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Review Article

Integrating Climate-Smart Agronomy, Soil Health and Precision Technologies for Sustainable Intensification: A Global Review

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Abstract

Climate change, soil degradation, water scarcity and rising input costs are jointly reshaping the conditions under which crops are produced. This review synthesises evidence on climate-smart agronomy, soil health management, conservation agriculture, agroforestry, integrated nutrient and pest management, water-smart irrigation and precision technologies, and examines how their integration can deliver sustainable intensification across diverse agroecological zones. The central argument is that no single practice is sufficient on its own. Productivity, adaptation and mitigation outcomes improve most consistently when practices are bundled, sequenced over several seasons, adapted to local soil, climate, market and labour conditions, and supported by extension, finance, seed systems and tenure security. The review compares yield, soil organic carbon, water productivity, nitrogen-use efficiency and economic outcomes across regions and farming systems, identifies where trade-offs are most acute, and proposes a practical decision framework for researchers, extension professionals and policymakers. It concludes that integrated, context-sensitive agronomy offers a credible pathway to higher and more stable yields, healthier soils, more efficient resource use and greater resilience for smallholder and commercial farmers alike, provided that institutional and social barriers to adoption are addressed alongside biophysical innovation.

Keywords: climate-smart agriculture; sustainable intensification; soil health; conservation agriculture; precision agriculture; agroforestry; nitrogen-use efficiency; water productivity

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1. Introduction

Agronomy is being asked to achieve more, on less land, under more variable weather, and with fewer environmental side effects than at any previous point in history (Lipper et al., 2014; FAO, 2013). Global demand for cereals, pulses, roots, oilseeds, fruits and vegetables continues to rise, while climate change alters rainfall timing, increases the frequency of heatwaves and droughts, and shifts pest and disease pressures (Porter et al., 2014; IPCC, 2022). At the same time, many cultivated soils have lost organic matter, structure and biological activity after decades of intensive tillage, monocropping and unbalanced fertilisation (Lal, 2015; Montgomery, 2017). Water resources are increasingly contested, fertiliser prices are volatile, and many farmers face labour shortages, insecure tenure and limited access to credit and reliable agronomic advice (Pretty et al., 2018; Giller et

al., 2021). These pressures mean that the familiar goal of raising yield per hectare is no longer enough. Agronomy must also raise yield stability, resource-use efficiency, profitability, nutritional output and ecosystem resilience, and it must do so in ways that farmers can actually adopt and sustain.

Sustainable intensification offers a useful organising concept for this challenge. It is commonly defined as producing more food and other agricultural outputs from the same area while reducing negative environmental impacts and increasing contributions to natural capital and environmental services (Pretty et al., 2018; Garnett et al., 2013). Climate-smart agriculture adds three explicit objectives: sustainably increasing productivity and incomes, adapting and building resilience to climate change, and reducing or removing greenhouse gas emissions where possible (Lipper et al., 2014; FAO, 2013). In practice, the two concepts overlap heavily. Both reject the idea that intensification must mean more external inputs alone. Both emphasise knowledge-intensive management, ecological processes, diversification, soil health and careful matching of genotype, environment and management. The difference is mainly one of emphasis: sustainable intensification foregrounds productivity and environmental outcomes, while climate-smart agriculture foregrounds climate risk and mitigation as well.

This review has three objectives. First, it synthesises the evidence on the major families of climate-smart agronomic practices and their effects on yield, soil, water, nutrient and economic outcomes. Second, it explains why bundled and sequenced practices generally outperform isolated practices, and where trade-offs, time lags and context dependence matter most. Third, it proposes an integrated decision framework that links diagnosis, practice selection, implementation, monitoring and institutional support. The review draws on peer-reviewed meta-analyses, long-term experiments, modelling studies and field research from Africa, Asia, Europe, the Americas and Oceania. It is intentionally broad because the most important lesson from the literature is cross-cutting: context determines performance, and integration determines durability.

2. Concepts, Definitions and Analytical Approach

Three terms are used repeatedly and deserve precise definition. Conservation agriculture is a system based on minimum soil disturbance, permanent soil cover and crop diversification or rotation (Pittelkow et al., 2015; Kassam et al., 2019). Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, reflected in physical structure, chemical fertility, organic matter and biological activity (Lehmann et al., 2020; Lal, 2015). Precision agriculture is the use of observation, measurement, modelling and targeted application to manage spatial and temporal variability within fields, so that inputs are applied at the right rate, in the right place and at the right time (Gebbers and Adamchuk, 2010; Balafoutis et al., 2017). Each concept is necessary but insufficient alone. Minimum tillage without cover or rotation is not conservation agriculture. High soil organic matter without adequate nutrients, water and pest control does not guarantee high yield. Precision equipment without sound agronomy merely applies the wrong recommendation more precisely.

