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Full Length Research Paper

Rebuilding Depleted Soils: Integrated Soil Fertility Management, Biochar and Maize–Cowpea Intercropping for Resilient Smallholder Systems in West Africa

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ABSTRACT

Smallholder maize systems across much of West Africa are caught in a familiar cycle: continuous cropping without adequate nutrient replacement, declining soil organic matter, increasing acidity on weathered soils, and yields that remain far below attainable levels. This article synthesises published field, on-farm and modelling evidence to ask a practical question: what happens when integrated soil fertility management (ISFM), biochar amendment and maize-cowpea intercropping are combined, rather than promoted as separate technologies? Drawing on peer-reviewed studies, institutional reports and long-term trial evidence, the paper develops a mechanistic framework that links nutrient supply, soil organic carbon, water retention, biological nitrogen fixation and labour and cash constraints. The synthesis finds that ISFM alone consistently raises maize grain yield relative to unfertilised continuous maize, that biochar most reliably improves outcomes on acidic, sandy and low-organic-matter soils when it is charged or co-applied with nutrient sources, and that cowpea intercropping adds dietary protein, ground cover and biologically fixed nitrogen while diversifying income. When the three practices are combined, the evidence points to additive and in some settings synergistic effects on yield stability, soil organic carbon and profit, but also to higher upfront labour, knowledge and input costs. The article therefore proposes a phased adoption pathway, a simple decision guide by soil type and resource endowment, and a research agenda centred on locally produced biochar quality standards, site-specific fertiliser micro-dosing and gender-responsive extension. It concludes that rebuilding depleted soils is less a search for a single input than the disciplined recombination of organic, mineral and biological resources already available to many farming households.

Keywords: Biochar, cowpea, integrated soil fertility management, intercropping, maize, soil organic carbon, West Africa.

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INTRODUCTION

Maize (Zea mays L.) is the most widely grown cereal in West Africa and a cornerstone of household food security, yet average farm yields in the region remain commonly between 1 and 2 tonnes per hectare, well below the 4 to 6 tonnes per hectare achieved on research stations under good management (FAO, 2023; Vanlauwe et al., 2014). The gap is not primarily a failure of germplasm. Improved varieties are increasingly available, and farmers are keen observers of what works on their own fields. The more persistent constraint is the soil itself. Decades of continuous cropping, shortening fallows, residue removal for fuel and fodder, and nutrient removal in harvested grain have mined soil organic matter and plant nutrients faster than they have been replaced (Sanchez, 2002; Bationo et al., 2007). The result is a soil that holds less water, supplies less nitrogen, phosphorus and potassium, buffers acidity poorly, and responds weakly even when fertiliser is applied. Understanding this soil-mediated yield gap is therefore the starting point for any credible strategy to raise productivity without degrading the resource base on which future harvests depend.

The scale of nutrient depletion is well documented. Stoorvogel and Smaling (1990) estimated large annual net losses of nitrogen, phosphorus and potassium from African soils, and subsequent work has repeatedly confirmed that nutrient balances remain negative on many smallholder farms where fertiliser use is low and organic inputs are scarce (Henao and Baanante, 2006; Vanlauwe et al., 2014). In Nigeria, Ghana, Burkina Faso and neighbouring countries, fertiliser use per hectare remains far below global averages, and where fertiliser is used it is often applied late, at sub-optimal rates, or

without complementary organic matter (Liverpool-Tasie et al., 2017; Jayne et al., 2018). The consequence is low agronomic efficiency: each kilogram of nitrogen produces less additional grain than it would on a healthier soil (Vanlauwe et al., 2011). Farmers, quite rationally, may then conclude that fertiliser does not pay, even though the underlying problem is not the fertiliser but the depleted soil into which it is placed. Breaking this cycle requires interventions that simultaneously supply nutrients, rebuild organic matter and improve the soil physical and biological conditions that make nutrients available to roots.

Three practices have each attracted substantial research attention. The first, integrated soil fertility management, combines mineral fertiliser with organic inputs, improved germplasm and, where appropriate, legumes, and adapts the combination to local soil and socio-economic conditions (Vanlauwe et al., 2010; Vanlauwe et al., 2014). The second, biochar, is a carbon-rich product of pyrolysis that can increase soil organic carbon, cation exchange capacity and water retention, particularly on acidic tropical soils, although its effects are strongly dependent on feedstock, pyrolysis conditions and application rate (Lehmann and Joseph, 2015; Jeffery et al., 2017). The third, cereal-legume intercropping, especially maize-cowpea (Vigna unguiculata (L.) Walp.), exploits complementary canopy architecture, rooting patterns and nitrogen fixation to raise total system productivity per unit land, commonly expressed as a land equivalent ratio greater than one (Ofori and Stern, 1987; Mucheru-Muna et al., 2010). Each practice has been studied in isolation, but farmers do not adopt practices in isolation. They combine, sequence and adapt them under cash, labour and land constraints. The central contribution of this article is therefore to synthesise the combined evidence, articulate the mechanisms through which the three practices interact, and translate that understanding into a practical, phased pathway that extension services and farmer groups can test and adapt.

