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Measuring what matters: soil health as the missing metric in climate-smart agriculture monitoring

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Climate-smart agriculture (CSA) has become a central framework for addressing the intersecting challenges of food security and climate change. Assessments of CSA have largely relied on measuring the adoption of practices and technologies rather than the ecological outcomes they are intended to deliver. This article argues that the absence of systematic soil health monitoring represents a critical measurement gap in CSA, limiting the ability to verify whether interventions genuinely enhance resilience, contribute to adaptation and mitigation, and sustain productivity. Drawing on two decades of research, we show that soil health underpins all three CSA objectives - adaptation, mitigation and productivity - through its role in regulating water availability, nutrient cycling, carbon storage and biodiversity conservation. We propose scaling outcome-based monitoring to complement practice-based monitoring, positioning soil health as an integrating metric that aligns climate, land degradation and biodiversity agendas. Standardized landscape monitoring approaches, including repeated georeferenced measurements of soil health indicators through frameworks such as the Land Degradation Surveillance Framework (LDSF), demonstrate that operationalisation is feasible and can generate longitudinal datasets. The recent embedding of soil health indicators within multi-level policy frameworks and reporting systems signals political support for implementing consistent soil health monitoring frameworks. Strengthening soil monitoring infrastructure is therefore essential for improving accountability, informing implementation and enabling performance-based climate finance.

KEYWORDS
climate resilience, ecosystem health, evidence-based decision-making, food systems, policy, soil health monitoring, soil organic carbon

Introduction

Healthy soil plays a foundational role in the functioning of terrestrial ecosystems and their provision of ecosystem services, including food production. More than 95% of global food production relies on soil (ITPS and GSP, 2023), and it is home to more than a quarter of global biodiversity (FAO, 2015). Soil constitutes the largest terrestrial carbon reservoir after the oceans (Prăvălie et al., 2021), and regulates water flows, sustains biodiversity, cycles nutrients, buffers climate shocks, and supports rural livelihoods (Anikwe and Ife, 2023).

Yet despite the essential ecosystem services that soil provides, more than one-third of the world's soils are degraded (UNCCD, 2022). Agrifood systems contribute approximately one-third of anthropogenic greenhouse gas emissions (GHG) (FAO, 2025a, 2025b), and unsustainable land management practices, particularly in agricultural systems, are a major driver of soil degradation, with over 60% of global land degradation occurring on agricultural lands (FAO, 2024). This reveals a stark contradiction: systems that depend heavily on soil resources, particularly in crop production and other land-based agricultural activities, are also among the primary drivers of their degradation.

Climate-smart agriculture (CSA) has emerged in recent decades as a widely adopted framework aimed at achieving synergies among three core objectives: sustaining agricultural productivity, enhancing climate adaptation and resilience, and reducing GHG emissions (FAO, 2009; Matteoli et al., 2020). CSA has been promoted by a wide range of stakeholders, and has informed research agendas, donor programming and policy discourse globally. Systems approaches are key to CSA, including landscape restoration, Nature-based Solutions (NbS), regenerative agriculture, agroforestry and agroecology (Bayala et al., 2021).

CSA has delivered important progress. It has mainstreamed integrated thinking and supported the dissemination of diverse practices and technologies such as improved seed varieties, drought-tolerant crops, conservation agriculture, agroforestry, improved water management and more (Zheng et al., 2024). In many contexts, CSA has intersected with broader NbS and landscape restoration efforts, particularly where soil restoration, biodiversity enhancement, and carbon sequestration are co-delivered. It has also catalyzed important policy and investment decisions (Bhatnagar et al., 2024). However, despite this progress, global assessments indicate that soil degradation persists, GHG emissions from agrifood systems continue to rise, and climate vulnerability in agricultural systems intensifies (IPCC, 2019; IPBES, 2018). While CSA has increasingly incorporated digital advisory tools, precision technologies, and institutional innovations, its long-term effectiveness ultimately rests on the condition and resilience of underlying soil systems (Wang et al., 2025).

