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Review Article

Climate-Smart Agronomy for Resilient Food Systems: Integrating Soil Health, Diversification, Precision Nutrient Management, and Water-Smart Practices

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Abstract

Agronomy stands at the centre of one of the most consequential challenges of the twenty-first century: producing more nutritious food on finite land while soils degrade, water becomes less predictable, input costs rise, and the climate changes. This review synthesises evidence on climate-smart agronomy as an integrated field practice rather than a menu of isolated technologies. It examines how conservation agriculture, crop diversification, legume intercropping, cover crops, integrated nutrient management, precision nitrogen management, agroforestry, and water-smart irrigation interact through soil organic matter, nutrient cycling, water retention, biological activity, and risk spreading. The synthesis shows that single practices can improve one outcome while leaving others unchanged, whereas carefully sequenced bundles are more likely to raise yield stability, soil health, resource-use efficiency, and farm income together. Benefits are strongly conditioned by rainfall, soil texture, market access, labour availability, tenure, gendered resource control, and the quality of advisory services. The review proposes a context-first decision framework that begins with diagnosis of soil constraints, water risk, and household objectives, then matches a small bundle of practices to that diagnosis, and finally supports adoption with seed systems, soil testing, weather information, finance, and learning networks. It closes with priorities for research, extension, and policy that can move climate-smart agronomy from promising plots to resilient landscapes.

Keywords: climate-smart agriculture; soil health; conservation agriculture; intercropping; integrated nutrient management; precision agriculture; water-use efficiency; sustainable intensification

1. Introduction

Agronomy has always been an applied science of place, season, and management. A variety that performs well in one soil and rainfall regime may fail in another, and a fertiliser rate that is profitable when rains arrive on time may become a loss when planting is delayed (Lobell et al., 2011; Challinor et al., 2014). Climate change has made this place- and season-dependence more consequential. Higher temperatures shorten crop cycles, increase evaporative demand, and alter pest and disease pressure, while rainfall becomes more variable within and across seasons (Porter et al., 2014; IPCC, 2022). At the same time, many farming landscapes carry the legacy of nutrient mining, loss of soil organic matter, compaction, erosion, and declining biological activity after decades of intensive monoculture and incomplete nutrient replacement (Lal, 2004; Montgomery, 2007). The result is not only lower average yield but also greater year-to-year variability, which matters greatly to households that consume much of what they grow and cannot easily insure against a failed season.

Climate-smart agriculture was developed as a response to this triple challenge: sustainably increase productivity and incomes, build adaptation and resilience, and reduce or remove greenhouse gas emissions where possible (FAO, 2013; Lipper et al., 2014). The concept is valuable because it insists that these goals be pursued together. In practice, however, the label has sometimes been applied to any single practice that sounds sustainable, even when evidence for one or more of its goals is weak in that context (Taylor, 2018; Newell et al., 2019). This review therefore treats climate-smart agronomy as a systems problem. It asks which combinations of practices work, for whom, under which soil and climate conditions, and what institutional support is needed for those combinations to persist beyond a project cycle.

2. Concepts and Analytical Approach

This review is based on a structured synthesis of peer-reviewed meta-analyses, systematic reviews, long-term experiments, and widely cited conceptual and empirical studies. Priority was given to evidence that reports outcomes across more than one dimension, for example yield together with soil organic carbon, nitrogen-use efficiency, water productivity, profitability, or labour. Where studies reported only a single outcome, they were interpreted cautiously because agronomic success in one dimension can mask costs in another, such as higher labour demand, residue competition with livestock, or increased nitrous oxide emissions after nitrogen addition (Giller et al., 2009; Powlson et al., 2014).

Three analytical distinctions organise the review. First, practices are distinguished from principles. Minimum soil disturbance, permanent soil cover, and diversification are principles of conservation agriculture, but the practices that express them differ across mechanised, animal-traction, and hand-hoe systems (FAO, 2013; Kassam et al., 2019). Second, outcomes are distinguished from mechanisms. Yield is an outcome; improved infiltration, rooting depth, nutrient synchrony, and pest regulation are mechanisms that may explain it. Third, average effects are distinguished from stability effects. A practice that raises mean yield by a small amount but sharply reduces the probability of very low yields in dry years can be more valuable to a risk-averse household than a practice with a larger mean gain but greater variance (Lobell et al., 2011; Hansen et al., 2019).