The review follows a narrative synthesis approach rather than a single formal meta-analysis, because the practices, outcomes, time scales and study designs in this field are highly heterogeneous. Priority was given to meta-analyses, systematic reviews and long-term experiments, supplemented by regional field studies that illuminate mechanisms and adoption constraints (Pittelkow et al., 2015; Kichamu-Wachira et al., 2021; Pretty et al., 2018). Where quantitative ranges are reported, they show direction and magnitude across diverse contexts. A 10 percent yield gain in one environment may be a 30 percent gain or a small loss in another, depending on soil, rainfall, crop, management history and input access (Giller et al., 2021; Corbeels et al., 2020). That variability is itself a finding: it is why diagnosis and local adaptation are central to good agronomy.

An agronomic practice should be judged on multiple criteria simultaneously. Yield is essential, but yield stability across seasons, labour demand, cash cost, risk, soil change, water use, nutrient losses, greenhouse gas balance and nutritional quality all matter to farmers and to society (Garnett et al., 2013; Smith et al., 2017). A practice that raises mean yield but increases downside risk in dry years may be rejected by risk-averse smallholders, rationally so. A practice that improves soil carbon but requires residue that is also needed for livestock feed creates a real trade-off in mixed crop-livestock systems (Corbeels et al., 2020; Giller et al., 2021). The framework in Section 7 therefore treats trade-offs explicitly rather than assuming win-win outcomes everywhere.

3. Conservation Agriculture and Soil Health

Conservation agriculture is one of the most widely studied agronomic systems in the world. A global meta-analysis based on 5,463 paired yield observations from 610 studies found that no-till alone, on average, reduced yields relative to conventional tillage, but that the response was highly variable and that under certain conditions no-till produced equivalent or greater yields (Pittelkow et al., 2015). The key modifiers were climate, soil, crop, residue retention, rotation and duration. No-till performed better in dry climates, on well-drained soils, when combined with residue retention and rotation, and after several years of continuous practice. It performed worse where soils were poorly drained, residues were removed, weeds were poorly controlled, or the system had not yet had time to rebuild structure and biology (Pittelkow et al., 2015; Kassam et al., 2019). The lesson is not that no-till fails or succeeds universally, but that its success depends on the full system.

Soil health provides the mechanistic explanation for many of these patterns. Minimum disturbance protects soil aggregates, fungal networks and earthworm channels. Permanent cover reduces erosion, moderates soil

temperature, conserves moisture and feeds soil organisms. Diversified rotations break pest and disease cycles, vary rooting depth and architecture, and, when legumes are included, add biologically fixed nitrogen (Kirkegaard et al., 2008; Lal, 2015). Over time, these processes can increase soil organic carbon, improve infiltration and water-holding capacity, enhance nutrient cycling and support more stable yields, particularly under stress (Lehmann et al., 2020; Montgomery, 2017). In Africa, a meta-analysis of climate-smart practices found significant increases in crop yield and soil organic carbon concentration, with mean effects of 9.2 percent and 14.7 percent respectively, although total nitrogen did not change significantly (Kichamu-Wachira et al., 2021). That pattern is plausible: carbon can accumulate faster than total nitrogen when residues are carbon-rich and nitrogen is limiting.

Cover crops and green manures deserve particular attention because they are the engine of many soil-health benefits. They protect the soil during fallow periods, scavenge residual nitrogen, suppress weeds, provide forage or food in some systems, and add diverse root exudates and residues (Blanco-Canqui et al., 2015; Kirkegaard et al., 2008). Their costs are real: seed, establishment, water use, management complexity and, in some cases, competition with the main crop. In water-limited environments, a cover crop that uses stored soil moisture can reduce the following crop if it is not terminated at the right time (Blanco-Canqui et al., 2015; Corbeels et al., 2020). In humid environments, the same practice can be strongly beneficial. Again, context and timing dominate. Long-term trials remain invaluable because soil changes are slow and early-season results can be misleading (Kassam et al., 2019; Lal, 2015).

