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Enhancing Soil Carbon in East Africa

The biophysical evidence, socio-economic incentives, and policy implications

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BMZ Federal Ministry for Economic Cooperation and Development

KALRO Kenya Agricultural & Livestock Research Organization

KIT Karlsruher Institut für Technologie

SLU Swedish University of Agricultural Sciences

EIAR Ethiopian Institute of Agricultural Research

University of Nairobi

Addis Ababa University

CGIAR

Research Program on Water, Land and Ecosystems

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I. Executive Summary

Soil is the largest carbon sink in the terrestrial biosphere and directly affects the global carbon cycle. Anthropogenic greenhouse gas (GHG) emissions drive global climate change and negatively impact the carbon cycle. The two most common GHGs, carbon dioxide and methane, both contain carbon (Center for Climate and Energy Solutions 2015). Physical disturbances to soil and other carbon sinks cause concomitant to release these carbon-based GHGs into the atmosphere. Every year, 24 billion tons of topsoil—which generally contains the most carbon and is the most fertile of all soil layers—is irreparably displaced by wind or water erosion (GIZ 2014). Such soil degradation drives both climate change and the loss of agricultural lands. Agricultural practices aimed at reducing disturbance and sequestering soil carbon, such as conservation tillage and cover crops, help prevent soil degradation and the release of GHGs into the atmosphere. As such, the agriculture industry has an important opportunity to manage soil organic carbon for improved food security, climatic risk resiliency, and climate change mitigation.

Soils are actively formed from organic materials, mineral particles, air, and water. Soil organic matter (SOM) is made of dead organic material at various decomposition stages and is an essential component of plant growth. It contributes to soil aggregate stability and nutrient and water holding capacity. Soil organic carbon (SOC) refers to the carbon content of SOM. Increased SOM equates to increased SOC, and both are indicators of healthy soil (Namirembe et al. 2020; Tessema et al. 2020). The SOM content of an agricultural topsoil typically ranges from 0% to 6%, and it takes 3 to 10 years to accumulate 1% SOM (Whitney 2018; Magdoff and van Es 2010). In general, for every 1% increase in SOM, there is a correlated crop yield increase of 12% (Magdoff and van Es 2010). SOM is often the first part of the topsoil to be lost since organic matter particles are lighter and more easily carried away by wind and water than the mineral components. In some soils, the loss of a few inches of topsoil can result in a 50% yield reduction (Magdoff and van Es 2010).

Soil best management practices (BMPs) are economically viable and support agricultural resiliency, environmental mitigation, and food security. Minimizing soil carbon losses contributes to carbon sequestration and reduces GHG emissions while providing numerous benefits to farmers. SOC is foundational to fertile productive soils, which are in turn critical to global food security (Figure 1). Agricultural practices play a critical role in the soil's chemical, biological, and physical condition. Ideally, organic matter inputs and decomposition rates are in balance, or steady state (Piikki et al. 2019). Many factors influence the achievement of steady state, including farm