In practice, the scaling of CSA has been primarily assessed through indicators of technology and practice adoption. These include metrics such as the area under CSA-related practices (e.g., conservation agriculture, agroforestry), the number of farmers adopting specific interventions (Kpadonou et al., 2017), and the dissemination of climate-resilient advisory services (Ma and Rahut, 2024). Such indicators have been widely used in project monitoring, reflecting a pragmatic focus on CSA implementation and uptake. Other indicators of CSA outcomes include increases in crop productivity or yield (Vatsa et al., 2023); increased local food security (Lipper et al., 2014; Santalucia, 2023) and positive impacts on smallholder livelihoods (Simutowe et al., 2025). In addition, many studies focused on barriers to adoption and implementation such as access to extension services, high initial costs, institutional and policy support, access to credit and gender disparities (Dicta Ogisi, 2023; Mnukwa and Mdoda, 2025).

This emphasis on CSA adoption highlights a critical measurement gap at the heart of CSA implementation - that while the uptake of practices is increasingly tracked, environmental outcomes are far less systematically assessed or interpreted along CSA principles, especially those related to soil health (Zougmoré et al., 2014). Studies often show divergence in the influence of CSA management practices on soil indicators such as soil organic carbon sequestration (Schreiner-McGraw et al., 2024). Simply put, while CSA has scaled adoption metrics, there is an opportunity to scale outcome-based monitoring verification, which is most important where CSA claims concern soil-mediated outcomes such as SOC, erosion, water regulation, nutrient cycling, biodiversity, or resilience. Monitoring soil health indicators constitutes a critical, yet often overlooked dimension of resilience within CSA.

This article provides a brief background on the central role that soil health plays in achieving the objectives of CSA. We then explore the scope for systematic soil and land health assessments to provide scalable, comparable, and policy-relevant data, linking local land management practices to measurable ecosystem outcomes. Finally, we demonstrate that integrating soil health metrics within CSA offers a practical pathway to advance coherence across global and regional policy agendas.

The role of soil health in enabling synergies among the three pillars of CSA

Soil health is commonly defined as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems" (ITPS, 2020). The concept builds on earlier notions such as soil fertility and soil quality, which have long encompassed physical, chemical, and biological dimensions of soils. However, soil health places greater emphasis on the soil as a dynamic, living system, highlighting its capacity to sustain ecosystem functions and related ecosystem services, buffer environmental shocks, and support long-term productivity. Moreover, soil health recognizes the full breadth of ecosystem services delivered by soil, whereas soil fertility tended to focus primarily on the production function, for example. There is growing momentum around the formal recognition of the importance of soil health, with growing multistakeholder collaboration to implement soil health solutions (Winowiecki et al., 2025b).

A substantial body of evidence demonstrates that soil health plays a central role in enabling synergies among the three pillars of CSA (i.e., productivity, adaptation, and mitigation) by supporting multiple functions simultaneously:

- Soil and climate adaptation: Research demonstrates that SOC improves aggregate stability, enhances water infiltration capacity, and increases water-holding capacity (Blanco-Canqui et al., 2013; Lal, 2020a; Bargués-Tobella et al., 2024). Soil with higher organic matter content can retain more moisture and reduce surface runoff and erosion during intense rainfall events, thereby stabilizing yields under climate stress.

- Soil and climate mitigation: Agricultural soils represent a significant carbon sequestration opportunity (Bondeau et al., 2006; Lal et al., 2021). Improved soil management, through practices such as cover cropping, reduced tillage, agroforestry, and integrated nutrient management, can increase SOC stocks while reducing nitrous oxide emissions associated with inefficient fertilizer use (Lal, 2006). Unsustainable agricultural and rangeland management practices can lead to a loss of soil carbon (Lal, 2002; Söderström et al., 2014; Winowiecki et al., 2015).
- Soil and agricultural productivity: Crucially, soil health influences not only yield levels but also yield stability and input-use efficiency. Systems with higher SOC and stronger biological functioning tend to produce more consistent yields across variable climatic conditions while improving the efficiency of water, fertilizer and nutrient cycling and use. Productivity, in this sense, is not merely a function of output maximization but of resilience, defined by stable production, efficient resource use and reduced vulnerability to climatic shocks (Kabato et al., 2025; Zampieri et al., 2020)

