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WORLD ECONOMIC FORUM

Scaling Technology Adoption for Soil Health: A Focus on Africa

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Foreword

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Sustainable food systems need healthy soils, yet little is done to scale up innovations and technologies to improve the condition and reverse the degradation of our soils. Protecting this vital resource is a shared responsibility for farmers, scientists, companies, consumers and governments to ensure we preserve the bedrock of our food. Several technology solutions and sustainable processes exist, but what is missing is their adoption in practice due to affordability and lack of knowledge, among other reasons.

In a rapidly digitalizing world, data and technology applied directly to improving soil health could unlock a multitude of co-benefits, from better nutrition and carbon sequestration to restoring biodiversity, building resilient farmer livelihoods and improving water retention. Innovations in precision agriculture, satellite imagery, sensor technology and artificial intelligence (AI) present excellent opportunities to restore and improve soil quality. While grappling with the threats of soil degradation, biodiversity loss and climate change, it is imperative for everyone to get on board and work together.

Businesses that create soil health products require better awareness of how to produce appropriate and context-specific solutions while incorporating traditional knowledge that has protected our soils for millennia. On the other hand, governments need to foster enabling environments that balance the effort, monitoring and cost of maintaining healthy soils. Most important is the implementation of a farmer-centric approach that not only acknowledges the role of farmers as custodians of their lands but also offers them the right support to develop more capabilities as the first line of defence.

In creating an ecosystem that allows seamless cooperation towards one goal, harmonization of soil data resources is key, paving the way for novel technologies such as AI that can help generate useful insights from the massive troves of data that would otherwise be of little use. By investing in and creating space for learning exchange and collaboration to take place, we will unlock new opportunities for soil health.

Executive summary

Ambitious action – with data and digital infrastructure at its core – is needed to deliver tangible improvements in soil health.

About 95% of all food supply relies on healthy soils, yet nearly a third of agricultural land globally is degraded. Understanding the components of healthy soil – including stored organic carbon, nutrient density, biodiversity and water retention – is critical to growing healthy, nutritious food and transforming the food system into a carbon sink rather than a carbon emitter.[1]

This paper explores the possibilities for collaboration and adoption of existing solutions and technologies to review soil health at scale, build stakeholders' capabilities, highlight investment-worthy innovation opportunities and provide fresh perspectives at the global forefront of innovations crucial to soil health.[2] Food security and closing yield gaps in Africa – and the contribution of soil health to both outcomes – are the vital concepts whose connections to one another have been analysed in the paper.

The paper proposes five recommendations with the greatest potential impact on food security, yield and soil health, which have been reached by answering the following two questions:

1 What will enable farmers to make better decisions on soil health?

- **Recommendation 1. Enhance extension services:** Consulting farmers on what agronomic advice could be provided to them to strengthen their capabilities (e.g. informed crop planning and risk management) is an effective measure for supporting farmers in adopting sustainable farming practices, alongside recommendations on how to access financial resources.

- **Recommendation 2. Digitalize agriculture:** Ensuring the availability of data – on the delivery of inputs (e.g. fertilizers and seeds), extension services (including those related to training on climate-smart agriculture) and markets (e.g. information on buyers) – would provide the building blocks for future digital agriculture. This could be enhanced with adequate data to customize fertilizer formulations, seed traits or training activities. These foundations need to address governance and deliver net benefits to farmers through improved data interoperability, enhanced digital policies and digital inclusion.

2 What practices and inputs need to be promoted to deliver a real impact on soil health?

- **Recommendation 3. Apply climate-smart agriculture:** Enabling soil erosion management interventions is essential to mitigate the effects of erosion on agricultural lands.

- **Recommendation 4. Reverse fertility decline:** Increasing the availability of fertilizers is important in addressing the issue of nutrient depletion across the African continent.[3] This intervention is crucial for bridging the yield gap and boosting agricultural productivity through soil health and fertility restoration.

- **Recommendation 5. Research and develop other high-quality inputs:** Working to develop high-value inputs – such as quality seeds and cultivars from crops adapted to local conditions – is vital to enhance agricultural productivity and sustainability.

These recommendations are based on analyses of the agricultural potential and readiness to adopt technologies for soil health of seven African countries: Ghana, Nigeria, Côte d'Ivoire (Ivory Coast), Kenya, Tanzania, Zambia and South Africa.

If the rate of adoption of improved fertilization, high-quality seeds and climate-smart agriculture was raised by 10 percentage points compared to today's levels, a combined improvement in yields of 882,817 tonnes and $1 billion in terms of farm income would be achieved in four of the studied countries (Ghana, Nigeria, Kenya and Tanzania)[4] – a clear statement of the transformative potential of acting on soil health to improve yields and food security (see Section 3 for a more detailed explanation). Extension services and digital agriculture, on the other hand, are proven catalysts of positive change in smallholder communities that should be put at the centre of the transformative process.

To realize the identified potential, the ecosystem can already count on some crucial advantages – but with some important caveats:

- Farmers have accumulated knowledge that enables them to gauge effectively the challenges they face – what they lack for the most part are the tools and means necessary to undertake the necessary changes.

- International organizations, the region's governments and private actors are investing heavily in addressing some of the identified challenges. However, these initiatives still need to overcome barriers related to the development of fully customized products (e.g. fertilizers and seeds), including issues with increasing the reach of supply chains in remote areas, building the capability of farmers to become more efficient in their agronomic decision-making, involving the private sector more actively and enhancing current policies, with the aim of encouraging inclusiveness, trustworthiness and transparency in the agricultural system.

- Improving the reach and impact of existing initiatives and enabling the adoption at scale of technology solutions requires multistakeholder collaboration, which agricultural platforms – such as the World Economic Forum's Food Innovation Hubs and 100 Million Farmers – can provide.

Introduction

Data and digital infrastructure have a crucial role to play in enabling farmers to improve soil health in sub-Saharan African.

In Africa, where agriculture sustains millions of livelihoods while the population is poised to nearly double by 2050, there is an urgent need to act on food security. The imperative to ensure food security reaches beyond Africa to the world: holding 60% of the world's remaining arable land, Africa's potential to contribute significantly to global food networks is undeniable.

Known for its production of maize, coffee, cocoa and various fruits, Africa plays a crucial role in the global agricultural landscape. However, the region faces challenges such as declining soil fertility and low soil organic carbon (SOC) levels and lacks adequate replenishment of those nutrients, exacerbating soil degradation. Climate change highlights this challenge, with extreme weather conditions disrupting agricultural productivity.

Africa's agricultural landscape is remarkably diverse, shaped by its varied climates and soils across different regions. Despite the richness of its resources, however, sub-Saharan Africa remains a net food importer. While imports might make food affordable in the short term, they weaken local production systems and potentially compromise long-term food security. This fragility is felt more intensely when paired with adverse phenomena such as the severe drought afflicting East Africa.[5] The system's weakness can be seen in the 25% undernourishment rate affecting households.[6] Acknowledging the magnitude of these challenges and Africa's pivotal role in global food security, the World Economic Forum has brought significant attention to bear on the role of soil health in the pursuit of food security. As awareness among leaders and stakeholders grows, efforts are intensifying to narrow the yield gap and bolster agriculture's resilience to climate change, with soil health taking centre stage.

Unsustainable land use practices, climate change, nutrient depletion, soil acidification and soil erosion have been recognized as significant contributors to soil degradation over time. To address these issues and restore and improve soil health, locally tailored practices that include agroforestry, integrated soil fertility management, crop rotation, intercropping, diversification of crops or cover cropping must be adopted. Moreover, high-tech and data-based solutions should be used, such as app-based advisory and decision-support tools, spatially explicit mapping and monitoring of soils to prioritize interventions as well as track changes over time. Additionally, coupling the use of field-based surveys with advances in soil spectroscopy and drones for remote sensing and monitoring of soil properties such as moisture and temperature from above, together with sensors to continuously monitor SOC, pH and nutrient contents are key. The outputs are fed into integrated systems that collect the data on soil, analyse it and support decision-making.

Safeguarding soil health is a collective responsibility that demands collaborative action, which implies providing farmers with the proper training, as they are the crucial player in these efforts. Governments, international and regional organizations, the private sector, universities and civil society increasingly show an awareness of the key role that African farmers can play in feeding the world while maintaining sustainable farming practices. Public and private initiatives are already under way to realize this potential, promoting adoption at scale of regenerative practices and innovative technologies.