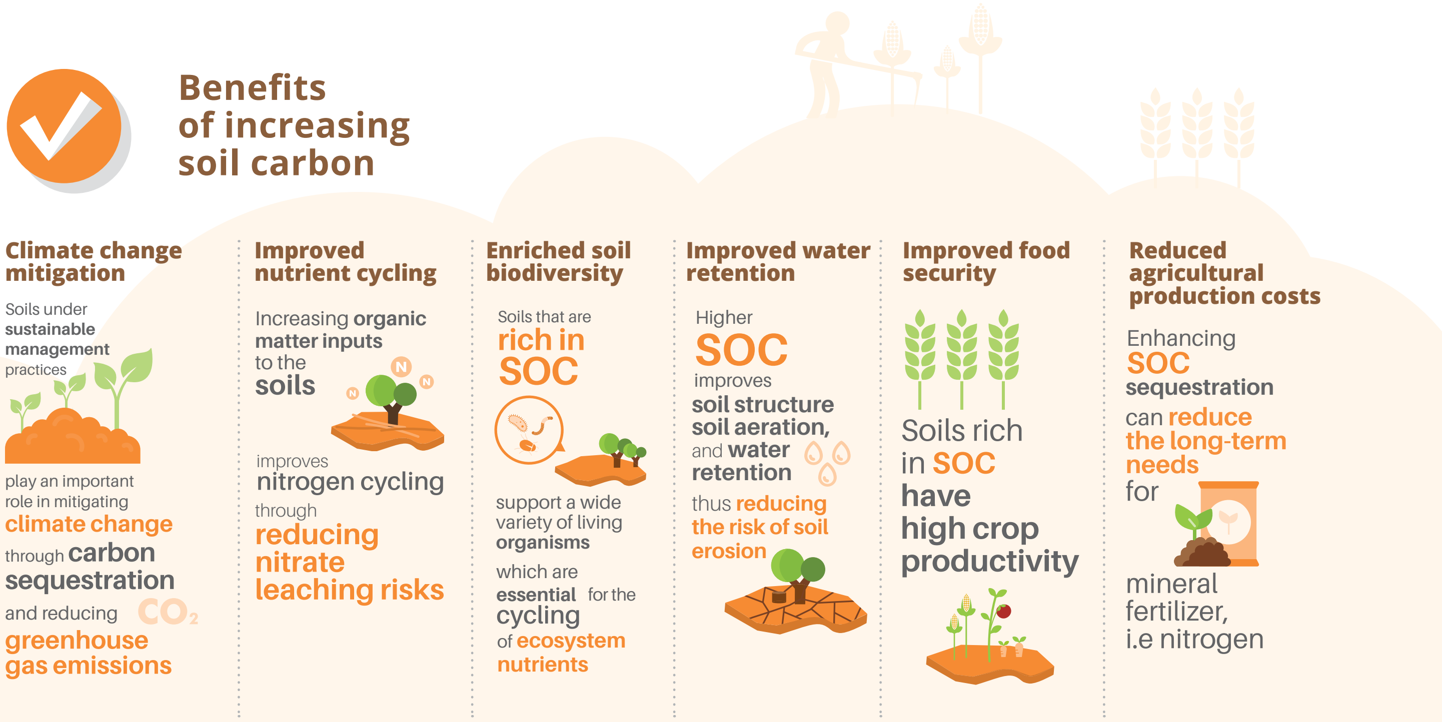

Figure 1. The benefits of soil carbon sequestration from farm to global levels (Nyawira et al. 2019).

management practices, soil type, and climate (Abera et al. 2021; Abegaz et al. 2020). Increased SOM, and hence SOC, reinforces nutrient cycling and reduces nutrient leaching. SOM also decreases the risk of soil erosion by improving soil structure, aeration, and water holding capacity. As SOM increases, long-term reliance on mineral fertilizers declines and soil biodiversity is enhanced (CIAT 2020). Resiliency of both the soil and the overall farm during weather extremes is directly linked to SOM. Healthy soils also support farm productivity, which in turn supports food security for both the farm family, through consumption of their harvest, and the broader community, through crop market sales. SOM and SOC also support the health of the biosphere; if global SOC increased by 0.4% annually, anthropogenic GHG emissions would significantly decline (4p1000, 2018).

Soil carbon BMPs enjoy broad international development support. Several initiatives have engaged stakeholders across the food value chain, including private sector actors, in soil carbon BMPs. Launched by the French government, the 4 per 1000 Initiative is an international partnership between voluntary stakeholders of the public and private sector. The initiative works to mitigate climate change and support food security by combating land degradation and fostering agricultural climate adaptation (4p1000 2018). The Food and Agriculture Organization of the United Nations created the Global Soil Partnership (GSP) in 2012 to foster an interactive collaboration of stakeholders, ranging from landowners to policy makers. The group focuses on improved governance for sustainable soil management, including stabilizing global SOC and restoring degraded soils (FAO 2020). The Soil Protection and Rehabilitation of Degraded Soil for Food Security (ProSoil) is a project administered by The German Agency for International Cooperation (GIZ) that aims to conserve soil and improve food security (Box 1). To date, ProSoil has protected 166,000 hectares of soil, increased smallholder production by 40%, and improved food security for 1.8 million people. The project will continue in select countries through 2025 (GIZ 2014).

These international soil projects operate worldwide and may play a key role in attaining multiple development goals in East Africa. Low adaptive capacity and reliance on climate-dependent agriculture makes Africa one of the most vulnerable global regions to climate change (Chere 2019). East Africa, including Kenya and Ethiopia, is characterized by eroded, low-fertility soils; low yields and land degradation are widespread (Chere 2019; Birnholz et al. 2017). Farming systems are typically rainfed and directly depend on climatic conditions, implying high exposure to climate change. Subsistence farming is the main source of food and income for 70% of the Kenyan population and 85% of Ethiopia's population (Chere 2019; Birnholz et al. 2017). Improved soil health for food security and climate change mitigation can thus bring marked sustainable improvements to East African livelihoods and food security. International efforts are advancing soil health agendas and there is strong scientific consensus that BMPs have significant impacts on SOC levels. BMPs mitigate SOC losses (Sommer et al. 2018; Nyawira et al. 2021), and in some East African cases, BMPs may even increase SOC levels within a decade (Abegaz et al. 2020; Namirembe et al. 2020; Abera et al. 2021).

BOX 1: PROSOIL KENYA

Smallholder farmers in Kenya's densely populated western region suffer from lower agricultural productivity and resulting food insecurity caused by land degradation. Crop yields have stagnated despite increased use of mineral fertilizers, hybrid seeds, and pesticides, primarily because smallholders are unable to access external inputs for improving soil fertility and productivity. To address soil conservation, the GIZ-led Soil Protection and Rehabilitation (ProSoil) programme in Western Kenya employs a participatory planning, implementation, and monitoring program aimed to enhance Soil Protection and Rehabilitation (SPR) measures in collaboration with stakeholders at all levels. The 18-month programme activity prioritizes micro-catchment areas where farmers can link soil protection and water retention measures from on-farm activities to measures conducted along off-farm riverbeds and slopes. ProSoil's implementing partners sensitize farmers to conservation agriculture techniques while concurrently collaborating with Water Resource User Associations (WRUAs) and farmer groups to include SPR measures in their management plans. The program is designed to engage key actors in efforts to improve soil rehabilitation and protection aimed to achieve higher yields and productivity for farmers (GIZ 2014).