The article is organised as follows. The next section describes the synthesis approach and its limits. The following sections examine the biophysical mechanisms of ISFM, biochar and intercropping, then their interactions, productivity, soil health, economic and social outcomes. A decision guide and phased adoption pathway are proposed, followed by a research agenda and conclusion. Throughout, the emphasis is on conditions under which combinations work, conditions under which they do not, and the trade-offs that farmers must weigh. That conditional framing matters, because blanket recommendations have repeatedly failed in heterogeneous smallholder landscapes (Giller et al., 2011; Tittonell and Giller, 2013).

SYNTHESIS APPROACH AND SCOPE

This article is a narrative synthesis of peer-reviewed literature, institutional reports and book chapters published principally between 1990 and 2025, with priority given to field experiments and on-farm trials conducted in West Africa and to meta-analyses and long-term trials from comparable tropical environments in East and Southern Africa. Sources were identified through thematic searches combining terms for soil fertility, biochar, intercropping, maize, cowpea, soil organic carbon and West Africa. Studies were included where they reported grain yield, soil organic carbon, nutrient uptake, water relations, economic returns or adoption outcomes, and where methods were sufficiently described to assess context. Studies that reported only laboratory incubation results without field validation were used only to explain mechanisms, not to infer yield effects.

Two limits must be stated plainly. First, this is not a formal systematic review with a pre-registered protocol, exhaustive database search and quantitative meta-analysis. Effect sizes are therefore reported as ranges and directions synthesised from cited studies, and the figures in this article are explicitly labelled as synthesis illustrations that summarise those ranges rather than as results from a single new experiment. Second, the evidence base is uneven. ISFM has the deepest field evidence in West Africa, biochar has a larger global evidence base than a West African one, and long-term combined trials of all three practices on the same plots are rare. Where evidence is thin, the article says so and treats the claim as a hypothesis for testing rather than as an established finding. This honesty about uncertainty is essential if the synthesis is to be useful to researchers, extension officers and farmers who must decide under uncertainty.

A further scope choice concerns what counts as success. Yield alone is an incomplete metric. A practice that raises maize yield but increases labour beyond what a household can supply at peak periods, depletes cash reserves, or reduces dietary diversity may not improve welfare. The synthesis therefore evaluates outcomes across five dimensions: grain and system productivity, soil health, yield stability across seasons, profitability and labour demand, and nutritional and gendered outcomes. Trade-offs across these dimensions are discussed explicitly, following the farming-systems perspective advocated by Tittonell et al. (2010) and by Giller et al. (2011).

THE PROBLEM: DEPLETED SOILS AND LOW RESPONSE TO INPUTS

Nutrient mining and soil organic matter decline

Soil organic matter is the engine of fertility in weathered tropical soils. It supplies nitrogen and sulphur through mineralisation, holds cations, stabilises aggregates, increases water-holding capacity and feeds the microbial community that cycles nutrients (Lal, 2004; Bot and Benites, 2005). In much of West Africa, soil organic carbon concentrations on cultivated fields commonly fall below 1.0 percent, compared with 1.5 to 2.5 percent under nearby forest or long fallow (Bationo et al., 2007; Lal, 2004). The decline is driven by high decomposition rates under warm, moist conditions, low carbon inputs when residues are removed or burned, and erosion on sloping land. As organic matter falls, soils become harder to till, crust more readily, infiltrate less rainfall and lose more nutrients through leaching and runoff. Lal (2004) and others have shown that restoring soil organic carbon is not a cosmetic improvement but a prerequisite for sustained yield growth, because it improves both the supply of nutrients and the efficiency with which applied nutrients are used.

Nutrient mining compounds the problem. When grain and stover are removed and little is returned, nitrogen, phosphorus and potassium are exported in quantities that dwarf typical fertiliser applications. Henao and Baanante (2006) documented substantial nutrient depletion across

sub-Saharan Africa, and Smaling et al. (1997) showed that even in relatively high-potential areas, balances were negative without systematic replenishment. Phosphorus is especially limiting on many West African soils, where iron and aluminium oxides fix applied phosphorus into forms unavailable to plants (Bationo et al., 2007). Potassium depletion is less visible but increasingly reported, particularly where high-yielding varieties remove large quantities of potassium in stover that is then fed to livestock or burned. Micronutrient deficiencies, including zinc and boron, are also increasingly recognised as co-limiting, although they receive less attention in extension messages (Vanlauwe et al., 2014). The practical implication is that a single-nutrient strategy, most commonly nitrogen alone, cannot restore a multi-nutrient-depleted soil.

