Unraveling pathways to the sustainable intensification of smallholder African agriculture: Long-term observatories for assessing benefits of ISFM to productivity enhancement and other ecosystem services

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Executive summary

Land degradation, and particularly soil fertility decline, poses a serious threat to crop production in Sub-Saharan Africa (SSA) because of an increasing pressure on land to meet the increasing demand for food caused by the growing population. In order to overcome the prevalent food insecurity and to eradicate poverty among smallholder farmers, there is a need for a paradigm shift in managing soil fertility by seeking options that optimize crop production per unit area through sustainable intensification (SI) in the face other drivers affecting productivity, including climate change. Sustainable intensification also includes the need to ensure that soil-related ecosystem services other than the production of food, feed, and fiber are retained. In recent years, Integrated Soil Fertility Management (ISFM) has formed the basis of many initiatives aiming at intensifying agriculture in Africa. ISFM 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. All inputs need to be managed following sound agronomic principles*'. While ISFM has been shown to increase crop productivity and input use efficiency in short term trials, its longer term impacts on soil health and yield stability remain largely unknown. There is a need to invest in long-term observatories to understand the processes associated with ISFM, its sustainability and identify the conditions for reversing soil degradation. Such long-term field trials also facilitate the optimization of ISFM across different cropping systems as affected by agro-ecological conditions and other drivers of change such as climate change. A group of scientists met in Kampala Uganda in November 2013 to discuss a strategy for a coordinated effort to establish long-term observatories for important cropping systems in relevant agro-ecological zones in SSA. The strategy is based on the establishment of multi-locational core and satellite trials along relevant agro-ecological, soil type, and degradation gradients.

Core trials will comprise a full suite of ISFM treatment combinations, across the different cropping systems, and will run for relatively long periods of time (at least 10 years). Satellite trials will be smaller and shorter term (minimum 3 years) and will comprise a sub-set of ISFM factors included in the core trials and their combinations. Satellite trials will evaluate ISFM components that can be used as entry point to maintain productivity on non-degraded lands and rehabilitate degraded lands whereas core trials will be used to assess the long-term impact of ISFM (i) on soil health, yield stability, and sustainability, and (ii) on rehabilitation of highly degraded lands. Key indicators of sustainability and provision of ecosystem services such as soil organic carbon (SOC), soil biodiversity, nutrient and water balances, yields and yield stability, and weed and pest dynamics will be monitored. The research team will include scientists with expertise in fields relevant to this initiative, including agronomy, soil science, agroecology, biometrics, simulation modeling, GIS, and socio-economics. Capacity building is an important component of the initiative, thus the team will actively engage postgraduate students at local and international (i.e. foreign) universities. Site selection will be aided by GIS to target the different cropping systems on representative soil types in the agro-ecological regions where the crops are generally grown. The initiative will consider densely populated areas where there is a greater need for SI. An open source database will be developed to enhance data management and sharing of information among the stakeholders in the different countries. Quantitative synthesis of data obtained from the trials will be handled with tools such as meta-analysis which are robust. Modeling and GIS tools will be used to extrapolate data, to extend the inference space under different environmental conditions where ISFM

performs. It is expected that these long-term observatories will provide a meaningful contribution to resolving the challenge of SI of smallholder farms in sub-Saharan Africa.

I. Background

The United Nations' Sustainable Development Goals underscore the need to judiciously manage soils to meet the growing food demand, and to eradicate poverty without compromising the soils' ability to produce food for future generations (Conway and Barbier, 2013). This is especially important in smallholder farming systems in Sub-Saharan Africa (SSA) where land degradation, and particularly soil fertility decline, poses a serious threat to crop production (Sanchez, 2002; Crawford and Jayne, 2010). A large proportion of smallholder farms in SSA are degraded and exhibit low productivity due to a variety of constraints including low nutrients, high vulnerability to erosion, and to moisture and disease stresses. Decades of soil nutrient mining, with low fertilizer use (average application rate of 8 kg ha^{-1}), have caused soils in SSA to become the poorest (in terms of being the most highly depleted in nutrients) in the world (Morris *et al.*, 2007; Crawford and Jayne, 2010). Additionally, increasing population pressure in the region has led to farm fragmentation into small sizes, elimination of traditional fallow periods, and agricultural expansion into steep areas and forests. Consequently, there is a need to respond to the food demand through SI of agricultural production systems (Pretty *et al.*, 2011), particularly for areas with high population densities. A threshold of at least 25 persons km^{-2} has been proposed as a requirement for the need for SI (Lele and Stone, 1989; Drechsel et al., 2001). A paradigm shift from low-yielding, extensive land practices to more intensive, higher-yielding practices is imperative, and this must begin with addressing the depleted soils. Past paradigms of soil fertility management focused on fertilizer or 'low-input' methods but rarely on both, and ignored the essential scientific fact that fertilizers are most effective and efficient in the presence of soil organic matter and well-conserved soil structure. Integrated Soil Fertility Management (ISFM) can resolve these issues.

ISFM 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. All inputs need to be managed following sound agronomic principles'* (Vanlauwe *et al.*, 2010). ISFM has been conceptually sketched as in Figure 1. Adopting this new paradigm has been shown to enhance both the agronomic and the

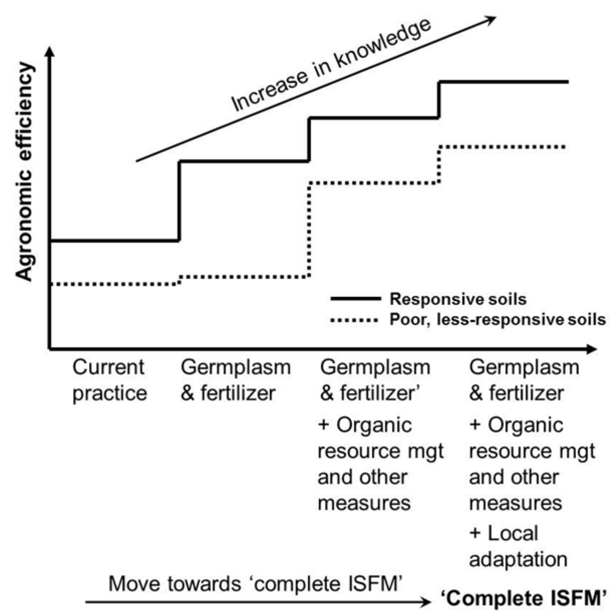

Figure 1: Conceptual relationship between the agronomic efficiency (*AE*) of fertilizers and organic resource and the implementation of various components of ISFM, culminating in complete ISFM towards the right side of the graph. Soils that are responsive to NPK-based fertilizer and those that are poor and less-responsive are distinguished. Soure: Vanlauwe *et al.* (2010).

economic use efficiencies of fertilizer (Vanlauwe *et al*., 2011). Many initiatives focusing on increasing agricultural productivity in smallholder farming systems in SSA, including the Alliance for a Green Revolution in Africa (AGRA), are adopting ISFM as the basis paradigm for addressing soil fertility depletion and increasing crop productivity (www.agra-alliance.org). Similarly, within the refreshed IITA Strategy 2012–2020, ISFM is one of the main pillars of the natural resource management research area. However, while ISFM has been shown to increase crop yields in the short term (Place *et al.*, 2003; Vanlauwe *et al.*, 2010), its longer term sustainability dimensions remain largely unknown. It is known, however, that the current soil health status and its associated primary and secondary limitations to plant growth will affect the impact of ISFM interventions on crop productivity and soil health rehabilitation. For instance, ISFM recognizes the fact that some soils require rehabilitation before an economic response to standard fertilizer can be expected (often referred to as 'non-responsive' soils) (Vanlauwe *et al*., 2007; Fofana *et al*., 2008). 'Soil degradation status', often equated with 'time since conversion from natural ecosystems to non-sustainable forms of agriculture', will thus be an important factor determining the short and long-term benefits of ISFM and the potential pathways farmers can adopt to revitalize crop productivity and restore soil health. Long-term observatories can shed light on the longer term benefits of ISFM and the possible pathways to SI through the appropriate deployment of ISFM components.

