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Review Article

Climate-Smart Integrated Soil Fertility Management for Resilient Smallholder Farming Systems in Sub-Saharan Africa: A Synthesis of Agronomic, Ecological and Socio-Economic Evidence

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Abstract

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Soil degradation, climate variability and low use of external inputs continue to constrain smallholder productivity across Sub-Saharan Africa, where most food is produced on farms of less than two hectares under rain-fed conditions. This article synthesises peer-reviewed, institutional and field-based evidence on climate-smart integrated soil fertility management (ISFM) as a pathway to raise productivity, strengthen adaptation and, where possible, reduce greenhouse-gas intensity per unit of food produced. Drawing on agronomic trials, meta-analyses, adoption studies and livelihood research, it examines how the combined use of organic and mineral inputs, improved germplasm, legume integration, conservation agriculture and agroforestry interacts with soil organic carbon, water retention, nutrient-use efficiency and household welfare. The synthesis shows that combining high-quality organic resources with mineral fertiliser generally outperforms either input alone for maize and other staples, particularly when improved varieties and good agronomy are included (Vanlauwe et al., 2010; Gram et al., 2020; Chivenge et al., 2022). Conservation agriculture and legume-based diversification improve soil cover, biological nitrogen fixation and resilience to dry spells, but their benefits are context-dependent and often emerge only after several seasons (Giller et al., 2009; Corbeels et al., 2020). Adoption remains uneven because of input costs, labour demands, insecure tenure, weak extension and market failures, and because benefits are mediated by gender, farm size, soil heterogeneity and access to information (Lipper et al., 2014; Mwongera et al., 2017). The article proposes a decision framework that matches ISFM options to soil type, rainfall regime, resource endowment and market access, and argues that scaling requires site-specific recommendations, blended finance, secure tenure, pluralistic extension and farmer-led experimentation. It concludes that ISFM is not a single technology but a set of principles that must be adapted locally if climate-smart agriculture is to deliver productivity, adaptation and mitigation together.

Keywords: *climate-smart agriculture; integrated soil fertility management; soil organic carbon; conservation agriculture; smallholder farmers; Sub-Saharan Africa; food security; nutrient-use efficiency*

1. Introduction

Agriculture in Sub-Saharan Africa (SSA) supports livelihoods for more than half of the population and supplies most of the region's food, yet yields of staple crops remain far below their agronomic potential (FAO, 2017; World Bank, 2019). Maize, cassava, sorghum, millet, rice and grain legumes dominate smallholder systems, but average maize yields in many countries are 1 to 2 tonnes per hectare, compared with 5 to 8 tonnes per hectare attainable under good management (Vanlauwe et al., 2010; Sanchez, 2015). The gap is not explained by a single factor. It reflects decades of nutrient mining, erosion, loss of soil organic matter, erratic rainfall, pests and diseases, limited access to improved seed and fertiliser, and weak markets and

institutions (Sanchez, 2002; Lal, 2004; Tittonell and Giller, 2013). Climate change intensifies these pressures by increasing temperature, altering rainfall distribution, lengthening dry spells and increasing the frequency of floods and droughts (IPCC, 2019; IPCC, 2022). For farmers who depend almost entirely on rainfall, a delayed onset or a mid-season dry spell can erase a season's investment in seed, labour and fertiliser.

Climate-smart agriculture (CSA) was proposed as a framework to pursue three objectives simultaneously: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing or removing greenhouse-gas emissions where possible (FAO, 2013; Lipper et al., 2014). The concept has been influential, but also contested, because trade-offs among the three pillars are real and because what is climate-smart in one place may not be in another (Taylor, 2018; Newell et al., 2019). Soil is central to all three pillars. Healthy soil stores carbon, holds water, supplies nutrients, supports biodiversity and buffers crops against climatic shocks (Lal, 2004; Lehmann and Kleber, 2015). Conversely, degraded soil amplifies climate vulnerability and forces farmers to clear new land, which drives deforestation and emissions (IPCC, 2019; FAO, 2017). Integrated soil fertility management offers a practical, soil-centred entry point for CSA. It is defined as a set of soil fertility management practices that necessarily include the use of fertiliser, organic inputs and improved germplasm, combined with the knowledge to adapt these practices to local conditions, to maximise agronomic use efficiency and improve crop productivity (Vanlauwe et al., 2010; Vanlauwe et al., 2014).