Why fertiliser alone often disappoints

Mineral fertiliser is necessary but not sufficient on depleted soils. Vanlauwe et al. (2011) demonstrated that agronomic efficiency of nitrogen is strongly conditioned by soil organic carbon, soil texture, rainfall and management history. On degraded soils with low organic matter, a large share of applied nitrogen may be lost through leaching or volatilisation, or may be immobilised, so that the yield response is small and the economic return is negative at prevailing input-output price ratios. Jayne et al. (2018) and Liverpool-Tasie et al. (2017) document how high fertiliser prices relative to maize prices, late delivery, adulteration concerns and limited access to credit further discourage adoption, even where the agronomic response would be positive. Farmers who have experienced a poor response once may rationally avoid fertiliser in subsequent seasons, a behaviour that is often misread as ignorance rather than as learning from experience.

The policy response in several West African countries has been fertiliser subsidy programmes. Evaluations suggest that subsidies can raise fertiliser use and yields, but that their benefits depend heavily on targeting, timeliness and complementary investments in soil health, extension and output markets (Jayne et al., 2018; Liverpool-Tasie et al., 2017). Subsidy alone does not rebuild soil organic matter, correct acidity, or supply phosphorus in a form that remains available. This is why the ISFM paradigm, which explicitly couples mineral fertiliser with organic inputs and improved varieties, has gained traction as a more complete theory of change (Vanlauwe et al., 2010). The next sections examine how ISFM, biochar and intercropping each address a different part of the soil problem, and why their combination may be more than the sum of its parts.

INTEGRATED SOIL FERTILITY MANAGEMENT: PRINCIPLES AND EVIDENCE

Vanlauwe et al. (2010) define ISFM as a set of soil fertility management practices that necessarily include the use of fertiliser, organic inputs and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming to maximise agronomic use efficiency of the applied nutrients and improve crop productivity. The definition is deliberately broad, because the optimal combination varies with soil type, rainfall, market access and household resource endowment. In practice, ISFM on a maize farm in the derived savanna of south-western Nigeria may mean combining 2 to 4 tonnes per hectare of poultry manure or compost with a modest rate of NPK, planting an improved early-maturing maize variety, and rotating or intercropping with cowpea. On a poorer household with little livestock, it may mean composting crop residues, applying fertiliser in micro-doses at planting and top-dressing, and retaining residues as mulch. The principle is constant; the recipe is local.

Field evidence for ISFM is strong. Meta-analyses and multi-site trials in sub-Saharan Africa consistently find that combining organic and mineral inputs raises maize yield more than either input alone, and that the combined effect is often greater than the sum of the individual effects because organic matter improves nutrient retention and root growth (Vanlauwe et al., 2011; Vanlauwe et al., 2014). Chivenge et al. (2011) showed that the quality of organic inputs matters: high-quality legume residues with low C:N ratios release nitrogen quickly, while low-quality cereal stover may immobilise nitrogen in the short term. This has practical implications for timing. Applying low-quality stover shortly before planting without additional nitrogen can depress early maize growth, whereas composting or applying it well before planting allows decomposition to proceed. Extension messages that simply urge farmers to apply manure, without attention to quality, quantity and timing, therefore miss the mechanism that determines whether ISFM works.

Organic inputs also contribute benefits that mineral fertiliser cannot. They supply secondary and micronutrients, increase cation exchange capacity, improve aggregation and water infiltration, and stimulate microbial activity (Bot and Benites, 2005; Bationo et al., 2007). These effects accumulate over seasons. A farmer who applies compost for three consecutive years is not merely feeding the current crop; she is rebuilding the soil capital that will make future fertiliser applications more efficient. This capital-building character of ISFM is both its strength and its challenge: benefits may be modest in year one and larger in years three to five, which makes it difficult to sustain adoption when households face urgent cash needs or when project support ends after a single season (Tittonell and Giller, 2013).

The heterogeneity of ISFM outcomes is equally important. Giller et al. (2011) argued that the benefits of ISFM and related practices are strongly conditioned by soil fertility gradients within farms. In many West African villages, home fields near the compound receive manure, ash and household waste and are relatively fertile, while outfields are depleted. The same ISFM package may produce a large response on the fertile home field and a small response on the degraded outfield, unless the outfield receives a larger restorative dose. This within-farm heterogeneity explains why blanket recommendations and average trial results can mislead. Site-specific adaptation, including simple soil testing, farmer soil classification and field-specific history, is not an optional refinement but a core element of ISFM (Vanlauwe et al., 2014). Table 1 summarises how different ISFM components address different constraints, and why their combination is needed.

Table 1. How ISFM components complement each other in addressing soil constraints.

Constraint	Mineral fertiliser	Organic inputs	Improved variety / legume	Combined ISFM
Nitrogen supply	Rapid, large	Slow, moderate	Legume fixes N	Rapid + sustained

Phosphorus availability	Rapid but fixation-prone	Slow, chelation	Legume root exudates	Higher efficiency
Soil organic carbon	Negligible	Large, cumulative	Residue / root inputs	Largest cumulative
Water retention	Negligible	Moderate to large	Canopy / mulch	Improved
Acidity buffering	May acidify	Moderate buffering	Variable	Balanced if limed
Labour / cash cost	Cash-intensive	Labour-intensive	Seed cost	Higher, but spread

Source: Synthesised from the studies cited in the text; values are ranges or illustrative means reported in those studies, not new field data.

