) and key sustainable strategies and priorities to overcome these barriers. This objective was realized through an evidence-driven survey and a summit meeting involving key leaders and actors from across international agricultural research centers (IARCS), national agricultural research and extension systems (NARES), national universities, extension agencies, developmental agencies, agronomic/soil researchers, the private sector, social scientists, regulatory agencies, and farmer organizations aimed at systematically identifying soil fertility barriers and the priorities to overcome these barriers. The focus of the evaluation was to identify opportunities for broader and greater impact on soil fertility-related issues across large geographical regions. The focus regions of interest were: West Africa (Senegal, Burkina Faso, Ghana, Niger, Mali), East Africa (Tanzania, Kenya), the Great Lakes region (Rwanda, Uganda, Burundi, Malawi), and Ethiopia, which was kept separate due to its unique agro-ecology. Distinct priorities were identified for each region. Countries were selected to align with the focus countries of the Feed the Future program (of the United States Agency for International Development, USAID) and strategic partners of the donor community. Detailed documents for the survey and summit methods, regionally specific results, survey responses, summit participants, and a combined summary of emerging recommendations are available at website of the Sustainable Intensification Innovation Lab (https://www.k-state.edu/siil/resources/soilfertility/index.html). The majority of the respondents represented expertise in the target countries; however, respondents also represented a broader community from 20 additional SSA countries (Fig. 1).