This article has three aims. First, it synthesises evidence on how ISFM components affect productivity, soil health, water relations and greenhouse-gas intensity. Second, it examines why adoption remains limited despite demonstrated agronomic benefits, paying attention to heterogeneity among farms, soils and households. Third, it proposes a practical, context-sensitive framework for designing, evaluating and scaling climate-smart ISFM in smallholder systems. The article is a narrative synthesis, not a single new field trial, and it draws deliberately on diverse sources so that agronomic, ecological and socio-economic perspectives are held together. Where evidence is mixed, the article says so. The argument is that ISFM works best not as a fixed package, but as a set of principles adapted through farmer experimentation, local soil knowledge and supportive institutions.

The remainder of the article is organised as follows. Section 2 describes the approach used to select and synthesise literature. Section 3 reviews the biophysical foundations of soil fertility and climate risk in SSA. Section 4 examines the core ISFM components and their interactions. Section 5 evaluates evidence on productivity, soil carbon, water and emissions. Section 6 analyses adoption, livelihoods and equity. Section 7 proposes a decision framework and scaling pathways, and Section 8 concludes with research and policy priorities.

2. Approach and Scope of the Synthesis

The synthesis was built by searching peer-reviewed journals, books, and reports from the Food and Agriculture Organization of the United Nations (FAO), the Intergovernmental Panel on Climate Change (IPCC), the World Bank, the International Institute of Tropical Agriculture (IITA), the Alliance of Bioversity International and CIAT, and national agricultural research systems. Priority was given to meta-analyses, long-term trials, multi-country studies and systematic reviews, supplemented by country case studies from Nigeria, Kenya, Ethiopia, Malawi, Zambia, Tanzania and Zimbabwe to ground the synthesis in contrasting agro-ecologies (Vanlauwe et al., 2010; Gram et al., 2020; Chivenge et al., 2022; Corbeels et al., 2020). Search terms combined climate-smart agriculture, integrated soil fertility management, conservation agriculture, agroforestry, soil organic carbon, nutrient-use efficiency, legume intercropping, biochar, compost and manure with smallholder, adoption and food security. Studies were included if they reported agronomic, soil, climate or livelihood outcomes for rain-fed smallholder systems in SSA or provided a conceptual or methodological contribution directly relevant to those systems. Single-season, single-site trials were treated as illustrative rather than definitive, and greater weight was placed on studies that reported soil properties, rainfall, management history and input quality, because those variables condition ISFM response (Tittonell and Giller, 2013; Vanlauwe et al., 2014).

Two interpretive cautions guided the synthesis. First, yields alone are an incomplete measure of climate-smartness. A practice that raises yield but depletes soil carbon, increases nitrous oxide emissions disproportionately, or increases labour beyond what a household can sustain may not be climate-smart in a broader sense (Lipper et al., 2014; Newell et al., 2019). The article therefore tracks multiple outcomes: yield, yield stability, soil organic carbon, water infiltration and retention, agronomic efficiency of nitrogen, labour, income and dietary diversity where reported. Second, averages conceal heterogeneity. Soils vary within a single farm, often because of historical management of home fields versus outfields, and households vary in labour, capital, tenure and market access (Tittonell et al., 2005; Zingore et al., 2007). A recommendation that is profitable on a fertile home field may fail on a degraded outfield. The framework in Section 7 is designed explicitly for that heterogeneity.

3. Soil Fertility, Climate Risk and the Smallholder Context

Many soils in SSA are inherently low in fertility, with low cation exchange capacity, low organic matter, acidity or aluminium toxicity, and phosphorus fixation in weathered tropical soils (Sanchez, 2002; Bationo et al., 2007). Decades of continuous cropping with little or no nutrient return have mined nitrogen, phosphorus and potassium, while erosion has removed topsoil and organic matter (Lal, 2004; Sanchez, 2015). Soil organic matter is particularly important because it influences structure,

water-holding capacity, nutrient retention and biological activity (Lehmann and Kleber, 2015; Lal, 2004). When organic matter falls, soils crust, infiltration declines, runoff increases, and crops become more vulnerable to dry spells even when total seasonal rainfall is adequate. This creates a feedback loop: poor soils produce little biomass, little biomass returns to the soil, and fertility declines further (Tittonell and Giller, 2013). Breaking that loop requires both nutrient addition and organic matter management, not one alone.