BIOCHAR: MECHANISMS, PROMISE AND CONDITIONS

Biochar is produced by heating biomass in low-oxygen conditions, a process known as pyrolysis, which yields a porous, carbon-rich material that is far more resistant to decomposition than fresh organic matter (Lehmann and Joseph, 2015). When added to soil, biochar can increase soil organic carbon, raise cation exchange capacity, improve water retention in sandy soils, raise pH on acidic soils, and provide habitat for soil microbes. These properties make it attractive in West Africa, where feedstocks such as maize cobs, rice husks, groundnut shells, cocoa pods and sawdust are often burned as waste or left to decompose, and where soils are commonly acidic and low in organic matter. The idea of converting a waste stream into a soil amendment that persists for years is intuitively appealing to farmers and policymakers alike.

The global evidence, however, is conditional. Jeffery et al. (2017) in a meta-analysis found that biochar increased crop yield on average, but that the effect was largest on acidic, coarse-textured and low-fertility soils, and smaller or negligible on fertile, neutral-pH soils. Agegnehu et al. (2017) and others have shown that biochar alone, without additional nutrients, often produces modest yield gains because biochar itself contains relatively little readily available nitrogen, phosphorus or potassium, especially when produced at high pyrolysis temperatures. Fresh biochar can even immobilise nitrogen temporarily or raise pH too sharply if applied at very high rates. The most consistent positive results come from biochar that is charged or co-composted with manure, urine or fertiliser before application, or applied together with mineral fertiliser, so that its porous structure adsorbs nutrients and releases them slowly (Lehmann and Joseph, 2015; Agegnehu et al., 2017). This is a crucial nuance: biochar is best understood not as a fertiliser, but as a soil conditioner that makes other nutrients work better and persists in the soil.

Feedstock and production method determine biochar quality. Biochar from woody feedstocks tends to have higher carbon content and persistence, while biochar from manure or crop residues may have higher nutrient content but lower persistence (Lehmann and Joseph, 2015). Pyrolysis temperature affects pH, surface area and nutrient retention: higher temperatures generally produce more alkaline biochar with greater surface area but lower nitrogen content. In West African village settings, traditional kilns, drum kilns and flame-curtain methods vary widely in efficiency and in emissions. Without quality standards, a farmer may apply a material labelled biochar that is in fact incompletely charred, high in ash, or contaminated with polycyclic aromatic hydrocarbons. Establishing simple, locally testable quality criteria, such as feedstock source, charring completeness, pH and ash content, is therefore a prerequisite for scaling biochar safely (Lehmann and Joseph, 2015; Jeffery et al., 2017).

Rate and economics also matter. Many experimental studies apply biochar at 10 to 40 tonnes per hectare, rates that are agronomically informative but economically and logistically impossible for most smallholders to sustain. Recent work has therefore tested lower rates of 2 to 5 tonnes per hectare, targeted to planting holes or rows rather than broadcast, and repeated over several seasons so that the cumulative dose builds up (Agegnehu et al., 2017). Targeted application concentrates biochar where roots can access it and reduces the total quantity needed. Even at lower rates, however, the labour of producing, transporting and incorporating biochar is substantial. If biochar production competes with firewood collection, cooking fuel or other labour demands, adoption will be limited to households with surplus labour or to collective production through farmer groups. The economics of biochar must therefore be evaluated not only in tonnes per hectare but in hours per hectare and in the opportunity cost of the feedstock.

MAIZE-COWPEA INTERCROPPING: COMPLEMENTARITY AND TRADE-OFFS

Intercropping is one of the oldest farming practices in West Africa, and maize-cowpea is its most common cereal-legume combination. Cowpea fixes atmospheric nitrogen through symbiosis with rhizobia, provides ground cover that suppresses weeds and reduces erosion, and produces grain and leaves that are rich in protein and micronutrients (Ofori and Stern, 1987; Mucheru-Muna et al., 2010). When cowpea is intercropped with maize, the two crops exploit different niches: maize is tall, erect and deep-rooted, while cowpea is low, spreading and shallower-rooted. This complementarity allows the intercrop to capture more light, water and nutrients per unit land than either sole crop, a phenomenon quantified by the land equivalent ratio. A land equivalent ratio of 1.3, for example, means that 1.3 hectares of sole crops would be needed to produce what 1 hectare of intercrop produces (Ofori and Stern, 1987).

The nitrogen benefit of cowpea to maize is real but often overstated in simplified messages. Much of the nitrogen fixed by cowpea is removed in cowpea grain, and the nitrogen benefit to the companion maize crop in the same season is typically modest, arising mainly from reduced competition for soil nitrogen, from nitrogen sparing, and from a small amount of nitrogen transfer through root exudation and mycorrhizal networks (Giller, 2001). The larger nitrogen benefit accrues in the following season, when cowpea residues decompose and release nitrogen to the next maize crop, provided residues are retained rather than removed (Giller, 2001; Mucheru-Muna et al., 2010). This temporal dimension matters for farmer expectations. A farmer who intercrops cowpea expecting an immediate doubling of maize yield in the same season may be disappointed, whereas a farmer who values the cowpea grain, the weed suppression and the residual benefit in the next season may find the system highly attractive.