3. Soil Health as the Foundation of Climate-Smart Agronomy

Soil health is best understood as the continued capacity of soil to function as a living ecosystem that sustains plants, animals, and people (Lehmann et al., 2020; Lal, 2004). It includes physical properties such as aggregation and infiltration, chemical properties such as pH, nutrient stocks, and cation exchange capacity, and biological properties such as microbial biomass, fungal networks, earthworm activity, and residue decomposition. These properties interact. Organic matter improves aggregation, aggregation protects organic matter, better aggregation improves infiltration and root exploration, and deeper roots return more carbon and capture more water and nutrients (Six et al., 2004; Blanco-Canqui and Ruis, 2018).

Long-term trials show that practices which add diverse organic inputs, reduce disturbance, and keep living roots in the soil for more of the year tend to increase soil organic carbon, although the rate depends on initial carbon, clay content, temperature, moisture, and the quantity and quality of inputs (Powlson et al., 2014; Chivenge et al., 2007). This matters for climate adaptation because each additional increment of organic matter can improve water-holding capacity and nutrient supply, and for mitigation because soil carbon storage, while finite and reversible, can complement emission reductions from more efficient fertiliser and energy use (Lal, 2004; Smith et al., 2020). The practical implication is that soil health cannot be purchased as a single input. It is built by a sequence of management decisions across rotations, residue use, manure and compost use, tillage, cover crops, and fertiliser strategy.

4. Conservation Agriculture: Principles, Evidence, and Trade-offs

Conservation agriculture combines minimum mechanical soil disturbance, permanent organic soil cover, and diversification through rotations or associations (FAO, 2013; Kassam et al., 2019). In principle, less disturbance preserves pore networks and fungal hyphae, cover reduces evaporation and erosion, and rotation breaks pest and disease cycles while varying root architectures and nutrient demands. In practice, results are heterogeneous. A meta-analysis of long-term maize experiments under rain-fed conditions found that conservation agriculture improved yield over time, especially where rotation and adequate inputs were used in lower-rainfall environments, whereas mulch in high-rainfall areas could reduce yield through waterlogging (Corbeels et al., 2020). Other syntheses report that no-till effects depend strongly on climate, soil texture, residue retention, and the duration of the trial, with benefits often emerging only after several seasons as soil structure recovers (Pittelkow et al., 2015; Blanco-Canqui and Ruis, 2018).

Trade-offs deserve explicit attention. Residues are valuable as mulch, but in mixed crop-livestock systems they are also feed, fuel, and construction material (Giller et al., 2009). Where residues are removed, the soil-cover principle fails even if tillage is reduced. Weed pressure can rise in early years of reduced tillage, increasing labour or herbicide use,

and poorly drained soils may need surface drainage or raised beds rather than blanket mulching (Pittelkow et al., 2015; Giller et al., 2009). Conservation agriculture is therefore best evaluated as a locally adapted system, not as a fixed package. Its success depends on whether farmers can retain enough cover, manage weeds affordably, and maintain rotation diversity without losing access to a remunerative crop.

5. Diversification: Rotations, Intercrops, Cover Crops, and Agroforestry

Diversification is the most robust risk-management strategy in agronomy because it spreads biological, market, and weather risk across species with different growth habits, rooting depths, nutrient needs, and sensitivities (Lin, 2011; Altieri et al., 2015). Rotations interrupt pest and disease cycles, allow legumes to contribute biologically fixed nitrogen, and create windows for cover crops and soil-building phases. Intercropping adds spatial diversity within the same season. Cereal-legume intercrops can produce more total grain, higher cereal protein, and more stable gross margins than the mean of sole crops, partly because legumes fix atmospheric nitrogen and cereals use soil nitrogen more completely when grown together (Bedoussac et al., 2015; Yu et al., 2016). The land-equivalent ratio commonly exceeds one in well-designed cereal-legume systems, meaning that intercropping produces on less land what sole crops would need more land to produce (Yu et al., 2016; Martin-Guay et al., 2018).

Cover crops extend living cover beyond the main season, protect soil, scavenge residual nitrogen, suppress weeds, and add biomass. A systematic synthesis found that multi-species, long-term cover crop mixtures increased soil organic carbon by a substantial margin and improved soil quality and yield in most studies, although outcomes varied by species, climate, and termination method (Blanco-Canqui, 2018). Agroforestry integrates trees into fields and landscapes, adding litter, shade, wind protection, fodder, fruit, timber, and habitat. Trees can improve infiltration and nutrient cycling and diversify income, but they also compete for light and water if species, spacing, and pruning are not matched to the crop and site (Jose, 2009; Kuyah et al., 2019). The central design question is not whether diversity helps in general, but which diversity, in which arrangement, at which density, serves the household's food, feed, cash, labour, and soil goals.