Long-term observatories play an important role in understanding the effects of soil and land management practices on soil fertility and yield stability as affected by agro-ecological conditions and other drivers of change, including climate change. While models can be used as a tool to simulate the long-term sustainability of ISFM, models are only as good as the information used to build and parameterize them, which is often based on short-term experiments. Thus, there is a need to carry out long-term studies to understand the long-term sustainability of ISFM. This will also enable the long-term monitoring of ISFM in response to a changing and variable climate (Swift *et al.*, 1994). With the need for SI, it is imperative to set up long-term observatories for understanding the sustainability of ISFM practices. A handful of soil fertility long-term observatories have been established, some still ongoing, in different agro-ecological regions of east, south and west Africa (Bationo *et al.*, 2012). These have provided valuable evidence of soil fertility decline, highlighted trends and dynamics of most measures instead of static snapshots. However, these existing trials were based on objectives that are not always aligned to today's research issues, thus often only addressing components of ISFM and not its full suite of components and their interactions. Other critical limitations of these trials include (i) most trials focused on cereal-based systems while nowadays it is commonly agreed that SI also applies to root and tuber-based systems, including cassava and banana/plantain, (ii) site selection for these trials was mainly driven by logistical (e.g., long-term security under on-station conditions) rather than scientific (e.g., capturing of a range of soil degradation conditions) arguments, (iii) designs and treatment structures are usually not standardized across a representative number of sites hindering cross-site comparisons, and (iv) data from such experiments are scattered, difficult to access and have remained unpublished. Nevertheless, their existence has provided invaluable insight on soil properties and crop productivity, and should be continued where possible.

The Water Land and Ecosystems (WLE) CGIAR research program (CRP) has taken on the SI challenge, aiming at increasing food production, restoring degraded lands, and expanding agricultural areas in ways that have minimum impacts to the environment, without diminishing the capacity to produce food in the future. The program focuses on external and internal drivers of change in agriculture, how these affect water, landscapes and ecosystem services, and how policy and management changes can be used to adapt production systems in a sustainable manner. This initiative is fully aligned with the SI goals of WLE. With support of WLE, a group of scientists from a relevant range of disciplines working at international and national agricultural research organizations met in Kampala, Uganda in November 2013 to debate and develop a strategy for long-term observatories for assessing benefits of ISFM to productivity enhancement and other ecosystem services. It is expected that these long-term observatories will provide a meaningful contribution to resolving the challenge of SI of smallholder farms in sub-Saharan Africa. It is also expected that these observatories will serve as a basis for generating information related to the monitoring of progress with natural resource metrics (e.g., input-response relationships) which is a major issue in WLE and other CRPs. Such observatories could serve as tools within sentinel sites to derive quantitative information on yield and ecosystem service benefits of improved soil management practices.

II. Justification and conceptual framework

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 (Post and Kwon, 2000; Guo et al., 2002; Lal, 2004a) and to rapidly declining crop yields (Tilman et al., 2002) (Figure 2). The rate of the decline depends on soil properties (texture, inherent fertility), management (degree of soil disturbance during production) and fate of crop (residues) (West and Six, 2007). A decline in SOC has been equated with a decline in overall soil fertility (Dalal and Mayer, 1986; Tiessen et al., 1994; Lal, 2004b; Liang et al., 2006; Bationo et al., 2007).

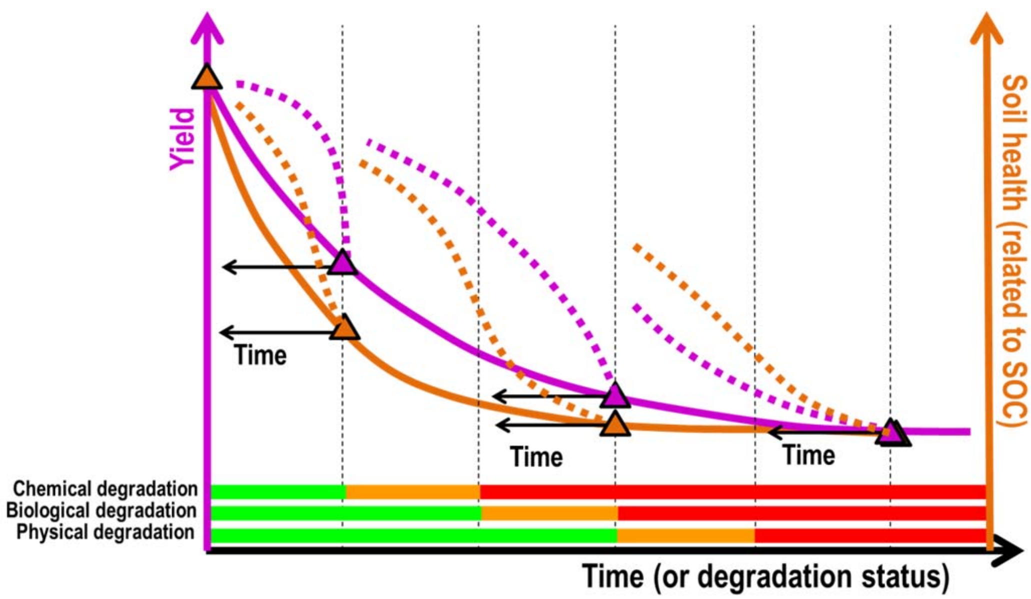

Figure 2: Conceptual descriptions of soil health (solid brown lines) and crop yield (solid purple lines) decline under low-input agricultural practices, the relative importance of the associated degradation processes in time (red = high, green = low), and the hypothesized rehabilitation trajectories (dotted lines) through intensification methods. Note that (i) the relative importance of the degradation processes is soil type-dependent – the various colors used in 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.

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 (Tittonell et al., 2005). For instance, while physical degradation is unlikely to be a major short-term issue for deep soils such as Nitisols and Ferralsols (Dudal and Deckers, 1993), it can occur quickly in soils with shallow topsoil (e.g. Lixisols). Since crop productivity is strongly related to soil health status, it follows similar, though not necessarily the same, degradation kinetics (Figure 2), partly because different crops have different nutrient and other growth requirements and are thus likely affected accordingly by changes in soil condition. If soil health is equated to SOC, then one could hypothesize that yield decline may be faster than soil health decline on clayey soils, as in such soils a lot of soil C is protected (Plante et al., 2006; Chivenge et al., 2011), while on sandy soils, yield losses likely lag behind SOC losses.

Trajectories to restore soil health status and associated crop productivity are unlikely similar to the degradation trajectories (Tittonell et al, 2005). For instance, while crop yields can decline rapidly, in situations 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 (Figure 2). In such cases, the additional crop residues produced, if used appropriately (e.g., either as surface mulch or returned after conversion to manure) could gradually regenerate soil health (Kong et al., 2005; Bationo et al., 2007). In situations 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 be raised to acceptable levels (Figure 2). In such cases, high external inputs, either organic inputs, lime, or mechanical amendments, may be required as part of the rehabilitation process, whereas technologies based on mineral fertilizer only are ineffective (Vanlauwe *et al*., 2010).

