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Review

Building Climate Change Adaptation and Resilience through Soil Organic Carbon Restoration in Sub-Saharan Rural Communities: Challenges and Opportunities

Alex Taylor ^{1,*}, Maarten Wynants ¹, Linus Munishi ², Claire Kelly ¹, Kelvin Mtei ³, Francis Mkilema ², Patrick Ndakidemi ², Mona Nasser ⁴, Alice Kalnins ¹, Aloyce Patrick ², David Gilvear ¹ and William Blake ¹

- ¹ School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth PL4 8AA, UK; maarten.wynants@plymouth.ac.uk (M.W.); claire.kelly@plymouth.ac.uk (C.K.); alice.kalnins@plymouth.ac.uk (A.K.); david.gilvear@plymouth.ac.uk (D.G.); william.blake@plymouth.ac.uk (W.B.)
- ² School of Life Sciences and Bio-Engineering, The Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania; linus.munishi@nm-aist.ac.tz (L.M.); francis.mkilema@nm-aist.ac.tz (F.M.); patrick.ndakidemi@nm-aist.ac.tz (P.N.); patrickaloyce@gmail.com (A.P.)
- ³ School of Materials, Energy, Water and Environmental Science, The Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania; kelvin.mtei@nm-aist.ac.tz
- ⁴ Ecological Design Thinking, Schumacher College, Totnes TQ9 6EA, UK; Mona.Nasser@schumachercollege.org.uk
- * Correspondence: alex.taylor-34@plymouth.ac.uk; Tel.: +44-(0)-1752-584709



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Abstract: Soil organic carbon (SOC) is widely recognised as pivotal in soil function, exerting important controls on soil structure, moisture retention, nutrient cycling and biodiversity, which in turn underpins a range of provisioning, supporting and regulatory ecosystem services. SOC stocks in sub-Saharan Africa (SSA) are threatened by changes in land practice and climatic factors, which destabilises the soil system and resilience to continued climate change. Here, we provide a review of the role of SOC in overall soil health and the challenges and opportunities associated with maintaining and building SOC stocks in SSA. As an exemplar national case, we focus on Tanzania where we provide context under research for the “Jali Ardhi” (Care for the Land) Project. The review details (i) the role of SOC in soil systems; (ii) sustainable land management (SLM) techniques for maintaining and building SOC; (iii) barriers (environmental, economic and social) to SLM implementation; and (iv) opportunities for overcoming barriers to SLM adoption. We provide evidence for the importance of site-specific characterisation of the biophysicochemical and socio-economic context for effective climate adaptation. In particular, we highlight the importance of SOC pools for soil function and the need for practitioners to consider the type of biomass returns to the soil to achieve healthy, balanced systems. In line with the need for local-scale site characterisation we discuss the use of established survey protocols alongside opportunities to complement these with recent technologies, such as rapid in situ scanning tools and aerial surveys. We discuss how these tools can be used to improve soil health assessments and develop critical understanding of landscape connectivity and the management of shared resources under co-design strategies.

Keywords: Soil organic carbon; systems thinking; whole system; interdisciplinary; sustainable land management

1. Introduction

Sustainable management of soils is critical to underpin food, energy and water security for future generations. In sub-Saharan Africa (SSA), these facets are threatened by increasing rates of soil degradation underpinned by a complex interaction between natural vulnerability and anthropogenic activities [1]. In SSA, detrimental land management practices can be traced across a series of governance shifts through history, often stemming

from disruption to indigenous systems at the start of the colonial period, and a change to rigid structures, which lacked adaptive capacity at the community scale [2]. Together with changing land use, a rise in global surface temperature is linked to increased occurrence of extreme weather events, which is predicted to intensify with continued warming [3,4]. This exacerbates soil degradation resulting in a destabilised soil system leading to fracturing of the provisioning, regulatory and supporting ecosystem services provided by healthy systems [5]. Soil degradation can be broadly classified as physical (e.g., loss of organic matter, impacts to soil structure and aggregate stability with subsequent erosion), chemical (e.g., contamination, nutrient depletion or salinization) and biological (loss of biological diversity), and the rate and processes by which these occur is highly site-specific in relation to both socio-economic drivers and environmental conditions [6]. In East Africa, soil loss has been largely attributed to erosion by water with an estimated mean soil loss of around 6.3 t/ha/yr, half of which is likely to be derived from croplands [7]. Efforts to reduce erosion by water must consider landscape connectivity in a holistic manner, which considers social and economic frameworks alongside an understanding of landscape hydrology [8–10]. Crucially, assessment and development of sustainable land management (SLM) must be embedded within a participatory approach, drawing on local knowledge and building practical systems of change from within the local community, ultimately fostering community-led management, which is not reliant upon but supported by external services [10–15].

Soil organic carbon (SOC) is a fundamental component for healthy soil function, exerting important controls on soil structure, water retention, biodiversity and nutrient cycling [16]. Maintaining and building effective SOC pools can, therefore, play a key role in climate change adaptation strategies, offering an opportunity to build resilience with triple-win (productivity-ecosystem-livelihood) benefits [17]. However, with conversion of natural vegetation to agriculture and subsequent intensive practice, biomass outputs often outweigh inputs, leading to a deficit in soil organic matter (SOM) and associated SOC [18,19]. In turn this impacts upon soil structure and drainage properties, facilitating overland flow and further soil and SOC loss, which lowers fertility and increases susceptibility to drought. Owing to SOC importance, building and maintaining healthy SOC pools is acknowledged in the United Nations Convention to Combat Desertification (UNCCD) as essential for unlocking the full potential of soil ecosystem services and achieving many targets under the global Sustainable Development Goals (SDG) framework [16]. Focus on SOC also serves to address United Nations Climate Change Conference of the Parties 2021 (COP26) *action on adaptation* agendas. The pivotal role of SOC in soil function has placed it as a key component in soil degradation assessments (e.g., Bunning et al. [20]), particularly given its sensitivity to land use change [19,21]. In 2017, the sub-Saharan Africa (SSA) Soil Fertility Prioritization Summit was designed to identify key barriers to improving soil fertility and, working with stakeholders across SSA, develop interdisciplinary, evidence-based strategies to overcome these barriers and implement change [22]. Summarising the findings of the summit, Stewart et al. [23] argued that previous attempts to overcome soil fertility issues in Africa have not adequately invested in overall soil health since the approaches have not considered broader social, regulatory and economic factors influencing the soil fertility supply chain, emphasising the importance of holistic, evidence-driven approaches to alleviating poverty associated with low soil fertility. A survey undertaken at the summit revealed that stakeholders regarded SOC deficiency as a key limiting factor in improving soil fertility in SSA, with identified barriers to improvement including the need for site-specific research, access to training and extension services, gender equality issues and access to local soil assessment tools.