Climate risk in SSA is not only about rising mean temperature, although warming increases evaporative demand and heat stress for crops and livestock (IPCC, 2022; FAO, 2017). It is also about variability and extremes: late onset, early cessation, false starts, intense storms and prolonged dry spells within the season (IPCC, 2019; Mwongera et al., 2017). For maize, a dry spell at flowering can reduce grain number sharply, while waterlogging after heavy rain can cause nitrogen loss through leaching and denitrification. Smallholders manage this risk through diversification, staggered planting, intercropping, varietal choice, off-farm income and social networks, but these strategies have limits when shocks are covariate, affecting whole communities at once (Lipper et al., 2014; World Bank, 2019). Climate-smart soil management must therefore be judged not only by average yield in a good year, but by performance in bad years, recovery after shock, and stability across seasons (Corbeels et al., 2020; Gram et al., 2020).

The smallholder context adds institutional and economic constraints. Most farmers cultivate small, fragmented plots, often under customary tenure that may be insecure for women and youth (FAO, 2017; World Bank, 2019). Access to fertiliser is constrained by price, distance, late delivery and concerns about adulteration, while access to credit is limited by collateral requirements and high interest rates (Bationo et al., 2007; Sanchez, 2015). Extension services are often thinly staffed, and advice may be generic rather than tailored to soil type and rainfall. Markets for inputs and outputs are imperfect, so a farmer who invests in fertiliser may not be able to sell surplus at a remunerative price. These realities explain why agronomically sound recommendations are not automatically adopted, and why the synthesis must integrate agronomy with economics and institutions.

4. Core Components of Climate-Smart ISFM

4.1 Mineral fertiliser: necessary but insufficient alone

Mineral fertiliser supplies nutrients in plant-available forms and at known concentrations, and it can raise yields quickly when other constraints are not binding (Sanchez, 2002; Vanlauwe et al., 2010). Yet fertiliser use in SSA remains low by global standards, often below 20 kilograms of nutrients per hectare, and agronomic efficiency is often low because soils are degraded, organic matter is low, rainfall is erratic, or varieties and planting practices are suboptimal (Bationo et al., 2007; Vanlauwe et al., 2014). Applying nitrogen to a soil with very low organic matter and poor structure may produce a modest response and increase losses through leaching and gaseous emissions. Micro-dosing, split application, placement near the plant, and combining fertiliser with organic inputs can improve efficiency, but they also require knowledge, labour and timely access (Bationo et al., 2007; Chivenge et al., 2022). Fertiliser subsidies have expanded access in several countries, but their fiscal sustainability, targeting and effects on soil health and private input markets remain debated (Sanchez, 2015; World Bank, 2019). The synthesis position is that mineral fertiliser is a necessary component of ISFM in most systems, but it is insufficient alone for rebuilding soil health or for climate resilience.

4.2 Organic inputs: manure, compost, crop residues and biochar

Organic inputs supply nutrients slowly, add carbon, improve structure and stimulate soil biology, but their nutrient concentrations are low and variable, and quantities available on small farms are often insufficient to meet crop demand alone (Vanlauwe et al., 2010; Gram et al., 2020). Manure quality depends on animal diet, storage and handling; compost quality depends on feedstock and maturity; crop residues are often needed for livestock feed, fuel or construction, creating trade-offs (Tittonell et al., 2005; Giller et al., 2009). Biochar, produced by pyrolysis of biomass, has attracted attention because it can persist in soil, improve water retention and reduce nutrient leaching, but its effects depend on feedstock, pyrolysis temperature, application rate and soil type, and evidence from African smallholder fields is still emerging (Lehmann and Kleber, 2015; Gram et al., 2020). The practical implication is that organic inputs should be valued for soil health and resilience, not only for immediate nutrient supply, and that their use should be targeted to the most responsive fields and to high-value crops where returns justify labour and transport costs (Zingore et al., 2007; Tittonell and Giller, 2013).