Table 1. Climate-smart agronomic practices, main mechanisms and expected outcomes

Table 1. Climate-smart agronomic practices, main mechanisms and expected outcomes

Practice family	Main mechanism	Key outcomes	Main constraint
Conservation agriculture	Soil cover, minimum disturbance, rotation	Soil carbon, moisture, erosion control	Weeds, residues, time lag
Agroforestry	Trees, nitrogen fixation, microclimate	Yield, income, soil fertility, shade	Land, tenure, competition
Integrated nutrient management	Balanced organic + mineral nutrients	Yield, nutrient-use efficiency	Soil testing, input access
Water-smart irrigation	Targeted water, scheduling	Water productivity, yield stability	Cost, energy, maintenance
Precision agriculture	Spatial and temporal targeting	Nitrogen and water efficiency	Data, connectivity, cost
Improved varieties	Stress tolerance, resistance	Yield stability, nutrition	Seed systems, trait trade-offs

4. Agroforestry, Diversification and Integrated Pest Management

Agroforestry integrates trees and shrubs into crop and livestock systems, and it is one of the most powerful ways to diversify income, nutrition and ecological function simultaneously (Jose, 2009; Mbow et al., 2014). Fertiliser trees such as Faidherbia albida, Gliricidia sepium and Sesbania sesban can fix nitrogen, provide leaf biomass, improve soil structure and offer shade and fodder. Parkland systems in the Sahel, alley cropping in humid zones, and silvoarable systems in temperate regions all illustrate the same principle: trees create vertical and temporal niches that annual crops alone cannot occupy (Mbow et al., 2014; Jose, 2009). A meta-analysis of agroforestry in sub-Saharan Africa reported substantial increases in crop yield and soil fertility where trees were well matched to site and management, while also noting that poorly chosen species, excessive shade or competition for water can reduce crop performance (Mbow et al., 2014). Species choice, spacing, pruning, tenure and market access for tree products are therefore agronomic decisions, not afterthoughts.

Crop diversification through intercropping, rotation, relay cropping and varietal mixtures also improves resilience. Intercrops can use light, water and nutrients more completely, suppress weeds and pests, and reduce the risk that a single crop failure becomes a household food crisis (Kirkegaard et al., 2008; Pretty et al., 2018). Cereal-legume intercrops are especially valuable because legumes fix nitrogen, improve protein supply and often improve soil biology, while cereals provide energy and stover (Giller et al., 2021). The agronomy is more demanding: planting dates, densities, spatial arrangement, fertiliser placement and harvest logistics must be coordinated. But the ecological payoff can be large, especially where land is scarce and farmers cannot afford to leave land fallow or to specialise in a single risky commodity.

Integrated pest management complements diversification by combining resistant varieties, cultural practices, biological control, monitoring and thresholds, and targeted chemical control only when justified (Pretty et al., 2018; Smith et al., 2017). Push-pull technology in East Africa, which uses Desmodium as an intercrop to repel stem borers and suppress Striga while Napier grass attracts pests to a trap border, is a striking example of agronomy,

ecology and farmer knowledge combined (Khan et al., 2014). It has increased maize yields, provided fodder, improved soil fertility and reduced pesticide need in many smallholder settings. Its success also illustrates a broader point: the most adoptable practices often solve several problems at once, rather than optimising a single variable.

5. Integrated Nutrient Management and Water-Smart Irrigation

Nutrient management is at the heart of agronomy because crops cannot produce high, stable yields without adequate and balanced nutrition, yet excess or poorly timed nutrients pollute water, emit greenhouse gases and waste farmers money (Sutton et al., 2013; Zhang et al., 2015). Integrated nutrient management combines mineral fertilisers, organic inputs such as compost, manure and crop residues, biological nitrogen fixation and, where appropriate, biochar and microbial amendments, with attention to soil pH, micronutrients and timing (Sutton et al., 2013; Vanlauwe et al., 2010). The evidence is consistent: organic inputs alone often cannot supply enough nutrients for high yields on depleted soils, while mineral fertiliser alone does not rebuild soil organic matter or structure. Combined use, at rates matched to soil tests and crop demand, generally gives the best yield, soil and economic outcomes (Vanlauwe et al., 2010; Zhang et al., 2015).