Against that background we explore the role of SOC in underpinning climate change adaptation and resilience in SSA. We focus on Tanzania as an exemplar national case in the context of a continuing research programme, the “Jali Ardhi” (Care for the Land) Project [13,15,24], which adopts a participatory and interdisciplinary approach to agro-pastoral land management assessment. Herein, this contribution aims to provide an

overview of the importance of SOC components for soil functioning followed by methods to improve and maintain SOC. In addition, an evaluation of barriers to change and opportunities for improved integrated assessment and SLM implementation is provided.

2. The Role of SOC in Climate Smart Agriculture

There is increasing recognition of the role of SOC functions in ecosystem service provision [16], with regard to regulatory services, such as carbon sequestration, flood regulation and contaminant immobilisation; cultural services, such as recreation; supporting services via healthy nutrient and microbial pools, and resulting provisioning services in the form of food, fuel and water supplies [5,25]. Healthy soil function supported by SOC can, therefore, be used as tool for adapting to climate change and building resilience in rural communities through appropriate SLM practice [26,27]. SOC is often conceptualised as comprising different pools, each with distinct roles and residence times in the soil system. The 'active' or labile pool is derived from organic matter (OM), which is highly susceptible to microbial decomposition and rapidly cycled (mineralised) (~1–2 years) to underpin soil nutrient supplies. This pool is largely influenced by the addition of recent material with relatively low C:N ratios and low molecular weight compounds, which can be readily decomposed and assimilated by soil microbes [28]. The 'slow' SOC pool relates to carbon which has been assimilated into microbial biomass and partially stabilised via mineral matrix interactions or within soil aggregates [29,30], with decadal residence timescales. A further highly stable or 'passive' pool comprises recalcitrant material with residence times > 100 years, exerting an important influence on soil cation exchange capacity (CEC) owing to a large number of charged functional groups [16]. The active SOC component, whilst critical for nutrient cycling, is also important for ensuring SOC stabilisation through microbial uptake and subsequent cycling to organo-mineral complexes in the slow pool [29]. Both the slow and passive pools play a key role in developing healthy soil structure with associated benefits such as aggregate stability and improved moisture retention. A functioning soil system maintains an effective balance between nutrient release and subsequent carbon loss via mineralisation, and SOC stabilisation.

Numerous studies highlight the decline of SOC under intensive agricultural systems in SSA [26,30–32] owing to a destructive spiral of degradation in which a lack of biomass return to the soils under cropping regimes, or loss of vegetation via overgrazing or land use change, impacts upon key soil functions, leaving soils vulnerable to erosion by wind and water, further exacerbating SOC reduction [17]. The soil functions underpinned by SOC are well documented (Figure 1) and include maintaining healthy soil structure and moisture retention, enhancing CEC, pH buffering, provision of nutrient pools and microbial diversity [33]. SOC depletion can, therefore, lead to physical, chemical and biological degradation. For example, Pabst et al. [31] assessed the impact of changing land use upon organic carbon and microbial activity in a range of systems on the southern slopes of Kilimanjaro, Tanzania. The authors studied representative systems such as savannah, coffee plantations, maize plantations and traditional home gardens, with findings highlighting depleted organic carbon and less stable microbial activity under intensive cropping systems, owing to a lack of organic matter supply and exacerbated by lower rainfall conditions in drier areas. Healthy microbial activity and carbon pools in home gardens reflected the use of agroforestry techniques, which involved adding mixed residues to soils, thus increasing available substrate for microbes.