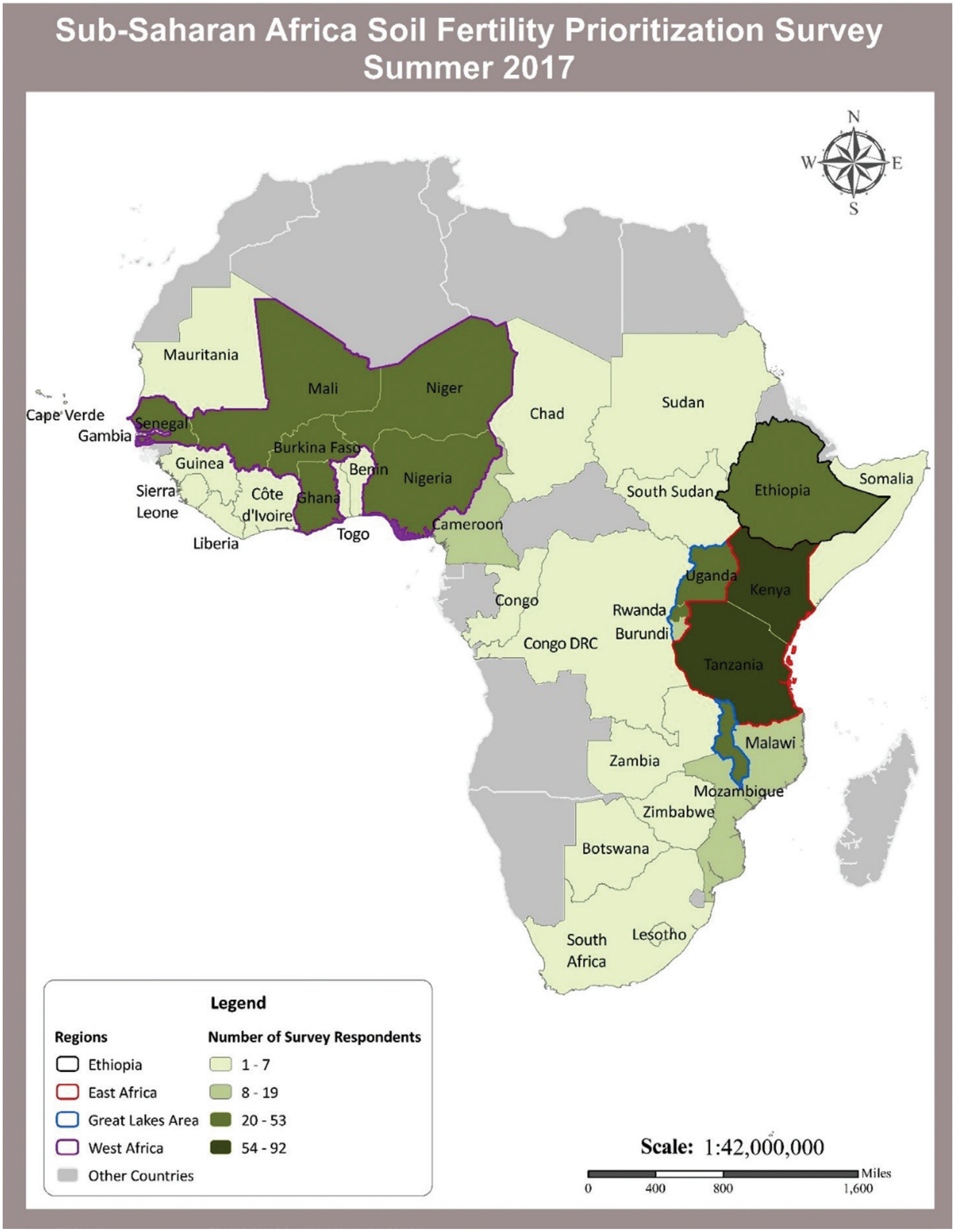

Fig. 1. Regions of sub-Saharan Africa included in this study and the number of survey respondents by country.

Survey methodology

An initial list of survey participants was compiled by drawing from the Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) institutional Listserv, the investigators' relevant contacts, the International Fertilizer Development Center's (IFDC) relevant contacts, the American Society of Agronomy public Listservs including the Sustainable Intensification community and communities within the Global Agronomy Section (i.e. Agronomic Solutions for Smallholders, Agronomy in Africa, Gaining Access to Agronomic Inputs), and authors of key publications. In addition, relevant contacts were requested from leading regional scholars working on soil fertility-related issues in SSA. In an effort to expand the study, a snowball technique was implemented whereby recipients were asked to identify other experts in the topic area. As a result of this request, an additional 81 names were added to the survey distribution list, resulting in a total of 1115 contacts.

The survey was developed to systematically identify evidence-driven soil fertility barriers, and to gather suggestions to overcome these barriers and to prioritize current and future innovations for research, development and, scaling. Leading biophysical and social scientists piloted the survey before its release. The survey sections included questions to rank a list of limiting factors regarding soil characteristics that contribute to poor crop yields, to rank lists of biophysical and socio-economic limitations to enhance soil fertility, to provide recommendations to improve soil fertility 5–10 years from now, and to report the respondents' demographics. Due to differences in soil conditions across SSA, the survey respondents were asked to select and identify with which geographical region they were most knowledgeable and to focus their responses to the selected region throughout the survey.

The survey was sent to participants in an online format in Qualtrics™ and they were given one month to complete it, with twice-weekly reminders sent until completion. Throughout the survey, respondents continued to provide contact information for others to be included in the survey. By the closing date, the survey had been distributed to 1157 contacts. From this distribution, a total of 491 individuals responded, representing a 42% response rate (Table 1). The responses were aggregated and descriptive statistics were used to summarize the quantitative data. For the open-ended questions, a content analysis was conducted to identify common themes and trends within each region.

Summit methodology

The summit meeting used the participatory and multi-disciplinary methodology described by Middendorf *et al.* (2019). On 14–15 August 2017, 35 participants convened for the Sub-Saharan Africa Soil Fertility Prioritization Summit in Dakar, Senegal. The participants were identified as key thought leaders on soil fertility issues in their respective regions, and represented IARCS, NARES, national universities, extension agencies, developmental agencies, agronomic/soil researchers, social scientists, regulatory agencies, the private sector, and farmer organizations. The summit built on the survey results and was designed to further explore the soil fertility limitations, solutions, barriers, and the strategies to overcome these barriers through a facilitated process.

Participants were assigned to regions based on their expertise and asked to identify solutions to nitrogen deficiency, low soil organic C content, phosphorous deficiency, and acidity, since these were the top soil limiting characteristics identified by the survey across all regions. Each region had 7–9 participants. For each limiting soil factor, each region separately identified their top solutions to overcome the limitation. Each participant then identified two biophysical and two socio-economic barriers to these solutions. Participants organized the barriers into clusters and titled the clustered barriers by theme. Participants then developed strategies to overcome the clustered barriers. This process was conducted for each limiting soil characteristic and separately for each region. All participants reviewed the regional solutions, and through consensus the common solutions across all regions were categorized and named. The participants then ranked the common solutions that they felt would provide the greatest impact on addressing soil fertility issues within SSA.