The 4R framework, applying the right source at the right rate at the right time in the right place, remains a practical guide (Sutton et al., 2013). Site-specific nutrient management, which uses soil tests, crop nutrient requirements, omission trials and increasingly remote sensing and models, helps translate that principle into field-specific recommendations (Dobermann et al., 2002; Zhang et al., 2015). In rice, maize and wheat systems, site-specific management has often maintained or increased yield while reducing nitrogen application and losses (Dobermann et al., 2002). Precision tools discussed in Section 6 extend this logic within fields. The challenge is institutional as much as technical: soil testing must be affordable, timely and trusted, fertiliser must be available in appropriate pack sizes and formulations, and advice must be delivered in a form farmers can use.

Water-smart agronomy is equally important because water, not land, is the binding constraint in many regions. Practices include rainwater harvesting, tied ridges, zai pits, mulching, deficit irrigation, alternate wetting and drying in rice, drip irrigation and scheduling based on soil moisture or weather data (Bouman et al., 2007; Pretty et al., 2018). Alternate wetting and drying in rice can substantially reduce water use and methane emissions while maintaining yield when managed carefully (Bouman et al., 2007). Drip irrigation can raise water productivity and nutrient-use efficiency by delivering water and fertiliser directly to the root zone, but its cost, maintenance, clogging risk and need for clean water and technical support limit adoption for many smallholders (Pretty et al., 2018). Deficit irrigation deliberately accepts a small yield reduction to save a large amount of water, and it can be economically rational where water is scarce or expensive. The best choice depends on crop value, water price and reliability, energy cost, soil type and farmer capacity, not on technology alone.

6. Precision Agriculture, Digital Tools and Improved Varieties

Precision agriculture has moved from experimental yield mapping to a set of practical tools that many farmers can now access through phones, satellites and low-cost sensors (Gebbers and Adamchuk, 2010; Balafoutis et al., 2017). Remote sensing, including satellite imagery and unmanned aerial vehicles, can detect spatial variation in canopy vigour, nutrient stress, water stress and pest damage earlier and more consistently than visual scouting alone. Soil sensors, weather stations, yield monitors and variable-rate applicators allow inputs to be varied within fields rather than applied uniformly (Balafoutis et al., 2017). In maize, precision nitrogen management based on crop models, remote sensing and machine learning has reduced nitrogen rates by 6 to 16 percent and increased nitrogen-use efficiency by 8 to 18 percent while maintaining yield and economic return in field studies (Li et al., 2023). Sensor-based nitrogen management in maize and wheat has similarly reduced fertiliser use by 20 to 35 percent in several reviews while sustaining or improving yields, although results depend on calibration, weather and crop stage (Cammarano et al., 2025).

Digital advisory services extend precision principles to farmers without expensive equipment. Mobile phone messages, interactive voice response, radio, video and farmer-to-farmer networks can deliver weather forecasts, planting-date advice, pest alerts, fertiliser recommendations and market prices (Pretty et al., 2018). When advisories are localised, timely, in the farmers language and linked to input access and credit, they can change decisions. When they are generic, late or disconnected from markets, they are ignored. The agronomic content still matters most: a precise message with a wrong recommendation is worse than no message. Co-design with farmers, validation in local trials and feedback loops are therefore essential, not optional.

Improved varieties are the other pillar of modern agronomy. Drought-tolerant maize, heat-tolerant wheat, submergence-tolerant rice, disease-resistant cassava and biofortified beans and sweet potato have each expanded the range of environments in which farmers can achieve stable yields and better nutrition (Cairns et al., 2013; Bailey-Serres et al., 2010). Genotype by environment by management interactions are central: a variety that excels under high input and good water may fail under low input and drought, and vice versa (Cairns et al., 2013). Agronomy and breeding must therefore be developed together. Planting density, fertiliser rate, sowing date and pest management should be optimised for the variety and the environment, not copied from a different system. Participatory variety selection, in which farmers evaluate varieties under their own management, often improves adoption because it incorporates traits breeders may overlook, such as taste, cooking time, storability and stover quality.