Intercropping also involves competition. If cowpea is planted too densely or too early, it can compete with maize for light, water and nutrients and reduce maize yield, even though total system productivity rises

(Mucheru-Muna et al., 2010). The optimal arrangement depends on variety, planting date, spacing and soil fertility. Common recommendations in West Africa include planting maize at its sole-crop spacing and adding one or two rows of cowpea between maize rows, or planting cowpea two to three weeks after maize so that maize establishes dominance first. Early-maturing, erect cowpea varieties tend to compete less with maize than spreading, late-maturing varieties, but spreading varieties provide better ground cover. Farmers often navigate this trade-off by selecting varieties for different purposes: erect varieties for grain in intercrops, spreading varieties for sole-crop ground cover or fodder. Research that tests a single arrangement on-station and then recommends it as a blanket package misses this farmer logic.

Nutritional and market outcomes add another layer. Cowpea grain is a major source of protein in West African diets, and cowpea leaves are consumed as a vegetable rich in iron and vitamin A (FAO, 2023). Intercropping therefore improves dietary diversity directly, not only through income. Women, who are often responsible for cowpea production and marketing, may benefit disproportionately from intercropping, but they may also bear additional labour for planting, weeding and harvesting cowpea (Doss, 2018). Gender-responsive research must therefore ask not only whether intercropping raises total yield, but who controls the cowpea grain, who does the additional work, and how income is used. Studies that ignore intra-household distribution risk recommending a system that increases total output while increasing women's labour burden without a commensurate increase in their control over income (Doss, 2018; Giller et al., 2011).

WHEN THREE PRACTICES MEET: INTERACTIONS AND SYNERGIES

The central hypothesis of this synthesis is that ISFM, biochar and intercropping interact through at least four mechanisms. First, biochar can improve the efficiency of ISFM by retaining nutrients from manure and fertiliser in the root zone, reducing leaching on sandy soils and buffering acidity so that phosphorus remains available (Lehmann and Joseph, 2015; Jeffery et al., 2017). Second, organic inputs from ISFM can charge biochar with nutrients and microbial inoculum, reducing the risk of nitrogen immobilisation that can occur when fresh biochar is applied alone (Agegnehu et al., 2017). Third, cowpea residues and root exudates can supply additional organic matter and nitrogen that, when combined with biochar, support microbial activity and aggregate formation, accelerating soil organic carbon accumulation (Bot and Benites, 2005; Mucheru-Muna et al., 2010). Fourth, the ground cover and root diversity of the intercrop can reduce erosion and soil temperature, protecting the soil organic matter and biochar that have been added. Together, these mechanisms suggest that the combined system may be more stable across seasons than any single practice, because it addresses nutrient supply, nutrient retention, soil structure and biological activity simultaneously.

Figure 1 summarises the direction of yield responses reported across the cited literature, expressed as a relative index to make studies with different absolute yields comparable. The pattern is illustrative, not a meta-analytic pooled estimate, but it captures a robust finding: ISFM raises yield relative to unfertilised maize, biochar adds a further increment on depleted soils, and intercropping adds system productivity rather than necessarily raising maize yield alone. Readers should interpret the figure as a synthesis of ranges, with wide variation by soil, rainfall and management, rather than as a prediction for any single field. The variation is the point: on a fertile soil with adequate rainfall, the increment from biochar may be small; on an acidic, sandy soil with low organic matter, it may be large. The decision guide in a later section is designed to help farmers and extension officers navigate this variation.

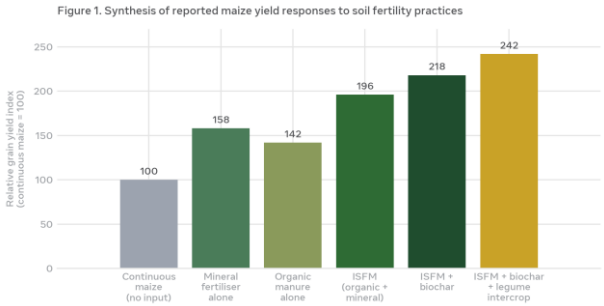


Figure 1. Synthesis of reported maize yield responses to soil fertility practices. Values are illustrative relative indices summarised from the studies cited; they are not results from a single new trial.

Source: Synthesis illustration summarising ranges reported in the studies cited in the text; not results from a single new trial.