Table 1. *Responses of survey participants by region*

Region	Number of responses	Percent
Ethiopia	38	8%
Great Lakes region	99	20%
West Africa	170	35%
East Africa	184	37%
Total	491	100%

Results

The most frequently reported and highly ranked limiting factors regarding soil characteristics that contribute to poor crop yields across all four regions were nitrogen deficiencies, phosphorous deficiencies, acidity, and low soil organic C content. For Ethiopia and the Great Lakes region, micronutrient deficiencies were also reported as part of the top five limiting factors, while low water-holding capacity was noted for West and East Africa (Table 2). Given these prioritized limitations, our recommendations to improve soil fertility have focused on overcoming these factors.

Survey respondents identified and ranked biophysical and socio-economic limitations to enhance soil fertility. In terms of biophysical limitations, all regions reported a need for access to quality soil testing and increased availability of inorganic fertilizers, with a particular focus on establishing regionally specific fertilizer response recommendations and improving the delivery of these recommendations to farmers. Both Ethiopia and the Great Lakes region indicated that retention of crop residues on the soil and availability of quality organic materials were barriers, while limited opportunities to maintain and build soil organic matter were reported for West and East Africa (Table 3). In terms of socio-economic/socio-cultural limitations, all regions emphasized that access to financial resources was a barrier, particularly for smallholders and subsistence farmers. The availability of public sector service providers to deliver appropriate nutrient management recommendations was also commonly noted and ranked highly as a barrier. The need for access to mechanization was reported for Ethiopia and West Africa, while barriers related to gender equity and the need to develop private sector resources were reported for the Great Lakes region and East Africa (Table 4). Although data were

Table 2. *Top five limiting soil fertility factors ranked by region*

Limiting factor	East Africa	Ethiopia	Great Lakes	West Africa
Nitrogen deficiency	1	1	1	2
Low soil organic carbon content	2	3	3	1
Phosphorus deficiency	3	2	4	3
Acidity	4	4	2	–
Micronutrient deficiency	–	5	5	5
Low water-holding capacity	5	–	–	4

Table 3. *Top five limiting biophysical factors ranked by region*

Limiting factor	East Africa	Ethiopia	Great Lakes	West Africa
Access to quality soil testing	1	1	1	3
Availability of inorganic fertilizers	2	4	2	1
Lack of fertilizer recommendations	4	2	3	5
Availability of manures	–	–	4	–
Retention of crop residues in soil	–	5	5	–
Suitability of fertilizer blends	3	–	–	–
Limited opportunities to increase soil organic matter	5	3	–	2
Availability of composts	–	–	–	4

Table 4. *Top five limiting socioeconomic factors ranked by region*

Limiting factor	East Africa	Ethiopia	Great Lakes	West Africa
Access to financial resources	1	1	1	1
Availability/capacity of public sector extension	2	2	2	2
Suitable information on the composition of manures and other C-rich soil amendments.	4	4	3	–
Availability of private sector service providers	3	3	4	4
Gender equity issues	5	–	5	–
Access to mechanization, as appropriate	–	5	–	5
Land tenure	–	–	–	3

collected at the regional level, the following common themes were identified across all regions: (1) a need for expanded research, leading to improved/updated recommendations for site- and region-specific conditions; (2) a need for local soil testing facilities/tools, particularly in rural areas, that can provide affordable, accurate services; (3) training for farmers, with a focus on peer-training and on-farm demonstrations; (4) a need to build the capacity of extension service providers; and (5) gender equity issues, which were noted in all regions except Ethiopia. These included women's lack of land ownership, lack of access to financial resources, and limited availability to participate in training sessions.

As part of the summit, common solutions were prioritized across SSA. This exercise was designed to synthesize the solutions across regions in an effort to focus on solutions that would provide the largest breadth and depth in addressing soil fertility issues across SSA. Through a consensus process, participants identified nine common solutions and ranked them for prioritization purposes to identify the most important ones. The participants identified the following priorities across all regions (with number of participant votes tin brackets): apply inorganic nitrogen and phosphorous (24); incorporation of organic resources (20); increase integration of legumes in crop systems (focus of biological N_2 fixation) (17); conservation agriculture (CA) practices (where appropriate) (11); liming acid soils (11); diversification of cropping systems (7); use of acid-tolerant crop varieties (2), and consider biochar where appropriate, economical, and environmentally feasible (1); and promoting the proliferation of beneficial microorganisms (0) (Table 5).

The survey results were complementary to the summit results and indicated that there are key biophysical and socio-economic barriers and strategies that can either create an enabling environment or hinder progress towards improving soil fertility across SSA. Access to inorganic fertilizer, its use, and related implementation issues were prominent solutions to building soil fertility; however, many related biophysical barriers (e.g. increased access and use of quality organic materials) and socio-economic barriers (e.g. access to resources both financial and agronomic, and access to appropriate fertility recommendations and extension support) were also identified as important solutions to building soil fertility (Tables 3–5).