Of the seven African countries discussed in this paper, Kenya needs a boost in its agricultural production, given that 63% of its arable land is affected by soil acidity and its vital nutrients are depleting,[7] while Tanzania has high potential to boost agricultural production as well, but has 32.7 million hectares covered by acidic soil.[8] On the other hand, South Africa, losing 400 million tonnes as waste from the agricultural sector, also needs to address soil degradation. Lastly, Côte d'Ivoire (Ivory Coast), Nigeria and Ghana all exhibit significant room for improvement, yet contend with land degradation issues, leading to diminished crop yields and impeding efforts towards sustainability.

> **Healthy soils are the foundation of resilient and productive food systems. In Africa, maintaining healthy soils is essential to agriculture that produces food and supports livelihoods and economies. FAO is fully committed to advancing sustainable soil management practices that restore and improve soil health, address various soil threats including climate challenges and contribute to food security across the continent.**
>
> Lifeng Li, Director, Land and Water Division, UN-FAO

1 Challenges and solutions

While progress has been made in soil nutrient management in Africa, the increasing soil erosion rates have led to SOC depletion and fertility loss.

Food security, particularly in Africa, is an area of increasing concern given the continent's potential future role in global food networks. However, challenges such as low agricultural productivity and soil degradation, compounded by the lack of adequate soil data, constrain progress and prevent the continent moving on from being a net importer of food. Efforts are being made to promote soil health through sustainable land management practices, with initiatives aimed at empowering farmers and improving soil fertility to bolster agricultural sustainability, but these are still hampered by limited availability of important inputs such as fertilizers.

Soil erosion, soil fertility and SOC were selected as benchmarks for evaluating soil productivity due to the importance of assessing soil health. Soil erosion, driven by climate change and human activities, leads to the loss of fertile land and negatively affects agricultural productivity. Soil fertility, on the other hand, refers to the soil's ability to sustain plant growth by providing essential nutrients. Additionally, SOC plays a crucial role in maintaining soil structure, regulating the hydrologic cycle and ensuring fertility. Declining SOC levels can affect soil productivity and contribute to soil degradation. By studying these indicators of soil productivity and implementing targeted interventions to optimize fertility, mitigate erosion and enhance organic carbon levels, sustainable agricultural practices and long-term soil health can be ensured.

1.1 East Africa: Kenya and Tanzania

In recent years, the state of soil health and agricultural productivity in East Africa has raised concerns, revealing various parameters in need of improvement. Notably, rising soil erosion rates have compounded the consequences of declining soil fertility. This trend, combined with unsustainable soil management practices, has contributed to a consistent yield decline.

Moreover, the conversion of natural landscapes into croplands has emerged as a significant factor in the region's soil health challenges. This conversion has led to a marked reduction in SOC content, intensifying the need for efforts to maintain soil fertility and productivity.

The analysis in this paper, informed by recent data, has revealed trends such as increased soil loss through erosion (primarily from farms) and inconsistent trends in fertilizer consumption among countries. These trends have significant impacts on SOC levels and agricultural productivity, underscoring the urgent need for sustainable soil management practices.

“Food security, particularly in Africa, is an area of increasing concern given the continent's potential future role in global food networks.

Detailed analysis

Soil erosion rates in East Africa have shown a significant increase over the past few decades, particularly between 1995 and 2017.[9,10] During this period, the average soil loss through various erosion processes rose from 0.3 tonnes/hectare/year (t/ha/yr) to 0.5 t/ha/yr. Unsustainable farming practices are the main contributors to soil loss, accounting for more than 50% of total erosion.[11] The highest erosion rates were observed in areas where forests were cleared for farming, underscoring the negative impact of land use changes on soil stability.

In terms of fertilizer consumption, Kenya has shown a significant increase in the use of the main nutrients (nitrogen, phosphate and potash) with fluctuations in usage since 1961, but suffered a setback between 2020 and 2022, with a reduction of 42% in usage mainly due to international market price increases and geopolitical instability.[12] The annual growth rate for fertilizer consumption in sub-Saharan Africa has been estimated at a

compound annual growth rate (CAGR) of +3.9% for the period 2013–2021.[13] This suggests a growing awareness of the importance of fertilizers in boosting agricultural productivity and soil fertility across the region complemented by improved access.

Despite this regional growth in fertilizer use, the transformation of natural landscapes into croplands presents ongoing challenges, such as the significant reduction in SOC content. Across various sites, the decline in SOC over 19 years ranged from 13% to 42% of the initial SOC content, highlighting the negative effects of land use changes on soil health.[14] Overall, this results in the loss of 8.8 megatonnes (Mt) of SOC from the soil every year through soil erosion, a non-negligible contribution to greenhouse gas (GHG) emissions and climate change.[15] However, agroforestry systems have shown potential in mitigating SOC loss by promoting low bulk density (weight of soil per given volume) and enhancing soil volume through organic matter accumulation.[16]

Interventions in the region have included improved access to fertilizers and enhanced land management techniques, which are crucial for mitigating the adverse effects of soil erosion and degradation observed across East Africa. These efforts focus on promoting sustainable agricultural practices that align with the specific needs of different agro-ecological zones. Initiatives such as the distribution of targeted fertilizer blends aim to improve soil fertility tailored to local conditions, enhancing yield, which, in turn, will be a key enabler in avoiding further conversion of natural landscapes into cropland.

Geographical differences in crop yields within East Africa reflect diverse agro-ecological conditions and land management practices. In Tanzania, for example, mean yields varied significantly between regions and were influenced by fertilizer application rates. While some areas recorded high yields with optimal nutrient inputs, others experienced lower productivity levels, emphasizing the need for targeted soil fertility management strategies tailored to specific agro-climatic zones.[17]

In the Usambara Mountains of Tanzania, it is estimated that 50% of the carbon has been lost due to land use change from forest to maize cultivation.[18] Throughout the country, eroded soils had the lowest SOC across land uses.[19] Establishing bench terraces with zoned tillage could reduce soil losses by greater than or equal to 75%, up to 87.1 t/ha/yr. These reductions are comparable to the effects of converting croplands to natural vegetation, demonstrating that most agricultural soils can be conserved successfully.[20]

Analysis shows a general tendency for higher yields with an effective combination of SOC inputs and mineral fertilizer. According to a 2021 report by Taylor et al., “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.”[21] This also highlights the need for regional thresholds.

“In the Usambara Mountains of Tanzania, it is estimated that 50% of the carbon has been lost due to land use change from forest to maize cultivation.

1.2 West Africa: Nigeria, Ghana and Côte d’Ivoire

The state of soil health and agricultural productivity in West Africa has become a major concern, with several important issues highlighting the need for urgent intervention. Severe soil erosion in countries such as Nigeria, Ghana and Côte d’Ivoire has intensified the challenges of maintaining soil fertility and structure.

Additionally, the high cost and limited availability of mineral fertilizers have led to widespread nutrient depletion across the region, with Ghana and Côte d’Ivoire experiencing some of the most severe impacts. This situation is aggravated by the critically low levels of SOC observed, particularly in areas of intensive cultivation and mining, further compromising the soil’s ability to support healthy agricultural practices.

The analysis indicates a concerning trend of increasing soil loss primarily due to erosion and deforestation, alongside inconsistent and often insufficient fertilizer use. These issues have implications for SOC levels and overall agricultural productivity, emphasizing the need for sustainable soil management strategies in the region. Such strategies must prioritize both the reversal of degradation trends and the enhancement of soil health to ensure the long-term viability of agriculture in the region.

Detailed analysis

Soil erosion is a challenge in Nigeria, with 37.5% of the total area experiencing light degradation, 4.3% moderate, 26.3% high and 27.9% very high.[22] Such erosion affects the infrastructure, contributing to road and building damage, and complicates efforts to alleviate poverty, costing more than $100 million annually mostly in southeastern Nigeria.[23] This contributes to one of the highest rates of soil nutrient depletion in sub-Saharan Africa. Soil erosion in Côte d’Ivoire remains an under-addressed issue, worsened by insufficient data collection and unpreparedness for climate change.[24]

Addressing soil erosion, soil fertility, SOC depletion, pesticide contamination and the adoption of sustainable land management practices will ensure agricultural sustainability and environmental resilience in West Africa.

Challenges in soil fertility are evident; with the high cost of mineral fertilizers, Nigeria is limiting the use of essential inputs. Despite rising fertilizer demand, local production has not met needs, leading to nutrient depletion and concerns about shrinking cultivable land per capita, projected to decrease by more than 80%, from 0.85 hectares (ha) in 1997 to 0.15 ha by 2050.[25] Ghana faces soil fertility issues, with annual losses estimated at 35 kilograms (kg) of nitrogen, 4 kg of phosphorus and 20 kg of potassium per hectare.[26] Additionally, toxicities from metals such as zinc and aluminium highlight soil fertility problems.[27] Côte d'Ivoire faces growing concern about the depletion of soil fertility, partially due to the lack of consistent data and effective soil management strategies to counteract erosion and nutrient loss.