Policy measures can help decrease SOC losses and increase successful SOC sequestration by addressing BMP implementation gaps. Despite their significant promise, adoption of BMPs is low, and several barriers exist in the implementation process. A lack of policy measures and infrastructure make knowledge dissemination difficult. Short political cycles and the drive for rapid outputs exclude soil protection measures from governmental budgets. Farmers need tools and information to support the BMP adoption, yet the initial cost of some services is alone enough to cause farmers to decide against adoption. Widespread lack of access to markets, information, and technical assistance further hinder BMP implementation. National policies that combine SOC sequestration goals across institutions can help reverse these trends. Expanded funding for geospatial mapping, mechanistic modelling, and long-term research to evaluate BMP impacts on SOC levels would support further refinement of optimum practices. Carbon markets create value when they are accessible to smallholder farmers. Farmer incentives can help offset the costs of BMP implementation, long-term maintenance, and grappling with minimal infrastructure and market access. Land tenure security, institutional capacity, farmer support networks, and weather information systems are foundational to farmer investments in their land.

II. Biophysical Context for Enhancing Soil Carbon in East Africa

Extreme regional climatic variability is a hallmark of the global climate change phenomenon. This is especially problematic for economies that rely on rain-fed agriculture. Ethiopia, for example, has recently experienced widespread crop failures and food shortages due to drought and a lack of agronomic infrastructure (Chere 2019). Water shortages instigate the loss of livestock, pest and disease outbreaks, and land degradation. In other regions, floods, heat waves, and high winds bring similar crippling damage to smallholder farmers. The impacts on the agricultural sector ripple outward to perpetuate cycles of poverty, hunger, and under-development.

Robust soils increase farm resiliency in the face of weather extremes. Organic matter makes soils more adaptable to climate change. High SOC levels are associated with improved soil structure and better water holding capacity, which in turn helps cushion crops from drought. Living or dead plant matter atop the soil insulates it from temperature extremes and sunlight, further supporting moisture retention. This organic matter layer also protects the soil from the impact of high winds and deluges, thus reducing soil erosion (4p1000, 2018).

There is strong scientific consensus that management practices that integrate conservation agriculture and ecological principles have significant impacts on SOM and SOC stocks (Korir 2020; Ma et al. in draft) (Figure 2). Scientific debate continues as to the amount of SOC sequestration agriculture can provide. It is clear that agronomic practices can mitigate climate change by reducing SOC losses, even if they do not go so far as to offset global anthropogenic GHG emissions (Sommer et al. 2018; Nyawira et al. 2021). Localized BMPs for East Africa in particular have demonstrated that it is agronomically possible to reduce losses, or in some cases, even increase SOC levels within a decade (Namirembe et al. 2020; Nyawira et al. 2021; Sommer et al. 2018). If maintained, these BMPs will continue augmenting SOC levels for an additional 10-20 years (4p1000, 2018; Abera et al. 2021). BMPs can even help restore lost carbon stock from land use conversions (Abegaz et al. 2020; Namirembe et al. 2020), improving soil health indicators and nutrient availability in the process (Korir 2020).

Beyond climate change mitigation, avoiding soil carbon losses or sequestering additional soil carbon offers a multitude of benefits for East African farmers. Soil carbon BMPs have widespread biophysical and socioeconomic value. For example, there is a positive correlation between SOC levels in the root zone and crop yield (Namirembe et al. 2020). Increased yields, in turn, strengthen food security and enhance livelihoods; these important co-benefits help create compelling arguments for enabling policy in the soil carbon sequestration policy arena.

Tools and information are key to adoption of BMPs at scale. Decision makers equipped with tools to predict and measure SOC stock

MANAGEMENT	FUNCTION
Conservation tillage practices	Reduce soil disturbance and respiration from the soils.
Crop residue retention	Increases organic matter inputs and soil nutrients, promotes soil water retention and reduces soil erosion.
Cover crops and crop rotation	Cover bare ground during planting seasons, reduce erosion and prevent nutrient losses through leaching and runoff. Improve SOC through increasing above- and below-ground vegetation biomass.
Fertilizer application	Improves the soil nutrient to maintain high crop productivity, which directly enhances SOC through increased biomass inputs.
Manure and compost application	Enhances nutrient supply to improve the health of crops and soils. Organic amendments improve soil structure and the water holding capacity in soils.
Intercropping	Intercropping cereal crops with legumes allows the crops to benefit from the nitrogen that is fixed by legumes. This increases crop production and enhances SOC through more above- and below-ground biomass transfer to the soils.
Agroforestry	Incorporation of trees in agricultural systems increases the above- and below-ground organic matter inputs. Trees reduce soil erosion, enhance soil water retention, and increase the organic matter inputs to the soils.

Figure 2. Examples of common soil best management practices (Nyawira et al. 2019).

are better prepared to support effective e.g., land use management, agricultural services, and climatic hazard preparedness. For example, the Global Soil Data Manager (GSDM) tool (Box 2) offers policymakers and extension officers data regarding priority areas for SOC management (CIAT 2019). Similarly, the Soil Organic Carbon App (Box 3) is an open access app that supports end user land management decisions by calculating the amount of SOC in a soil profile and the potential impact of a given agricultural practice on sequestration across time and geographic scales. Mechanistic modelling tools have also proven useful in predicting BMP suitability, risks, and implementation options (Nyawira et al. 2021; Ma et al. in draft; Abegaz et al., under review). Model simulations with different scenarios can be used to predict and assess the effects of large scale interventions on SOC in smallholder farming systems (Figure 3) (Ma et al. in draft). Using these model results, a new on-line tool has been developed to provide high-level summaries of soil carbon benefits that can be achieved from different agronomic management practices across broad agricultural landscapes in Kenya and Ethiopia (Box 4).