The following recommendations were developed through a combined analysis of the survey and summit data and have been

Table 5. *Prioritization of proposed solutions arising from the summit meeting*

Proposed solutions	No. participant votes
Application of inorganic N and P (source nutrients)	24
Application of organic resources	20
Integration of legumes in crop systems (focus of biological N_2 fixation)	17
Conservation agriculture practices, where appropriate	11
Liming acid soils	11
Diversification of cropping systems	7
Use and grow acid-tolerant crop varieties	2
Consider use of biochar, where appropriate and economical and environmentally feasible	1
Promote proliferation of beneficial microorganisms	–

organized by emerging themes across all regions. Where appropriate, the recommendations include unique themes identified within a region. The survey and summit provided a rich and diverse view of barriers, strategies, and solutions for overcoming the identified primary soil limitations. Most of the recommendations presented are known and are based on established strategies; however, the evidenced-based process and methodology for prioritizing these recommendations make these findings useful for setting out action plans for future investments and strategies to improve soil fertility in SSA. This section provides emerging recommendations from the diverse inputs, but the reader is referred the *SSA Soil Fertility Prioritization Survey Report* and the *SSA Soil Fertility Prioritization Summit Report* for a complete presentation of the results specific to each region (Pierzynski *et al.*, 2017; Middendorf *et al.*, 2017; Stewart *et al.*, 2017). This is strongly encouraged when considering soil fertility initiatives in a specific region or focusing on overcoming a specific soil limitation. The four emerging themes are: (1) strengthening inorganic fertilizer-based systems; (2) access to and use of quality organic inputs; (3) capacity building along the entire knowledge-transfer value chain; and (4) strengthening farming systems research and development across biophysical and socio-economic factors.

Emerging themes and priorities across regions

Strengthening inorganic fertilizer-based systems

The availability of inorganic fertilizer, its use, and related implementation factors were a prominent theme identified and prioritized across all regions to overcome nutrient deficiency (i.e. participants prioritized N and P deficiency; micronutrient deficiency was also prioritized for Ethiopia and the Great Lakes region) and to improve soil fertility. However, the existing barriers to inorganic fertilizer use that were identified were numerous and spanned both biophysical and socio-economic considerations. The availability and affordability of quality inorganic fertilizers was consistently identified across all regions, as was the lack of: access to financial resources or credit to purchase fertilizers, quality soil testing, region- and crop-specific fertilizer application recommendations, opportunities to build and maintain soil organic matter to improve fertilizer responses, and skilled public and private sector service providers to deliver and support appropriate nutrient management recommendations to farmers (i.e. right source, right rate, right time, right place).

Further, participants recommended the use and development of region- and crop-specific fertilizer blends, which may include micronutrients where fertilizer trials indicate a response. Essential to this process is the need for well-trained public and private extension service providers and for information communication technologies. This would require investment in the quantity of people being trained and the quality of the training for those providing recommendations to farmers and conducting applied research to support their efforts. Many comments specifically suggested public extension services; however, pluralistic extension services will likely also be appropriate, an approach that includes a variety of service providers, such as all research actors, IARCS, NARES, national universities, developmental agencies, NGOs, the private sector, and farmer organizations. There is a need for improved linkages between these multiple organizations and the overall certification and standardization of quality recommendations. The use of smart phones and other technologies is also strongly encouraged in dissemination of knowledge and information.

Access to and use of quality organic inputs

Increasing access to and use of quality organic materials was consistently identified and prioritized by all regions for the goal of improving soil fertility. However, the barriers identified to increased access and use of quality organic materials were numerous and spanned both biophysical and socio-economic considerations. Critical barriers included lack of access to: sufficient quantities of animal manures and other carbon-rich amendments, suitable information on their composition, skilled public and private sector service providers to deliver appropriate management recommendations, and the ability to retain crop residues in the soil. Intrinsic factors, such as adverse climatic conditions (i.e. limited precipitation and extreme temperatures) and soil texture (i.e. sandy soils), were also identified as critical barriers. Low-input agriculture, limited appropriate scale mechanization for CA, the multiple competing interests for crop residues, such as animal feed, home construction, fuel for cooking, and the impact of open grazing policies, were also noted as critical barriers.