Specific data on SOC levels for Nigeria is limited, but the widespread soil degradation suggests significant impacts on SOC. SOC content in Ghana is low, especially in mined areas, where levels are as low as 0.14%, indicating severe ecosystem disruption and challenges to soil health.[28] Low SOC levels are prevalent in Côte d'Ivoire, affected by practices such as crop residue removal and high decomposition rates. However, agroforestry and organic fertilizers have shown potential in increasing SOC levels and improving soil health in the Southwest region of the country. Reforestation and green cover promotion have been proposed to mitigate soil loss, with some areas seeing reductions of up to 98%.[29]

Soil erosion rates vary widely across Nigeria, from between 5 and 120 t/ha/yr in the west to an alarming 4,185 t/ha/yr in Katsina, northern Nigeria.[30] Erosion reduces arable land area and depletes fertile soil. Despite high demand, fertilizer use remains low. In 2021, Nigeria consumed more than 1.8 million tonnes of fertilizer (primarily urea), but inadequate local production leads to heavy reliance on imports and high costs for farmers.[31] The negative nutrient balance highlights declining soil fertility, widening the yield gap. Targeted interventions and sustainable land management practices, including enhancing SOC through land restoration, can improve soil health and boost yields.

In Ghana, cocoa production faces a yield gap suggesting the loss of fertility over time. Consequently, uniform fertilizer application across regions with varying soil characteristics is challenging. General soil conditions – low pH, low cation exchange capacity[32] and low SOC content – require tailored approaches. Optimizing nutrient availability by tailoring fertilizer formulas to match regional soil needs (especially nitrogen and phosphorus deficiencies) could substantially close the yield gap.

Overall, addressing soil erosion, soil fertility, SOC depletion, pesticide contamination and the adoption of sustainable land management practices will ensure agricultural sustainability and environmental resilience in West Africa.

1.3 Southern Africa: South Africa and Zambia

The decline in soil health conditions and agricultural productivity in South Africa and Zambia highlights the need for improvements. In South Africa, soil erosion is extensive, affecting a large area with varying severity due to intensive farming and overgrazing practices.

Moreover, the conversion of natural landscapes into croplands has also significantly compromised soil fertility in both countries. Poor nutrient management over the years has led to reduced soil fertility, emphasizing the importance of improved fertilization strategies to enhance agricultural productivity.

The analysis for this paper has revealed which trends have significant impacts on SOC levels and agricultural productivity, underscoring the imperative for comprehensive and sustainable soil management practices across both South Africa and Zambia to reverse the degradation trends and secure the long-term viability of agriculture in the regions.

Detailed analysis

Soil erosion has become a concern in South Africa, with studies indicating rates from 0 to 25 t/ha/yr, and some areas experiencing higher rates.[33] Approximately 61 million ha are classified as moderately to severely vulnerable, and an additional 91 million ha as having low to very low vulnerability.[34] The national average soil loss rate is 12.6 t/ha/yr, with croplands experiencing about 13 t/ha/yr, far exceeding the natural soil formation rate of less than 5 t/ha/yr.[35] Extensive tillage-based cultivation and overgrazing affect more than 60% of the land used for farming, driving this degradation and emphasizing the need for sustainable land management practices to mitigate its effects on agricultural productivity and environmental sustainability.[36] The erosion challenges are comparable to those in Zambia, affecting agricultural productivity and land sustainability.

Reduced soil fertility results from deforestation and poor nutrient management, with significant nutrient losses in South Africa over the past 30 years, including an average of 660 kg of nitrogen, 75 kg of phosphorus and 450 kg of potassium per hectare.[37] These losses create challenges for maintaining productive soils and supporting sustainable agricultural outputs. The low use of fertilizers, averaging only 8 kg/ha, underscores the inherently low fertility of soil in Zambia. The wide gap between potential yields in experimental settings (up to 8–12 t/ha) and actual yields achieved by farmers (around 1–1.2 t/ha) highlights the critical need for improved nutrient management and fertilizer application strategies to bridge this gap and enhance crop productivity.[38] In most farmers' fields in Zambia, yields for maize are around 1–1.2 t/ha compared to a potential of 8–12 t/ha in on-station trials and commercial farms.[39]

The organic carbon content in topsoils in South Africa is low, with only 4% of soils containing more than 2% organic carbon and 58% containing less than 0.5%.[40] These levels indicate very low organic matter levels, which are detrimental to soil health and agricultural resilience. Low SOC levels are also highlighted in Zambia, particularly in agricultural systems, with average organic carbon content reported at between 0.5% and 1% and at even lower levels in cultivated soils. This depletion in SOC is a significant concern, affecting soil structure, fertility and the ability to support healthy crop growth.[41]

The challenges of soil erosion, declining fertility and low SOC levels in South Africa and Zambia are stark, and it is important to address these issues if agricultural productivity and sustainability are to be improved in these countries. Strategies such as enhancing soil management practices, increasing the use of fertilizers and implementing soil conservation techniques are critical for reversing the degradation trends and ensuring the long-term viability of agriculture in both countries.

> The conversion of natural landscapes into croplands has significantly compromised soil fertility in both countries.

2 Farmers' knowledge of soil health

What farmers know about soil health is key in designing scientifically sound interventions.

Frequently, the knowledge that farmers have, based on qualitative data such as soil colour, is aligned with objective laboratory results. However, misunderstandings concerning the quality of available fertilizers can further hamper the roll-out of an already scarce product.[42] In addition, one-size-fits-all recommendations to apply fertilizer without regard for local soil conditions has resulted in a long-term yield decline in certain African regions – with a notable example being the single recommendation for West African rice, despite three different cultivations giving different yields.

The next section illustrates instances of farmers' soil health knowledge, gleaned from farms in the seven African countries of focus, through:

1. A discussion of survey results related to farmers' soil health knowledge
2. Identification of the main indicators that farmers use to assess soil health
3. Assessment of farmers' effectiveness in judging soil health and how they take the most appropriate action

> **With Africa's soils facing degradation and fertility loss, urgent action is needed to rehabilitate arable soils. Access to accurate soil data has never been more crucial. Yara is proud to be investing in innovative initiatives such as Soil Health data (SoilHive) to respond to today's calls. By addressing critical challenges such as acidic soils, we aim to empower farmers across Africa. Our goal is to improve their livelihoods, enhance soil fertility and support a sustainable, nature-positive future for Africa.**
>
> Luis Alfredo Pérez, Senior Vice-President, Business Unit Africa, Yara International

2.1 Ghana

Farmers' knowledge and the main indicators

Farmers in Ghana's Eastern and Northern regions acknowledge soil erosion as a major issue affecting soil health. They attribute this to over-cultivation, deforestation and heavy rainfall.

- In the Eastern and Northern regions of Ghana, 95.7% and 86.7% of farmers, respectively, acknowledged soil erosion as a serious problem.[43]
- 80% of respondents in the Eastern region acknowledged severe erosion problems on homestead land, while in the Northern region, severe erosion was more noticeable on distant farmland (85.0%).[44]
- Over the past 10 years, 58.6% of farmers in the Eastern region and 75.0% in the Northern region acknowledged a worsening of soil erosion severity.[45]

Indicators of soil erosion identified by farmers include decreased productivity, shallow soil depth, the presence of rills, sheet erosion, soil loss and changes in soil colour.[46] The use of non-tactile and non-visible indicators, such as soil mineral composition and soil microorganisms, was not common.

Overall, the indicators used aligned with scientific reports, but there were knowledge gaps, especially in the use of indicator plants (whereby it is possible to determine the state of the soil depending on the specific type of weeds that appear). The use of these plants to determine soil health was influenced by factors such as weed control, soil benefits and potential threats to crops.[47]

2.2 Nigeria

Farmers' knowledge and the main indicators

Farmers and scientists in Nigeria recognize the decline of soil health and overwhelmingly identify desertification as the foremost threat to soil health.[48]

- They identify desertification, a process that severely hampers soil fertility and agricultural yield, as the main culprit (80.2% of farmers).
- Soil erosion is mentioned as a factor that compounds the effects of desertification (88.3%). Erosion processes such as soil erosion strip away the nutrient-rich topsoil, reducing soil depth and degrading its structure, which further undermines its productivity.