Figure 1. Mean yield responses by practice family

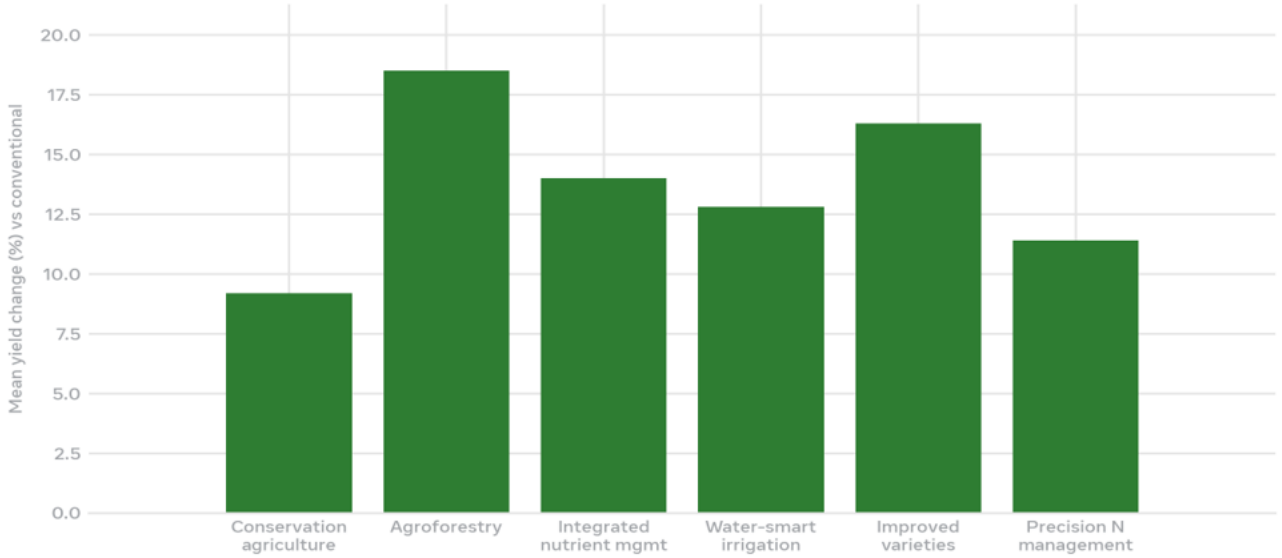

Figure 1. Mean yield responses reported across the practice families reviewed in Sections 3 to 6. Values vary by crop, soil, climate and management history.

Figure 3. Five-step decision framework for climate-smart agronomy

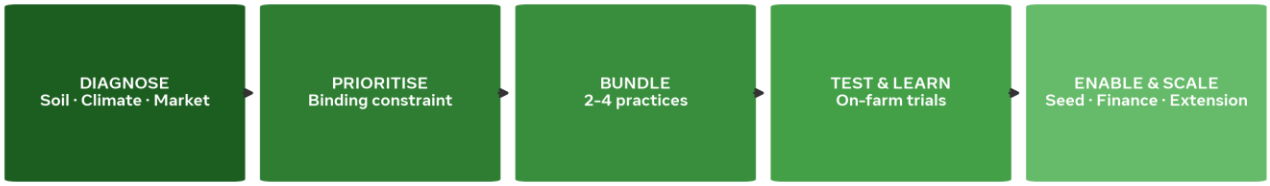

Figure 3. The framework links diagnosis to prioritisation, bundling, testing and enabling conditions. It is applied in Section 7.

7. Bundling, Trade-offs and a Decision Framework

The strongest finding in the literature is that bundled practices outperform isolated practices, but only when bundles are coherent and locally adapted (Pretty et al., 2018; Kichamu-Wachira et al., 2021; Giller et al., 2021). A plausible bundle for a rainfed maize-legume system might combine minimum tillage, residue retention, legume rotation or intercrop, integrated nutrient management, improved drought-tolerant seed, timely planting and integrated pest management. A plausible bundle for irrigated rice might combine alternate wetting and drying, site-specific nitrogen management, improved varieties, integrated pest management and residue management. In each case, the practices reinforce one another: soil cover conserves moisture, legumes add nitrogen, precision nitrogen reduces losses, and improved varieties convert better soil and water into grain. Figure 1 presents mean yield responses by practice family, and Table 1 organises practices by their main mechanisms and outcomes. Figure 3 presents the five-step decision framework used to select and sequence the bundle.