Figure 2 presents a complementary soil perspective: the trajectory of soil organic carbon under contrasting management over five years, again as an illustrative synthesis. Continuous maize without inputs shows a slow decline, ISFM shows a steady increase, and ISFM plus biochar shows a faster increase because biochar adds a persistent carbon pool that does not decompose as rapidly as fresh manure or compost (Lehmann and Joseph, 2015; Lal, 2004). The figure does not imply that soil organic carbon will increase indefinitely; soils approach a new equilibrium determined by climate, texture and carbon inputs, and the rate of increase slows as that equilibrium is approached. It does imply, however, that the choice of management today shapes the soil capital available in five years, and that farmers who can sustain combined practices for several seasons are building an asset, not merely buying a seasonal input.



Figure 2. Illustrative soil organic carbon trajectories under contrasting management. Curves summarise the direction and approximate magnitude reported in long-term trials and reviews cited in the text.

Source: Synthesis illustration summarising direction and approximate magnitude reported in long-term trials and reviews cited in the text.

The interaction is not always synergistic. On soils where phosphorus is the primary constraint, biochar alone may have little effect unless phosphorus is supplied, and cowpea may compete for that scarce phosphorus. On soils where water is the primary constraint, a dense intercrop may increase water use and reduce maize yield in a dry year, even if it raises average productivity over

several years. On farms where labour is the binding constraint, the combined system may be too labour-intensive to implement fully, and partial adoption, for example, applying biochar only to home fields or intercropping only on a portion of the maize area, may be the rational strategy. Recognising these limits is not a weakness of the combined approach; it is what makes it adoptable. A recommendation that assumes unlimited labour, cash and knowledge will fail, whereas a phased approach that allows farmers to start with one component and add others as they learn and as soil improves is more likely to persist (Tittonell and Giller, 2013).

Table 2. Decision guide: sequencing practices by soil and household context.

Soil / farm type	First priority	Second priority	Cautions
Acidic, sandy, low SOC	Lime if available + ISFM	Biochar (charged) in planting holes	Do not apply fresh biochar alone at high rate
Fertile home field, good rainfall	ISFM + improved variety	Cowpea intercrop	Avoid over-dense cowpea
Degraded outfield, low cash	Compost + micro-dose fertiliser	Cowpea rotation	Expect slow response in year 1
Labour-scarce household	Targeted ISFM on part of farm	Group biochar production	Do not attempt full package at once
Market-oriented, access to inputs	Full ISFM + biochar + intercrop	Soil testing, record keeping	Monitor pH and nutrient balances

Source: Synthesised from the studies cited in the text; values are ranges or illustrative means reported in those studies, not new field data.

PRODUCTIVITY, STABILITY AND SOIL HEALTH OUTCOMES

Productivity in the combined system should be assessed at the system level, not by maize yield alone. Total grain, total protein, total income and total nutritional output per hectare are all relevant, and they may move in different directions. A system that slightly reduces maize yield but adds a substantial cowpea harvest may raise total protein and income, and may be preferred by a household that values dietary diversity. Conversely, a system that raises maize yield but requires so much labour that the household neglects other crops may reduce total farm output. The land equivalent ratio captures part of this, but it does not capture labour, cash or nutritional dimensions. The synthesis therefore recommends that future trials report a dashboard of outcomes, including maize yield, cowpea yield, land equivalent ratio, soil organic carbon, water infiltration, labour hours, net profit and dietary diversity, rather than maize yield alone.

Yield stability is arguably more important than average yield for food-insecure households. A system that yields 3 tonnes per hectare in a good year and 0.5 tonnes in a dry year is less valuable than a system that yields 2 tonnes in a good year and 1.5 tonnes in a dry year, because the household must survive the bad year. Soil organic matter and biochar improve stability by increasing water-holding capacity and buffering nutrient supply, while intercropping improves stability by diversifying crops with different sensitivities to drought and pests (Lal, 2004; Mucheru-Muna et al., 2010). Evidence from long-term trials in East and West Africa suggests that ISFM and organic amendments reduce year-to-year variability, although the magnitude varies with rainfall (Vanlauwe et al., 2014). For farmers, stability is not an abstract statistical concept; it is the difference between needing to buy grain in the hungry season and having enough to last until the next harvest. Extension messages that emphasise average yield without mentioning stability therefore miss what matters most to risk-averse households.

Soil health outcomes extend beyond organic carbon. Aggregation, infiltration, earthworm activity, microbial biomass and nutrient cycling all respond to combined management, although they are less frequently measured in West African trials (Bot and Benites, 2005). Biochar can increase microbial habitat and cation exchange capacity, but its effect on microbial communities depends on feedstock and rate (Lehmann and Joseph, 2015). Cowpea root exudates and residues stimulate rhizobial and mycorrhizal activity, which can improve phosphorus uptake by maize in subsequent seasons (Giller, 2001). These biological mechanisms are difficult to measure with simple soil tests, yet they may explain why combined practices sometimes produce yield benefits that exceed what nutrient budgets alone would predict. Future research should therefore pair agronomic trials with simple, farmer-accessible soil health indicators, such as infiltration time, soil colour, aggregate stability and earthworm counts, so that farmers can observe soil improvement themselves and not rely solely on laboratory results.