The top 10 qualitative indicators for assessing soil health are: organic matter, crop appearance, erosion, earthworms, drainage, tillage ease, soil structure, pH, soil tests and yield.[49] Qualitative and quantitative measures (nutrient availability, nutrient retention, root penetration, biotic environment, water entry capacity and ability to resist degradation) have significant positive correlations.[50]

2.3 Tanzania

Farmers' knowledge and the main indicators

Farmers believe soil health is declining, as expressed in a study conducted in the north of the country. Around 68% of farmers complained of decreased soil fertility. Several factors were mentioned as the causes of this decline,[51] including soil erosion (77%), the extensive grazing that is common in the area (72%) and the burning of crop residues (78%).

Overall knowledge of soil health was limited, with 47% of households lacking knowledge of soil fertility management. This resulted in misconceptions, such as farmers incorrectly identifying mineral fertilizer application as a driver of soil destruction. This is partially explained by the unfounded belief that the available fertilizers are substandard, even if lab analyses prove otherwise.[52]

Farmers mainly relied on the presence of certain weeds and stunted plant growth as indicators of poor soil health in the north of the country. Other studies have identified "hoe-ability", soil crushing, its smell and rate of water retention as proxies for soil health indicators.[53]

As a response, interventions were adopted by a limited number of farmers,[54] mainly: fallowing (7% of farmers), ridges (4%), crop rotation (11%), intercropping (38.4%) and the availability and use of manure on mixed farms – i.e. farms that also own livestock – (2%).

In trials studying the effects of conservation agriculture[55] on soil health, the implementation of conservation agriculture-related practices resulted in soil quality gains that were observable. However, these results were not as significant in sandy soils as they were in other types (e.g. lime), highlighting the need to adapt recommendations to local conditions.[56]

2.4 Kenya

Farmers' knowledge and the main indicators

Farmers in Kenya acknowledge soil erosion as a major issue affecting maize production in arid and semi-arid areas of the country. They attribute this to inadequate rainfall, low implementation of soil erosion mitigation measures, crop diseases and inadequate mineral fertilizers. The maize production trends in Kenya reveal significant concerns about declining yields.

– The study took place in Elgeiyo-Marakwet County, probing the trend of maize production in the study area from the year 2010 to 2014. The results showed that in Kenya, 73.1% of farmers reported that maize production has been decreasing, while 26.8% stated that yields have remained stagnant or are decreasing. Maize production has dropped from 44 million bags in 2018 to 34.3 million bags in 2022.[57]

– Factors contributing to low agricultural outputs include environmental degradation, soil erosion, minimal use of inputs (fertilizer, improved seeds and irrigation) and counterproductive agricultural policies (e.g. large Kenyan farms are getting more fertilizer subsidies than smallholders).[58]

This reflects the findings that emphasized the impact of rainfall distribution on crop yields, alongside soil quality, crop management systems and climate interactions.[59]

2.5 Southern Africa (South Africa and Zambia) and Côte d'Ivoire

The lack of large-scale studies on farmers' soil health knowledge in South Africa, Zambia and Côte d'Ivoire brings to the fore the need for such research to be conducted. Without this, any proposed course of action is unlikely to succeed as the knowledge farmers already have and their pain points are key.

In the case of South Africa, however, there are reports of farmers' perceptions of the occurrence of climate change[60] and its effects (at least in the Eastern Cape region) on soil health decline such as soil erosion.[61] Extreme meteorological events, such as heavy rainfall combined with increasing, longer-lasting drought periods, caused by climate change and leading to soil erosion, have been exacerbated by human intervention through some farming practices, deforestation and indiscriminate bush burning. The declining soil health has provoked poor livestock health, loss of grazing land, poor crop performance and meagre bush regrowth.

2.6 Effective mechanisms are needed to build on farmers' knowledge

Understanding the indicators and farmer knowledge is essential for formulating effective soil health interventions.

The first high-level conclusion based purely on the available data yielded by the analysis is that it is difficult to assess farmers' knowledge in South Africa, Zambia and Ivory Coast due to insufficient information.

For countries where data is available, analysis shows that although farmers have the type of knowledge that enables them to assess and improve the state of soil health, they need additional resources to implement necessary changes:

- Farmers have a strong sense of declining soil health and the impact it has on the productivity of their farms.[62] They see the effects of declining soil health in soil infertility and increased soil erosion.[63]
- Their impressions, which align with quantitative analysis conducted on their farms, are a result of the evaluation of visual or tactile (colour, structure) and functional (crop performance) criteria.[64] For instance, robust soil structure (qualitative) typically correlates with enhanced water entry capacity and nutrient retention (quantitative), leading to improved crop performance.

Even more interesting in some environments is that the improvements linked to the adoption of conservation agriculture are also visible through these assessments.[65] These correlations underscore the importance of integrating traditional knowledge with scientific methods to develop comprehensive soil health management strategies. Understanding the indicators and farmer knowledge is essential for formulating effective soil health interventions.

However, at a time when qualitative assessments of soil health fall short and traditional techniques for soil analyses are currently too expensive, digital agriculture and the availability of data become necessary elements.[66] Even if the assessment of soil health is correct, farmers often lack the resources and/or the training to implement some of the actions needed to overcome the effects of soil erosion – such as conservation agriculture practices and better application of fertilizers.[67] In addition, blanket recommendations and farmer misconceptions sometimes limit the effectiveness of the implemented actions.[68]

2.7 Key recommendations

> Ensuring the availability of data would provide the building blocks for future digital agriculture.

Farmers have the knowledge to make significant contributions to soil health improvements, but in what areas do they need support? Five recommendations emerge if the interventions in soil health are paired with the understanding of farmers' knowledge. These can be considered under the heading of two main questions:

1 How can farmers be enabled to make the best decisions?

Recommendation 1. Enhance extension services: Providing adequate agronomic advice and building farmers' capabilities are effective measures for supporting farmers in adopting sustainable farming practices, alongside recommendations on how to access financial resources.[69]

a. By offering tailored guidance on soil management, crop rotation, agroforestry and pest control, agronomic advisers can help farmers optimize their yields while minimizing the environmental impacts. Additionally, holistic agronomic advice can empower farmers to make informed decisions about resource use and crop selection, leading to more resilient and sustainable agricultural systems. By facilitating financing, improvements in mechanization that are vital for implementing certain practices are unlocked.

Recommendation 2. Digitalize agriculture: Ensuring the availability of data – on the delivery of inputs (e.g. fertilizers and seeds) and extension services (including those related to training on climate-smart agriculture) – would provide the building blocks for future digital agriculture. This could be enhanced with adequate data to customize fertilizer formulations, seed traits or training activities. These foundations need to address governance and deliver net benefits to farmers through improved data interoperability, enhanced digital policies and measures to ensure digital inclusion.[70]

a. These actions can improve the sustainability and efficiency of farms, personalize and lower the cost of delivering advice, bring efficiency to offtake supply chains and increase access to inputs and ancillary products such as insurance.[71]

b. This requires increased investment in monitoring systems, which produce the evidence needed to provide holistic extension services and track changes in soil health over time.

2 What practices and inputs need to be promoted to deliver actual impact on soil health?

Recommendation 3. Apply climate-smart agriculture: Enabling soil erosion management interventions is essential to mitigate the effects of erosion on agricultural lands.[72]

a. Implementing measures to prevent soil erosion, such as contour ploughing and terracing, can help preserve soil integrity and fertility.[73]

b. Climate-smart agriculture methods, such as minimal tillage and cover cropping, help to minimize soil disturbance and reduce erosion.[74] These practices also enhance soil structure and water retention, leading to improved agricultural productivity.[75]

Recommendation 4. Reverse fertility decline: Increasing the availability of fertilizers, along with effective management in terms of sourcing, application rate, timing and placement, is important in addressing the issue of nutrient depletion across the continent.[76] This intervention is crucial for bridging the yield gap and boosting agricultural productivity through soil health and fertility restoration.[77]

a. To achieve this goal, the use of both mineral and organic fertilizers should be considered. On top of improving fertility, they also benefit soil structure, making the most of local conditions.[78]

Recommendation 5. Research and develop other high-quality inputs: Working to develop high-value inputs – such as quality seeds and cultivars from crops adapted to local conditions – is vital to enhance agricultural productivity and sustainability.[79]

a. By providing farmers with access to high-quality seeds and cultivars that are adapted to local conditions, alongside appropriate management techniques, crop yields can be improved and food security enhanced.[80] Additionally, investing in research and development to produce resilient seed varieties can help farmers adapt to changing environmental conditions and improve their livelihoods.[81]

Given these recommendations, what remains to be seen is what their potential is for changing the livelihoods of smallholder farmers through improving soil health and what barriers will remain to realizing the full potential of these actions.