4.3 Improved germplasm and good agronomy

Improved varieties, including drought-tolerant and early-maturing maize, improved cassava, and improved legumes, can raise yield potential and reduce risk, but their benefit depends on seed quality, timely planting, spacing, weeding and soil fertility (Vanlauwe et al., 2010; FAO, 2017). A drought-tolerant variety on a nutrient-depleted soil will still yield poorly, and a high-yielding variety that requires more water may fail in a dry year. Good agronomy, including optimal plant population, timely weeding, and pest and disease management, often contributes as much to yield as the variety itself (Tittonell and Giller, 2013; Corbeels et al., 2020). ISFM therefore treats germplasm and agronomy as inseparable from soil management. Farmer participatory variety selection and on-farm trials can help match varieties to local soils and rainfall, and to farmers' preferences for taste, storability and marketability, which are often overlooked in breeding programmes (FAO, 2017; Mwongera et al., 2017).

4.4 Legume integration, rotation and intercropping

Legumes fix atmospheric nitrogen through symbiosis with rhizobia, provide protein-rich food and feed,

diversify income, and break pest and disease cycles (Giller, 2001; Giller et al., 2009). Maize-legume intercropping and rotation are among the most widely studied ISFM practices in SSA. Meta-analyses and reviews show that maize-legume systems can improve total system productivity, land-equivalent ratio, soil nitrogen and dietary diversity, though maize yield in intercrops may be lower than in sole maize in a given season because of competition (Giller et al., 2009; Chivenge et al., 2022). The net benefit depends on legume species, density, timing, soil phosphorus and inoculation. Soybean, groundnut, cowpea, common bean and pigeon pea each have different niches, markets and labour requirements. Phosphorus is often the limiting nutrient for legume fixation, so legumes may themselves need phosphorus fertiliser or inoculant to perform well (Giller, 2001; Vanlauwe et al., 2010). Extension that promotes legumes without addressing phosphorus, seed systems and markets is unlikely to sustain adoption.

4.5 Conservation agriculture and soil cover

Conservation agriculture is based on three principles: minimum soil disturbance, permanent soil cover, and crop diversification or rotation (FAO, 2013; Corbeels et al., 2020). Minimum tillage can reduce erosion, preserve soil structure and save labour and fuel, while mulch and cover crops protect the soil surface, reduce evaporation, suppress weeds and feed soil organisms (Giller et al., 2009; Corbeels et al., 2020). Evidence from SSA is mixed. Some studies report higher yields, better soil moisture and higher soil organic carbon under conservation agriculture, especially after several years and when combined with adequate fertiliser and weed control (Corbeels et al., 2020; Gram et al., 2020). Others report yield penalties in the early years, increased weed pressure, difficulty retaining residues where livestock graze freely, and labour trade-offs (Giller et al., 2009; Corbeels et al., 2020). The synthesis therefore treats conservation agriculture as a promising but context-dependent component of ISFM, not as a universal prescription. Its success depends on residue availability, weed management, herbicide access where appropriate, and community arrangements for livestock grazing.

4.6 Agroforestry and multipurpose trees

Agroforestry integrates trees with crops and livestock, providing shade, windbreaks, fodder, fuelwood, fruit, timber and income, while improving soil through litter, root turnover and, in the case of nitrogen-fixing trees, biological fixation (Garrity et al., 2010; FAO, 2017). Faidherbia albida, Gliricidia sepium, Sesbania sesban and other species have been studied widely in southern and eastern Africa, with evidence of improved maize yields under Faidherbia canopies in Zambia and Malawi (Garrity et al., 2010; Corbeels et al., 2020). Trees also contribute to carbon sequestration and landscape resilience, but they require land, labour, protection from grazing and browsing, and time to mature. Tenure security is critical: farmers are less likely to plant trees if they fear losing the land or the tree (World Bank, 2019; FAO, 2017). Agroforestry is therefore best viewed as a medium- to long-term investment that complements, rather than replaces, annual ISFM practices.

Table 1. Components of climate-smart ISFM, mechanisms and constraints. Source: synthesis of Vanlauwe et al. (2010), Giller et al. (2009), Corbeels et al. (2020) and FAO (2013).