6. Integrated and Precision Nutrient Management

Nitrogen is both the most yield-limiting nutrient in many systems and the most easily lost through leaching, volatilisation, denitrification, and erosion. Global nitrogen-use efficiency remains low in many farming systems, with a widely cited average near one-third for cereals, although values vary greatly by crop, soil, climate, and management (Cassman et al., 2002; Bali et al., 2018). Integrated nutrient management combines mineral fertiliser, manure, compost, legume nitrogen, and, where appropriate, biofertilisers and lime, with the aim of supplying nutrients in the right amount, form, place, and time while rebuilding soil organic matter and correcting acidity or micronutrient deficiencies (Agegnehu and Amede, 2017; Vanlauwe et al., 2015). Evidence from sub-Saharan Africa and South Asia shows that combining organic and mineral sources often outperforms either alone, especially on degraded soils where organic matter limits nutrient retention and water storage (Vanlauwe et al., 2015; Chivenge et al., 2007).

Precision management adds spatial and temporal targeting. Soil testing, leaf-colour charts, chlorophyll meters, canopy sensors, satellite imagery, and variable-rate application help align nitrogen supply with crop demand and within-field variability (Bali et al., 2018; Mulla, 2013). Sensor-based nitrogen management in wheat has been reported to save fertiliser while maintaining yield and reducing residual soil nitrogen, although gains depend on calibration, timely operations, and access to equipment and advice (Bijay-Singh et al., 2015). The 4R framework, right source, rate, time, and place, remains a useful discipline, but it must be adapted to small fields, fragmented plots, and limited cash flow. Splitting nitrogen, banding near the root zone, incorporating urea, and using urease or nitrification inhibitors where appropriate can reduce losses, while liming acid soils can unlock large responses to other nutrients (Snyder et al., 2009; Agegnehu and Amede, 2017).

7. Water-Smart Agronomy

Water productivity, the grain or biomass produced per unit of water consumed, is often more important than yield alone in water-scarce environments (Bouman, 2007; Molden et al., 2010). Agronomic practices affect every part of the water balance: infiltration, evaporation, transpiration, runoff, deep drainage, and storage. Mulch and cover reduce evaporation and runoff, while improved aggregation increases infiltration and plant-available water. Early planting, shorter-duration varieties, and optimum plant density can shift the crop cycle toward periods of better water availability and reduce exposure to terminal drought (Challinor et al., 2014; Hansen et al., 2019). In irrigated systems, alternate wetting and drying in rice, deficit irrigation, drip irrigation, and improved scheduling can reduce water use and, in some cases, methane emissions without a proportionate yield penalty, provided that timing, soil type, and salinity are carefully managed (Bouman, 2007; Carrijo et al., 2017).

Rainwater harvesting, tied ridges, zai pits, contour bunds, and conservation structures are especially important where rainfall is intense but brief. These structures slow water, increase infiltration, and protect soil, but they require labour and maintenance and can fail if they are not matched to slope, soil depth, and rainfall intensity (WOCAT, 2020). Weather and seasonal forecasts, when communicated in usable form, help farmers choose planting dates, varieties, and input levels. The value of a forecast depends less on its statistical skill than on whether it arrives early enough, is trusted, is understood, and can be acted upon with available seed, labour, and credit (Hansen et al., 2019; Vaughan et al., 2019).

8. Bundles, Synergies, and Context: A Decision Framework

The strongest lesson from the literature is that bundles outperform isolated practices when they are matched to a diagnosed constraint. For example, combining legume rotation, residue retention, and targeted nitrogen can simultaneously add nitrogen, protect soil, and improve nutrient synchrony, whereas nitrogen alone on a compacted, low-organic-matter soil may be poorly retained (Vanlauwe et al., 2015; Agegnehu and Amede, 2017). Similarly, combining

drought-tolerant varieties with soil cover and water harvesting addresses both the crop and the soil-water environment, rather than asking a variety alone to overcome poor soil (Challinor et al., 2014; Hansen et al., 2019). Table 1 summarises these combinations and their main mechanisms, while Figure 1 presents an indicative synthesis of reported yield and soil carbon gains across practices. The values are reflecting direction and relative magnitude drawn from the cited syntheses and should not be read as universal constants.

A context-first framework can be stated in five steps. First, diagnose the field: soil texture, organic matter, pH, nutrient status, compaction, slope, drainage, and water risk. Second, clarify household objectives: food security, cash income, livestock feed, labour constraints, and risk tolerance. Third, select a small bundle, typically two to four practices, that addresses the dominant constraint without creating an unmanageable labour or cash burden. Fourth, test the bundle on a small area with a farmer-managed comparison and simple records of costs, labour, yield, and soil observations. Fifth, adapt and scale what works, using farmer groups, demonstration fields, and local input suppliers to reduce learning and transaction costs (Giller et al., 2009; Pretty et al., 2018). This approach respects the fact that adoption is a learning process, not a one-time purchase.