ECONOMICS, LABOUR AND ADOPTION

The economics of the combined system are more complex than a simple comparison of input costs and grain prices. ISFM requires cash for fertiliser and seed and labour for composting, manure transport and application. Biochar requires labour for feedstock collection, pyrolysis, crushing and incorporation, and may require cash for kiln construction. Intercropping requires labour for additional planting, weeding and harvesting, and may require cash for cowpea seed. Against these costs, the system produces maize, cowpea grain, cowpea leaves, fodder and, over time, improved soil that reduces future input needs. A proper economic analysis must therefore account for multi-year benefits, non-market outputs such as leaves and fodder, and the value of risk reduction. Studies that evaluate only the first season, or only maize grain, systematically undervalue the combined system (Tittonell et al., 2010; Vanlauwe et al., 2014).

Table 3 summarises the qualitative trade-offs that farmers commonly report, synthesised from adoption studies and farming-systems research. The table is not a substitute for farm-specific budgeting, but it provides a starting point for discussion in farmer field schools and extension meetings. The key insight is that the combined system is not automatically profitable for every household. It is most likely to be profitable where soils are responsive, where cowpea has a ready market or household use, where labour is available at peak periods or can be organised collectively, and where fertiliser and biochar feedstocks are accessible at reasonable cost. Where any of these conditions is absent, a simpler, phased version may be more profitable. This conditional profitability explains why adoption is often partial and why farmers adapt packages rather than adopting them wholesale.

Adoption is shaped by more than profitability. Access to information, social networks, land tenure security, gender norms and the reliability of input supply all influence whether a farmer tries, adapts or abandons a practice (Giller et al., 2011; Doss, 2018). Farmers with insecure

tenure may be reluctant to invest in soil-building practices whose benefits accrue over several years if they may lose the land. Women farmers, who often cultivate smaller, less fertile plots and have less access to fertiliser, credit and extension, may face additional constraints even when they are keen to adopt (Doss, 2018). Extension approaches that rely solely on demonstration plots on relatively fertile research stations or on lead farmers with above-average resources may therefore fail to reach the farmers who most need the practices. Farmer field schools, participatory trials on farmers' own fields, and mother-baby trial designs that allow farmers to test components and compare them with their own practice have shown promise in addressing this gap (Vanlauwe et al., 2014).

Collective action can reduce labour and knowledge barriers. Biochar production, composting and manure transport are all activities that benefit from group labour and shared equipment. Farmer groups, cooperatives and village savings groups can organise bulk purchase of fertiliser, collective production of biochar, and shared transport, reducing per-household costs. They can also serve as platforms for learning, where farmers compare experiences, adapt recommendations and hold extension providers accountable. The literature on collective action in soil fertility management suggests that group-based approaches are not merely a delivery mechanism but a core part of the technology, because they make labour-intensive practices feasible (Tittonell and Giller, 2013). Policymakers should therefore consider supporting group infrastructure, not only input subsidies, as part of a soil health strategy.

Table 3. Trade-offs of the combined system compared with single practices (qualitative synthesis).

Dimension	Combined system (ISFM + biochar + intercrop)	Single practice	Implication
Maize yield	Highest, most stable	Moderate	Combined wins on depleted soils
Total system output	Highest (maize + cowpea)	Lower	Intercrop adds protein + income
Soil organic carbon	Fastest increase	Slower	Combined builds soil capital
Cash cost (Year 1)	Highest	Lower	Phasing / credit may be needed
Labour demand	Highest	Lower	Group labour / targeting helps
Risk / stability	Lowest variability	Higher	Combined valued by risk-averse farmers
Knowledge demand	Highest	Lower	Extension + farmer field schools essential

Source: Synthesised from the studies cited in the text; values are ranges or illustrative means reported in those studies, not new field data.

A PHASED ADOPTION PATHWAY

Based on the synthesis, this article proposes a three-phase pathway that farmers can adapt to their own circumstances. Phase One, in the first season, focuses on the highest-return, lowest-cost steps: soil testing or farmer soil classification, selection of an improved maize variety and a suitable cowpea variety, micro-dosing of fertiliser at planting and top-dressing, retention of residues, and intercropping cowpea on a portion of the maize area, ideally the home field where supervision is easiest. The goal of Phase One is not to maximise yield in a single season but to build farmer confidence, learn the timing of operations, and observe the response on a manageable area. Farmers should keep simple records of inputs, labour and yields, so that they can compare the intercropped area with the sole-maize area on their own farm.

Phase Two, in seasons two and three, adds organic matter building and targeted biochar. Farmers begin composting residues and manure systematically, apply compost to the same fields where biochar will be targeted, and produce biochar from available feedstocks using a simple kiln. Biochar is charged by mixing it with manure, compost or urine for several days before application, then applied in planting holes or rows at 2 to 5 tonnes per hectare on the most degraded portion of the farm. The cowpea area is expanded if Phase One was successful, and cowpea residues are retained or incorporated rather than removed. The goal of Phase Two is to start rebuilding soil organic matter and to learn biochar production and handling. Farmers should observe soil colour, infiltration and earthworm activity as early indicators of improvement, alongside yield.