As highlighted above, restoring soil heath may involve various management practices depending on the process and level of degradation, soil types and other biophysical conditions. ISFM encompasses the application of various amendments and management practices, preferably simultaneously to facilitate positive interactions between such components (Figure 1). While ISFM is commonly depicted as a ‘step diagram’ with an increasing number of components deployed (fertilizer, improved germplasm, organic resources, local amendments, etc) resulting in higher agronomic efficiencies (and thus crop yields under constant input application rates), there is no chronological sequence underlying the steps, except for non-responsive soils where rehabilitation measures (e.g., high rates of organic inputs) are required before fertilizer and improved germplasm (Figure 1). A better understanding of the most logical integration of ISFM components over time and space as a function of soil degradation status would add substantial value to the specificity of ISFM recommendations. ISFM also recognizes the varying resource endowments of smallholder farmers (often translated into ‘farmer typologies’, encompassing aspects of gender since relatively ‘poorer’ families commonly have a larger proportion of female-headed households) and the consequent variable investment options farmers have. Depending on the nature of the ISFM components deployed (both in terms of specific components and the quantities applied of these components), soil health and crop productivity rehabilitation trajectories can take on different shapes and underlying kinetics (Figure 3).

Note that yields in the yield rehabilitation domain are either attainable yields (on the boundary line encompassing the maximum yields) or lower, based on the nature of the ISFM components used (e.g., inclusion of all ISFM components may result in higher yields than application of sole fertilizer, dependent on the nature of the yield limiting factors). Trade-offs need to be considered between short term gains in productivity and longer-term gains in soil health status, especially since many smallholder farmers are reluctant to take risk and often prioritize short-term benefits (Herrero et al., 2010). Trade-offs between investments in rehabilitation efforts between different plots within a farm that are at different stages of degradation will also be important for inclusion in ISFM recommendations (Nelson et al., 2009).

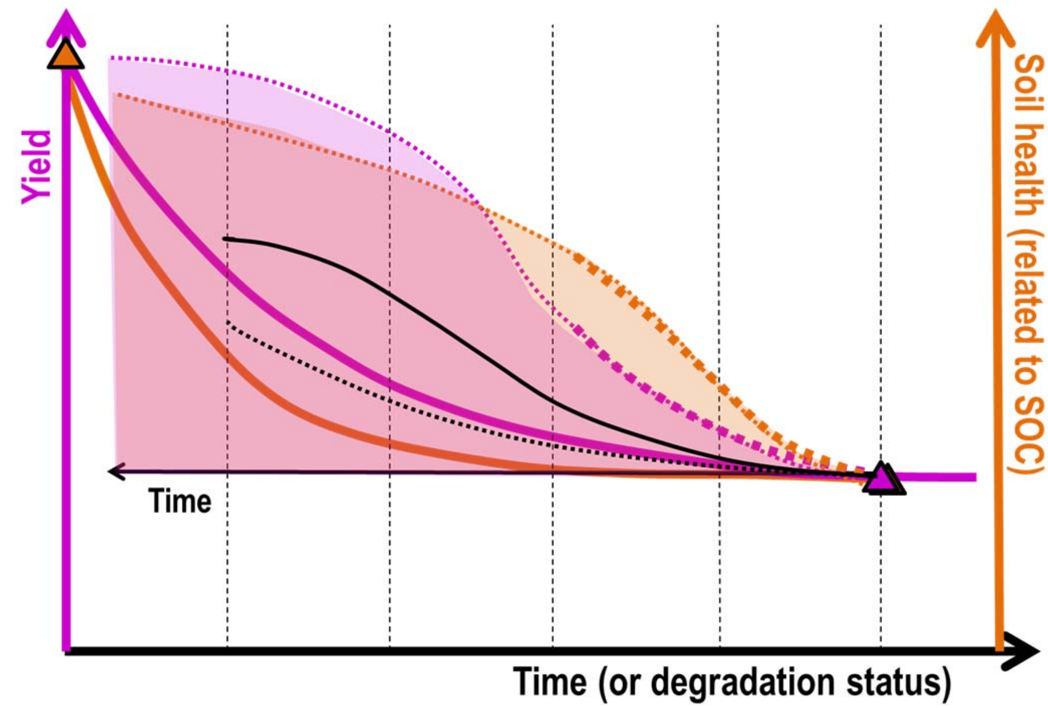

Figure 3: Rehabilitation efforts (brown for soil, purple for yield) are expected to consist of a diverse range of pathways, depending on the exact nature of the degradation processes, the ISFM components and their combinations deployed, and the resources available to farming families. Note that the boundary lines are the best possible scenarios when applying the complete set of ISFM practices. The rehabilitation trajectory followed by a relative poor family that only has limited access to resources, e.g., manure, may rather follow the trajectories in black (full line referring to soil health, dotted line to yield). In presence of minimal rehabilitation efforts, the trajectories may remain close to the 'degraded' yield and soil health levels.

III. Research questions and hypotheses

Based on the above framework, the following 'sustainability questions' form the basis of this strategic document but are not exclusive of other relevant questions:

1. Under which, if any, 'degradation conditions' is ISFM a viable entry point towards the restoration of soil health, including the build-up of SOC?

Possible hypothesis: The ISFM framework provides enough flexibility in the rehabilitation strategies and their relative emphases to address all stages of degradation.

2. Under which, if any, 'degradation conditions' can in-situ practices result in rehabilitating crop productivity and soil health and when is the deployment of external inputs a necessity?
Possible hypothesis: In-situ practices, e.g. cover crops, intercropping, are sufficient in relatively less degraded systems, but external inputs (e.g., relatively high inputs of organic matter, deep plowing, lime application) are necessary to rehabilitate strongly degraded soils.
3. Can ISFM give high and more stable yields that are less sensitive to, e.g., drought stress? How much time is needed for ISFM to provide such stable yields?
Possible hypothesis: ISFM can provide higher and less variable yields in the medium-term even for relatively strongly degraded systems.
4. Which specific ISFM components (or their interactions) are essential to deliver on higher, more stable yields and improved soil health conditions? Or are some ISFM components rather 'optional'?
Possible hypothesis: Not all ISFM components contribute equally to enhanced yields and soil health status, and the relative contribution of these will depend on the degradation status, and the overall set of factors limiting crop yield.

IV. Goal, specific objectives, and expected outputs

IV.1. Goal

The goal of this initiative is to contribute to the knowledge base underlying the SI of agriculture in SSA through a detailed understanding of (i) the sustainability dimensions of ISFM practices in relation to crop productivity and soil health and (ii) the pathways that can result in achieving these sustainability dimensions in relation to actual degradation conditions.

This goal is aligned to the following Intermediate Development Outcomes (IDOs) of WLE:
IDO 1: Sustainable increases in land, water and energy productivity in rainfed and irrigated agro-ecosystems
IDO 5: Increased resilience of communities through enhanced ecosystem services in agricultural landscapes

IV.2. Specific Objectives

1. Entry points: To assess the potential of ISFM to restore crop productivity and soil health along a degradation gradient for a representative set of farming systems x soil type combinations.

2. Sustainability: To evaluate the sustainability/resilience aspects of ISFM interventions for a representative set of farming systems x soil type combinations.