Trade-offs must be named honestly. Residue retention competes with livestock feed and fuel in mixed systems. Cover crops use water and labour. Agroforestry trees can shade crops and occupy land. Drip irrigation requires

capital and maintenance. Precision tools require data, connectivity and literacy. Conservation agriculture may increase weed pressure in the early years and may require herbicides or more labour for weeding (Pittelkow et al., 2015; Corbeels et al., 2020). Legume intercrops can reduce cereal yield in a good year even while they stabilise total system output and nutrition. None of these trade-offs means the practice is bad. They mean that agronomy is a management problem, not a shopping list. The task is to find the combination that gives the best net outcome for a particular farm, household and landscape, and to sequence changes so that early wins build confidence and cash flow for later, slower investments such as soil carbon.

A practical decision framework has five steps. First, diagnose: assess soil, climate, water, pests, markets, labour, tenure, gender roles and farmer goals, using soil tests, weather records, field history and farmer knowledge. Second, prioritise: identify the one or two binding constraints that, if relieved, will give the largest improvement. Third, bundle: select two to four complementary practices that address those constraints and reinforce one another, with clear guidance on timing, rates and spacing. Fourth, test and learn: establish small, farmer-managed comparisons, monitor yield, cost, labour, soil and water, and adjust. Fifth, enable: link adoption to seed, fertiliser, finance, insurance, extension and market access, and address tenure and collective action where trees, water or grazing require it (Lipper et al., 2014; Giller et al., 2021). Table 2 provides a diagnostic checklist that can be adapted to different regions. Table 2 is placed in Section 8 and Figure 2, which shows the soil organic carbon trajectory, is placed in Section 9.

8. Adoption, Equity, Economics and Policy

Table 2. Diagnostic checklist for selecting a climate-smart agronomy bundle

Diagnostic question	What to measure	Why it matters
What limits yield most?	Soil test, field history, pest survey	Targets the binding constraint
How variable is rainfall?	Weather records, farmer recall	Chooses water and variety strategy
What residues and labour exist?	Livestock, labour calendar	Resolves residue and labour trade-offs
What markets and inputs exist?	Seed, fertiliser, credit, buyers	Ensures bundle is feasible
Who decides and who benefits?	Gender, tenure, youth roles	Ensures equity and adoption

Adoption is the decisive test of agronomic research. A practice that works on a research station but is not adopted has not yet solved the problem. Adoption depends on perceived benefit, risk, cost, labour, complexity, compatibility with existing systems, access to inputs and markets, social norms, gender and tenure (Giller et al., 2021; Pretty et al., 2018). Women farmers often face particular constraints in access to land, credit, extension and labour, even though they provide a large share of agricultural labour in many regions. Youth may be more open to digital tools but less able to access land. Older farmers may have deep local knowledge but less labour. Agronomic recommendations that ignore these differences will systematically miss the people who most need them.

Economics must be calculated from the farmers perspective, not only from yield per hectare. Partial budgets that include seed, fertiliser, labour, machinery, water, transport and risk are more informative than yield alone (Smith et al., 2017). A practice that raises yield by 15 percent but raises cost by 30 percent or labour by 40 percent may not be adopted, especially where cash and labour are scarce at planting or weeding. Conversely, a practice that slightly reduces mean yield but greatly reduces variance, labour or input cost may be highly valuable. Insurance, savings, credit and social protection can help farmers take on the short-term risk of trying a new practice, while subsidies, if used, should be time-bound, targeted and linked to learning rather than to permanent dependence on a single input (Lipper et al., 2014).

Policy and institutions shape what is possible at scale. Secure tenure encourages investment in soil, trees and irrigation. Functional seed systems ensure that improved varieties are available, affordable and true to type. Extension systems that combine public, private, NGO and farmer-to-farmer channels can reach more farmers with better advice. Markets that reward quality, nutrition and sustainability can make soil-building practices profitable. Research systems that fund long-term trials, participatory breeding, on-farm experimentation and open data will generate the evidence that farmers and policymakers need (Kassam et al., 2019; Pretty et al., 2018). Climate finance, payments for ecosystem services and carbon markets may help, but they must be designed to benefit smallholders, avoid perverse incentives and measure outcomes credibly, rather than imposing high transaction costs on the poorest farmers.