Understanding current and potential SOC levels is crucial to instituting optimal climate change mitigation measures and policies. While the ultimate goal of BMPs is to sequester SOC, this is not always achievable; in this cases, reducing or avoiding SOC losses still offers substantial benefits (Nyawira et al. 2021). For example, one assessment of smallholder management practices impacts on SOC levels

BOX 2: THE GDSM TOOL

Spatial soil datasets, also known as digital soil maps, are a valuable and underused resource that provides crucial information for national-level agricultural decion making. The Global Soil Data Manager (GSDM) application is an open-source online tool that allows users to access, assess, and improve local areas of open continental and global soil datasets for Africa. GSDM's interface enables optimization of soil sampling campaigns based on spatial variation of soil properties and information availability. Users can also upload local data sets to validate and enhance the maps' accuracy (principles described in Nijbroek et al. 2018; Söderström et al. 2017). The GSDM was developed by The Swedish University of Agricultural Sciences (SLU) and the International Center for Tropical Agriculture (CIAT) under the auspices of CGIAR Research Program on Water, Land and Ecosystems (WLE). The GSDM can be accessed at: gsdm.online

BOX 3: SOC APP

The Soil Organic Carbon (SOC) App is an open access calculation and visualization tool developed by CIAT with support from CGIAR and GIZ. The app calculates a soil's ability to sequester carbon by estimating the amount of sequestered organic carbon (tons/hectare) within a given soil profile and the quantitative impact of soil conservation management practices on sequestration over time and at different scales (Sommer et al. 2015). The platform enables users to visualize the organic carbon content of a soil of their choice. This information is key for decision makers aiming to assess the degree of efficiency with which planned degraded land restoration efforts will enhance SOC content and, concomitantly, mitigate climate change. The SOC App provides outputs for understanding the magnitude of SOC sequestration that can be achieved through various conservation agriculture practices under differing variables. Such a toolset is critical for knowing how and where measures can be taken to increase SOC in sufficient quantity (e.g., 0.4% per year globally) to offset carbon emissions and mitigate climate change. The SOC app is available at https://wle.cgiar.org/solutions/soil-organic-carbon-app