Soil's contribution to these pillars, embedded within broader social, economic and institutional contexts, is illustrated in Figure 1. While soil processes are largely biophysical, soil health outcomes are also shaped by social, economic and institutional conditions. For example, land tenure security directly influences whether farmers will invest in long-term soil restoration (Stevens, 2022), and access to extension services, credit, and markets shape the adoption of CSA practices (Jena and Tanti, 2023). Gender and youth inequities influence decision-making power over land and inputs (Crossland et al., 2022; Crossland et al., 2021; Newbery et al., 2024), while indigenous and local knowledge systems often contain deeply rooted soil stewardship traditions and spiritual weight (Lal, 2024). Soil health also contributes to human well-being and health by increasing crop nutrient density (Montgomery et al., 2022), filtering pollutants from water and the air, provisioning biomedical resources, and supporting global peace and security by reducing social tension caused by famines and pandemics (Lal, 2020b). As such, soil health is shaped by various ecological processes and governance structures and is inseparable from rural livelihoods, food security, nutrition and health, and social equity.

The CSA measurement gap

CSA initiatives have often measured success through practice and technology adoption indicators (Bonilla-Findji et al., 2021; Chen et al., 2018), rather than outcome-based metrics such as soil health. These metrics rest on the implicit assumption that adoption of CSA automatically leads to improved soil health. However, this assumption has rarely been tested through longitudinal data.

This gap can be addressed through improved baseline establishment and monitoring design. However, in practice, short project cycles, fragmented indicator systems, and limited integration of soil health metrics have constrained the systematic collection of biophysical outcome-based data. As a result, standardized and comparable soil health data across CSA contexts remains limited. Without baseline measurements and long-term tracking, it is difficult to verify whether CSA interventions meaningfully improve soil health and deliver sustained benefits across the core objectives of CSA.

Why soil is the missing resilience metric

Incorporation of outcome-based monitoring is critical for the next phase of CSA. There is an urgent need to complement activity-based monitoring with outcome-based reporting using indicators that capture changes in soil-mediated ecosystem functions and services, including climate and water regulation, nutrient cycling, and habitat provision for biodiversity. In this context, monitoring measurable changes in soil carbon and other key soil health indicators over time is essential. Such indicators provide insight into underlying ecosystem processes that are central to assessing climate adaptation and mitigation outcomes. Only by tracking these outcomes can CSA credibly demonstrate its contribution to broader climate and restoration goals.

Longitudinal, outcome-based soil health monitoring allows practitioners to assess the impacts of land management practices, support adaptive management, and prioritize interventions to improve landscapes and livelihoods. This requires hard data to reveal the impact of CSA interventions on soil health. Soil health monitoring has already demonstrated long-term resilience and improved the effectiveness of NbS initiatives in the United Kingdom (Giuliani et al., 2024).

Operationalizing soil health monitoring at scale

Consistent and robust monitoring frameworks that enable us to generate vital data on the impacts of land management on soil health, and to leverage these data to inform policy and practice are needed for evidence-based decision making. This necessitates data standardization, comparability, and repeatability in measurement that can be implemented over diverse contexts. Key elements to a successful monitoring framework include: (1) On-the-ground data collection with active participation of local communities streamlined with robust, easy to use data collection tools; (2) Development of relational databases for easy uploading and harmonization of data, enabling rapid data processing, analysis; (3) Data analytics, including combining field data with remote sensing data to track trends over time; (4) Interpretation and sharing of data and outputs for decision support for stakeholders. The indicators should follow the S. M. A. R. T framework, ensuring they are specific, measurable, attainable, relevant and time-bound (Doran, 1981), and indicator selection must depend on repeatability, functional relevance, sensitivity to change, and context-specific thresholds. Moreover, data collection must include biological, chemical and physical metrics alongside land use, historical and social indicators that demonstrate a holistic perspective on soil health. This process and its essential elements are illustrated in Figure 2.