ISFM component	Main mechanism	Typical benefit	Key constraint
Mineral fertiliser	Rapid nutrient supply	Higher yield, higher N-use efficiency when combined	Cost, access, low response on degraded soils
Manure / compost	Organic matter + slow nutrients	Soil structure, water retention, biology	Low quantity, variable quality, labour
Crop residues / mulch	Soil cover + carbon	Reduced erosion, moisture conservation	Competing uses, grazing, pests
Legume intercrop / rotation	Biological N fixation	System productivity, protein, diversification	P demand, seed, competition, market
Conservation agriculture	Minimum tillage + cover + rotation	Soil health, moisture, erosion control	Weeds, residues, early yield penalty
Agroforestry	Tree litter, N fixation, shade	Carbon, fodder, income, resilience	Tenure, time to benefit, labour
Improved seed + agronomy	Genetic potential + management	Yield, stability, pest tolerance	Seed quality, timely inputs, knowledge

5. Evidence on Productivity, Soil Carbon, Water and Emissions

The strongest and most consistent finding in the literature is that combining organic and mineral inputs improves maize productivity and agronomic efficiency compared with either alone, especially when improved varieties are used (Vanlauwe et al., 2010; Gram et al., 2020; Chivenge et al., 2022). A meta-analysis of combining organic and mineral nitrogen for maize in SSA found greater productivity and agronomic efficiency for combined applications than for sole applications when total nitrogen exceeded a threshold, and that combining mineral fertiliser with high-quality organic resources increased agronomic efficiency and reduced soil organic carbon losses (Gram et al., 2020). A synthetic review of ISFM in semi-arid areas reported maize yield increases of 15 to 145 percent under ISFM, with yields varying by site, season and management (Chivenge et al., 2022). Long-term trials in Nigeria and elsewhere show that ISFM can sustain yields over decades, whereas continuous cropping without inputs leads to declining yields and soil carbon (Vanlauwe et al., 2010; IITA, 2023). Figure 1 summarises this pattern in illustrative form: the largest gains come not from a single input, but from integrated packages.

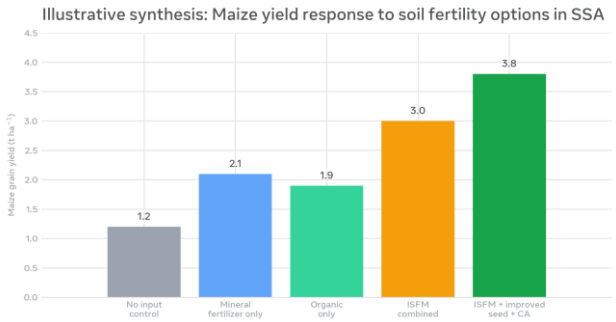


Figure 1. Illustrative synthesis of maize yield response to soil fertility options. Values are illustrative, drawn from the range reported in Vanlauwe et al. (2010), Gram et al. (2020) and Chivenge et al. (2022), and are not from a single trial.

Soil organic carbon is both an indicator and a driver of soil health. Practices that add organic matter, retain residues, reduce tillage and diversify rotations tend to increase or maintain soil organic carbon, while practices that remove residues and disturb soil tend to deplete it (Lal, 2004; Lehmann and Kleber, 2015; IPCC, 2019). However, carbon sequestration in tropical soils is limited by high decomposition rates, and gains are often modest and reversible if management changes (Lehmann and Kleber, 2015; Corbeels et al., 2020). The climate benefit of soil carbon should therefore not be overstated. A more robust framing is that soil organic matter improves adaptation: it increases water-holding capacity, infiltration and nutrient buffering, which help crops survive dry spells (Lal, 2004; IPCC, 2019). In other words, soil carbon is valuable even if its mitigation value is modest, because it underpins resilience.

Water relations are a key pathway through which ISFM delivers climate-smartness. Mulch and cover reduce evaporation and surface crusting, minimum tillage preserves pores and aggregates, and organic matter improves infiltration and storage (Corbeels et al., 2020; Lal, 2004). In semi-arid areas, these effects can matter more than nutrient supply in a dry year, because a crop that cannot access water cannot use nutrients (Chivenge et al., 2022; Corbeels et al., 2020). Conversely, in high-rainfall areas, improved drainage, raised beds and timely planting may matter more than moisture conservation. This reinforces the need for site-specific recommendations rather than blanket advice.