Table 1. Climate-smart agronomic bundles and their main mechanisms.

Bundle	Core practices	Main mechanism	Likely outcome
Soil-first bundle	Rotation, cover crop, manure/compost, reduced tillage	Organic matter, aggregation, infiltration	Higher water retention, steadier yield
Legume-led bundle	Cereal-legume intercrop, rotation, targeted P	Biological N fixation, nutrient synchrony	Higher protein, lower N fertiliser need
Precision N bundle	Soil test, split N, sensor or leaf chart, banding	Right rate, time, place	Higher N-use efficiency, lower losses
Water-smart bundle	Mulch, tied ridges, early planting, tolerant variety	Infiltration, evaporation control, drought escape	Higher water productivity, lower crop failure
Tree-integrated bundle	Alley trees, pruning, legume understory	Litter, shade, deep nutrient capture	Diversified income, soil carbon gain

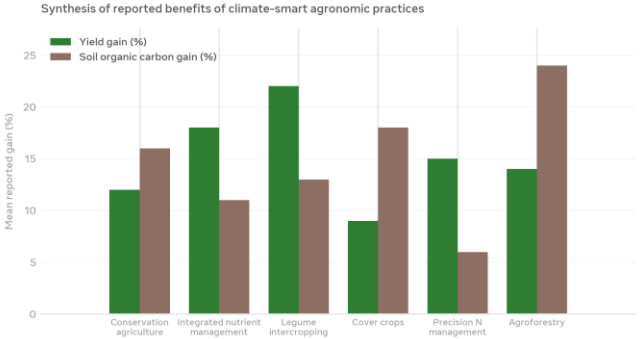

Figure 1. Synthesis of reported yield and soil organic carbon gains by practice, based on the meta-analyses and reviews cited in the text. Values vary by soil, climate, and management.

9. Adoption, Equity, and Institutions

Adoption of climate-smart agronomy is shaped by more than agronomic performance. Secure tenure encourages investment in soil because the farmer expects to capture future benefits. Access to seed of adapted varieties, fertiliser, and organic inputs at the right time determines whether a recommended bundle can be implemented at all. Labour is often the binding constraint, particularly where conservation practices increase weeding or residue management, and where men and women have different control over labour, income, and land (Giller et al., 2009; Farnworth et al., 2017). Women farmers may face additional barriers to extension, credit, and inputs, even though they contribute substantially to crop production and household food security. Gender-responsive advisory services, timing and location of training, and attention to who controls the income from a new practice are therefore not optional additions; they affect whether adoption is equitable and durable (Farnworth et al., 2017; Huyer et al., 2015).

Extension systems are moving from one-way transfer of recommendations toward facilitated learning, farmer field schools, participatory trials, digital advisories, and peer networks (Pretty et al., 2018; Anderson and Feder, 2007). Digital tools can deliver weather, pest, price, and soil information at scale, but their benefits depend on connectivity, language, literacy, trust, and the relevance of the advice to a specific field (Fabregas et al., 2019). Finance also matters. Index insurance, input credit, savings groups, and contract arrangements can reduce the risk of trying a new practice, but poorly designed credit can increase indebtedness if the practice fails in a bad year. Policy can help by supporting soil testing laboratories, local seed multiplication, compost and manure markets, and public research on locally adapted bundles, rather than subsidising a single input in isolation (Lipper et al., 2014; Pretty et al., 2018).

10. Measuring What Matters

A climate-smart agronomy programme should be judged on a balanced set of indicators, not on yield alone. Table 2 proposes a practical indicator set that can be measured with farmer records, simple field observations, and, where available, soil tests and remote sensing. Yield stability can be tracked as the coefficient of variation across seasons and the frequency of very low yields. Soil health can be tracked through organic carbon, infiltration time, aggregate stability, and earthworm counts. Nutrient performance can be tracked through partial factor productivity and nitrogen balance. Water performance can be tracked through water productivity and days of water stress. Economic performance can be tracked through gross margin, return to labour, and benefit-cost ratio. Social performance can be tracked through adoption persistence, workload by gender, and dietary diversity where diversification adds nutrient-rich crops (Pretty et al., 2018; Lehmann et al., 2020).