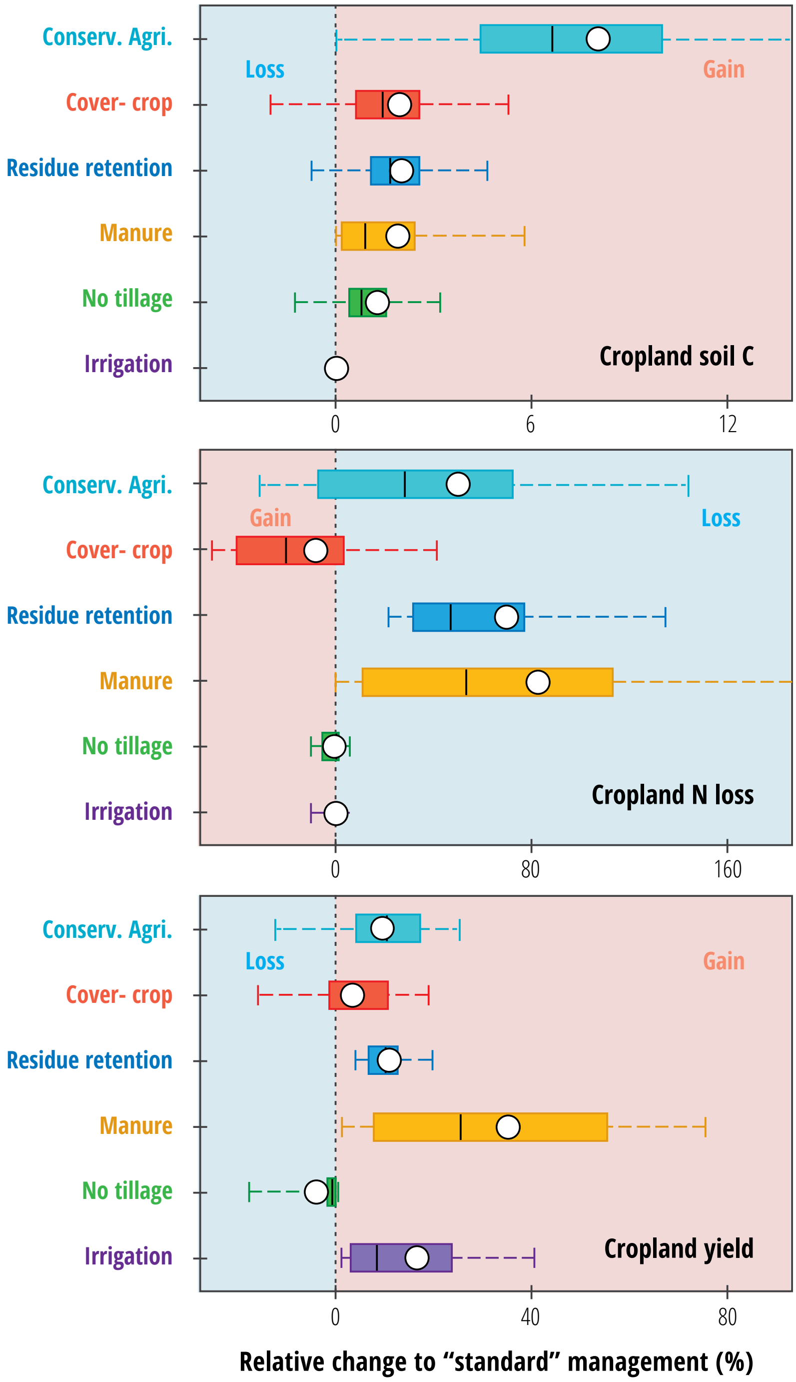

Figure 3. Examples of modelled relative responses of SOC, nitrogen loss (gaseous and leaching), and yield to various management options averaged over cropland areas in Ethiopia and Kenya (Ma et al. in draft). *Statistical box denotes the 25th and 75th percentile; whiskers represent the 5th and 95th percentile; white dots indicate the average.*

BOX 4: DASHBOARD TOOL FOR EXPLORING MANAGEMENT SCENARIO

A new on-line tool has been created to provide high-level summaries of soil carbon benefits that can come from the adoption of different practices across broad landscapes. This information is based on a modeling process designed to understand large-scale adoption of improved crop management practices, geographies, and input dataset description. Users of this tool can explore the spatial maps spanned across Ethiopia and Kenya, then select specific management practices and examine the impact of those management practices on keys outputs such as soil organic carbon, nitrogen leaching, and crop yield. The spatial outputs are available at ~10 km resolution grid cells and estimated for the year 2030 based on information from climate models. Users also have options to download summary tables, maps, and original modeling output. Additionally, a coarse-scale cost-benefit analysis (CBA) that presents the relative increase in cost associated with specific agriculture practices and how much benefit in yield can return over the time horizon of analysis, accounting for discount and exchange rate. The tool can be accessed at https://agbiogeo.shinyapps.io/crop_manage_lpjguess/

and overall potential for further soil carbon sequestration found that, in the absence of BMPs, minimal carbon inputs in a continuous cropping regime caused SOC to decline. When BMPs were adopted, SOC losses slowed, stopped, or even reversed (Abegaz et al. 2020; Korir 2020). In another study in highlands of Ethiopia, conservation agricultural practices such as reduced tillage catalysed SOC sequestration in agricultural lands (Abera et al. 2021).

A novel approach of estimating achievable SOC sequestration in Ethiopia and Kenya is helping to provide insights into targeting interventions by soil texture. This approach uses the boundary plane model, which accounts for soil texture and SOC, to make realistic assessments of achievable SOC sequestration under current technical and agronomic conditions in the area of interest (Piikki et al. 2019). The result is *target SOC*, the maximum amount of SOC sequestration given certain conditions, and *achievable SOC*, the difference between current and target SOC (Figure 4) (Piikki et al. 2019). Farmers currently below achievable SOC have high potential for increasing sequestration with targeted management practices. The boundary plane approach assessed the achievable SOC sequestration that can be attained without major changes to farming systems. The boundary plane model can also be used to map soil sequestration hot spots—that is, the potential geographic areas where the greatest SOC increases can be attained.

The Sustainable land management program (SLMP) of Ethiopia has had positive impacts on SOC sequestration, and there remain opportunities to further enhance sequestration. A random forest machine learning model was applied by extending the boundary plane model to consider soil, climate, and topographic information. This enabled researchers to estimate SOC sequestration status as a result of sustainable land management practices (Abera et al. 2021). The study identified spatial hotspots of achieved SOC sequestration, target SOC, and achievable SOC via SLM practices. Achievable SOC sequestration potentials were then spatially modelled and mapped to facilitate land management targeting to reach achievable SOC at the landscape level. The highest SOC is obtained by leveraging a combination of physical, e.g., bunds or terraces, and biological interventions.

Realistic targets for climate mitigation are informed by appropriate BMPs and an understanding of SOC levels. CIAT compiles an ongoing, open access list of 'Soil Best Bets' BMPs that defines and explains the methodology and technology needed for implementation (CIAT 2020). These practices are evaluated against several parameters, including resource requirements, tradeoffs, effectiveness, and climate change adaptation. Users can make comments and add new BMPs. This compilation supports farmer and extension agent learning and discussion in an open forum across a variety of crops. Information access and knowledge sharing, together with tools, support the implementation of optimized soil carbon sequestration practices.