3. Ecosystem services: To evaluate potential on- and off-site ecosystem services delivered by ISFM in the short and longer term.

4. Upstream and downstream partnerships: To deliver knowledge to ISFM dissemination campaigns through networking and provide a set-up for engaging with partners on future research issues in the context of ISFM.

5. Capacity development: To strengthen the capacity of stakeholders in the evaluation and delivery of ISFM interventions to end users.

IV.3. Expected Outputs

The following outputs, amongst others, are expected to be delivered by this initiative:

1. A better understanding of the entry points to soil recovery through ISFM and the specific contributions of the ISFM components needed for rehabilitating degraded soils for the different cropping systems.

2. Identification of ISFM components appropriate for specific biophysical and socio-economic constrains of smallholder farmers and farming systems.

3. A better understanding of the sustainability of ISFM and the aspects that can be adopted for SI in the African cropping systems.

4. Identification of on-farm and off-farm ecosystem services provided by ISFM.

5. Databases, tools, and knowledge that can be used to scale out ISFM approaches within heterogeneous landscapes.

6. Empowerment of farmers and development agents through the development of decision support tools for best management practices based on above findings.

7. Strengthened capacity through postgraduate students (PhD and MSc) training.

V. Research and partnership approach

To address the questions related to the sustainability of ISFM in smallholder farming systems in SSA, a strategic team of multidisciplinary researchers will be formed to set up long-term observatories at multiple locations (Figure 4). These observatories will be established under rainfed conditions in different agro-ecological regions (AEZ) targeting important farming systems, including the millet-sorghum belt in the West-African Sahel, cassava in West and Central Africa, maize in East, Southern and West Africa, and the highland perennial systems in East and Central Africa. Consequently, climatic gradients, in terms of mean annual of precipitation and mean annual temperature will be embedded within the long-term observatories while climate variability over seasons will necessarily be built-in due to the long-term nature of trials. Within above farming systems, important soil types will form a second factor in designing the long-term observatories network.

GIS and remote sensing tools will be used in conjunction with simulation models at the onset to select sites and to design the experiments (Figure 4). GIS can be used to interpolate and extrapolate data, e.g. yield data under different rainfall regimes and using packages such as ARCGIS map and classify areas of different productivity potential. Simulation

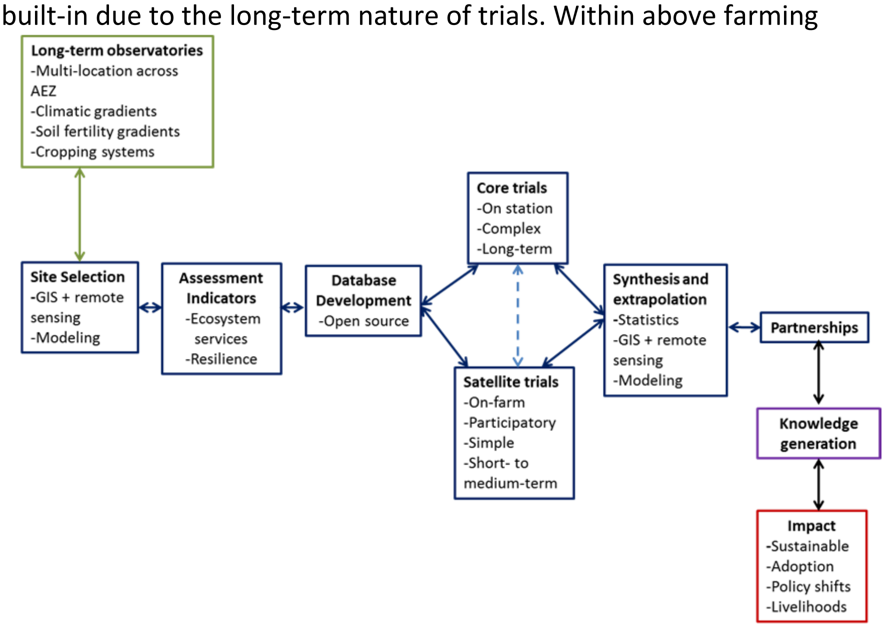

Figure 4: A schematic representation of the strategies and approaches to addressing sustainability of Integrated Soil Fertility Management (ISFM) in Sub Saharan Africa (SSA) through setting up long-term observatories through collaborative research to generate knowledge that will have impact on smallholder farming systems.

modeling will be used for predicting changes under different practical scenarios and hence be used in designing the long-term observatories. Assessment indicators for provision of key ecosystem services and for resilience of the ISFM practices will be selected. An open source database will be developed to provide a platform for the efficient sharing and management of data obtained across the regions.

Core trials will be long-term and near complete factorial designs, comprising of the full suite of ISFM treatment combinations for the different cropping systems (Figure 4). These will be strategically located in the targeted domains (based on farming system x soil types). Satellite experiments will be implemented along soil fertility degradation ranges (Figure 2) within the same cropping system x AEZ x soil type domains and consist of a more simplified design, e.g., using a cumulative inclusion of all ISFM components. Input rates will be related to resources available to different types of farmer families (often equated with farmer typologies). These trials will be conducted to address selected ISFM concerns of the farmers. Farmer feedback will be obtained from the satellite trials to ensure that promising options are also realistic and adapted to farmer conditions.

Information generated from the trials, both core and satellite will be synthesized using statistical tools (Figure 4). The data generated from the core trials will inform on the sustainability and resilience of the different aspects of ISFM whereas data from satellite trials will inform on the short- to medium-term (3 to 5 years) effects of selected aspects of ISFM under the different cropping systems. Such data, particularly from core trials, will feed back into the models, improving the model structures based on long-term observations. Models are essential for extrapolating data to different locations and future climates since it is impossible to establish long-term observatories under all possible scenarios. GIS will be used to interpolate and extrapolate information to other sites with different characteristics.

Partnerships will be drawn from National Agricultural Research centers (NARS), CGIAR, other international development agencies, and universities in and outside Africa (Figure 4). The latter are important for teaching and co-supervision of graduate students, since capacity building is an important component of the initiative. The initiative will draw expertise from multiple disciplines, including soil, crop, and agronomy sciences. Modeling, statistical, and GIS expertise will also be sought. It will also be essential to engage competent field technicians to manage the experiments and judiciously collect and record data. Especially in relation to the satellite trials, economic and social expertise will be engaged to ensure that these dimensions are included in the evaluation criteria of the ISFM components and their combinations. While traditional research approaches have overlooked gender disparities, the proposed project will actively engage women farmers and women scientists in the research activities. This is because women and men have different roles in farming systems with disproportionate access to and control of resources (Gumede *et al.*, 2009). Given the multidisciplinary nature of the proposed core trials, the involvement of different institutions, the evolution of objectives over time and complex local scenarios to contend with, it will be essential for the coordination team to ensure flexibility in the designing of the core trials, which are systematically managed, without compromising their scientific integrity.

The initiative will actively seek to build capacity of young scientists in different disciplines by participating in the research activities (Figure 4). Graduate students and postdoctoral researchers from different universities will be involved in different aspects of the long-term observatories.

These will be involved more in process research utilizing tools such as stable isotopes in field, microplot and incubation studies to study particular processes that are associated with ISFM and its sustainability over time and quantify the contributions of such processes to the functioning of ISFM where possible. The interactions with other technologies such as conservation agriculture will be elucidated by including these in the treatment structure. The process studies will complement the field trials and are important to elucidate the underlying mechanisms associated with ISFM. Lessons from these experiments will provide a scientific wealth of information to be used for promoting sustainable land use management practices that will cushion farmers against emerging global environmental changes.