Measurement must be honest about trade-offs and time lags. Soil carbon changes slowly and may be difficult to detect in one or two seasons, while labour costs are

immediate. A practice that looks unattractive in year one may become attractive by year three as soil structure improves and weed seed banks decline. Conversely, a practice that raises yield in a wet year may fail in a dry year if it increases crop water demand. Long-term trials, on-farm comparisons, and panel surveys are complementary: trials reveal mechanisms under controlled conditions, on-farm trials reveal feasibility under real management, and panel surveys reveal persistence, adaptation, and equity over time (Giller et al., 2009; Pittelkow et al., 2015). Figure 2 summarises how bundled practices are judged to contribute across the broader climate-smart goals, emphasising that equity and mitigation often require deliberate design rather than emerging automatically from higher yield.

Table 2. A balanced indicator set for climate-smart agronomy.

Dimension	Indicator	Practical measurement
Productivity	Grain yield, total system yield	Harvest records, crop cuts
Stability	Yield CV, frequency of low-yield years	Multi-season farmer records
Soil health	Soil organic carbon, infiltration, earthworms	Soil test, timed infiltration, counts
Nutrient efficiency	Partial factor productivity, N balance	Input and harvest records
Water	Water productivity, stress days	Yield per rainfall/irrigation, field notes
Economics	Gross margin, return to labour	Cost, labour, price records
Equity and nutrition	Workload by gender, dietary diversity	Household survey, recall

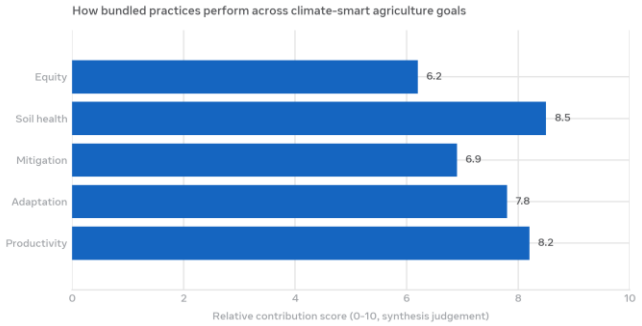

Figure 2. Relative contribution of bundled climate-smart practices across productivity, adaptation, mitigation, soil health, and equity goals, based on synthesis judgement from the cited evidence.

11. Future Research and Policy Priorities

Several priorities emerge. First, research should report bundled practices and their interactions, not only single-factor effects, and should include labour, gender, cost, and risk outcomes alongside yield and soil carbon. Second, breeding and agronomy should be better integrated so that varieties are evaluated under the soil, residue, and intercrop conditions in which they will actually be grown, including under low-nutrient and water-limited conditions (Challinor et al., 2014; Ceccarelli, 2015). Third, soil health research should develop low-cost, field-ready indicators that farmers and extension workers can use without a full laboratory, and should clarify how long benefits persist if a practice is discontinued. Fourth, digital agronomy should be evaluated for who benefits, who is excluded, and whether advice changes decisions, not only whether it is delivered (Fabregas et al., 2019; Hansen et al., 2019). Fifth, policy research should compare the cost-effectiveness of different support instruments, such as input subsidies, soil-testing subsidies, weather-index insurance, extension, and payments for ecosystem services, for the same agronomic outcome.

Policy should reward outcomes that farmers and society value together: stable food production, healthy soils, efficient nutrient and water use, and diversified livelihoods. That implies investing in public goods such as soil information systems, weather services, seed systems for legumes and cover crops, and extension capacity, and aligning fertiliser, water, and land policies so they do not pull in opposite directions. It also implies protecting the land rights and voice of smallholders, women, and youth so that climate-smart agronomy is not only technically sound but also socially legitimate (FAO, 2013; Lipper et al., 2014).

12. Conclusion

Climate-smart agronomy is not a single technology and not a slogan. It is a disciplined way of matching soil, crop, water, nutrient, and diversity management to a specific field and household, learning from comparisons over several seasons, and building the institutions that make good practice affordable and persistent. The evidence reviewed here supports a clear conclusion: soil health is the foundation, diversification is the risk strategy, integrated and precision nutrient management is the efficiency strategy, and water-smart practice is the resilience strategy. When these are combined in a small, locally adapted bundle and supported by seed, soil information, weather advice, finance, and equitable extension, agronomy can raise productivity, stabilise yields, improve resource-use efficiency, and contribute to climate adaptation and mitigation. The task now is less to discover a new universal package than to strengthen the diagnostic, learning, and support systems that allow millions of farmers to assemble the right bundle for their own fields.

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Conflict of Interest

The authors declare no conflict of interest.

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