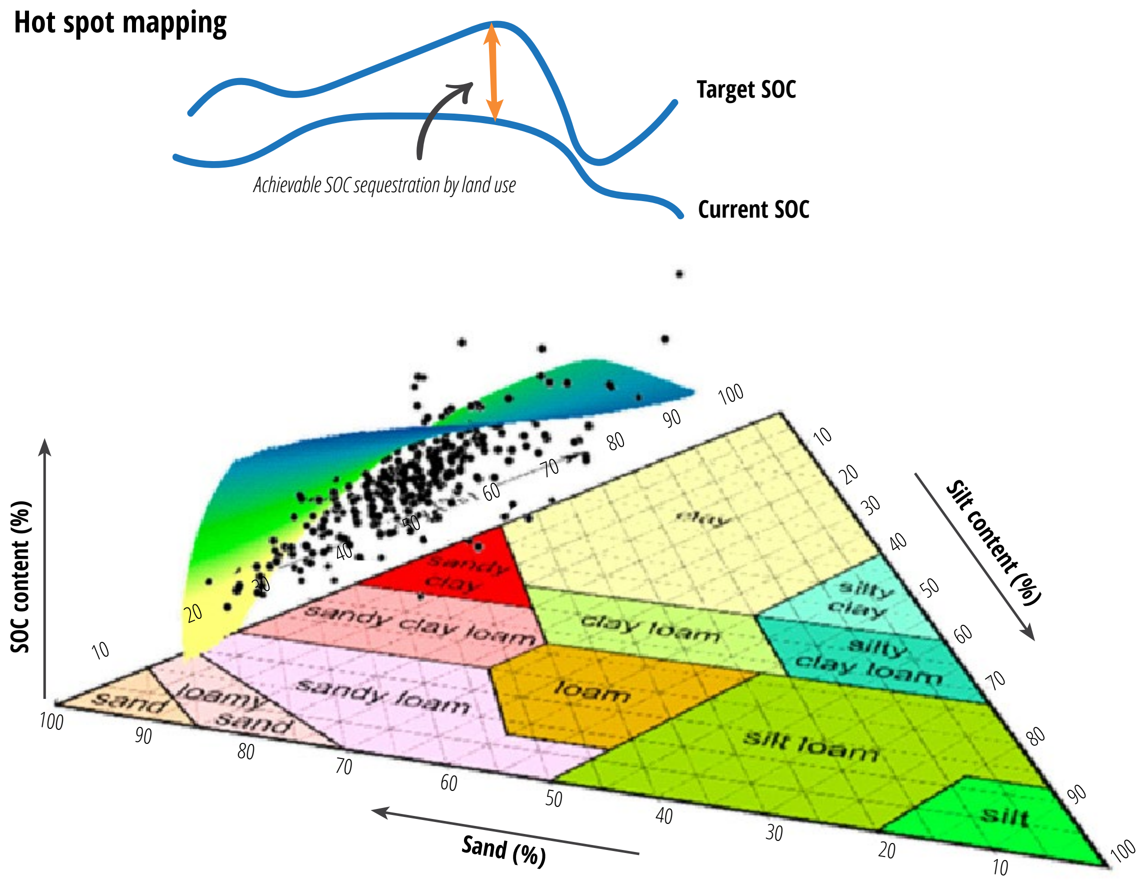

Figure 4. The SOC sequestration that is achievable without changing production system and land use is the difference between the modelled target SOC content and the current SOC content (Piikki et al. 2019).

III. Socioeconomic Opportunities and Barriers to Soil Carbon BMP Adoption

Soil carbon BMPs offer clear advantages to farmers as well as the national community at large. East Africa, for example, would benefit greatly from efforts to support soil carbon BMPs. Land degradation and low SOC stock are prevalent throughout the region. Where BMPs have been implemented, they are often only partially or incorrectly practiced, such that full potential benefits remain unrealized; nevertheless, adoption rates have been slow, particularly in diverse developing agricultural landscapes such as those of Ethiopia and Kenya (Ng'ang'a et al. 2019a).

Farmer household diversity and the site-specificity of BMP gains make streamlined recommendations and policies difficult. Significant variations in farmer household age, gender, and resource access, as well as farm size and land use, among other factors, challenge universal BMP implementation. Research to date shows mixed results for any one BMP, suggesting that the benefits are highly site-specific and that technical information and research findings are thus not necessarily transferable from one community to the next; environmental, cultural, and historical factors could also play a role (Ng'ang'a et al. 2019b). While some costs of BMPs are known, family labour and in-kind household contributions are very difficult to quantify and thus often remain unaccounted in studies. Long-term research profiling which BMPs hold the greatest potential for which areas is the best bet for addressing this challenge.

Farmer access to resources and perception about BMP benefits heavily influence adoption decisions (Ng'ang'a et al. 2019b). Most soil BMPs have an initial upfront cost and do not offer returns on investment for multiple years. Livestock holdings, farm size, market access, land tenure stability, and access to extension services all affect a farmer's BMP adoption decision-making (Ng'ang'a et al. 2019b). Risk-reducing mechanisms, including farm credit access and off-farm income sources, are in many cases the primary predictors of BMP adoption (Ng'ang'a et al. 2019b). On the other hand, unstable land tenure, poor access to financial credit, and a lack of practical technical information make effective BMP implementation nearly impossible. Farmer age, gender, and education heavily influence farmers' access to these resources. For example, systematic discrimination means most women farmers have smaller plot sizes, less tenure security, poorer extension access, and weaker credit as compared to men farmers (Ng'ang'a et al. 2019b). The implementation of BMPs is therefore likely to be less feasible and riskier for women heads of household.