Capacity building along the entire knowledge-transfer value chain

Capacity building along the entire soil fertility, knowledge-transfer value chain (KTVC) was consistently identified and prioritized by all regions for the goal of improving soil fertility in terms of knowledge creation, knowledge transfer, and building the capacities of institutions and facilities. For overcoming N, P, and micronutrient deficiencies as well as low soil organic C, acidity, and low water-holding capacity, the lack of capacity along the KTVC was consistently identified as a critical barrier to improve soil fertility. Specifically, the lack of skilled public and private sector extension service providers and supporting information-transfer platforms was heavily emphasized, although the lack of capacity of national agricultural research institutions, farmers and end users, soil analysis testing laboratories and technicians was also emphasized. Many survey and summit respondents prioritized capacity building for a wide range of extension services, which was inclusive of IARCS, NARES, national universities, developmental agencies, NGOs, the private sector, and farmer organizations.

Respondents clearly indicated that knowledge development and capacity building are essential strategies to improve soil fertility. Survey and summit participants identified and prioritized the need for a wide range of well-trained public and private sector extension and service providers along with all research actors connected to regionally specific research. Emphasis was placed on expanding the capacity of this sector by: improving their training and strengthening linkages between research, extension services, and farmers; expanding research, leading to improved/updated recommendations for cropping system-, site-, and region-specific conditions; increasing the capacity of local soil testing facilities or mobile platforms that can provide affordable and accurate services; increasing farmer training, with a focus on peer-training and on-farm demonstrations; and encouraging private sector investment. Public sector agencies should take the lead in creating platforms that can bring all active partners together for effective engagement and operation of policies and activities.

In an attempt to improve access to information on fertilizer use and the composition carbon-rich amendments, respondents recommended the need for capacity building of farmers, private and public extension service providers, and lab facilities, with a particular focus on connecting these groups to region- and crop-specific research on inorganic and organic fertilizer amendments. The development of the private sector and enabling agricultural policies were also recommended to increase the availability of private sector service providers to deliver soil fertility management recommendations.

Strengthening farming systems research and development across biophysical and socio-economic factors

There were numerous integrated biophysical and socio-economic strategies identified and prioritized as critical factors for improving soil fertility in SSA. Prioritized socio-economic strategies included: integrating access to financial resources into the farming system to improve soil fertility outcomes; ratifying appropriate policies that provide market stability for both farm inputs and outputs and enabling land ownership and grazing policies that support soil fertility improvements; establishing enabling conditions for private sector investment; strengthening the soil fertility KTVC; empowering women to enable improved soil fertility management and decision-making; and increasing access to mechanization that enables minimum tillage, thereby increasing soil fertility and reducing erosion and environmental contamination. The survey and summit participants clearly prioritized both biophysical and socio-economic factors, integrated together across the farming system to improve soil fertility.

Discussion

The combined biophysical and socio-economic results provide a clear picture of the interdisciplinary and interconnected nature of the priorities to improve soil fertility across each sub-region. Plans to improve soil fertility across SSA need to take an integrated approach, inclusive of the identified biophysical and socio-economic factors. Action plans that focus only on a singular or narrow factor, such as inorganic fertility availability or mineral fertilizer recommendations, will likely fall short of improving soil fertility in most regions. Each of the prioritized factors need to be improved in such a way that no individual identified priority is limiting. For example, although it may be evident that the use of inorganic fertilizers can improve crop yields, incorporating this approach exclusively without the inclusion of appropriate recommendations (i.e. right source, right rate, right time and right place or method), reliable extension services, access to financial resources, incorporation of organic amendments, and enabling policies will likely not be successful in increasing adoption of soil fertility-improving innovations. A perspective of the current status of the soil fertility landscape and evaluation of the most limiting biophysical or socio-economic factors in a given region is critical for recommending the appropriate action plan to improve soil fertility.

Emerging themes and priorities across regions

Strengthening inorganic fertilizer-based systems.

Action plans to overcome nutrient deficiency and improve soil fertility by increasing the availability and use of inorganic fertilizer must also devote significant consideration to the prioritized biophysical and socio-economic barriers. If any one of the prioritized factors are limiting, increased availability and use of inorganic fertilizer alone will likely not achieve sustained soil fertility. As such, it is our recommendation to encourage an interdisciplinary systems approach to increase inorganic fertilizer availability and use for the goal of improving soil fertility. This recommendation aims to strengthen the entire inorganic fertilizer system, from the supply of quality inorganic fertilizers to the capacity-building of extension service providers to provide recommendations to farmers. This systems approach will require the strengthening of access to quality and affordable inorganic fertilizers, financial resources and credit to purchase fertilizers, quality soil testing (i.e. lab- or mobile-based), regionally specific fertilizer application recommendations, opportunities to build and maintain soil organic matter to improve fertilizer responses, and skilled public and private sector service providers to deliver and support appropriate nutrient management recommendations for farmers. An inclusive perspective of each of these factors in a given region is essential to identify which barriers are limiting and are in greatest need of resource investments. Critical to this recommendation is the need for systems and platforms that can integrate and connect these services.