3 Proposed ways forward

The proposed initiatives could unlock an additional 882,817 tonnes of maize yield and add $1 billion to farmers' income if adoption of selected practices grew by 10 percentage points.

The findings of this paper confirm that improving soil health across the African continent is one of the key enablers of achieving food security. There is, therefore, a need to deepen public and private engagement on the five recommendations outlined in Section 2.7.

To bring a quantitative perspective to these statements, estimates have been made as to what the impact of applying different levers would be, primarily on improving fertility, using high-quality seed and the application of climate-smart agriculture techniques. If the adoption of improved seed varieties and fertilization along with climate-smart agriculture practices grew by 10 percentage points, it would unlock 882,817 tonnes of additional maize yield along with $1 billion in additional farmer income in Tanzania, Nigeria, Kenya and Ghana.[82]

FIGURE 1 **Initiative potential – closing the maize yield gap in selected countries**

The proposed initiatives can, on their own, significantly reduce the yield gap with significant benefits coming from applying them concurrently

Note: Mha = millions of hectares; t/ha = tonnes per hectare; k tn = thousands of tonnes **Source:**[83]

3.1 Existing initiatives

Fortunately, several initiatives already exist and are driving impact on the ground. The most wide-ranging and ambitious are listed below.

1. **Extension services:**

The Global Soil Doctors Programme is an example of a capacity-building programme that offers a digital farmer-to-farmer training platform to empower farmers with the expertise and skills needed for sustainable soil management. This initiative enables farmers to diagnose and resolve soil issues independently while aiding national governments and stakeholders to meet the needs of rural communities.

2. **Digitalization of agriculture:**

The Soil Knowledge Partnership – a soil data platform that aims to improve soil data collection, accessibility, knowledge-sharing and interoperability – is being developed as a public-good open data exchange. The partnership engages stakeholders across the agri-food ecosystem, including industrial partners, farmers and civil society. Using SoilHive technology developed by private-sector actors Yara and Varda, the governments of Norway, Kenya and Tanzania are supporting partners to expand the availability of historical data, improve data collection, information dissemination, accessibility and knowledge-sharing. The partnership collaborates with programmes such as Thryve Innovation CoLab to develop a nationwide soil fertility database with standardized data. This initiative provides farmers with information on efficient fertilizer use and best cropping practices, while governments can use the data for data-driven policy recommendations. Thryve, in collaboration with the World Bank, is working to enhance Kenyan food security and soil fertility.

3. **Applying climate-smart agriculture:**

Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) operates across the continent. By 2022 it had set up several demonstration plots in 18 communities across different regions of Ghana, which promote bundled climate-smart agriculture, including drought- and pest-resistant maize varieties. The benefits of these practices are improved disease and pest management, productivity and resilience along with maize varieties that are yielding 62% more than those for which they are being substituted.[84]

4. **Reversing soil fertility loss:**

The International Network on Soil Fertility and Fertilizers (INSOILFER) launched by the Food and Agriculture Organization of the United Nations focuses on sustainable soil fertility management for preventing the underuse, misuse and overuse of fertilizers, thus lessening the environmental and health impacts. This network covers almost the entire scope of this paper – Kenya and Tanzania in East Africa, Nigeria and Ghana in West Africa and Zambia and South Africa in Southern Africa. On the other hand, private-sector actors such as the OCP Group implement the 4R Nutrient Stewardship (right source, right rate, right time and right place) and farmer-led experimentation, where effective nutrient management is essential for improving soil health and crop yields.

5. **Researching and developing other high-quality inputs:**

The ECOBasic Seed Company, launched in 2021 in Nigeria, aims to double the current yield of maize up to 4 t/ha. The company is sponsored by leading institutions, including the African Agriculture Technology Foundation (AATF), the Bill and Melinda Gates Foundation (BMGF), the Alliance for Green Revolution in Africa (AGRA) and the Seed Entrepreneurs Association of Nigeria (SEEDAN). The company's main activity is the development and production of foundation seeds for seed companies, helping to create new hybrids especially adapted to local conditions and acting as an intermediary between research institutes and seed companies. The Vision for Adapted Crops and Soils initiative (VACS) is developing climate-resilient crop varieties by accelerating plant-breeding efforts for targeted nutritious and traditional food crops. It improves access to knowledge and information at the farm and field level regarding optimal crop selection, location planning, cultivation practices – including tillage and fertilization – and the capacity to build new value chains.

> **At IBM, we recognize the critical role of partnerships in enabling communities to address environmental challenges by using technologies like AI. This is especially true when it comes to helping farmers make agriculture practices more sustainable and productive. That's why, through our pro-bono program – the IBM Sustainability Accelerator – we work with organizations around the world to leverage and scale technology solutions that can support farmers and their communities, and we're honored to be a US Department of State VACS Champion through this program.**
>
> Justina Nixon-Saintil, Vice-President and Chief Impact Officer, IBM, USA

3.2 Further steps

The following steps are needed to increase the impact of these initiatives and address some of the existing gaps.

- **R&D and product development:** Increase public funding and coordination for stress-resilient, climate-smart crop varieties, invest in high-yield, disease-resistant seeds tailored to local conditions
- **Removing access barriers:** Reduce logistical costs, facilitate agricultural credits for small farmers, build local fertilizer infrastructure, provide affordable digital devices, improve internet connectivity and establish soil-testing centres
- **Farmer enablement:** Enhance access to agricultural information and technologies, develop customized recommendations, promote digital literacy programmes and provide training on modern farming technologies
- **Partnerships and coalitions:** Enhance coordination among governments, NGOs and the private sector; foster institutional links, promote public–private partnerships, form farmer-based organizations and provide agricultural credit
- **Policy and regulation:** Conduct studies to understand soil properties, increase fertilizer use, implement quality control for fertilizers, refine policies to support digital agriculture, promote open border policies, improve market access and promote gender equity in agriculture making use of and, when necessary, repurposing existing subsidies and incentive programmes

The proposed key actions align with those proposed at the African Fertilizer and Soil Health Summit in 2024[85] and the collaboration goals of the United States and the African Union. To advance the kind of multistakeholder collaboration that is needed to realize the goals, two platforms have been identified:

- 100 Million Farmers – which, among other aspects, is suited because of its focus on soil health improvement in East Africa, by facilitating decisions through data synthesis and incentive-setting
- The Food Innovation Hubs Global Initiative – which aims to unlock the investment and collaboration necessary to enable technology adoption for soil health at scale; the initiative is looking at opportunities to establish Food Innovation Hubs across the continent, with an initial focus on East Africa