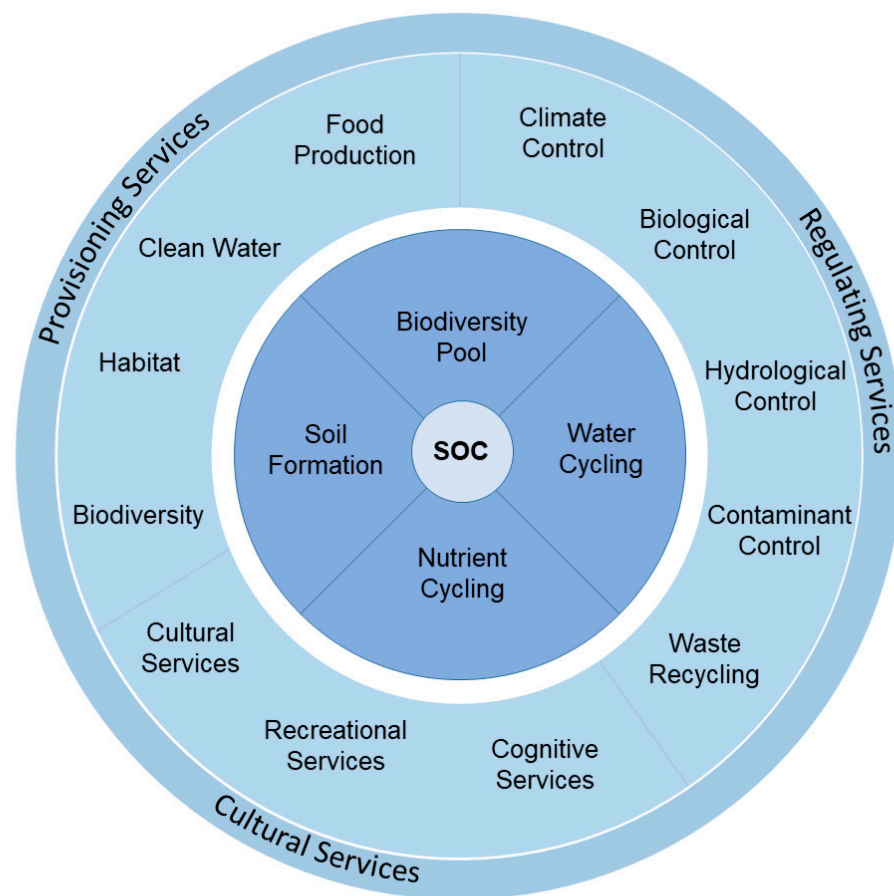


Figure 1. Soil functions (inner circle) and ecosystem services (outer circle) underpinned by soil organic carbon. Adapted from Laban et al. [34].

In many smallholder agricultural communities there is often a trade-off between available biomass to return to soils and the need for fodder, with crop residues often used for the latter [18]. It is important, therefore, that systems are developed whereby OM can be effectively allocated to soils to build the SOC resource during cropping regimes, whilst maintaining needs for fodder and fuel. In a study of SOC in a range of Tanzanian soils, Winoiecki et al. [21] demonstrated a linear relationship between SOC and total nitrogen, and showed that cultivation practices had led to depletion of soil C by around 50% in comparison to semi natural sites. Similarly Solomon et al. [19] showed clearing woodland for cultivation of maize and beans without fertiliser inputs led to > 50% reduction in N and C in Tanzanian Luvisols, with improvements shown for homestead systems where manures and fallow rotations were applied. This is in line with the findings of others whereby, in time, routine allocation of OM to the soil can increase yields, potentially offsetting shortfalls in biomass allocation [35]. At the global scale, meta-analyses suggest a positive linear relationship between SOC and cereal yields to around 2% SOC, beyond which yield improvements tend to plateau [36]. Analyses show a general tendency for higher yields with effective combination of quality SOC inputs and mineral fertiliser [36,37]. In dryland environments, achieving SOC concentrations to around the 2% threshold is likely to be challenging although, where SOC is < 1%, there is evidence to suggest that relatively minor increases can have a positive effect on yield [36].

Despite the well-documented benefits of OM allocation to soils in SSA, interactions between OM and the surrounding environment are complex, with functional benefits depending upon a number of physicochemical factors and appropriate management decisions. The active SOC pool is readily influenced by the addition of OM with relatively low C:N ratios, such as legume crops, and it is this rapidly cycled component which has

been shown to have a positive effect on crop yield, and which is more sensitive to land use change [19,31,33]. In contrast, studies focusing upon the relationship between different SOC pools and crop yield have shown negative relationships between mineral associated (slow) SOC pools and yield in experimental plots, possibly owing to organo-mineral complexes reducing plant available nutrient supplies [30]. This highlights the need to consider the role of specific SOC pools in land management planning rather than total SOC per se, through additions of effective types of OM. However, long-term soil structural benefits obtained from stabilised SOC pools are particularly important in the context of soil aggregate formation and stability. Aggregate stability is often a key focus in land degradation assessment and SOC can promote soil aggregation through a variety of mechanisms, such as clay-humic complexes with polyvalent cations, and via the binding effects of microbial products [38]. Hydrophobicity of organic substances can also reduce the wetting of aggregates and promote stability [33]. Additionally, the type of OM amendments and soil textural class are both important factors in determining the size of aggregates [38]. Other studies highlight the importance of SOC interactions with sesquioxides, particularly Al-sesquioxides, which most likely exert an important influence on SOC stability and soil aggregation in low activity clay soils in SSA [39].

It follows, then, that management programmes require a thorough assessment of (i) soil properties and (ii) the types and quantity of OM available for application. With regard to the latter, and in relation to benefits to soil fertility, OM can be classified according to its ability to provide available nutrients and, thus, its benefits to crop yield. Palm et al. [40] suggested a plant residue quality index for tropical agroecosystems based upon the nitrogen, lignin and polyphenol content of a range of residues, deriving predictors of available nutrient release to underpin farm applications of OM. Those classed as higher quality residues generally displayed lower lignin and phenol and higher nitrogen content, and were likely to be effective as direct land applications. It was suggested that those with higher lignin and phenol content should be applied in conjunction with higher quality residue or mineral fertilisers. Integrated soil fertility management (ISFM) approaches are a common component of SLM programmes in SSA, and the quantity and types of OM applied, and their interaction with mineral fertilisers is of key importance in determining crop yields [37,41,42]. For example, Gram et al. [37] assessed the effect of OM type and mineral N applications upon maize yields in SSA. Here, the authors applied the OM quality index of Palm et al. [40] with the addition of a subgroup for manures, to include materials such as animal manure and composts. Highest yields were achieved where mineral N was combined with high quality OM, and where 50% of the available N was derived from OM. Interestingly, positive linear relationships were found between sole applications of OM and yield for the high quality OM and manure. A linear response was not shown for the low quality residues (e.g., maize and groundnut residues), which when applied alone, showed a limited effect upon yield and relied upon a higher application of mineral N for any marked yield increase. At higher application rates the use of lower quality residues led to a decline in yield potentially owing to N immobilising effects of phenols [41]. Additionally, sole application of mineral fertiliser did not show a linear response in yield likely owing to thresholds in plant uptake beyond applications of ~100kgN/ha. Overall agronomic efficiency (application rate versus yield) and yield response were found to be more stable with sole applications of quality OM, likely reflecting wider benefits associated with other factors such as moisture retention. Only applications of OM had a positive effect on SOC and it was assumed that any biomass increase from sole applications of mineral N was not returned to the soil, and that excess available N may have facilitated SOC decline.