Recommended strategies prioritized from the survey and summit results include the need for improved access to well-equipped soil analysis labs and/or mobile testing equipment (e.g. spectral, agro-ecologically interpolated fertilizer recommendations) that can provide affordable, research-based, and crop- and region-specific recommendations to farmers. Soil analysis labs or mobile soil analysis platforms must be linked with regionally specific fertilizer response trials in order to provide appropriate recommendations. In particular, soil testing practices should address soil chemical characteristics that limit crop responses to fertilizer or plant nutrient supplements in addition to assessing plant-available nutrients. Since most soils are nutrient deficient and will likely remain so, improving basic soil conditions to increase the likelihood of a crop response to nutrient additions is critical. In many cases, extensive correlation and calibration studies to determine the proper amount of fertilizer to add in order to achieve maximum yields or to allow build-up of plant nutrients would not be needed. Simple fertilizer-response curves (nutrient added versus yield), obtained through applied research, would be sufficient and extremely valuable, especially with a consideration for economic return. Precision nutrient-management practices and soil-water conservation principles such as micro-dosing, zaï, fertilizer deep placement, and half-moon, and improved versions of these with compost will likely each have an important role in improving the agronomic, economic, and environmental outcomes to inorganic fertilizer use (Twomlow *et al.*, 2010; Zougmoré *et al.*, 2014).

On the socio-economic side, the lack of financial resources was a prioritized barrier identified in all regions. In order to support the use and adoption of inorganic fertilizers, participants recommended linking farmers to financial resources such as microfinancing programs, voucher or subsidy programs with an exit strategy, farmers' cooperatives, crop insurance programs, improved policy/infrastructure and supply chains, and economically optimum fertilizer recommendations (Wortmann and Sones, 2017). Smallholder farmers have limited resources to invest in their cropping systems and it is critical to note that not all fertilizer applications that increase crop yield are economically valuable to the farmer, especially on degraded soils where nutrient-use efficiency is low.

Access to and use of quality organic inputs.

Both the quantity and quality of organic materials were of concern and the results are supportive of an organic resource database, as suggested by Palm *et al.* (2001). The issue of land tenure (i.e. long-term access to the same land) was identified for West Africa, and access to mechanization, where appropriate, was identified for both Ethiopia and West Africa. Depending on the unique agro-ecology and typologies of the producers of each system and region, various organic matter technologies were identified and are recommended to increase organic C and essential plant nutrients in the soil through the addition of carbon-rich materials. In order to increase biomass production, these carbon-rich materials could include manures or composts, legumes (as crops, or in agroforestry as shrubs/bushes and trees), or low C:N ratio crops, the retention of crop residues, cover crops or green manures, or use of inorganic fertilizers as identified by research (Shepherd *et al.*, 1995; Snapp *et al.*, 1998; Bayu *et al.*, 2005). The option of adding biochar was specifically recommended for West Africa, although there is much research needed to determine its suitability in SSA (Gwenzi *et al.*, 2015). Ethiopia, the Great Lakes region, and East Africa listed solutions that are consistent with integrated soil fertility management (ISFM), including crop rotations, cropping systems, optimizing C:N ratios through improved crop–livestock–soil management, and improved information and recommendations on soil fertility management. All regions listed components of CA and improved agriculture practices related to reducing soil erosion and use of no-till practices. Reduced tillage, stone lines, grass bands, tied ridges, and contour ridging have each been shown to be suitable techniques for reducing erosion in SSA (Zougmoré *et al.*, 2014; Ligonja and Shrestha, 2015). Agroforestry systems were particularly highlighted in West Africa and mentioned for parts of East Africa.