9. Conclusions and Future Research Priorities

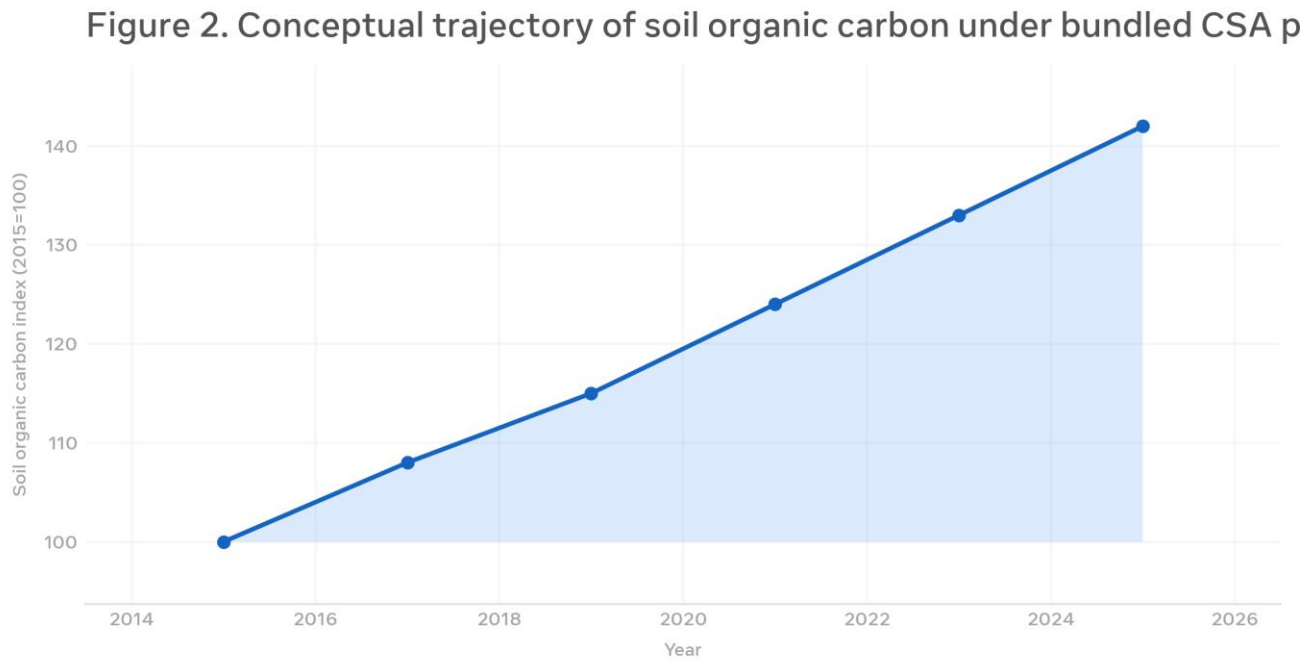

Figure 2. Soil organic carbon index (2015 = 100) under bundled practices. The increase reflects cumulative residue, cover-crop and organic-input effects.

This review concludes that integrated climate-smart agronomy offers a credible and evidence-based pathway to sustainable intensification, but that its success is conditional. The conditions are clear: diagnose before prescribing, bundle complementary practices, adapt to local soil, climate, market and social conditions, sequence changes to manage trade-offs and time lags, monitor multiple outcomes, and support adoption with seed, finance, extension and tenure security (Lipper et al., 2014; Pretty et al., 2018; Giller et al., 2021). Where those conditions are met, the literature shows higher and more stable yields, improved soil organic carbon and structure, better water and nutrient-use efficiency, diversified income and nutrition, and reduced emissions intensity. Where they are not met, even promising practices can disappoint, increase labour or risk, or be abandoned after a project ends.

Future research should prioritise five areas. First, more long-term, multi-location trials that measure yield stability, soil, water, economics, labour and nutrition together, not yield alone (Kassam et al., 2019; Lal, 2015). Second, better understanding of genotype by environment by management interactions, including for orphan crops, pulses, roots and vegetables that matter for nutrition (Cairns et al., 2013). Third, low-cost, scalable precision and advisory tools that work with limited connectivity, literacy and data, and that are validated with farmers (Balafoutis et al., 2017). Fourth, rigorous studies of adoption, equity and scaling, including gender, youth, tenure and collective action, and of the institutional arrangements that sustain practices after projects end (Giller et al., 2021). Fifth, integrated modelling and monitoring that link field, farm, landscape and food-system outcomes, so that agronomic choices can be judged on food security, livelihoods, climate and biodiversity together (Garnett et al., 2013; IPCC, 2022). Agronomy has always been an applied, integrative science. Its next advance will come not from a single breakthrough practice, but from better integration of practices, knowledge, institutions and farmers experience.

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Conflict of Interest

The authors declare no conflict of interest.

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