Greenhouse-gas outcomes of ISFM are nuanced. Nitrogen fertiliser can increase nitrous oxide emissions, a potent greenhouse gas, especially when applied in excess, at the wrong time, or to waterlogged soils (IPCC, 2019; Gram et al., 2020). Organic inputs can also emit nitrous oxide and methane during decomposition if managed poorly. However, emissions intensity, emissions per tonne of grain, often declines when ISFM raises yield, because the same emissions are spread over more food (Gram et al., 2020; IPCC, 2019). Combining organic and mineral inputs, splitting nitrogen, placing fertiliser near the plant and avoiding application before heavy rain can reduce losses (Vanlauwe et al., 2014; Chivenge et al., 2022). Agroforestry and soil carbon sequestration can offset some emissions, but accounting is complex and permanence is uncertain (Garrity et al., 2010; IPCC, 2019). The synthesis conclusion is that ISFM should aim to reduce emissions intensity and avoid emissions hotspots, rather than claim large net sequestration without evidence.

Table 2. Summary of expected outcomes of well-managed climate-smart ISFM. Source: synthesis of cited meta-analyses and reviews.

Outcome	Direction under well-managed ISFM	Evidence strength	Notes
Maize / staple yield	Increase, often large	Strong, meta-analyses	Largest with combined inputs + improved seed
Yield stability	Increase in variable seasons	Moderate	Soil water and diversity buffer shocks
Soil organic carbon	Maintain / modest increase	Moderate	Reversible; tropical decomposition high
Water infiltration / retention	Improve	Moderate to strong	Mulch, organic matter, minimum tillage
N agronomic efficiency	Increase with combined inputs	Strong	Gram et al. (2020) meta-analysis
N2O emissions per ha	May increase with N rate	Moderate	Intensity often falls as yield rises
Labour demand	Often increases	Moderate	Compost, mulching, weeding
Household income	Increase if markets work	Moderate	Depends on prices, tenure, labour

Cassava, sorghum, millet and rice deserve attention alongside maize, because they are critical for food security in different agro-ecologies. Cassava tolerates poor soils and drought better than maize, but it also depletes soil nutrients if grown continuously without return, and its productivity responds to ISFM, including manure and mineral fertiliser, especially potassium (Sanchez, 2002; FAO, 2017). Sorghum and millet in the Sahel and northern Nigeria benefit from micro-dosing, manure, stone bunds and zai pits that concentrate water and nutrients (Bationo et al., 2007; FAO, 2017). Rice in lowlands and irrigated systems benefits from integrated nutrient management, alternate wetting and drying, and residue management, which can reduce methane emissions while maintaining yield (IPCC, 2019; FAO, 2017). A maize-centred view of ISFM would miss these crops and the farmers who depend on them.

6. Adoption, Livelihoods and Equity

Adoption of ISFM and CSA practices in SSA is often partial, sequential and reversible, rather than a one-time switch to a full package (Mwongera et al., 2017; Lipper et al., 2014; Corbeels et al., 2020). Farmers may adopt improved seed but not fertiliser, or fertiliser but not manure, or legumes in one field but not another, depending on cash, labour, soil and market conditions. This is rational. A farmer who cannot afford fertiliser for all fields will target it to the most responsive field or the highest-value crop (Zingore et al., 2007; Tittonell et al., 2005). A farmer who lacks labour for composting may

use manure on the home field only. Studies that measure adoption as a binary variable therefore miss much of the story. A more useful approach is to measure intensity, combination and adaptation: which components, on which fields, at what rates, and with what modifications (Vanlauwe et al., 2014; Mwongera et al., 2017).

Economic barriers are central. Input costs, transport costs and interest rates make fertiliser and improved seed expensive relative to output prices, especially when markets are thin and prices are volatile (Bationo et al., 2007; World Bank, 2019). Labour is another constraint: composting, mulching, manure transport and minimum-tillage weeding are labour-intensive, and labour peaks at planting and weeding when households are already stretched (Giller et al., 2009; Corbeels et al., 2020). Tenure insecurity discourages long-term investments such as agroforestry, terracing and soil carbon building, because the farmer may not capture the future benefit (FAO, 2017; World Bank, 2019). Gender matters: women often have less access to land, inputs, credit, extension and markets, and bear a disproportionate share of labour, yet they are central to food production and household nutrition (FAO, 2017; Lipper et al., 2014). Youth face similar constraints, and may be less interested in farming if it is seen as low-return and drudgery. Figure 2 illustrates the relative importance of barriers as reported in synthesised survey literature; the exact shares vary by country, but cost, climate risk and extension gaps recur.