Many of the factors that enable or constrain BMP adoption can be predicted with geospatial mapping. There is a significant correlation between the physical distance from farm to resources, including markets, credit, and extension services, and likelihood of BMP adoption (Maina 2020). The closer a farm is to these essential services, the more likely the farmer is to adopt BMPs. This implies that regional connective infrastructure, including roads and public transportation, would enable agricultural BMPs. Similarly, physical proximity of (and membership in) a local cooperative or farmer group improves access to the information, technical skills, and inputs needed to support BMPs (Maina 2020).

IV. Policy Perspectives and Recommendations

Ethiopia and Kenya have extensive land degradation that has reduced SOC, limited agricultural production, and even brought on famine (Omiti et al. 2021). Historically, policymakers and development agencies have focused on improved land management strategies, such as soil and water conservation, to battle degraded soils and improve food security. Projects funded by governments and international development agencies often lack institutional cooperation and coordinated objectives. These competing interests preclude national-level alignment, further challenging local implementation.

Today, soil carbon is viewed as a public good and a community development issue. Land degradation and soil carbon loss are closely intertwined and are treated as a one-in-the-same issue by governments and the international community. The close relationship between land health and soil carbon has allowed for the creation and strengthening of policies on a tangible environmental issue that also directly support far less visible GHG mitigation measures. For example, the United Nations General Assembly adopted soil carbon as a Sustainable Development Goal (SDG) in 2015 with the goal of attaining land degradation neutrality at the international level by 2030 (Omiti et al. 2021). Both Kenya and Ethiopia have ratified and domesticated all international agreements on climate change and soil carbon (Omiti et al. 2021), and soil carbon will be important in supporting these countries in achieving their UN Framework Convention on Climate Change (UNFCCC) Nationally Determined Contributions (NDC) targets to reduce greenhouse gas emissions and adapt to climate change impacts. Several ongoing international projects support these policy priorities in Ethiopia and Kenya, including ProSoil and the Sustainable Land Management Program (GIZ 2016) (Box 5).

Analyses of past policy, research, and development interventions shed light on promising options for achieving broader success within East African soil carbon policy. Land tenure has a varied past in East Africa, and land insecurity creates resistance to long-term investments in land health (Omiti et al. 2021). Given that soil BMPs have return periods of 10 to 30 years, policies that offer farmers land tenure security would directly increase soil carbon BMP adoption rates. Cross-institutional policy alignment is another strong predictor of effectiveness. Coordination across environmental, sustainable development, food security, and other relevant national policy in terms of soil carbon BMPs will help reduce bottlenecks and conflicting messages to the agricultural sector, offer synergistic strength to institutions, and even remove budgetary barriers. In Kenya and Ethiopia, integrating SOC into the carbon market

BOX 5: SUSTAINABLE LAND MANAGEMENT IN ETHIOPIA

Burgeoning population density and land conversion are amplifying Ethiopia's pressure on natural resources. Lowland grazing fodder and agricultural soil productivity have been particularly affected. Land degradation and erosion, coupled with changing climate, threaten food security and stability in the region. The European Union Support to the Sustainable Land Management Program aims to promote natural resource conservation while strengthening livelihood activities via a three-pronged approach: (1) scale-up and adopt sustainable land and water management technologies, (2) strengthen capacities, knowledge and skills of key stakeholders involved in sustainable land management, and (3) implement effective program management and coordination from federal to district levels. EU Support to SLMP targets 33,000 households in the rural communities located adjacent to the Bale Mountains National Park and the Yayu Forest Biosphere Reserve in Oromia region. These eco-regions house watersheds with high natural capital, and are particularly threatened by livestock movement and other anthropogenic activities. The program supports the national SLMP development and environmental goals to improve the livelihoods, food security, and economic well-being of the country's farmers, herders, and forest resource users and restore Ethiopia's eco-system resources (GIZ 2016).

and establishing a new national carbon value chain may be particularly fruitful in this regard. Transparently outlining carbon credit assessment methods, pricing, measurement, reporting, multi-step verification, and payment systems will significantly support the success of such an initiative (Omiti et al. 2021). An international support network of countries where carbon markets and carbon value chains are already monetized could support the early success of such efforts in Kenya and Ethiopia. For example, the Kenya Agricultural Carbon Project (KACP), launched by the World Bank's BioCarbon Fund in 2009, coordinates a local carbon market for 30,000 smallholder farmers in Western Kenya (Kenya Agricultural Carbon Project 2020).

Both short-term and long-term policy measures are needed to address the immediacy of the issue and the length of time it will take to reach achievable goals. Food security, crop productivity, and climate change are issues of today, and tangible gains can be realized in a few seasons of soil carbon BMPs. At the same time, it can take a decade to centuries after BMPs are implemented to attain a steady state of SOC (Namirembe et al. 2020; Piikki et al. 2019). It takes decades of data to hash out the impact of management decisions from those of environmental conditions and natural soil dynamics. Maintaining resource-intensive BMPs for decades can be prohibitively expensive to farmers and research stations without the promise of financial support (Namirembe et al. 2020). As such, both decisive policy action and decades-long commitments to the research and farming communities are key to a successful paradigm shift toward effective soil carbon BMPs (Abegaz et al. 2020). Policy commitments to long-term research enable robust investments in monitoring and evaluation on time scales that elucidate the full impacts of soil carbon BMPs. Similarly, national commitments to long-term farm-level implementation support reduces risk for producers, builds awareness of the importance of the issue, and inspires confidence that soil carbon BMP investments are worthwhile.