Clearly the type and quantity of OM amendments needs consideration in relation to the local environment and the challenge in many smallholder systems is stimulating and maintaining biomass inputs to, ideally, achieve a balanced system, less reliant upon external inputs. Sole applications of OM can lead to significant yield improvements but the quality of inputs is of key importance. Attention must, therefore, be upon fostering SLM practice which can provide a broad range of quality organic matter of sufficient quantity

to underpin food security. The application of lower quality residues in the context of soil erosion control should not be ignored, however, given the potential for residue barriers to reduce soil loss and, in turn, maintain SOC stocks [43,44]. In time, soils can achieve healthy microbial communities to assist with nutrient supply, root growth and disease resistance as well as structural improvements to aid moisture retention, infiltration and aeration. These factors combine to support resilience to uncertain climatic regimes. Building soil health in degraded systems is, however, likely to take time and it can often take a number of years to accrue benefits associated with SOC targeted approaches [27]. It is, therefore, important to incorporate carefully calculated ‘quick win’ incentives within management schemes to maintain perceptions of effectiveness and cost–benefit [45].

Understanding the role of SOC highlights the importance of undertaking detailed local–level land evaluations to assess land suitability and potential within an integrated management context. That is, one in which the physicochemical requirements are considered alongside social and economic structures, to enable the selection of optimal SLM practices [20]. It is crucial that resource planning is undertaken with stakeholders at all stages, supported by an enabling and policy-responsive framework. Ziadat et al. [46] describe the importance of a land resource planning (LRP) approach to foster the adoption of appropriate land use measures, aligned with the local ecological, economic and social context to support resilience to climate change and promote sustainable development. This integrated approach involves targeting key areas for change, assessing land potential, identifying appropriate SLM measures and implementing change, supported by appropriate financial mechanisms and performance monitoring. Cataloguing SLM measures in relation to a range of environments is an important decision support component, offering stakeholders a means to access data relating to potential SLM options, their effectiveness and, importantly, challenges and opportunities relating to their implementation. An example of such a database is the World Overview of Conservation Approaches and Technologies (WOCAT) Global SLM Database; a search engine enabling case study information to be accessed for a range of SLM technologies and approaches. Below, we provide a synthesis of typical SLM practices applied within agro-pastoral communities in SSA, documenting their application and effectiveness in terms of enhancing SOC and climate change resilience.

3. Common SLM Methods to Maintain and Enhance SOC

There is a general lack of empirical data comparing the effects of land management techniques upon SOC in SSA, hampered further by differences in the approaches to measuring and reporting SOC across existing studies [47]. The effects of land management are also likely to be highly varied according to a range of environmental factors, presenting challenges for comparison between studies and highlighting the importance for site-specific assessments [48,49]. Nevertheless, the impacts of agriculture and poor management practice upon SOC are well documented and, site-specific variability aside, there is a broad body of evidence to support both the importance of SOC in dryland environments and the conservation measures that can be implemented to provide positive changes to soil health [34,50]. Sustainable management practices require an integrated approach to provide synergy between soil moisture, nutrients and structure to maintain and build SOC stocks and prevent net loss. Here, we summarise a range of approaches applied in rural communities, which specifically document the effects of land management upon SOC.

Diverse climatic zones in SSA naturally influence background SOC stocks such that upland humid areas with higher rainfall and biomass will often see greater SOC relative to semi-arid lowlands, where rainfall shortage and fluctuation is a limiting factor [36]. In semi-arid rangeland environments, livestock grazing pressure can lead to loss of total vegetation cover, leaving soils exposed and vulnerable to water and wind erosion. In turn this impacts upon the root systems and seed banks of native plants and stimulates encroachment by invasive species [10]. Management practice is focused upon restoration of native vegetation cover by improving mobility across varied grazing lands or through enclosure schemes, which may be combined with reseeded of native species. Exclusion

zones can be implemented by physical barriers, an agreed set of communal rules or, in some cases, established bylaws in more extensive grazing lands (often hundreds of hectares) [15]. Mixed systems may also effectively combine stall feeding with soil-stabilising plants used on hillslope cropland [51]. Where management strategies are functioning, the benefits associated with enclosure systems are well reported in the literature, with evidence of successful regeneration of palatable, perennial vegetation [17,52]. In turn this can effectively increase the SOC stock in comparison to overgrazed open areas [51] (Table 1), and improve drought resilience through provision of fodder and diversification of income [53,54]. Traditional mobile corral systems (Boma) have also been shown to provide benefits for vegetation cover and SOC even after short periods of use [51,55].

In croplands, reduced tillage, planting of cover crops and effective crop rotation form the basis of conservation agriculture (CA), which has been shown to provide benefits associated with improved SOC [50]. High erosion risk crops, such as maize, can be interplanted with a variety of cover crops, most notably legumes (e.g., *Mucuna pruriens*; *Lablab purpureus*), to increase vegetation cover both during crop growth and post-harvest. Cover crops have been shown to have multiple benefits in cropping systems by reducing rainsplash erosion, increasing SOM, improving overall fertility and providing an additional source of palatable produce, particularly useful in mixed farming systems [56,57]. Application of OM mulches (e.g., crop residues) can also be beneficial for reducing runoff and providing improvements to soil health and crop yields [45,58,59]. As previously discussed, however, the quality of OM is an important consideration [47] and difficulties of returning crop residues to the soil often arise where fodder is required [18]. The use of multiple cropping systems and agroforestry schemes may provide additional fodder sources, enabling crop biomass to be reinvested in the soil, and a balanced livestock-cropping system also presents opportunities for manure application to soils, which may have benefits for plant nutrient uptake [18,59].