The Land Degradation Surveillance Framework (LDSF) is an example of a robust field-based monitoring approach that enables systematic assessments of soil health, land degradation and vegetation diversity (Vågen, 2025). Implemented in over 45 countries

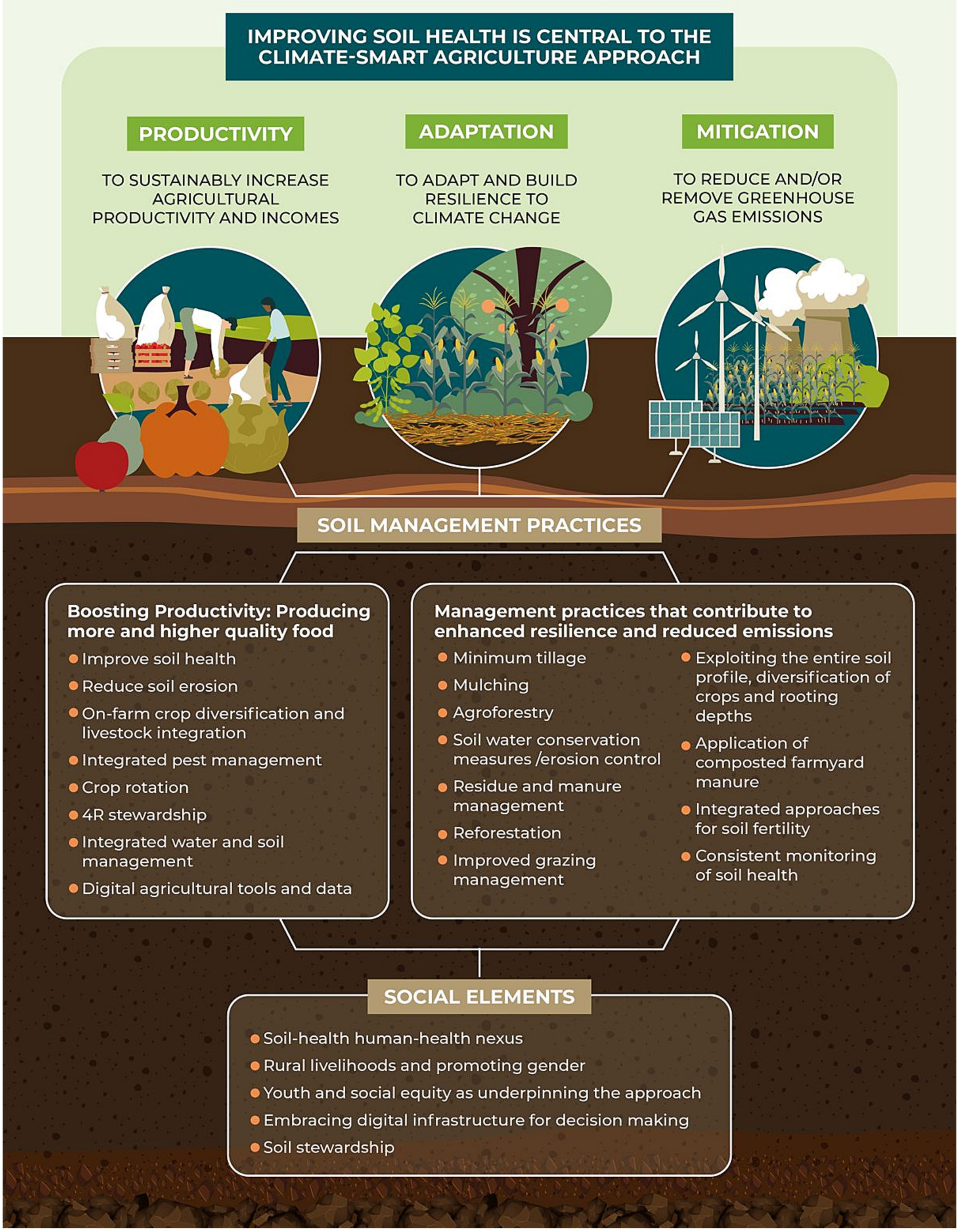

FIGURE 1
Soil health management as a central component of CSA (Source: CIFOR-ICRAF).