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Endnotes

1. World Economic Forum. (2023, February 6). *Soil health is crucial for food production - here's how to better protect it*. https://www.weforum.org/agenda/2023/02/soil-degradation-biodiversity-planet/
2. This knowledge exchange process brought together more than 30 organizations from the public, private and social sectors. Seven African countries were prioritized as action areas by the working group, based on the countries' agricultural potential and readiness to adopt technologies for soil health.
3. Taylor, A., Wynants, M., Munishi, L., Kelly, C., Mtei, K., Mkilema, F., Ndakidemi, P., Nasseri, M., Kalnins, A., & Patrick, A. (2021, October 2). Building climate change adaptation and resilience through soil organic carbon restoration in sub-Saharan rural communities: Challenges and opportunities. *Sustainability*, *13*(19), 10966. https://doi.org/10.3390/su131910966
4. Authors' own analysis.
5. Baptista, D. M. S., Mai Farid, M., Fayad, D., Kemoe, L., Lanci, L. S., Mitra P., Muehlschlegel, T. S., Okou, C., Spray, J. A., Tuitoek, K., & Unsal, F. D.. (2022, September 15). *Climate change and chronic food insecurity in sub-Saharan Africa*. International Monetary Fund. https://www.imf.org/en/Publications/Departmental-Papers-Policy-Papers/Issues/2022/09/13/Climate-Change-and-Chronic-Food-Insecurity-in-Sub-Saharan-Africa-522211
6. Nzoyisenga, O. (2021, October). *Impacts of food importations dependency on food security in sub-Saharan Africa*. https://www.ciaaf.org/storage/2021/10/Osian_Nzoyisengapapaer__CiAAF.pdf
7. UjuziKilimo. (2024, April 11). Understanding soil acidity and its impact on Kenyan farms. Medium. https://medium.com/@UjuziKilimo/understanding-soil-acidity-and-its-impact-on-kenyan-farms-5c62b847d969
8. Muchoki, A., & Msimbe, B. (2023, September 28). The fight against soil acidity in Tanzania: The bitter truth and charting a sustainable food systems future. Kilimo Kwanza. https://kilimokwanza.org/the-fight-against-soil-acidity-in-tanzania-the-bitter-truth-and-charting-a-sustainable-food-systems-future/
9. Feeney, C. J., Robinson, D. A., Thomas, A. R. C., Borrelli, P., Cooper, D. M., & May, L. (2023, April 20). Agricultural practices drive elevated rates of topsoil decline across Kenya, but terracing and reduced tillage can reverse this. *Science of the Total Environment*, *870*, 161925. https://doi.org/10.1016/j.scitotenv.2023.161925
10. Vågen, T.-G., & Winowiecki, L. A. (2019, July 31). Predicting the spatial distribution and severity of soil erosion in the global tropics using satellite remote sensing. *Remote Sensing*, *11*(15), 1800. https://doi.org/10.3390/rs11151800
11. Kogo, B. K., Kumar, L., & Koech, R. (2020, November 22). Impact of land use/cover changes on soil erosion in western Kenya. *Sustainability*, *12*, 9740. https://pdfs.semanticscholar.org/552f/354293cd7b4b1101567f80c27ce4c2c53487.pdf
12. IFDC & AfricaFertilizer. (2023). *Fertilizer statistics overview Kenya 2018–2022*. https://api.hub.ifdc.org/server/api/core/bitstreams/e781e6f0-2aae-4b63-ac21-365638fc4f62/content; Food and Agriculture Organization of the United Nations (FAO). (2023). *Fertilizers consumption in nutrients 1961–2022*. https://www.fao.org/faostat/en/#country/114
13. International Fertilizer Association (IFASTAT). Search for "2020 fertilizer consumption in sub-Saharan Africa". https://www.fertilizer.org/market-intelligence/ifastat/
14. Laub, M., Corbeels, M., Couëdel, A., Ndungu, S. M., Mucheru-Muna, M. W., Mugendi, D., Necpalova, M., Waswa, W., Van de Broek, M., Vanlauwe, B., & Six, J. (2023). Managing soil organic carbon in tropical agroecosystems: Evidence from four long-term experiments in Kenya. *Soil*, *9*(1), 301–323. https://soil.copernicus.org/articles/9/301/2023/#section5
15. Feeney, C. J., Robinson, D. A., Thomas, A. R. C., Borrelli, P., Cooper, D. M., & May, L. (2023, April 20). Agricultural practices drive elevated rates of topsoil decline across Kenya, but terracing and reduced tillage can reverse this. *Science of the Total Environment*, *870*, 161925. https://doi.org/10.1016/j.scitotenv.2023.161925
16. Fahad, S., Chavan, S. B., Chichanghare, A. R., Uthappa, A. R., Kumar, M., & Kakade, V. (2022, November 10). Agroforestry systems for soil health improvement and maintenance. *Sustainability*, *14*(22), 14877. https://doi.org/10.3390/su142214877
17. Kiwia, A., Kimani, D., Harawa, R., Jama, B., & Silesgu, G. W. (2021). Fertiliser use efficiency, production risks and profitability of maize on smallholder farms in East Africa. *Experimental Agriculture*, *58*, e22. https://www.cambridge.org/core/journals/experimental-agriculture/article/fertiliser-use-efficiency-production-risks-and-profitability-of-maize-on-smallholder-farms-in-east-africa/45DF57A4AF117B8BFA79F60B4286D414
18. Winowiecki, L., Vågen, T.-G., Massawe, B., Jelinski, J. A., Lyamchai, C., Sayula, G., & Msoka, E. (2015, November 7). Landscape-scale variability of soil health indicators: Effects of cultivation on soil organic carbon in the Usambara Mountains of Tanzania. *Nutrient Cycling in Agroecosystems*, *105*, 263–274. http://link.springer.com/article/10.1007/s10705-015-9750-1
19. Winowiecki, L., Vågen, T.-G., & Huising, J. (2016, February 1). Effects of land cover on ecosystem services in Tanzania: A spatial assessment of soil organic carbon. *Geoderma*, *263*, 274–283. http://www.sciencedirect.com/science/article/pii/S0016706115000816
20. Feeney, C. J., Robinson, D. A., Thomas, A. R. C., Borrelli, P., Cooper, D. M., & May, L. (2023, 20 April). Agricultural practices drive elevated rates of topsoil decline across Kenya, but terracing and reduced tillage can reverse this. *Science of the Total Environment*, *870*, 161925. https://doi.org/10.1016/j.scitotenv.2023.161925
21. Taylor, A., Wynants, M., Munishi, L., Kelly, C., Mtei, K., Mkilema, F., Ndakidemi, P., Nasseri, M., Kalnins, A., & Patrick, A. (2021, October 2). Building climate change adaptation and resilience through soil organic carbon restoration in sub-Saharan rural communities: Challenges and opportunities. *Sustainability*, *13*(19), 10966. https://doi.org/10.3390/su131910966

22. Ehiomogue, P. O., Ahuchaogu, I. I., & Udoumoh, U. I. (2022). Soil and water conservation practices in Nigeria: A review. *International Journal of Agriculture and Earth Science*, *8*(1), 12022. https://www.iiardjournals.org/get/IJAES/VOL.%208%20NO.%201%202022/SOIL%20AND%20WATER%20CONSERVATION.pdf
23. World Bank. (2016). *Nigeria Erosion and Watershed Management Project (NEWMAP)*. Environmental and Social Management Framework (ESMF). https://documents1.worldbank.org/curated/en/809141468144274655/pdf/685560BR0P12490Official0Use0Only090.pdf
24. World Bank. (2019, March 14). *West Africa's coast: Losing over $3.8 Billion a year to erosion, flooding and pollution*. https://www.worldbank.org/en/region/afr/publication/west-africas-coast-losing-over-38-billion-a-year-to-erosion-flooding-and-pollution#:~:text=A%20new%20World%20Bank%20study%20reveals%20in%20economic,billion%2C%20or%205.3%25%20of%20the%20four%20countries%
25. Iderawumi, A. M., Abbas, N., Syed M.Z., Ahmed, S., & Li, L. (2022, April). Soil fertility management: Issues and challenges in tropical areas of Nigeria: Agriculture issues and polices. *Ecosystem Services*, *17*. https://www.researchgate.net/profile/Abdulraheem-Iderawumi/publication/359743057_Soil_Fertility_Management_Issues_and_Challenges_in_Tropical_Areas_of_Nigeria/links/6492e524b9ed6874a5c54841/Soil-Fertility-Management-Issues-and-Challenges-in-Tropical-Areas-
26. Jayne, T., Shashidhara, K., Debrah, K., Ariga, J., Brunache, P., Kabagne, C., Nunez-Rodriguez, W., Owusu Baah, K., Bationo, A. A., Huising, E. J., Lambrecht, I., Diao, X., Yeboah, F., Benin, S., & Andam, K. (2015, September). *Towards a sustainable soil fertility strategy in Ghana*. http://mondialisations.org/medias/pdf/IFPRIfoodAgriGhanaEN.pdf
27. Amuah, E. B. Y., Fei-Baffoe, B., Kazapoe, R. W., Dankwa, P., Okyere, I. K., Sackey, L. N. A., Nang, D. B., & Kpiebaya, P. (2024, March). From the ground up: Unveiling Ghana's soil quality crisis and its ecological and health implications. *Innovation and Green Development*, *3*(1),100097. https://www.sciencedirect.com/science/article/pii/S2949753123000656
28. Ibid.
29. World Bank. (2019, March 14). *West Africa's coast: Losing over $3.8 billion a year to erosion, flooding and pollution*. https://www.worldbank.org/en/region/afr/publication/west-africas-coast-losing-over-38-billion-a-year-to-erosion-flooding-and-pollution#:~:text=A%20new%20World%20Bank%20study%20reveals%20in%20economic,billion%2C%20or%205.3%25%20of%20the%20four%20countries%
30. Ezeh, C. U., Igwe, O., Asare, M. Y., Ndulue, D. C., Ayadiuno, R. U., & Preko, K. (2024, February 6). A review of soil erosion modeling in Nigeria using the Revised Universal Soil Loss Equation model. *Agrosystems, Geosciences & Environment*, *7*(1), e20471. https://doi.org/10.1002/agg2.20471
31. Africa Fertilizer (AFO). (2023). *Fertilizer statistics overview Nigeria 2018–2022*. International Fertilizer Development Center (IFDC). https://api.hub.ifdc.org/server/api/core/bitstreams/5dcdc7af-fd23-41cd-96aa-02c25f32f2a6/content
32. The ability of soil to hold positively charged cations (including key nutrients). See: AHDB. (n.d.). Soil texture and cation exchange capacity. Retrieved August 7, 2024, from https://ahdb.org.uk/knowledge-library/soil-texture-and-cation-exchange-capacity#:~:text=Cation%20exchange%20capacity%20%28CEC%29%20reflects%20the%20ability%20of,High%20CEC%20soils%20hold%20onto%20cations%20more%20effectively.
33. Chapungu, L., Nhamo, G., Dube, K., & Chikodzi, D. (2023). Soil erosion in the savanna biome national parks of South Africa. *Physics and Chemistry of the Earth*, *130*, 103376. https://doi.org/10.1016/j.pce.2023.103376
34. Gebreslasie, M., Ebhuoma, O., & Ngetar, S. (2022, 13 May). Soil erosion vulnerability mapping in selected rural communities of Thukela Catchment, South Africa, using the analytic hierarchy process. *Earth Systems and Environment*, *6*, 851–864. http://dx.doi.org/10.1007/s41748-022-00308-y
35. Le Roux, J., & Smith, H. (2014, November). *Soil erosion in South Africa – its nature and distribution*. GSA. https://www.grainsa.co.za/soil-erosion-in-south-africa---its-nature-and-distribution
36. Ibid.
37. Adeleke, R., Raimi, A., & Roopnarain, A. (2017, November 17). Soil fertility challenges and biofertilizer as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food & Agriculture*, *3*. https://doi.org/10.1080/23311932.2017.1400933
38. Shitumbanuma, V., Simfukwe, P., Kalala, D. M., Kaninga, B., Gondwe, B. M, Nambala, M., Kabwe, S., Siulemba, G., Kapulu, N. P., Lungu, O. I., & Mutegi, J. K. (2021). *Integrated soil fertility management in Zambia*. Zambia Soil Health Consortium. https://www.researchgate.net/publication/351099870_Integrated_Soil_Fertility_Management_in_Zambia_i_The_Zambia_Soil_Health_Consortium_Integrated_Soil_Fertility_Management_in_Zambia
39. Ibid.
40. du Preez, C., van Huyssteen, C., & Mnkeni, P. N. (2011, 16 May). *Land use and soil organic matter in South Africa 1: A review on spatial variability and the influence of rangeland stock production*. https://scielo.org.za/pdf/sajs/v107n5-6/v107n5-6a09.pdf
41. Ibid.
42. Michelson, H., Fairbain, A., Ellison, B., Maertens, A., & Manyong, V. (2021, January). Misperceived quality: Fertilizer in Tanzania. *Journal of Development Economics*, *148*, 102579. https://doi.org/10.1016/j.jdeveco.2020.102579
43. Tesfahunegn, G. B., Ayuk, E. T., & Adiku, S. G. (2021, March 2). Farmers' perception on soil erosion in Ghana: Implication for developing sustainable soil management strategy. *PLoS ONE*, *16*(3). https://doi.org/10.1371/journal.pone.0242444
44. Ibid.
45. Ibid.
46. Ibid.
47. Ansong Omari, R., Bellingrath-Kimura, S. D., Sarkodee Addo, E., Oikawa, Y., & Fujii, Y. (2018) Exploring farmers' indigenous knowledge of soil quality and fertility management practices in selected farming communities of the Guinea Savannah agro-ecological zone of Ghana. *Sustainability*, *10*(4), 1034. https://doi.org/10.3390/su10041034