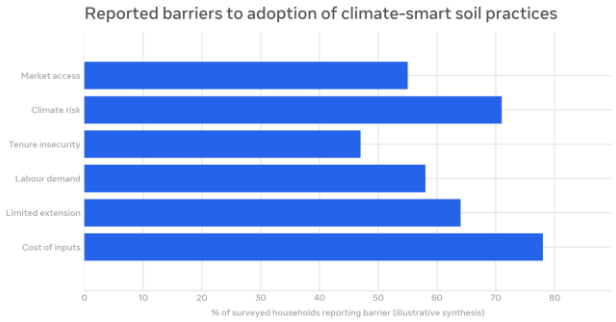


Figure 2. Illustrative synthesis of barriers to adoption. Shares are illustrative, synthesised from Bationo et al. (2007), Mwongera et al. (2017), Corbeels et al. (2020) and Lipper et al. (2014).

Extension and knowledge systems are critical mediators. Pluralistic extension, combining public extension, farmer field schools, lead farmers, radio, mobile phone messages, agro-dealer advice and private services, tends to reach more farmers than a single channel, but quality varies (FAO, 2017; Mwongera et al., 2017). Farmer field schools and participatory trials that let farmers compare options on their own fields are particularly effective for ISFM, because they build confidence and allow adaptation (Vanlauwe et al., 2014; Tittonell and Giller, 2013). Digital tools, including soil maps, weather forecasts, input e-vouchers and mobile extension, can help, but they require connectivity, literacy, trust and content in local languages (FAO, 2017; World Bank, 2019). Soil testing and site-specific recommendations are promising, but they must be affordable and linked to input supply; a soil test that recommends a fertiliser the farmer cannot buy is of little value.

Livelihood outcomes of ISFM extend beyond yield. Higher and more stable yields can improve food availability, dietary diversity, income and resilience, and can reduce the need to clear new land (FAO, 2017; Lipper et al., 2014). Conservation agriculture and agroforestry can also provide fodder, fuelwood and ecosystem services (Garrity et al., 2010; Corbeels et al., 2020). However, benefits may be delayed, and households that are food-insecure may prioritise immediate consumption over long-term soil investment (Tittonell and Giller, 2013; World Bank, 2019). Social protection, savings groups, input credit and insurance can help bridge that gap by reducing risk and smoothing consumption, allowing farmers to invest in soil health without jeopardising immediate needs (Lipper et al., 2014; World Bank, 2019). Evaluations should therefore track food security, income, labour, gender and resilience, not only yield.

7. A Decision Framework and Scaling Pathways

The framework proposed here has four steps: diagnose, match, test and support. Diagnosis begins with soil, rainfall, farm and household characteristics: soil texture, organic matter, acidity, nutrient status, slope, rainfall amount and distribution, farm size, labour, capital, tenure, market access and gendered roles. Simple, low-cost tools, including soil test kits, farmer soil classification, rainfall records and farm sketches, can be combined with laboratory analysis where available (Sanchez, 2002; Vanlauwe et al., 2014). The goal is not a perfect map, but a usable classification that distinguishes, for example, fertile home fields from degraded outfields, high-rainfall from semi-arid zones, and resource-endowed from resource-constrained households (Tittonell et al., 2005; Zingore et al., 2007).

Matching selects ISFM options that fit the diagnosis. On fertile, well-watered home fields, a full ISFM package with improved seed, balanced fertiliser and manure may be profitable. On degraded outfields, the first step may be to rebuild organic matter with manure, compost, legumes and residue retention before investing heavily in mineral fertiliser, because response will be low until soil health improves (Vanlauwe et al., 2010; Tittonell and Giller, 2013). In semi-arid areas, water-harvesting, mulching and drought-tolerant varieties may be prioritised over high fertiliser rates (Chivenge et al., 2022; Corbeels et al., 2020). In high-rainfall areas, drainage, phosphorus and legume integration may matter more. For households with little cash, legumes, manure and labour-intensive soil conservation may be the entry point, with mineral fertiliser added as cash flow improves. For households with access to markets and credit, a more input-intensive package may be feasible. Table 3 illustrates this matching logic.

Table 3. Illustrative matching of ISFM options to farm and soil types. Adapted from Tittonell et al. (2005), Zingore et

al. (2007), Vanlauwe et al. (2014) and Corbeels et al. (2020).