In the literature, the benefits associated with CA appear to be highly site-specific, linked to climate and soil type (e.g., Swanepoel et al. [49]), and small-scale management of available OM resources. For example, Castellanos-Navarrete et al. [60] showed that integrated applications of crop residue and manure did not provide adequate nutrients to cropland, with large nutrient losses from manure supplies owing to poor storage practices. Residues and manures are also often inadequate for supplying plant available P, and in SSA effective P application via OM mulch requires careful consideration of the type and source of available plant material [61]. In the short-term, some studies report that CA has overall limited influence upon crop yield and food security for the smallholder in SSA (e.g., Corbeels et al. [62]), often linked to failure to adapt systems to local settings in terms of environmental factors and socio-economic needs and constraints [63]. In the context of climate change resilience, however, the role of CA for SOC management requires a shift in profitability assessment to include longer-term environmental, social and economic gains likely to be seen with well-adapted CA systems, particularly in drylands where drought resilience is going to be of increasing importance [49,62,63].

SLM can be implemented to reduce soil and SOC loss by various runoff interception techniques; forms of physical barriers designed to directly break the structural connectivity components in the landscape and, in doing so, act as rainwater harvesting (RWH) methods. These methods can draw upon in situ, micro-scale structures, capturing water and sediment at the planting zone [64–66] or be larger, macro-scale structures, which are designed to channel water into the cropped area [64,67]. Both approaches have the capacity to increase and maintain SOC by reducing soil loss, capturing sediment and associated SOM, and by improving moisture and nutrient retention, which benefits microbial pools and biomass. Water storage structures, such as reservoirs, can also help to maintain biomass during the dry season. To offset labour costs associated with larger structures, novel techniques utilise existing structures acting as runoff pathways, such as roads and tracks, to harvest overland flow [68].

Table 1. Examples of quantified impacts of sustainable land management (SLM) practice on SOC in sub-Saharan Africa (SSA).

Intervention	Location	Aridity	Impact on SOC	Sample Depth (cm)	Land Management Timeframe (yr)	Associated Yield Impact	Source
Agroforestry	Amhara and Oromia regions, Ethiopia	Semi-arid - subhumid	Total SOC increase 28% relative to traditional maize cropping. $p < 0.05$	0–15	8.5 (median)	n/a	[69]
Agroforestry	Mt Kilimanjaro (Machame to Lake Chala), Tanzania	Semi-arid - humid	Total SOC ~23% increase relative to conventional agriculture	Horizon-based sampling	nd	nd	[31]
Enclosure	Dida-Hara, Ethiopia	Arid - semi-arid	Evidence of total SOC increase 8–30% relative to grazed areas. No statistical significance ($p > 0.05$)	0–30	Enclosure timescales: <20; 20–30; >30	n/a	[70]
Enclosure	Chepareria Ward, Kenya	Semi-arid	Mean total SOC increase by 27% relative to open grazing. POC increase up to 55%. $p < 0.001$	0–40	Enclosure timescales: 3–10; 10–20; >20	n/a	[71]
Enclosure	Amhara and Oromia regions, Ethiopia	Semi-arid - subhumid	Total SOC increase 68%. $p < 0.05$	0–15	13 (median)	n/a	[69]
Fanya-juu	Makueni County, Kenya	Semi-arid	Total SOC increase ~30% relative to conventional agriculture	0–85	35–40	Improved maize yield based on farmer estimates	[66]
Grow Biointensive Sustainable Agriculture (GBSA)	Kilmambogo; Thika; Muranga, Kenya	Semi-arid - subhumid	Total SOC (assumed Walkley and Black method) increase 30% over study period. $p < 0.05$	nd	4	~70% increase in maize; 60% increase in sweet potato	[35]
Homestead (manure application and fallow)	Naberera, Tanzania	Semi-arid	Total C increase > 100% relative to conventional cultivation. $p < 0.05$	0–10	10	nd	[19]

Table 1. Cont.

Intervention	Location	Aridity	Impact on SOC	Sample Depth (cm)	Land Management Timeframe (yr)	Associated Yield Impact	Source
Legume intercropping	Salima; Dowa; Balaka; Nkhotakota, Malawi	Sub humid - humid	Total SOC increase 33–73% relative to conventional cropping	0–100	10	nd	[72]
Mulching	Lushoto District, Tanzania	Semi-arid - subhumid	Total SOC increase ~15–30% relative to control (no mulch). $p < 0.05$	0–30	2–3	up to 56% greater maize yield	[73]
Reduced tillage	Buffelsvlei and Zeekoegat, South Africa	Subhumid	Site-specific. Up to 18% increase in total SOC in clay soil. $p < 0.001$	0–30	6–8	No clear links to increasing yield. Greater dependence upon climatic factors and soil type	[49]
Ridge tillage with organic matter (OM) incorporated	Mbozi District, Tanzania	Subhumid	Total SOC increase ~30% using ridges with OM	10–20	1–2	> 100% maize increase compared to traditional tillage; 45% increase in bean yield	[65]

4. Examples of Barriers to SLM Adoption in SSA

Land degradation in SSA has many drivers [74] and, in the past, a top-down approach to SLM has led to failures in effective implementation often owing to a lack of consideration for differing community structures and the environment at the local level. It is now generally recognised that SLM must be targeted to specific communities in participatory approaches, which consider the unique socio-economic and governance contexts as well as environmental factors [15,17,24]. These approaches focus on empowering local communities to identify, manage and ultimately reverse land degradation practices to restore soil health and boost resilience to climate change.