VI. Methodology

VI.1. Site selection

Site selection for core trials will be guided by farming system x soil type combinations of SSA for the different agroecological zones (Figure 5). Population density influences the need for intensification and thus will be considered in the selection of sites for core trials. For this initiative only areas with population densities above 25 persons km^{-2} will be considered (Lele and Stone, 1989). The soil types are grouped in 4 clusters; soils with limited nutrient stocks and limited profile development (Arenosols, Cambisols, Leptosols, Regosols); soils with poor chemical status (Nitisols, Ferralsols, Acrisols, Alisols); soils with high nutrient status (Lixisols, Luvisols, Fluvisols, Plithosols); and Vertisols which have high base status but limited by physical properties due to shrink-swell properties (IUSS, 2006). Homogeneity tests will be carried out in one or more seasons to establish portions of land with similar yield responses. The satellite trials will be implemented in the same domains as the core trials, but along a soil fertility degradation gradient carried out across different soil types, taking into consideration farmer typologies such as gender and resource endowment. Input types and rates will be varied for the different typologies and along the degradation gradients.

VI.2. Selection of indicators

Key parameters to be monitored in the long-term observatories include crop yield and yield stability, water and nutrient balances, soil biodiversity and soil organic carbon (SOC), runoff and soil losses, soil acidity, and weed and pest dynamics. In conjunction with crop yield, the stability of yields is particularly important for choosing ISFM practices that maintain good yields under the changing and variable climate. This should be coupled with assessments of nutrient balances which give an indication of agronomic efficiencies of the different treatments. Nutrient balances are particularly essential, given that nutrient additions are core to ISFM. Additionally, it is important to ensure efficient utilization of added nutrients while minimizing losses to the environment. For e.g. with N it is important to reduce nutrient loads that end up in water sources to promote aquatic ecology but also to reduce water treatment costs for drinking water. Reducing gaseous losses of nitrous oxide to the atmosphere is important for mitigating climate change.

Soil organic C is important indicator of soil health and provides a measure of sustainability of the ISFM interventions. Some of the measurements e.g. microbial biomass C, provide short-term changes associated with intervention while some e.g. total SOC become more apparent in the long-term. Sampling depth needs to be harmonized across the different sites to allow for cross site comparisons. Enhancing SOC sequestration is a topical issue, for mitigating and adapting to climate change. ISFM should ideally enhance SOC sequestration and thus reduce greenhouse gas emissions and promote the soil to act as a sink of atmospheric carbon dioxide. Soil biodiversity is also an important indicator of soil health and can be used an early indicator of the effects of intervention. Other indicators to be monitored are soil water balance as the long-term observatories are carried out under rainfed conditions, soil acidity, which strongly influences nutrient availability; weed dynamics which exhibit competition for resources with crop plants, and runoff and soil losses. The successful monitoring of these indicators requires careful planning and a thorough initial site characterization so as not to jeopardize future analyses.

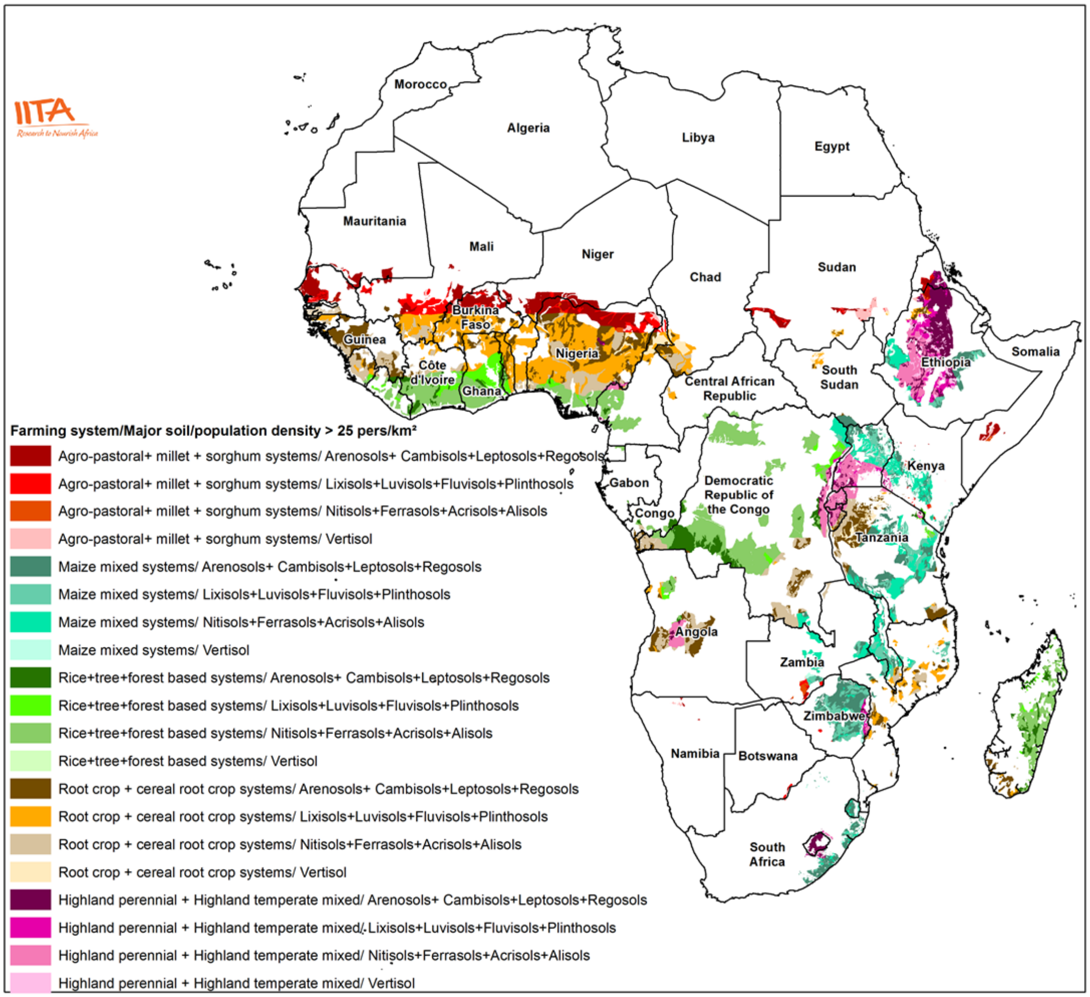

Figure 5: A map showing the target domains considered for areas with more than 25 persons km^{-2}. Domains are defined along combinations of major farming systems and combinations of major soil types (FAO classification). Source: IITA GIS unit.