across the global tropics, the LDSF is the largest geo-referenced database of soil and land health indicators, enabling the production of accurate soil properties maps (Vågen et al., 2012; Vågen et al., 2016; Winowiecki et al., 2022). It combines a simple but robust field sampling design, laboratory analysis using soil spectroscopy to reduce cost, and advanced data analytics coupled with remote sensing. The LDSF can be integrated with other approaches, including household surveys and citizen science tools such as the Regreening App, addressing key monitoring bottlenecks. Applying this approach could help evaluate how CSA practices influence soil health, and the resulting evidence can then inform decision-making, as described in Box 1.

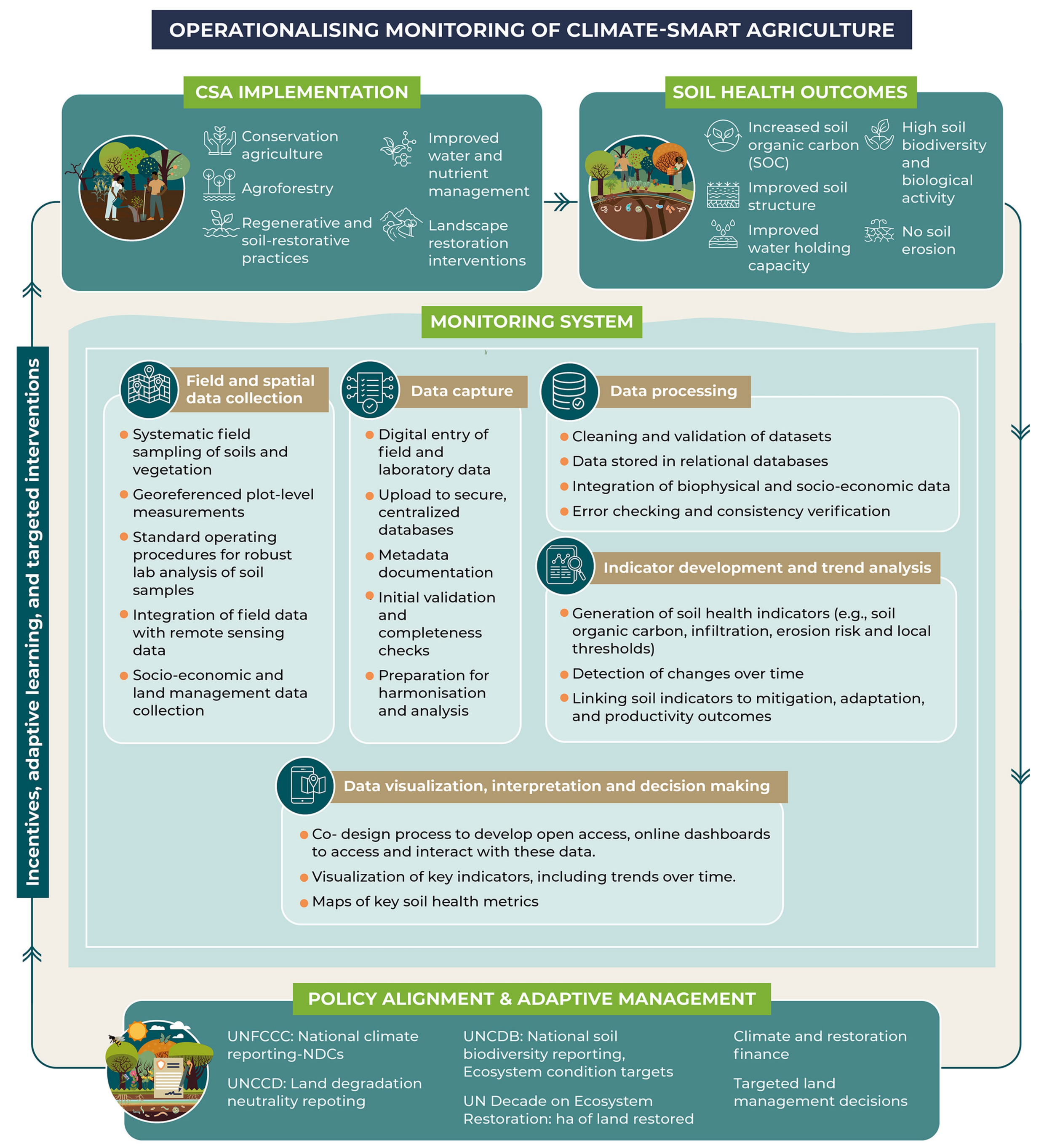

FIGURE 2
Operationalizing soil health monitoring through CSA and in alignment with policy (Source: Authors).

Policy alignment opportunities

Over the past decade, there has been significant progress in embedding CSA within global policy discourse, including the three Rio Conventions (Figure 2). Under the Climate Convention (UNFCCC), CSA is widely referenced as an approach that simultaneously advances mitigation, adaptation and food security. The Convention to Combat Desertification (UNCCD) includes SOC in the Land Degradation Neutrality framework. The Convention on Biological Diversity, through the Kunming–Montreal Global Biodiversity Framework, calls for monitoring ecosystem integrity, including soil biodiversity and ecological function. However, reporting systems and specific indicators across the Rio Conventions still require further harmonization (WWF, 2024). For example, while SOC is recognized under UNCCD, its systematic integration into adaptation metrics, biodiversity monitoring, and CSA performance frameworks remains underdeveloped.

Crucially, it is at the level of Member States that these shifts must take place. Land Degradation Neutrality (LDN), Nationally Determined Contributions (NDCs), National Adaptation Plans (NAPs), national biodiversity strategies and National Agricultural Investment Plans are where budgets are allocated, policies are implemented and progress is measured. It is within and across these national and local systems that soil monitoring must be

BOX 1 Subnational monitoring of soil and land health: the application of the LDSF in Makueni County, Kenya