Adoption of SLM is heavily influenced by the perception of benefits associated with carrying out alternative practices, owing to a lack of capital which often evokes a risk averse attitude in rural communities [75]. The use of field-based training and trial plots has become a useful tool for influencing SLM uptake through direct, evidence-led schemes whereby benefits associated with sustainable land practice can be clearly demonstrated [76]. Education and awareness is a common barrier to SLM (Table 2) and, therefore, field-based projects also serve as an important outlet for training and experiential learning to provide the foundation for change at the community level. Once facilitated, there are numerous indicators that social capital, such as shared learning and trust, is important for underpinning community cohesion, with the development of community groups strongly facilitating education and diffusion of knowledge relating to SLM [76–78]. Such groups may also be effective in offsetting opportunity costs associated with labour shortages, another common barrier to SLM uptake [79]. In contrast, however, where systems are based on kinship networks, adoption of SLM can be hindered owing to the perceived insurance role of the network and the sharing of any individual gains during periods of hardship [78].

Although the perception of benefits is highly influential, of crucial importance is the nature in which these benefits are obtained throughout the year, with cash flow and fluidity identified as vital factors in SLM adoption. The ability of poorer households to generate benefits at key times of the year, rather than the magnitude of benefits per se, influences the choice (or combination of choices) of SLM practice [80]. Since many SLM practices accrue direct or indirect benefits with time [63] this often becomes a barrier where poor communities have to rely upon short term gains. This highlights the need for ‘quick win’ opportunities to work alongside longer-term goals in SLM programmes [53]. The situation can be exacerbated where land tenure is insecure, with rented land often less likely to be invested in for the long-term [78]. Insecure land tenure and resulting land conflicts can impact upon long-term soil health, hindered by a lack of land policy targeted at the local level, which fails to adequately address cultural norms and transboundary relationships between land users [81]. There are additional problems associated with willingness to contribute to the management of shared, common land resources, particularly in pastoral communities, where motivating individual actions for the benefit of a community can create challenges. Exploring the social dynamic in Massai communities in Tanzania, Rabinovich et al. [82] found willingness to protect shared resources was strongly linked to the development of group norms and community identity focused on sustainable practices, with participation in decision making and access to group discussions likely to play a key role in enhancing SLM adoption.

Numerous studies identify inadequate access to reliable, local markets as a barrier to income, in turn, impacting as an opportunity cost upon SLM adoption (Table 2). Problems associated with a lack of variety of produce can mean that markets become flooded with certain produce, leading to price reductions. Additionally, larger markets are often at distance from smallholders who then rely on intermediate traders to purchase their products. Rural communities often receive low prices in such situations and a lack of storage facilities for perishable produce enhances the need to sell upon harvest and further reduces the bargaining power of rural communities [83]. There are, however, contrasting findings with regard to the link between income and SLM adoption. In some examples, accessible

local markets enable income generation and allocation of funds into soil conservation measures [84], or perceived income increases likelihood of SLM adoption [76]. In other areas, income is negatively correlated with SLM adoption, particularly where income is generated from off-farm activities, with surplus likely to be allocated to basic household needs rather than to SLM practice [85,86]. This shows the importance of considering opportunity costs associated with capital surplus rather than capital surplus per se. Relationships between income and SLM adoption can also be influenced by land unit distinction where more profitable fields in, for example, more favourable growing locations, are less likely to be targeted for SLM practice [86]. This could potentially create challenges with regard to land management that enhances landscape unit connectivity and subsequent loss of soil and nutrients to erosion [10].

Table 2. Common factors affecting adoption of sustainable land management (SLM) in examples from Tanzania and Kenya.

Intervention	Location	Adoption Factors	Limiting Factors	Source
Rainwater harvesting (RWH) techniques	Chome-Makanya Catchment, Tanzania	-Effective external financial support -Evidence-based benefits -Gradual introduction -Effective local-level governance	-Access to markets -Translation of policy into practice -Access to credit facilities -Willingness of extension officers to incorporate local/traditional knowledge	[75]
RWH, buffer strips, mulching, organic matter (OM) application	Lushoto, Tanzania	-Low risk practices -Evidence-based benefits-Cash flow and liquidity benefits	-Opportunity cost: labour and finance -Perceived risk -Timescale of return	[80]
Intercropping, mulching, manure application	Vihiga and Kakamega counties, Kenya	-Social capital: shared learning -Understanding of plot characteristics	-Education -Access to loans	[77]
Intercropping, reduced tillage, rotation, manure application	Karatu; Mbulu; Mvomero; Kilosa, Tanzania	-Land tenure security -Social capital: shared learning -Market integration -Timing of benefits -Low risk practices	-Tenure (land rental) -Market access -Distance to plot (from residence) -Kin networks	[78]
Mixed soil and water conservation measures	Usambara Mountains and Pare Mountains, Tanzania	-Awareness of soil degradation -Availability of family labour -Social capital: shared labour	-Off farm income	[85]
Terracing, RWH methods	Uporoto Mountains, Tanzania	n/a	-Labour -Reliance on erosion risk practices for short-term benefits	[79]
Conservation agriculture (CA)	Arusha Region, Tanzania	-Knowledge/training -Demonstrable benefits -Flexibility of CA practice -Good organisational structure and linkage of promoting groups -Compatibility with local customs/norms -Acceptability (village leaders)	-Cost and liquidity -Complexity of CA practices -Availability of social networks -Administrative set up at regional level -Market accessibility -Availability of quality control structures (i.e., CA practice monitoring)	[87]

Table 2. Cont.