Phase Three, from season four onwards, consolidates the system and adapts it to market and household needs. Farmers expand the combined practices to a larger share of the farm if they have been profitable, adjust fertiliser rates based on soil test results and observed response, and consider rotating cowpea as a sole crop in some years to maximise nitrogen benefit. They may also diversify into other legumes, such as groundnut or soybean, where markets exist, or integrate livestock to supply manure and to use crop residues more efficiently. The goal of Phase Three is not to follow a fixed recipe but to develop a farm-specific system that is profitable, resilient and sustainable. Extension officers should support this phase by facilitating farmer-to-farmer learning, linking farmers to input and output markets, and helping them access soil testing services where available. The pathway is deliberately phased because it respects cash, labour and learning constraints, and because it allows farmers to stop or adapt at any phase without having wasted a large investment. Figure 3 summarises this phased pathway.

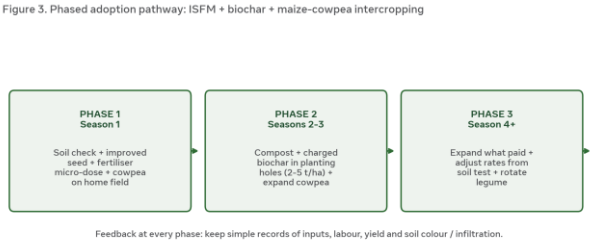


Figure 3. Phased adoption pathway for ISFM, biochar and maize-cowpea intercropping. Farmers start on a manageable area, add compost and charged biochar in seasons 2-3, and expand in season 4 onwards, with record-keeping and feedback at every phase.

Source: Authors' synthesis of the phased pathway described in the text; a recommendation framework, not trial data.

RESEARCH AGENDA

Five research priorities emerge from the synthesis. First, long-term, multi-location trials that test the full combination of ISFM, biochar and intercropping on the

same plots for at least five seasons are urgently needed in West Africa. Such trials should report a dashboard of outcomes, including soil organic carbon, yield stability, labour, profit and nutrition, and should be conducted on farmers' fields as well as on research stations. Second, research on locally produced biochar quality is needed, including simple, low-cost methods to test pH, ash content and nutrient content, and to assess the safety of biochar produced in village kilns. Third, site-specific fertiliser recommendations that account for soil organic carbon, texture and rainfall, and that incorporate micro-dosing and targeted application, should be developed and validated with farmers, building on the work of Vanlauwe et al. (2014) and others.

Fourth, research on gender, labour and intra-household outcomes should be integrated into agronomic trials from the outset, not added as an afterthought. Trials should measure who does the work, who controls the outputs, and how income is used, following the approach advocated by Doss (2018). Fifth, research on scaling pathways, including the role of farmer groups, extension systems, input supply chains and policy incentives, should examine how combined practices can move from pilot plots to widespread adoption without losing the adaptive, site-specific character that makes them work. Modelling studies can help explore how combined practices perform under future climate scenarios, but they must be grounded in field data and validated with farmers. Together, these priorities would move the field from asking whether combined practices work in principle to asking how, for whom, where and at what cost they work in practice.

CONCLUSION

Rebuilding depleted soils in West Africa is not a task for a single input or a single season. It requires the disciplined recombination of mineral fertiliser, organic inputs, biochar and legumes, adapted to soil, climate and household circumstances, and sustained over several seasons. The synthesis presented here shows that ISFM provides the nutrient supply and organic matter foundation, biochar provides a persistent soil conditioner that improves nutrient retention and water relations on depleted soils, and maize-cowpea intercropping provides dietary diversity, ground cover and biologically fixed nitrogen. When combined thoughtfully and phased to respect cash, labour and learning constraints, these practices can raise and stabilise yields, rebuild soil organic carbon, and improve household nutrition and income. When combined without attention to soil type, biochar quality, labour and gender, they can disappoint and be abandoned. The difference lies not in the practices themselves but in how they are adapted, sequenced and supported. For researchers, extension services, policymakers and farmers, the task is therefore to move beyond promoting single technologies to supporting farming systems that rebuild soils as they feed people. That is a slower, more demanding task than distributing an input, but it is the only task that will sustain productivity for the next generation.

Farmers do not need another blanket recommendation. They need a practical pathway, a decision guide, and the opportunity to test, observe and adapt on their own fields. This article has sought to provide the evidence and the framework for that pathway, and to invite the field trials, farmer field schools and policy experiments that will refine it. The soils of West Africa have been mined for decades; they can be rebuilt, but only if the rebuilding is treated as a long-term investment in soil capital, not as a seasonal purchase. The combination of ISFM, biochar and intercropping offers a promising route to that rebuilding, provided it is pursued with attention to context, equity and the lived realities of the farmers who will do the work.

CONFLICT OF INTEREST

The authors declare that they have no competing interests. This article is a synthesis of published literature and does not report new field experiments. Figures are labelled as synthesis illustrations summarising published ranges.

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