VI.3. Database development

An open source database will be developed to enhance data and information management as this can play a pivotal role in enhancing agricultural productivity and addressing the problem of food insecurity. Management and analysis of ever increasing research data sets and information have been recognized as key elements of efficient research support. The development of a web-based information system on long-term observatories will be of immense value to researchers, policy makers, educators and extension staff. Such an information system will make available to interested researchers a flexible and adaptable information system able to manage information so as to fit the needs of field trials whilst being simple to use and reliable. The database can be valuable in identifying gaps in research in terms of identifying trends in yield response, gaps in productivity, economic viability of nutrient application, and trends in soil fertility. The tool will be adaptable and open, to encourage the exchange of data between the different stakeholders involved in the long-term observatories. Implementation will follow the Consortium Office's Open Access Strategy, which envisions CGIAR data and information to be easily available, accessed, and applied to improve agriculture-related development outcomes. It will include soils parameters (biological, chemical physical), pests and predators (weeds, insects and disease), crop factors (growth, yield, and quality), socio-economic factors and management practices, and geographical data and weather conditions. The database will enhance capacity building among agricultural researchers in the advanced management of highly integrated information services in support of research, technology transfer and extension. Data will be used by e.g. modelers for calibrating and validating crop improvement and productivity for understanding yield today and making projections into the future. It will provide improved data and information sharing on long-term observatories and provide models on adaptation packages combining the best crop variety with the best soil management technologies and with the most appropriate water management. The database will be linked to Agtrials.org, http://www.agtrials.org/, the information portal developed by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). The portal provides access to a database on the performance of agricultural technologies at sites across the developing world as well as other initiatives such as IITA E-Research platform. This will enable a powerful visualization of trial data across different regions and cropping systems.

VI.4. Core trials

The detailed designs of the core trials will be informed by the specific hypotheses for the different cropping systems. The core trials will be relatively long-term (e.g., > 10 years) and will need to have large plot sizes to allow for repeated soil sampling with minimum destruction. Major trial design considerations including replication, randomization, plot sizes, and research and cost efficiency will be adhered to. Two issues to consider are (a) the block structures and (b) treatment structures. Under block structures, interest will be on the identification or construction of blocks with minimum variation within and high variation across blocks, e.g. an area or site could be a replicate or constitute a complete experiment. The homogeneity of an area will be tested over at least one year, by growing the target test crop while monitoring the yield responses. The treatment structure will be factorial as it is conceived that there will be several factors. However, depending on size and treatment management considerations, treatment structures may be incomplete factorial or could be constructed using stepwise approaches or some form of confounding and augmented schemes may be used. An example of a design of a core trial is given in Table 1 where a local practice is compared with improved ISFM and other components such as biochar, liming, mulching, etc. There will be several design options that may be employed with efforts made to ensure efficiency in the management of the experimental process. Considerations will be made on availability of organic resources, whether produced in-situ or cut and carry.

The long-term rehabilitation prospects of ISFM will depend on the number of components of ISFM deployed and the degradation status of the soil. For example, highly degraded or non-responsive soils require more rigorous rehabilitation measures e.g. high rates of organic inputs before a response to fertilizer or improved germplasm can be observed (Figure 3). Thus, the path to rehabilitation may take a long time to recovery if low quality or low rates of or no organic resources are added to such non-responsive soils. Similar trajectories are faced by resource poor families with limited access to resources, whose soil rehabilitation path will likely take a longer time to recovery (black dotted line; Figure 3) compared to their resource endowed counterparts whose soils rehabilitation pathway will likely be faster and attain greater yields (Purple dotted line; Figure 3). Thus, to gain a full understanding of the pathways to rehabilitation of degraded soils and attainment of sustainability, there is a need to have various interactions between ISFM components in the core trials (to cover the whole spectrum of trajectories under the boundary line).

Table 1: Potential treatment structure of a core trial. Note that the types of inputs and their rates can vary based on specific limitations. Note also that '+' means 'with' and '0' means 'without'.

Variety	Fertilizer	Organic resource	Tillage	Others (e.g. liming)
Local	0	0	+	0
Local	+	0	+	0
Local	0	+	+	+
Local	+	+	+	+
Local	0	0	0	0
Local	+	0	0	0
Local	0	+	0	+
Local	+	+	0	+
Improved	0	0	+	0
Improved	+	0	+	0
Improved	0	+	+	+
Improved	+	+	+	+
Improved	0	0	0	0
Improved	+	0	0	0
Improved	0	+	0	+
Improved	+	+	0	+

A stakeholder meeting will be essential before finalizing the treatment setup for the different cropping systems. Depending on the availability of organic resources, the application rates will need to be practical and achievable. The frequency of application of the organic resources, whether annually or after every so many years will be considered, bearing in mind the labor constraints for smallholder farmers. Considerations for modifying the application rates of the fertilizer and organic resources will be made based on soil fertility observations from two seasons before to ensure that data are available for making the right decisions. Scenarios will be set up and simulated using models to best guide on such decisions.

Management of the trials will be harmonized for similar cropping systems in the different regions. Plant population and timing of operations will be agreed upon. Weed, pest and disease management will necessarily be included in the monitoring and management of the trials. Dynamics of pests and predators will be documented to evaluate potential links with certain aspects of ISFM intervention. From statistics perspectives, guidance on management, including monitoring of trials shall be laid out and strictly enforced through efficient operations tracking system that will be developed (and staff trained appropriately). Standard procedures on measurements shall be developed and applied uniformly. Observations shall necessarily be on long-term (repeated measures) basis. Standard data recording protocol shall be developed with the agronomists, socio-economists, biochemists and soil fertility experts among others. Statistical analyses may include trend (longitudinal) analysis (e.g. time series, repeated measures ANOVA, analysis of variance modeling (including Generalized Linear, Mixed models, with and without covariates and trial-data defined covariance structures on random terms in the model) and others. Meta-analysis or combined analysis will be undertaken to link results from the core with the satellite trials.

VI.5. Satellite trials

Satellite trials will be implemented in the same domains as the core trials, consisting of selected components of core trials. Satellite trials will comprise a minimum set of ISFM option combinations, set along a soil fertility degradation gradient incorporating farmer typologies through choice and rate of application of the inputs. A set of best ISFM practices will be evaluated close to or at the boundary line for land rehabilitation (Figure 2). Augmented block procedures and stepwise or specifically selected treatments will be used (Table 2) following a one farm – one replicate design.

Table 2: Potential treatments structure of a satellite trial, using a cumulative design. Note that for cumulative designs, the sequence in which components are added is crucial towards their success. Note also that '+' means 'with' and '0' means 'without'.

Variety	Fertilizer	Manure	Tillage	Others (e.g., lime)
Local	0	0	+	0
Improved	0	0	+	0
Improved	+	0	+	0
Improved	+	+	+	0
Improved	+	+	0	0
Improved	+	+	0	+

VI.6. Modeling support

Soil-plant simulation models such as APSIM (Keating *et al.*, 2003), DSSAT (Jones *et al.*, 2003), CENTURY (Parton et al., 1987), RothC (Coleman *et al.*, 1997) will be used as a tool to better design the long-term observatories e.g. to determine treatments and rates of nutrient application, planting times, optimal soil sampling frequency. These models summarize our current understanding of the long-term soil processes and the way they are influenced by soil characteristics, climatic factors and management. Thus, they can be used to represent our current hypotheses concerning the dynamics of the soil degradation and restoration processes and hence serve as tools to test these hypotheses against the field data that will be collected in the long-term observatories. The models will also be used to extrapolate trial results to sites with different soils and climates, to longer time periods (trends over longer times and yield stability) and to a future climate. The choice of particular models for a site (or area) will depend on the process(es) expected to be dominant, and the ability of the models to simulate the cropping systems that matter at the site. For sites where water availability is a key constraint, year-to-year variation in the timing of the rains and the occurrence of dry spells typically causes large inter-annual variations in yield, complicating the observation of yield increases over time with soil productivity restoration. Since yield stability is an important aspect of restoring soil productivity, including sites with erratic rainfall, the FAO water productivity model AquaCrop (Raes *et al.*, 2009; Steduto *et al.*, 2009) will be used to better understand the year-to-year variation in observed yield in relation to the rainfall pattern. Scenarios for timing of planting, fertilizer application and weeding relative to the rainfall pattern will be tested. The model does not simulate the long-term soil degradation/restoration processes, but is well suited to predict the occurrence of water stress and its effect on crop yield. AquaCrop can moreover be calibrated to the soil fertility level of a site, and in this way account for possible gradual improvements in soil productivity over time, and its interaction with water availability that varies between growing seasons.