Intervention	Location	Adoption Factors	Limiting Factors	Source
Terracing, Fanya juu, buffer strips, agroforestry, mulching	Usambara Highlands, Tanzania	-Access to extension services -Attitude/willingness	-Size of farm fields/plots -Opportunity costs: finance	[86]
Buffer strips, mulching, tree planting, contour ridges, stall feeding	Kondoa District, Tanzania	-Access to extension services -Household size (labour availability) -Crop income -Market access-Education and awareness	-Cessation of donor funding -Land shortages -Population pressure	[84]
Terracing, Fanya juu, buffer strips	Usambara Highlands, Tanzania	-Micro-credit schemes -Social capital: shared labour -Gradual introduction -Mixed cropping	-Opportunity costs: labour -Market accessibility	[88]
Micro-and macro-RWH	Same District, Tanzania	-Social capital: shared labour -Long-term external (NGO) support -Local governance structure -Field demonstrations	-Opportunity costs: finance; labour -Lack of technical support	[76]

5. Opportunities to Support SLM Adoption through Interdisciplinary and Cross-Sector Collaboration

Clearly successful regeneration and maintenance of SOC for healthy soils requires a detailed understanding of the complex interaction between people and landscape resources at the local-scale [17]. For context here, we describe the approach to assessing climate adaptation gaps and building resilience within the “Jali Ardhi” (Care for the Land) project in Tanzania [13]. Fundamental to this project, and elsewhere, is a participatory approach to developing sustainable land use programmes, aimed at empowering communities to build resilience to soil erosion challenges from the bottom-up, in a system that, whilst receiving external support, ultimately becomes self-sustaining. Kessler et al. [89] describe the importance of building resilience-based stewardship at the village level, underpinned by motivation and stewardship principles, which are both closely linked with awareness of the natural environment, and people-land-resource connectivity [10]. Kessler et al. [89] make a distinction between extrinsic motivation, relating to externally derived incentives, and intrinsic motivation, which is a self-driven appreciation for natural systems. Whilst extrinsic motivation can play an important role in the protection of soil resources (e.g., Kelly et al. [15]), the Jali Ardhi project also aims to build intrinsic motivation by reducing awareness barriers and highlighting landscape-people connections at the village-scale. The preceding sections have described the importance of SOC in underpinning soil health and, in turn, healthy functions and services, which support community resilience. It has also been highlighted that the effectiveness of SLM practices is highly site-specific and detailed environmental (social, economic and natural environment) surveys are, therefore, crucial to support planning. Such surveys should be used to characterise the site to ensure effective targeting of SLM practice and to provide a benchmark against which to assess the effectiveness of SLM. Although we recognise the importance of tailoring these surveys to the local setting, to support knowledge exchange it is important for practitioners to standardise assessment criteria as far as is practicable and the local level land resources assessment methodology (LADA-Local) detailed by Bunning et al. [20] provides one such format. This survey aligns closely with reporting templates developed by WOCAT and offers an opportunity for projects to contribute to the Global SLM Database, providing a valuable open-access resource for decision support.

Within the Jali Ardhi suite of projects we have identified opportunities to supplement the LADA-Local approach with other survey technologies to help to develop a broader understanding of the landscape features and, importantly, to help connect the land users’ understanding of their activities to landscape processes and subsequent gain in terms of climate change resilience. For example, Blake et al. [10] describe the use of unmanned aerial vehicle (UAV) surveys and geographic information system (GIS) outputs to identify hydrological connectivity between landscape units. The resulting outputs highlighted the need to consider transboundary linkages across landscape units to reduce soil loss, which ultimately requires inter-community cooperation for effective mitigation. Identification of transboundary connections also offers an opportunity for practitioners to explore the development of payment for ecosystem services (PES) approaches to SLM [17,90,91]. Aerial outputs can provide an important platform for community-based resource mapping exercises and a catalyst for wider debate on community decision making, which are important components in participatory SLM programmes [20,46,89]. Other examples draw on GIS for effective targeting of mitigation practice by considering hydrological pathways and soil type in conjunction with planning for water storage zones [92].

More recently, rapid in situ assessment tools have been developed, which offer user friendly platforms to assist in the assessment of soil health and management. An example is the Land-Potential Knowledge System (LandPKS), a smart phone application technology which aids the collection of local-level biophysical data, including soil carbon and wider soil health characteristics, to support effective land use planning [93]. The LandPKS tool has been trialled in Tanzania with potential to be integrated into national and regional land planning policy frameworks [94]. The wider adoption of such approaches has obvious

limitations in terms of access to smart phone services although there is evidence to support growing access to mobile phones amongst rural communities in Tanzania and their use in enhancing agricultural productivity [95]. An additional, complementary technique used in the Jali Ardhi project is rapid screening of SOC and nutrients using a near infrared soil scanner (AgroCares, Netherlands) [96], which enables high spatial resolution measurements of total SOC and nutrients to be obtained in situ. Both the LandPKS and soil scanner can be used, not only to complement the LADA-local process, but also to raise awareness of soil health and functioning as part of a participatory, 'citizen science' approach [96]. We, therefore, adopt a two-way process of undertaking the necessary site characterisations alongside joint learning with the local community using 'new' technologies, helping to negate barriers associated with awareness and building motivation and stewardship potential. Importantly, the combination of survey approaches applied helps to identify SOC pools by considering the active SOC component [20] as well as total SOC and soil nutrients (soil scanner). Potential solutions for land management improvements can then be supported by the use of LandPKS and OM indices (e.g., Palm et al. [40]), together with community collaboration to identify appropriate strategies for change. This approach does require collaboration and support from local institutions for supply and training in the use of the technologies, at least initially, to build knowledge and capacity at the local level. Quantitative analyses can also be integrated with more qualitative local-scale indicators such as soil colour, which can be adopted by communities and used more readily going forward.