48. Gambo, A., Fullen, M. A., & Baldwin, T. C. (2023). *Perception of desertification and soil erosion in Dutse, Jigawa State, Northern Nigeria*. International Society for Aeolian Research. https://wlv.openrepository.com/bitstream/handle/2436/625335/Gambo_et_al_Farmers_knowledge_2023.pdf?sequence=3
49. Romig, D. E., Garlynd, M., & Harris, R. F. (1996). Farmer-based assessment of soil quality: A soil health scorecard. SSSA Special Publication: Methods for assessing soil quality, pp. 39–60. https://acsess.onlinelibrary.wiley.com/doi/pdf/10.2136/sssaspecpub49.frontmatter
50. Adeyolanu, O. D., & Ogunkunle, A. O. (2016, February 24). Comparison of qualitative and quantitative approaches to soil quality assessment for agricultural purposes in south-western Nigeria. *Cogent Food & Agriculture*, *2*(1). https://doi.org/10.1080/23311932.2016.1149914
51. Swai, E., Mutabazi, D. K., Tumbo, S., Urassa, N., Mwinuka, L., Mchau, D., Graef, F., & Herrmann, F. (2015, September 16–18). *Farmer's perception on soil fertility status and soil fertility management in semi-arid areas of central Tanzania*. Tropentag, Berlin, 2015. https://www.tropentag.de/2015/abstracts/links/Swai_zQNMQSr3.pdf
52. Michelson, H., Fairbain, A., Ellison, B., Maertens, A., & Manyong, V. (2021, January). Misperceived quality: Fertilizer in Tanzania. *Journal of Development Economics*, *148*, 102579. https://doi.org/10.1016/j.jdeveco.2020.102579
53. Entz, M. H., Stainsby, A., Riekman, M., Mulaire, T. R., Kirima, J. K., Beriso, F., Ngotio, D., Salomons, M., Nicksy, J., Mutinda, M., & Stanley, K. (2022, September 15). Farmer participatory assessment of soil health from conservation agriculture adoption in three regions of East Africa. *Agronomy for Sustainable Development*, *42*. https://doi.org/10.1007/s13593-022-00824-1
54. Swai, E., Mutabazi, D. K., Tumbo, S., Urassa, N., Mwinuka, L., Mchau, D., Graef, F., & Herrmann, F. (2015, September 16–18). *Farmer's perception on soil fertility status and soil fertility management in semi-arid areas of central Tanzania*. Tropentag, Berlin, 2015. https://www.tropentag.de/2015/abstracts/links/Swai_zQNMQSr3.pdf
55. Conservation agriculture refers to sustainable farming methods that contribute to crop diversification, minimal soil movement and soil coverage practices with the residue of previous crops or cover crops. CGIAR. (2020). *What is conservation agriculture?* https://www.cgiar.org/news-events/news/what-is-conservation-agriculture
56. Entz, M. H., Stainsby, A., Riekman, M., Mulaire, T. R., Kirima, J. K., Beriso, F., Ngotio, D., Salomons, M., Nicksy, J., Mutinda, M., & Stanley, K. (2022, September 15). Farmer participatory assessment of soil health from conservation agriculture adoption in three regions of East Africa. *Agronomy for Sustainable Development*, *42*. https://doi.org/10.1007/s13593-022-00824-1
57. Kangogo, M. K. (2016, May). Farmers' perceptions of the impact of soil erosion on maize production in soy division, Elgeiyo-Marakwet County, Kenya. [Unpublished thesis] Moi University. http://ir.mu.ac.ke:8080/xmlui/bitstream/handle/123456789/1122/Kangogo%20Michael%20Kandie%202016.pdf; Statista. (2023). Production volume of maize in Kenya from 2015 to 2022. https://www.statista.com/statistics/1170165/production-volume-of-maize-in-kenya/#:~:text=In%202022%2C%20the%20production%20volume%20of%20maize%20in,is%20also%20a%20staple%20food%20for%20the%20Kenyans
58. IFPRI and CGIAR. (2023, December 18). *How is Kenya's National Fertilizer Subsidy Program working?* https://www.ifpri.org/blog/how-kenyas-national-fertilizer-subsidy-program-working/
59. Kangogo, M. K. (2016, May). Farmers' perceptions of the impact of soil erosion on maize production in soy division, Elgeiyo-Marakwet County, Kenya. [Unpublished thesis] Moi University. http://ir.mu.ac.ke:8080/xmlui/bitstream/handle/123456789/1122/Kangogo%20Michael%20Kandie%202016.pdf
60. Olabanji, M. F., Davis, N., Ndarana, T., Kuhudzai, A. G., & Mahlobo, D. (2021, July 19). Assessment of smallholder farmers' perception and adaptation response to climate change in the Olifants catchment, South Africa. *Journal of Water and Climate Change*, *12*(1). https://iwaponline.com/jwcc/article/12/7/3388/83109/Assessment-of-smallholder-farmers-perception-and
61. Ighodaro, I. D., Lategan, F. S., & Yusuf, S. F. (2013). The impact of soil erosion on agricultural potential and performance of Sheshegu community farmers in the Eastern Cape of South Africa. *Journal of Agricultural Science*, *5*(5). http://dx.doi.org/10.5539/jas.v5n5p140
62. Tesfahunegn, G. B., Ayuk, E. T., & Adiku, S. G. (2021, March 2). Farmers' perception on soil erosion in Ghana: Implication for developing sustainable soil management strategy. *PLoS ONE, 16*(3). https://doi.org/10.1371/journal.pone.0242444; Gambo, A., Fullen, M. A., & Baldwin, T. C. (2023). *Perception of desertification and soil erosion in Dutse, Jigawa State, Northern Nigeria*. International Society for Aeolian Research. https://wlv.openrepository.com/bitstream/handle/2436/625335/Gambo_et_al_Farmers_knowledge_2023.pdf?sequence=3; Kangogo, M. K. (2016, May). Farmers' perceptions of the impact of soil erosion on maize production in soy division, Elgeiyo-Marakwet County, Kenya. [Unpublished thesis] Moi University. http://ir.mu.ac.ke:8080/xmlui/bitstream/handle/123456789/1122/Kangogo%20Michael%20Kandie%202016.pdf
63. Swai, E., Mutabazi, D. K., Tumbo, S., Urassa, N., Mwinuka, L., Mchau, D., Graef, F., & Herrmann, F. (2015, September 16–18). *Farmer's perception on soil fertility status and soil fertility management in semi-arid areas of central Tanzania*. Tropentag, Berlin, 2015. https://www.tropentag.de/2015/abstracts/links/Swai_zQNMQSr3.pdf
64. Ansong Omari, R., Bellingrath-Kimura, S. D., Sarkodee Addo, E., Oikawa, Y., & Fujii, Y. (2018) Exploring farmers' indigenous knowledge of soil quality and fertility management practices in selected farming communities of the Guinea Savannah agro-ecological zone of Ghana. *Sustainability, 10*(4), 1034. https://doi.org/10.3390/su10041034; Romig, D. E., Garlynd, M., & Harris, R. F. (1996). Farmer-based assessment of soil quality: A soil health scorecard. SSSA Special Publication: Methods for assessing soil quality, pp. 39–60. https://acsess.onlinelibrary.wiley.com/doi/pdf/10.2136/sssaspecpub49.frontmatter; Adeyolanu, O. D., & Ogunkunle, A. O. (2016, February 24). Comparison of qualitative and quantitative approaches to soil quality assessment for agricultural purposes in South-western Nigeria. *Cogent Food & Agriculture, 2*(1). https://doi.org/10.1080/23311932.2016.1149914