Ultimately, the success of soil carbon initiatives is dependent on farmers consistently choosing to apply BMPs on their farms. Farmers face an array of decisions every day, including whether to take on the cost and risk of committing labor, time, and materials to implementing new BMPs. The urgency of short-term needs often precludes investment in profitable long-term opportunities. Here, governments have the opportunity to support BMP adoption by taking on some of the farm-level cost and risk through financial mechanisms such as credit, insurance, and subsidies. Policy that supports decentralized soil carbon incentive programs foster locally adapted BMPs whose results can ultimately be transferred and scaled. Such local adaptation is particularly important to breaking the adoption barrier in areas with a wide range of socioeconomic conditions and degrees of access to inputs (Piikki et al. 2019; Mbow et al. 2019). Farmer organizations and extension service organisations are excellent candidates to serve as clearinghouses of technical support and incentive programs. Examples of incentive programs may include direct payments and capacity building tailored to age, gender, and education level. An 'ideal client' model that targets young women farmers helps ensure that policies are inclusive, thus supporting widespread adoption and ultimately, success of the policy.

National-level measures support the connectivity access necessary for effective soil carbon BMP implementation. Political prioritization of infrastructure such as roads, mobile service networks, cold chain infrastructure, and processing facilities support resource access, market access, and off-farm income diversification. Establishing and expanding farm credit, warehouse receipts, crop insurance, social security, and other risk-reducing and risk distribution instruments help ensure that farmers can continue to support their livelihoods even while taking risks on new BMP adoption. Weather forecasts, knowledge platforms, extension services, and early-warning systems empower farmers to make fully informed management decisions (Chere 2019). Remote sensing, GIS, and cloud technology have become increasingly important in both agricultural research and service provision; policy supporting local infrastructure and capacity building will support a burgeoning demand for big data and artificial intelligence-based services (Chere 2019). Perhaps most importantly, affirmative policy action to ensure that women researchers, extension agents, policymakers, service providers, community leaders, and farmers are empowered to make decisions at all stages will help ensure that soil carbon programming serves everyone (Kanyenji et al. 2020).

National policy can leverage existing programming and private sector activity to support continued progress in soil carbon sequestration. Several soil conservation and food security projects are underway in East Africa, presenting both partnership opportunities and existing momentum to the governments of Ethiopia and Kenya. Collaboration with GIZ and the GSP to extend and enhance successful outreach could prove a particularly fruitful investment for the agricultural ministries of both countries. Public funds can also be leveraged to de-risk carbon markets; fund start-up, loans, grants, and subsidies; establish carbon value chains; and other efforts that ultimately catalyze the monetization and self-sustenance of soil carbon initiatives.

V. A Path Forward for Enhancing Soil Organic Carbon in East Africa

Soil carbon plays a crucial role in climate change mitigation and agricultural productivity. Reducing soil carbon losses and SOC sequestration are two major opportunities for helping mitigate future climate change and offset GHG emissions. Agricultural decision making heavily informs the fate of soil carbon. The same soil BMPs that support climate change mitigation also support continued agricultural productivity and, in turn, food security and rural livelihoods. Several international organizations are working towards increased food security and soil carbon sequestration in East Africa. Nevertheless, numerous barriers continue to impede widespread adoption of soil carbon BMPs. Well-designed national policies, realized at the local level, can help address the implementation gaps.

Going forward, a suite of national measures, implemented at the local level, will be key to continued progress in soil carbon sequestration:

Policy

- ☑ Policy acknowledgement of close correlations between land degradation, GHG emissions, agricultural production, and food security
- ☑ Soil carbon is important in countries' achievement of their UNFCCC NDC targets, and can be included
- ☑ Alignment of policy and coordination across institutions

Capacity

- ☑ Accurate, user-friendly decision support tools for designing programs and targeting interventions based on site-specific biophysical and socioeconomic conditions
- ☑ Local institutional capacity, particularly in terms of farmer organizations

- Women decision-makers at policy, research, programming, community, and farm levels
- Utilize holistic approaches to technical and agronomic support adapted to gender, age, education level, environmental site, and cropping system that consider both crop productivity and carbon sequestration

Markets

- Integration of soil carbon into carbon markets
- Creation of new carbon sequestration opportunities through value chain interventions
- Input market access services that promote soil carbon enhancement interventions

Productive resources, infrastructure

- Transparent and equitable land tenure and farm credit processes
- Affordable, reliable mobile network infrastructure and hardware
- Creating farmer incentives to offset initial BMP cost and long-term maintenance
- Extension, advisories, and risk management
- Robust extension systems providing farmers information on soil carbon enhancement
- Weather forecasting, agro-advisory and early warning systems
- Risk reduction and risk distribution instruments, including insurance and social security

Research

- Committed funding for long-term research and evaluation of BMPs
- Monitoring programs designed to evaluate the long-term fate of SOC in croplands and grasslands under varying management practices
- Funding and support for geospatial mapping and mechanistic modelling research

The great majority of these measures provide additional benefits far beyond soil carbon sequestration, and are aligned with various national and international policy priorities and commitments. This extent of intervention co-benefits enables cost-efficiency and simultaneous achievement of multiple objectives.

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