The Jali Ardhi approach is summarised in Figure 2 and encapsulates the need for whole farm systems assessment to build resilience within rural communities [12]. The land-people-resource assessment step described above is followed by a selection of potential SLM options (the SLM 'toolbox') for the local environment, drawing upon survey outputs and valuable knowledge exchange databases such as the WOCAT Global SLM database, which provides a platform for cataloguing SLM options and, importantly, a range of mechanisms to offset the common barriers identified in Table 2. Hence, such databases can be effectively utilised for decision support. The process can also be complemented by input from local agricultural advisors. The biophysical survey results and community input derived in step one are then presented with the SLM options 'toolbox' to the community during a participatory co-design process to define achievable SLM targets. It is crucial that all stakeholders are actively involved in this process to identify barriers and solutions from the outset. If transboundary connectivity issues have been identified in step one, then this stage should also involve an inter-community discussion to identify common goals. It is also important for extension officers to take part in the co-design process to ensure future support is in line with community targets, and to help to overcome institutional barriers, particularly those associated with market access and effective credit strategies [12]. Implementation strategies can then be agreed within the community with field-led demonstrations playing an important role in facilitating community group formation and shared learning, and an opportunity to overcome risk aversion.

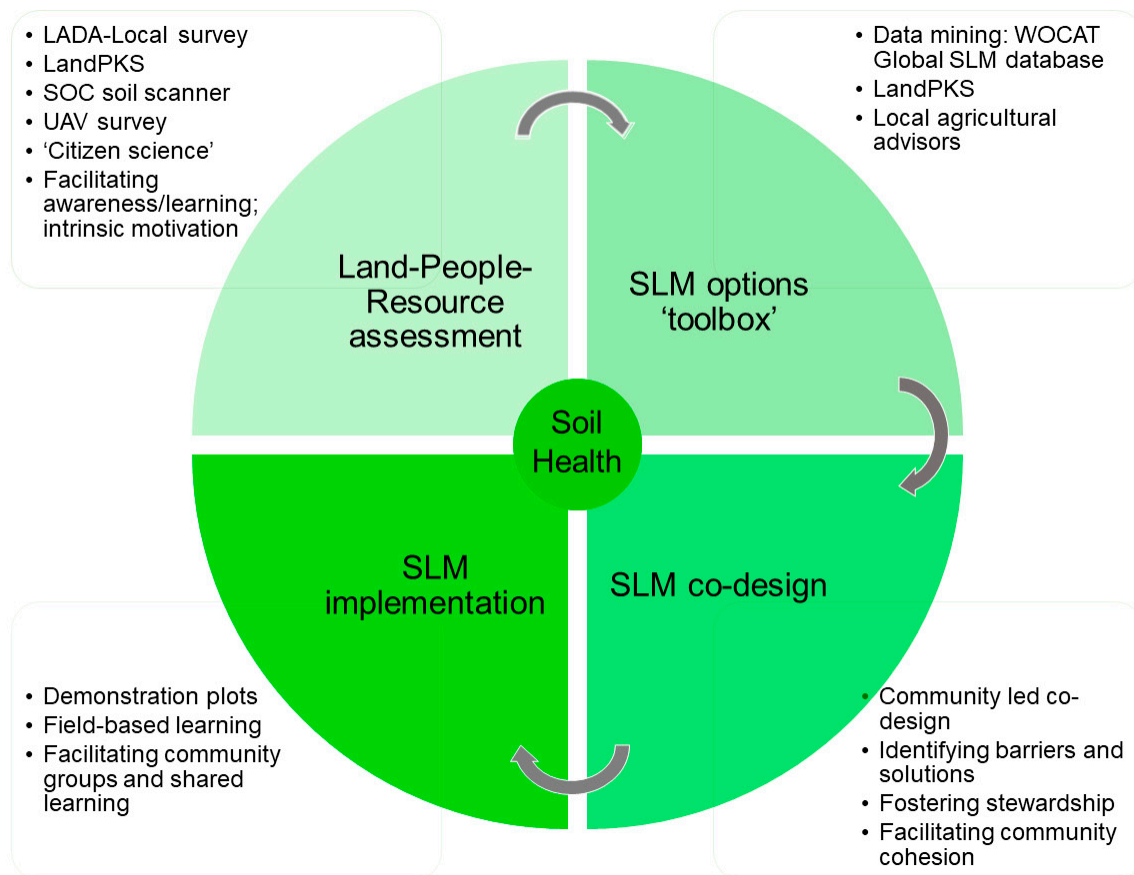


Figure 2. Pathway to change under the Jali Ardhi project.

6. Conclusions

Soil organic carbon plays a pivotal role in soil health and supports a range of ecosystem services crucial for building climate change responses in rural communities in SSA. SOC has been prioritised as a key component for improving soil fertility in SSA with failure to adequately assess local-level social, economic and biophysical factors identified as key barriers to change. Here, we focus upon the importance of SOC as a foundation for soil health and resilience with a key focus upon Tanzania as an exemplar national case. Significant SOC loss through unsustainable agricultural practice leads to soil degradation spirals, exacerbated by climate change, with rural communities often facing challenges associated with returning biomass back to soils to underpin healthy soil functions. Whilst returning adequate OM quantity to soil systems is crucial, practitioners should also focus upon OM quality as a foundation for nutrient pools and fertility, and stimulating soil stability within balanced, diverse farm systems. Here, we present a *whole-system approach* which draws upon standardised local level assessment procedures, supplemented by more recent technologies, which are utilised in participatory soil systems learning programmes alongside local biophysical assessments. Reliable community level assessments are used as the foundation for developing community co-design and implementation of SLM strategies to build resilience to a range of challenges through SOC pools. With predicted intensifying of climate challenges, the approach offers an opportunity to assess climate change adaptation gaps and promote the adoption of locally relevant SLM strategies. Restoring and maintaining soil ecosystems through effective SOC management can protect livelihoods and contribute to the *action on adaptation* targets under the United Nations Climate Change Conference of the Parties 2021 (COP26) agenda.

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