Optimum strategies to increase access to and use of quality organic materials will depend on the unique agro-ecology of the region, with the prioritized goal of building or maintaining soil C to improve soil fertility. However, it should be stated that the survey and summit results do not necessarily support the concept of C sequestration for improved soil fertility that is often discussed in the scientific literature. Rather, the greatest benefits of frequent C additions to the soil will be realized through improvements in soil physical properties and as part of ISFM practices, without necessarily increasing soil C stocks. Improving access to and utilization of quality soil- and organic material-testing labs or mobile analysis systems, skilled private and public extension service providers, improved mechanization, and enabling polices are critical to overcoming the identified and prioritized barriers. Most of the organic material strategies are knowledge-intensive and thus a significant investment should be made in building this capacity for both regional knowledge creation and delivery of improved organic material technologies.

The need for basic and applied research was clearly identified and prioritized by all regions for the purpose of increasing access to and use of quality organic materials. Applied research on crop-residue management, tillage, soil erosion, cropping systems, cover crops, and soil compaction will be essential. For basic research, soil microbial processes as related to soil health and nitrogen fixation, biochar, use of soil-applied polymers, and the optimization of C and nutrient flows are also recommended. Policy and development issues that enable the application of carbon-rich materials and the retention of crop residues in the soil are strongly encouraged. Policy briefs related to open grazing, land ownership, issues related to burning of brush and crop residues, and the promotion of soil quality improvement are highly recommended. Strategies for appropriate mechanization related to providing planters at an appropriate scale (e.g. hand-held, or two-row drawn by animals or single-axle tractors) and other equipment needed for CA and minimum-tillage practices were also recommended.

Capacity building along the entire knowledge-transfer value chain.

Capacity building across the entire soil fertility KTVC was strongly identified as a catalyst for both of the previously identified themes of strengthening inorganic fertilizer systems and increasing access to and use of quality organic materials. We recommend the prioritization of capacity building along the entire soil fertility KTVC and integration of a wider range of stakeholders as part of any action plan to increase soil fertility in SSA. This is consistent with the recommendations of Snapp *et al.* (2003) of engaging a wide array of stakeholders with a focus on maximizing returns from smaller input purchases as compared to higher, blanket recommendations for fertilizers. Past efforts have placed particular focus on creating doctoral- and masters-level researchers to enable knowledge creation, which is still of high priority; however, the survey and summit participants also emphasized the need for greater capacity building along the entire KTVC to improve the bi-directional delivery of existing knowledge to and from farmers and end users. Participants noted that numerous proven strategies and innovations to overcome soil fertility barriers have existed for decades, yet their bi-directional dissemination to farmers is limited. The KTVC to and from research and farmers adds value to the original innovation, adapts the original innovation to fit region- and farmer-specific parameters, and thus should be strengthened to improve soil fertility. The use of mobile platforms and information communication technologies is also strongly encouraged. Further priority should be given to building the capacity of public and private extension service providers, soil analysis technicians, farmers and end users, and to institutions and physical infrastructure. This would require investing in building the number and skills of a variety of public and private extension service providers, laboratory or mobile soil-testing technicians, and farmers, and strengthening te linkages between researchers, soil analysis facilities/mobile testing platforms, and farmers—all with the goal of increasing the adoption and scaling of proven innovations and practices by farmers.

Strengthening farming systems research and development across biophysical and socio-economic factors.

Farming systems concepts were routinely identified and prioritized as critical to improving soil fertility in SSA, which is consistent with the recommendations of Giller *et al.* (2011). Farming systems recommendations expanded upon the traditional biophysical farming systems strategies to include socio-economic factors for improving soil fertility. African farming systems are highly heterogeneous, both agro-ecologically and socio-economically, thus 'best-fit' innovations must aim to minimize trade-offs and maximize synergies across both biophysical and socio-economic parameters. Depending on the region, biophysical recommendations such as integration of legumes, crop–livestock integration, crop rotations and diversification, agroforestry, and adopting crop varieties with improved N and P efficiency were prominent recommended strategies for improving soil fertility, and are supported in the literature (Shepherd *et al.*, 1995; Snapp *et al.*, 1998; Pretty *et al.*, 2018). Water management was also an integrated recommendation for releasing the potential of a soil's fertility, such as drip irrigation, CA, zaï, and half-moon, and by promoting management practices that increase water-holding capacity such as increased soil organic C and aggregate stability (Xie *et al.*, 2014; Zougmoré *et al.*, 2014). Participants also identified the need for evaluation of farming systems for synergies and trade-offs associated with the adoption of various innovations. This farming systems and innovation assessment should consider impacts across multiple domains such as productivity, economics, environment, social, and human conditions (Musumba *et al.*, 2017; https://sitoolkit.com/). This same approach has been noted for assessing sustainable development goals (SDGs) to ensure well-being, economic prosperity, and environmental protection (Pradhan *et al.*, 2017). We find that the goal of increasing soil fertility, as recommended by this paper, has strong synergies and limited trade-offs with the following SDGs: #2 zero hunger; #1 no poverty; #3 good health and well-being; #8 decent work and economic growth; and #10 reduced inequalities. To minimize potential trade-offs while improving soil fertility, prudent attention must be given to SDGs #15 life on land, #6 clean water and sanitation, #13 climate action, #12 responsible consumption and production, and #5 gender equality.