The 2023–2025 UK PACT project, "*Delivering nature-based solution outcomes by addressing policy, institutional, and monitoring gaps in forest and landscape restoration*," applied the LDSF to strengthen Kenya's monitoring capacity and provide county decision makers with evidence to guide NbS interventions.

The LDSF was used to assess soil and land health as well as management practices across two 10,000 ha landscapes in Kalamba and Mbooni in 2024 and 2025. About 59% of farmers were applying inorganic fertilizers, 31% were using farmyard manure, and almost 84% were implementing some form of soil and water conservation in croplands. In Mbooni, 90% of cropland plots had trees, while this number was 75% in Kalamba, highlighting the importance of agroforestry in the study area.

The highest concentrations of SOC were found in woodlands (median = 30 gC/kg), while median SOC in croplands was about 11.1 gC/kg. Within croplands, plots applying farmyard manure had somewhat higher SOC (12.7 g/kg) than plots without this practice (11.1 g/kg). Soil erosion prevalence (sheet, rill or gully) was high in croplands at about 66% of the plots surveyed. Maps of SOC were developed at 30 m resolution to track changes over time.

These findings directly informed localized planning priorities. The high erosion prevalence in croplands and relatively low SOC levels relative to woodland benchmarks point to potential intervention areas for county investment in soil and water conservation. The difference in SOC between plots with and without farmyard manure provides evidence for extension services to promote organic soil management. Finally, the uptake of agroforestry in Mbooni can be documented against national restoration targets, like Kenya's AFR100 commitments, and used to demonstrate progress in sub-national reporting cycles. It is critical to support systematic, evidence-based stewardship of land resources, strengthening resilience, contributing to sustainable food systems, and better connecting local practice with national climate and land-use goals (Winowiecki et al., 2025c).

institutionalized if global commitments are to translate into measurable realities (AICCRA, 2022), and many countries are making headway in this regard (Diwediga et al., 2022; Winowiecki et al., 2025a).