Farm / soil type	Priority ISFM entry point	Supporting measures	Expected first benefit
Fertile home field, good rainfall	Improved seed + balanced NPK + manure	Split N, timely weeding	Higher yield, higher efficiency
Degraded outfield, low SOM	Manure / compost + legume + residues	Lime if acidic, P for legumes	Soil structure, gradual yield rise
Semi-arid, sandy soil	Mulch + zai / bunds + micro-dose	Drought-tolerant variety, early planting	Moisture, stability
High-rainfall, acidic soil	Lime + P + legume rotation	Drainage, improved seed	Better P availability, legume N
Resource-constrained household	Legume + manure + residues	Savings group, input credit	Low-cost fertility, food diversity
Market-oriented household	Full ISFM + CA + agroforestry	Contract, storage, insurance	Income, resilience, carbon

Testing should be farmer-led and iterative. Mother-baby trials, farmer field schools, innovation platforms and on-farm comparisons allow farmers to evaluate options under their own conditions, modify them and share results (Vanlauwe et al., 2014; Mwongera et al., 2017). Researchers and extension workers should record not only yield, but also labour, costs, soil change and farmer preferences, so that recommendations are based on full livelihood outcomes. Support requires institutions: affordable inputs, timely delivery, credit, insurance, secure tenure, pluralistic extension, and markets that reward quality and surplus (FAO, 2017; World Bank, 2019). Blended finance, including subsidies targeted to soil health, results-based payments, and carbon finance where credible, can help, but must be designed to avoid dependency and distortion (Lipper et al., 2014; Newell et al., 2019). Scaling should be understood as scaling of principles and capacities, not only of a fixed package: scaling out to more farmers, scaling up to policy, and scaling deep to change norms and knowledge (FAO, 2017; Mwongera et al., 2017).

Nigeria illustrates both the challenge and the opportunity. Nigeria has diverse agro-ecologies, from humid forest in the south to Sudan savanna in the north, and a large smallholder population growing maize, cassava, yam, sorghum, millet, rice and legumes (FAO, 2017; World Bank, 2019). Soil fertility depletion, erratic rainfall, insecurity in some areas, and input and market constraints affect productivity, while programmes on climate-smart agriculture, soil mapping, fertiliser quality and extension reform offer entry points (Sanchez, 2015; FAO, 2017). A climate-smart ISFM strategy for Nigeria would combine site-specific soil recommendations, legume integration in cassava and maize systems, conservation agriculture where residues can be retained, agroforestry in appropriate zones, and stronger seed and fertiliser systems, with attention to gender, youth and tenure. It would also require coordination across federal, state and local institutions, and learning from farmer experimentation in each agro-ecological zone.

8. Conclusion and Priorities

Climate-smart ISFM is not a silver bullet, but it is one of the most promising pathways to raise smallholder productivity, strengthen resilience and reduce emissions intensity in Sub-Saharan Africa. The evidence is clearest that combining organic and mineral inputs with improved germplasm and good agronomy outperforms single inputs, and that legumes, soil cover, minimum tillage and agroforestry can improve soil health and water relations when adapted to local conditions (Vanlauwe et al., 2010; Gram et al., 2020; Chivenge et al., 2022; Corbeels et al., 2020). The evidence is also clear that benefits are heterogeneous, delayed in some cases, and mediated by labour, tenure, markets and knowledge. Scaling therefore requires site-specific recommendations, farmer-led testing, supportive institutions and attention to equity.

Three research priorities stand out. First, long-term, multi-site trials that track soil carbon, water, emissions, labour, income and nutrition together, not only yield, are needed to judge climate-smartness more fully (IPCC, 2019; Corbeels et al., 2020). Second, research on soil heterogeneity, digital soil mapping, and low-cost soil testing should be linked to input supply and extension, so that recommendations are usable (Sanchez, 2002; Vanlauwe et al., 2014). Third, research on adoption, gender, youth, tenure and institutional design should be integrated with agronomy from the start, because the best agronomic option will fail if it does not fit household realities (Mwongera et al., 2017; Lipper et al., 2014). Policy should prioritise secure tenure, pluralistic extension, affordable and quality inputs, blended finance, and markets that reward sustainable production, while avoiding one-size-fits-all packages. If those conditions are met, climate-smart ISFM can help smallholders in Sub-Saharan Africa produce more food, on healthier soils, in a changing climate.

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