These results indicate that soil fertility should not be viewed as simply a means for increasing crop productivity alone but rather the keystone for providing nutritious food, economic well-being, and resilient and sustainable livelihoods. Soils provide nearly all elements that compose and support the functions of the human body, either directly from plants and grains or indirectly through animals. Thus, the way in which we manage our soils and farming systems changes the efficiency of the flow of these nutrients to support human health (i.e. 'modified one health approach'). In addition, soil fertility and vegetative vigor in SSA are directly linked to poverty reduction (Heger *et al.*, 2018). As such, the fertility of the soil should ensure economic well-being to smallholders. Improvements to soil fertility should also be assessed as a critical factor for increasing systems resilience from climate change and political and social unrest, as well as supporting sustainability to meet the needs of the current population without negating the ability of future generations to meet their needs. Although not identified through our assessments, sustainable consumption in addition to sustainable production practices should also be viewed as essential to moving towards sustainable farming systems (Pradhan *et al.*, 2014).

As such, we recommend that action plans aimed at improving soil fertility in SSA on smallholder farms take an integrated farming systems approach that encompasses both biophysical and socio-economic methodologies. Biophysically, improved farming systems integration with legumes, livestock, and/or agroforestry, where agro-ecologically appropriate, can provide access to *in situ* fertilizer, quality organic materials, income resilience, nutrition and food security, and resilience to climate variability and social unrest, and as such can increase the farmer's ability to improve her/his soil fertility. Socio-economically, increasing women's empowerment, access to financial resources, access to bidirectional knowledge transfer, access to appropriate scale mechanization, and enabling political environments were highly recommended by participants in increasing the farmer's ability to improve her/his soil fertility.

Conclusions

To address soil fertility problems in SSA, an integrated approach should be adopted that simultaneously addresses the following four identified themes in combination rather than in isolation: (1) strengthening inorganic fertilizer-based systems; (2) access to and use of quality organic inputs; (3) capacity building along the entire knowledge-transfer value chain; and (4) strengthening farming systems research and development across biophysical and socioeconomic factors. Soil initiatives should focus on providing holistic solutions covering both biophysical and socio-economic aspects for actors along the entire value chain and on creating enabling environments for adoption. Although fertilizer and organic sources of nutrients are still central to our recommendations, future initiatives must also include socio-economic and farming systems approaches. A broader view of soil fertility improvement, using all available options including both inorganic and organic sources of nutrients and socio-economic and farming system approaches, should be implemented. Farming systems approaches should aim to maximize synergies and minimize trade-offs across productivity, economic, environmental, human, and social domains as a pathway to improve livelihoods. All actors in the value chain from private industry, government and non-government agencies, research, education and extension services should be engaged. There is a critical need for improved linkages among partners and organizations. Public sector agencies can play a significant role in creating a platform for bringing together and linking key partners in research, education, extension, service providers, input providers, and farmers. There are reasons to be optimistic about food production in SSA; however, we must ensure that productivity gains are also driving improved livelihoods of smallholder farmers. SSA soil initiatives that only aim to increase crop productivity will fall into the same trap as the last half century where productivity has increased but not the per capita well-being (i.e. food and nutrition security and poverty reduction). Future investments in soils must support resilient and sustainable livelihoods that both provides the nutrition and economic return to improve human and social well-being.

Acknowledgements

This paper was made possible by the support of the American People provided to the Feed the Future Innovation Lab for Sustainable Intensification through the US Agency for International Development (USAID). The contents are the sole responsibility of the authors and do not necessarily reflect the views of USAID or the US Government. Program activities are funded by the USAID under Cooperative Agreement No. AID-OAA-L-14-00006. We thank the International Fertilizer Development Center (IFDC) for supporting this effort, and the survey and summit participants for providing their key input. The authors wish to thank Dr Jerry Glover and Dr John Peters of USAID; and Dr Scott Angle and Dr Upendra Singh of IFDC for providing scientific advice and guidance.

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