VI.7. Synthesis and extrapolation

The proposed core and satellite trials will be conducted under different agro-ecological regions and on different soil types. Consequently, there is a need to adapt robust statistical analyses procedures for effective synthesis of the study findings. While procedures such as meta-analyses have been mostly used reviewing independent studies (Gurevitch and Hedges, 1999; Rosenberg et al., 2000), such methods will be useful for quantitatively synthesizing data obtained from the proposed studies by statistically comparing results from multiple independent core and satellite trials. Results from individual empirical experimental sites need to be synthesized to extend the inference space across the full array of environmental conditions under which ISFM performs. Meta-analytic procedures will synthesize data from the core trials and provide an intrinsic link on the ISFM components and the conditions under which they best perform. Such analyses are critical for understanding tradeoffs among ecosystem services and implementing best management systems to minimize negative impacts of ISFM compared to soil fertility management alternatives. Meta-analyses are robust and have been historically underused in agronomy to develop evidence-based management options (Dore et al., 2011) but have become the gold standard in medical sciences (van Tulder et al., 2003). This approach has been successfully used to assess changes in SOC stocks following changes of different land use systems (Guo and Gifford, 2002), ecological studies (Knorr et al., 2005) and agronomy (Tirl-Padre and Ladha, 2006; Chivenge et al., 2011; Vanlauwe et al., 2011). Thus, the proposed experimental trials will greatly benefit from meta-analytic procedures for synthesizing the results obtained under ISFM in the different regions under different environmental conditions for the different cropping systems.

The core and satellite trials can only be conducted under a limited set of conditions. In this initiative, results from the ISFM core trials at a limited number of locations will be extrapolated to other sites (with different soil, climate, or management conditions) using models such as DSSAT, APSIM and MonQI coupled to GIS. GIS techniques will allow extrapolation of obtained results to alternative locations and scenarios, thereby permitting the quantification of temporal and spatial variability. Integrating the crop/soil simulation models to GIS provides a powerful tool for synthesizing information about the different components of a system, summarizing results, and extrapolating and scaling-out the results obtained in limited area to other areas at various spatial and temporal scales. The soil-crop models will also be coupled with climate models to run ISFM scenarios for future climates to predict yield responses and changes in soil properties. To achieve this, minimum data sets for model calibration and validation will be obtained from the different ISFM trial sites including daily weather, soil properties, crop yield, phenology and canopy cover, and timing of all management practices.

VI. 8 Partnership arrangements for knowledge exchange

The proposed long-term observatories will involve several institutions in various regions. Efforts will be made to develop strategic alliances that would enable better functioning and collaborative efforts of the team. A meeting will be held before setting up the long-term observatories where all proposed institutions, i.e. respective NARS, universities and other research and development institutions will be represented. Regional coordinators will be selected for east/central, west and southern Africa. For each proposed core site, a coordinator will also be selected. A project log-frame for monitoring and evaluation will be developed and used for checking outputs, implementation of activities, assumptions and any negative effects of the project. For each output, a set of milestones with timelines will be developed. Periodic review meetings will be held to assess progress, reasons for any divergence and strategically adapt the plan to address any emerging issues. Graduate students will be closely mentored and be required to write progress reports periodically.

There is a need to get cooperation and understanding of the research objectives and design of the farmers on whose land work will be done. Since the results from the trials will be beneficial for the whole farming community at a site, meetings will be held with the local authorities and farmers to emphasize the importance of setting up the experiments and coming up with measurable assessments even if it means losing crop yields in parts of their most productive fields. Farmers will be compensated in the event of serious crop failure. Farmer exchange visits, field days and farmer field schools will be held to enhance communication and dissemination of technology to the farmers. The participation of social and policy scientists, and development agencies will be necessary to enable dissemination of information to farmers and to policy makers to effect necessary changes.

VI.9. Capacity building

Postgraduate students, PhD and MSc, and postdoctoral researchers will be engaged at local, regional and European universities to conduct research within the different aspects of the project. Female students will be encouraged to participate. The students will work on specific aspects of ISFM that enhance our understanding of the processed involved, e.g. use stable isotopes as tracers to understand nutrient dynamics under manipulation, or economists to collect intensive data on operations to quantify returns for the farmer. Mentorship will be provided by professors at the Universities, the international scientists and the scientists working at the national agricultural research centres. Efforts will be made to empower innovator farmers to encourage farmer-to-famer extension of technologies through farmer exchange visits, and farmer field days among other activities. Stakeholder meetings will be held to facilitate dialogue among researchers, extension and farmers for effective linkages.

VII. Results framework

Table 3: Measurable activities, outputs and outcomes

Activity	Output	Indicator
Specific Objective 1: Entry points: To assess the potential of ISFM to rehabilitate crop productivity and soil degradation along a degradation gradient for a representative set of farming systems x soil type combinations		

1.1. Hold regional and local stakeholder meetings involving farmers and extension for different cropping systems to determine the ISFM needs. 1.2. Simulate scenarios for several ISFM options across soil types with different degradation intensities using e.g. APSIM 1.3. Formulate the general structure of the experimental designs and setup for the different cropping systems for the satellite trials. 1.4. Formulate the parameters to be monitored and measured. 1.5. Surveying the different areas for selection of sites with soil fertility gradients. Characterization of the sites. 1.6. Setting up satellite trials on soil fertility gradients 1.7. Monitoring and managing satellite trials. 1.8. Data collection, analyses and synthesis into reports.	1.1. Stakeholder meetings held. 1.2. ISFM scenarios simulated and used to develop treatment combinations. 1.3. A better understanding of the entry points to soil recovery through ISFM developed 1.4. ISFM components needed for rehabilitating degraded soils for the different cropping systems identified 1.5. ISFM options adapted to specific biophysical and socio-economic conditions of smallholder farmers in SSA that enhance management of finite soil resources developed.	1.1. Stakeholder meeting reports. 1.2. ISFM options needed as entry points for rehabilitating degraded lands identified and documented. 1.3. Number of trials established. 1.4. Number of farmers participating.
Specific Objective 2: Sustainability: To evaluate the sustainability/resilience aspects of ISFM interventions for a representative set of farming systems x soil type combinations.		
2.1. Holding a stakeholder meeting for determining the treatment structure and finalizing the experimental designs and setup for the different cropping systems for the core trials. 2.2. Using GIS and remote sensing for selecting sites for the core trials. 2.3 Using simulation modeling for determining the treatment structure. 2.4. Formulating the parameters to be monitored and measured in the core trials. 2.5. Formulating and measuring initial characterization parameters for the core trials. 2.6. Collection of soil samples for archiving. 2.7. Planting target test crops in the first season to determine field homogeneity. 2.8. Setting up the core trials for the different cropping systems. 2.9. Management and monitoring the core trials 2.10. Data collection, statistical analyses and syntheses of information.	2.1. Field homogeneity tests conducted. 2.2 Core trials established 2.3. Processes involved in ISFM functioning identified and quantified. 2.4. ISFM aspects that can be adopted for sustainable intensification identified for the different African cropping systems. 2.5. Long-term sustainability of the different components of ISFM identified. 2.6. ISFM technologies that lead to increased crop production identified.	2.1. Number of core trials established. 2.2. Reports on the core trials. 2.3. Number of publications. 2.4. Number of packages of ISFM technologies that increase crop yields developed.
Specific Objective 3: Ecosystem services: To evaluate potential on- and off-site ecosystem services delivered by ISFM.		
3.1. Assessing crop yield responses to and yield stability under ISFM technologies 3.2. Assess nutrient and water balances under ISFM 3.3. Assess soil organic carbon, soil biodiversity 3.4. Syntheses of	3.1. On-farm and off-farm ecosystem services provided by ISFM identified. 3.2. Information on the efficient utilization of limited resources through ISFM developed.	3.1. Number of reports on the ecosystem services under ISFM. 3.2. Number of scientific publications.