Integrating measurable soil health indicators into policy frameworks, strategies and local sectors can strengthen accountability, enhance policy coherence and improve the integrity of public expenditure. For example, investment flows can shift from financing inputs toward supporting interventions that demonstrably improve SOC, reduce erosion, enhance water retention and stabilize yields. Encouragingly, discussions on embedding soil health metrics more systematically within continental policy frameworks are gaining momentum, for example, in Africa through the Comprehensive Africa Agriculture Development Programme (CAADP) Strategy and Action Plan (2026–2035) [African Union (AU), 2025].

Conclusion

Two decades of research have provided consistent evidence that healthy soils are indispensable to climate-resilient food systems. Soil health directly underpins the core objectives of CSA and is the biophysical foundation through which CSA delivers resilience. Yet despite its importance, soil remains the missing resilience metric across much of the CSA landscape. Monitoring systems in many countries primarily measure the adoption of CSA, rather than the outcomes these practices are intended to produce. As a result, programmes report widespread uptake while lacking evidence that agroecosystems themselves are becoming more resilient. Without measuring soil health, it remains difficult to verify whether CSA is achieving system-level resilience or simply promoting a portfolio of practices.

Outcome-based soil health monitoring offers a pathway to close this gap. By measuring specific soil health indicators, it becomes possible to align research, policy and implementation across climate, land degradation and biodiversity agendas. A robust monitoring infrastructure centred on soil health also shifts attention away from short project cycles and toward long-term stewardship, tracking changes over time. Encouragingly, operationalizing this type of monitoring is feasible. The LDSF demonstrates that consistent, standardized and spatially explicit soil and land health monitoring can be implemented at scale.

A call to action for CSA monitoring reform

The next phase of CSA requires a shift in emphasis: from scaling practices to measuring outcomes; from project-based reporting to landscape-level assessment; and from short-term interventions to sustained land stewardship.

We present the following calls to action:

- Adopt outcome-based reporting in addition to practice-based.
- Link soil outcomes to resilience metrics, with yield stability, water-use efficiency and climate shock buffering explicitly tied to soil parameters.
- Embed soil indicators as foundational performance metrics in CSA monitoring systems.
- Standardize soil indicators to enable aggregation and comparison across reporting systems.
- Integrate soil monitoring within local, national and global frameworks.
- Request outcome-based reporting as a funding pre-condition, requiring verified soil health indicators.
- Fund monitoring infrastructure to accompany CSA interventions.
- Support longitudinal monitoring commitments.
- Support proven monitoring systems, such as the LDSF, that demonstrate that rigorous soil monitoring is feasible at scale.
- Institutionalize soil monitoring within agricultural extension services, statistical systems and national environmental reporting mechanisms.
- Integrate soil metrics into national and regional strategies.
- Institutionalize cross-ministerial coordination and joint oversight of soil data systems to avoid fragmented reporting.
- Prioritise soil data as strategic infrastructure for national resilience planning.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

LW: Conceptualization, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

AB-T: Conceptualization, Writing – original draft, Writing – review & editing. RChe: Conceptualization, Writing – original draft, Writing – review & editing. HL: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. ST: Conceptualization, Writing – original draft, Writing – review & editing. DA: Writing – original draft, Writing – review & editing. JB: Writing – original draft, Writing – review & editing. RCha: Writing – original draft, Writing – review & editing. JH: Writing – original draft, Writing – review & editing. AK: Writing – original draft, Writing – review & editing. LN: Writing – original draft, Writing – review & editing. IB: Writing – original draft, Writing – review & editing. LO: Writing – original draft, Writing – review & editing. ZP: Writing – original draft, Writing – review & editing. SS: Writing – original draft, Writing – review & editing. ZS: Writing – original draft, Writing – review & editing. BT: Writing – original draft, Writing – review & editing. T-GV: Writing – original draft, Writing – review & editing. RL: Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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