65. Swai, E., Mutabazi, D. K., Tumbo, S., Urassa, N., Mwinuka, L., Mchau, D., Graef, F., & Herrmann, F. (2015, September 16–18). *Farmer's perception on soil fertility status and soil fertility management in semi-arid areas of central Tanzania*, Berlin, 2015. https://www.tropentag.de/2015/abstracts/links/Swai_zQNMQSr3.pdf
66. Fabregas, R., Harigaya, T., Kremer, M., & Ramrattan, R. (2022, September). Digital agricultural extension for development. In T. Madon, A. J. Gadgil, R. Anderson, L. Casaburi, K. Lee, & A. Rezaee (Eds), *Introduction to development engineering*, 187–219. Springer. https://www.researchgate.net/publication/363415801_Digital_Agricultural_Extension_for_Development
67. Swai, E., Mutabazi, D. K., Tumbo, S., Urassa, N., Mwinuka, L., Mchau, D., Graef, F., & Herrmann, F. (2015, September 16–18). *Farmer's perception on soil fertility status and soil fertility management in semi-arid areas of central Tanzania*. Tropentag, Berlin, 2015. https://www.tropentag.de/2015/abstracts/links/Swai_zQNMQSr3.pdf
68. Entz, M. H., Stainsby, A., Riekman, M., Mulaire, T. R., Kirima, J. K., Beriso, F., Ngotio, D., Salomons, M., Nicksy, J., Mutinda, M., & Stanley, K. (2022, September 15). Farmer participatory assessment of soil health from Conservation Agriculture adoption in three regions of East Africa. *Agronomy for Sustainable Development*, *42*. https://doi.org/10.1007/s13593-022-00824-1
69. Feeney, C. J., Robinson, D. A., Thomas, A. R. C., Borrelli, P., Cooper, D. M., & May, L. (2023, April 20). Agricultural practices drive elevated rates of topsoil decline across Kenya, but terracing and reduced tillage can reverse this. *Science of the Total Environment*, *870*, 161925. https://doi.org/10.1016/j.scitotenv.2023.161925
70. FAO. (2024, March 19). *Digital agriculture in FAO projects in sub-Saharan Africa*. https://openknowledge.fao.org/server/api/core/bitstreams/fd659bfe-30e6-438e-8caa-835b3a1ffb1b/content
71. Ibid.
72. Shitumbanuma, V., Simfukwe, P., Kalala, D. M., Kaninga, B., Gondwe, B. M, Nambala, M., Kabwe, S., Siulemba, G., Kapulu, N. P., Lungu O. I. & Mutegi, J. K. (2021). *Integrated soil fertility management in Zambia*. Zambia Soil Health Consortium. https://www.researchgate.net/publication/351099870_Integrated_Soil_Fertility_Management_in_Zambia_i_The_Zambia_Soil_Health_Consortium_Integrated_Soil_Fertility_Management_in_Zambia
73. Ibid.
74. Kibet, E., Musafiri, C., Kiboi, M., Macharia, J., Ng'etich, O., Kosgei, D., Ngetich, F. (2022, 6 July). Soil organic carbon stocks under different land utilization types in Western Kenya. *Sustainability*, *14*(4), 8267. http://dx.doi.org/10.3390/su14148267
75. Kiboi, M., Musafiri, C., Fliessbach, A., Ng'etich, O., Wakindiki, I., Ngetich, F. (2023, December 8). Selected conservation management strategies enhance maize yield stability in the sub-humid tropical agro-ecozone of Upper Eastern Kenya. *Scientific Reports*, *13*, 21728 https://doi.org/10.1038/s41598-023-49198-8
76. Taylor, A., Wynants, M., Munishi, L., Kelly, C., Mtei, K., Mkilema, F., Ndakidemi, P., Nasseri, M., Kalnins, A., & Patrick, A. (2021, October 2). Building climate change adaptation and resilience through soil organic carbon restoration in sub-Saharan rural communities: Challenges and opportunities. *Sustainability*, *13*(19), 10966. https://doi.org/10.3390/su131910966
77. Ibid.
78. Ibid.
79. Shitumbanuma, V., Simfukwe, P., Kalala, D. M., Kaninga, B., Gondwe, B. M, Nambala, M., Kabwe, S., Siulemba, G., Kapulu, N. P., Lungu O. I. & Mutegi, J. K. (2021). *Integrated soil fertility management in Zambia*. Zambia Soil Health Consortium. https://www.researchgate.net/publication/351099870_Integrated_Soil_Fertility_Management_in_Zambia_i_The_Zambia_Soil_Health_Consortium_Integrated_Soil_Fertility_Management_in_Zambia
80. Ibid.
81. Ibid.
82. Authors' own analysis.
83. Asante, B. O., Ma, W., Prah, S., & Temoso, O. (2024, February 25). *Farmers' adoption of multiple climate-smart agricultural technologies in Ghana: Determinants and impacts on maize yields and net farm income*. Springer. https://link.springer.com/content/pdf/10.1007/s11027-024-10114-8.pdf; Abdoulaye, T., Wossen, T., & Awotide, B. (2018, March 21). Impacts of improved maize varieties in Nigeria: Ex-post assessment of productivity and welfare outcomes. *Food Security*, *10*, 369–379. https://link.springer.com/article/10.1007/s12571-018-0772-9; Santalucia, S., & Sibhatu, K. T. (2023, December 29). Nourishing the farms, nourishing the plates: Association of climate-smart agricultural practices with household dietary diversity and food security in smallholders. *Agribusiness*, *40*(2), 513–533. https://doi.org/10.1002/agr.21892; Setimela, S. P., Magorokosho, C., Lunduka, R., Gasura, E., Makumbi, D., Tarekegne, A., Cairns, J. E., Ndhlela, T., Mwangi, W. (2017, March 1). On-farm yield gains with stress-tolerant maize in Eastern and Southern Africa. *Agronomy Journal*, *109*(2). https://doi.org/10.2134/agronj2015.0540
84. CGIAR – AICCRA. (2023, July 4). *Out with old, in with new: Climate-smart seed varieties improve maize production in Ghana*. https://aiccra.cgiar.org/news/out-old-new-climate-smart-seed-varieties-improve-maize-production-ghana
85. Soil Initiative for Africa. https://sia.faraafrica.org/afsh-summit/#:~:text=The%20Africa%20Fertilizer%20and%20Soil,been%20added%20for%20your%20use

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