	3.3. Yields and yield stability of crops under ISFM documented. 3.4. Nutrient and water dynamics under ISFM quantified. 3.5. SOC sequestration under ISFM quantified in the long-term for the different cropping systems.	
Specific Objective 4: Upstream and downstream partnerships: To deliver knowledge to ISFM dissemination campaigns through networking and provide a set-up for engaging with partners on future research issues in the context of ISFM.		
4.1. Identification of boundary partners interested in sustainable intensification of smallholder agriculture though ISFM approaches 4.2. Identification of information needs from boundary partners 4.3. Production of communication and information tools, adapted to the specific information needs to boundary partners 4.4. Organization of awareness creation and information dissemination activities with partners 4.5. Survey to determine the numbers of farmers practicing ISFM and the components being used.	4.1. Boundary partners interested in sustainable intensification of smallholder agriculture through ISFM approaches identified. 4.2. Needs of the boundary partners documented. 4.3. Communication tools suitable for boundary partners developed.	4.1. Number of boundary partners identified. 4.2. Needs of boundary partners identified. 4.3. The tools of communication developed.
Specific Objective 5: Capacity development: To strengthen the capacity of stakeholders in the evaluation and delivery of ISFM interventions to end users.		
5.1. Translating obtained information into forms accessible to boundary partners. 5.2. Conducting field days, farmer exchange visits, farmer field schools to enhance communication among the stakeholders and to transfer information on ISFM technologies to smallholder farmers. 5.3. Recruiting and training postgraduate students and postdoctoral fellows.	5.1. Brochures and pamphlets on ISFM technologies developed and translated into relevant languages. 5.2. Field days, farmer field schools and exchange visits held. 5.3. Postgraduate students and postdoctoral fellows recruited and trained.	5.1. Number of brochures and pamphlets developed. 5.2. Number of field days, farmer field schools and farmer exchange visits. 5.3. Number of participating farmers. 5.4. Number of MSc and PhD students graduating.

VIII. Implementation strategy

This document presents an overall, SSA-wide strategy, encompassing all major farming systems. It is unlikely that the strategy will be implemented through a single source of funding. That said, the strategy is amenable to modular implementation, provided that the major principles described in this document are respected (e.g., site selection, treatment structures, databases). Obviously, depending on the terms of reference of specific requests for proposals, the level of detail in terms of, e.g., the results framework, partnership arrangements, or budgets, would need to be adjusted.

Secondly, when moving into implementation, the selection of target countries and research teams would need to include practical dimensions in terms of genuine interest, logistics (e.g., long-term accessibility), and availability of a minimum level to technical capacity. Risk assessment and mitigation issues would also need to be considered when making final decisions on sites and team, especially for an effort that requires longer-term commitments. Earlier work on long-term soil management trials has been successfully implemented in Nigeria, Burkina Faso, Niger and Ghana in West Africa, Kenya, Uganda, and Tanzania in East Africa, Cameroon, Rwanda, and Democratic Republic of Congo in Central Africa, and Malawi, Zimbabwe and Mozambique in Southern Africa, noting that these countries are certainly not exclusive of others. The partners will be drawn from National Agricultural Research Systems (NARS), Advanced Research Institutes (ARIs), and Non-Governmental Organizations (NGOs), particularly those that have shown interest in and have had some involvement with ISFM. The engagement of national extension services in all the countries will be essential, to bridge the communication linkages with farmers and for promotion of ISFM strategies among smallholder farmers.

Thirdly, interactions between this initiative and initiatives aiming at setting up metrics and tools to assess these in relation to SI and natural resource management would be essential to ensure (i) that the target indicators in this initiative are influenced by state-of-the-art approaches and tools and (ii) that the information and knowledge gathered is fed back into such initiatives. It is very likely that the long-term observatories will generate substantial interest from other initiatives aiming at quantifying metrics, a theme that's currently very prominent within the CGIAR system and beyond.

Fourthly, efforts will be made to link this initiative with other investments in ISFM and SI. For instance, Makerere University (Uganda), Kwame Nkrumah University (Ghana), and the University of KwaZulu-Natal (South Africa), have, with the support of AGRA, been involved in projects to train African students in agronomy and soil fertility management. Several universities in Europe and USA have also been involved in training African students in food security-related aspects. Taking advantage of such linkages will enhance the success of the current initiative. AGRA is also facilitating country-specific soil health consortia within which this initiative should operate. These consortia assemble the various stakeholders interested in accessing information on and promoting improved soil management practices. Various investments from the Bill and Melinda Gates Foundations on soil health would benefit from information gathered in this initiative and effective collaboration with these would also ensure that knowledge generated would reach many beneficiaries in SSA. Interactions with existing soil management networks (e.g., the African Network for Tropical Soil Biology and Fertility (AfNET), facilitated by CIAT and the Soil Fertility Consortium for southern Africa (SOFECSA), facilitated by the University of Zimbabwe) will also be crucial for team formation and information dissemination.

IX. Budget notes

While it is difficult to provide detailed budget estimates due to the uncertainty about the final scope of this initiative and the varying costs for staff, supplies, and coordination between various countries in SSA, some important budget components would need to be considered at the level of the overall initiative, the participating countries, and the individual observatories.

Overall initiative

→ Project leadership: Once this initiative becomes operational at scale, overall project coordination would be needed, including technical and financial support staff. Support for travel and consultancies (e.g., biometrics) would also be required.

→ Planning and evaluation meetings: Regular meetings would be required to address common issues, evaluate progress, and take major decisions on the way forward, amongst other.
→ Partnerships: Funds would be required for exposing information generated to the international research and development community. Interactions with other initiatives would also require travel and communication support.
→ Engagement of ARI partners: Support would be required to seed active engagement from ARI experts interested in soil fertility management issues. Such support could consist of travel support to planning meetings, consultancies for specific activities, and PhD/MSc student facilitation.

Participating countries
→ Technical supervision: Within participating countries, technical coordination and support staff would be required to ensure a smooth implementation of the program. Such staff would require support for transport, consumables, computing equipment, and regular interactions.
→ Data collection and transmission: Funds would be required for data collection and transmission (e.g., tablets) and shipment of soil and plant samples for analysis.
→ Capacity building: Within-country capacity building is a crucial component of this initiative and funds would be required for local or regional PhD/MSc training programs.

Individual observatories
→ Trial establishment and management: Funds would be required for setting up and managing the core and satellite trials. A core trial could costs between 5,000 and 8,000 USD per season while a satellite trial could cost between 1.000 and 3,000 USD per season, depending on local costs for labor, transport, and inputs.
→ Analyses: This initiative will require a substantial investment in soil and plant analysis. While it is difficult to give specific ranges, this is likely going to attract another 50% of the costs of a respective core or satellite trial.

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