International Scholars Journals

Advances in Agriculture and Agricultural Sciences ISSN 2756-326X Vol. 12 (12), pp. 001-010, December, 2026. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Author(s) retain the copyright of this article.

Review Article

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

Amara Okafor[1], Daniel Mwangi[2], Priya Sharma[3], Lucas Ferreira[4], Emily Carter[5], Yuki Tanaka[6]

[1] *Department of Crop Science, University of Ibadan, Ibadan, Nigeria*
[2] *Department of Agricultural Sciences, University of Nairobi, Nairobi, Kenya*
[3] *Department of Agronomy, Punjab Agricultural University, Ludhiana, India*
[4] *Department of Soil Science, University of São Paulo, Piracicaba, Brazil*
[5] *Department of Plant and Soil Sciences, Cornell University, Ithaca, USA*
[6] *Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo, Japan*

Manuscript Timeline: Received 10 October, 2026; Revised 24 November, 2026; Accepted 06 December, 2026; Published 15 December, 2026.

Abstract

Agriculture must simultaneously increase food production, adapt to a changing climate, protect soil and water resources, and reduce greenhouse gas emissions. This review synthesises evidence on climate-smart agriculture, 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 synthesis draws on peer-reviewed studies, meta-analyses, long-term experiments, and authoritative assessments covering cereal, legume, root, and mixed crop-livestock systems in Africa, Asia, Latin America, Europe, North America, and Oceania. Findings indicate that no single practice is sufficient on its own. Bundled practices that combine minimum soil disturbance, permanent soil cover, diversification, integrated nutrient management, and context-specific precision tools consistently improve soil organic carbon, water retention, nutrient-use efficiency, yield stability, and farm income relative to conventional practice, although benefits depend on soil type, climate, farm size, labour, tenure, market access, and institutional support. The review identifies mechanisms linking soil biology, soil structure, and plant nutrition to resilience, clarifies trade-offs involving labour, residue competition, initial costs, and pest dynamics, and proposes a decision framework for selecting, sequencing, and scaling practices. It concludes that sustainable intensification is most achievable when agronomic innovation is combined with farmer knowledge, extension, climate services, inclusive finance, secure tenure, and supportive policy, and it outlines priorities for future research on long-term, systems-level, and equity outcomes.

Corresponding author: Amara Okafor — amara.okafor@ui.edu.ng

Keywords: climate-smart agriculture; soil health; sustainable intensification; conservation agriculture; precision agriculture; agroforestry; food security

1. Introduction

Global agriculture faces a triple challenge that is now widely recognised in agronomic, environmental, and development literature. By mid-century, the world will need substantially more food, produced on a finite and in many regions degraded land base, under a climate that is warmer, more variable, and more prone to extremes (FAO, 2013; IPCC, 2019; Godfray et al., 2010). At the same time, agriculture is both a contributor to climate change and one of the sectors most exposed to its consequences. Conventional intensification based on high rates of tillage, monoculture, and unbalanced fertiliser use has raised yields in many places, but it has also depleted soil organic matter, accelerated erosion, reduced biodiversity, polluted water, and increased emissions in numerous systems (Lal, 2004; Pretty, 2008; Tilman et al., 2011). The central question for agricultural science is therefore not whether to intensify, but how to intensify in ways that restore ecological function, stabilise yields, and improve livelihoods.

Sustainable intensification has emerged as a guiding concept for answering that question. It seeks to increase output per unit of land, labour, water, and nutrient input while reducing negative environmental externalities and enhancing resilience (Pretty et al., 2011; Garnett et al., 2013; Rockström et al., 2017). Climate-smart agriculture, articulated by FAO (2013) and further developed in subsequent assessments, adds explicit attention to three pillars: sustainably increasing productivity and incomes, adapting and building resilience to climate change, and reducing or removing greenhouse gas emissions where possible. Agroecology complements these frameworks by emphasising ecological processes, biodiversity, recycling, and farmer knowledge (Altieri, 1995; Gliessman, 2015; Wezel et al., 2020). Precision agriculture contributes tools for observing variability and targeting inputs more accurately (Gebbers and Adamchuk, 2010; Mulla, 2013). This review argues that the greatest gains arise not from promoting any one of these approaches in isolation, but from integrating them into locally adapted bundles.

The purpose of this review is fourfold. First, it clarifies the conceptual links among climate-smart agriculture, soil health, sustainable intensification, agroecology, and precision agriculture. Second, it synthesises evidence on the biophysical mechanisms through which key practices affect soil, water, nutrients, pests, and crops. Third, it evaluates outcomes across productivity, resilience, environmental, economic, and social dimensions, with attention to heterogeneity and trade-offs. Fourth, it proposes a practical framework for choosing, sequencing, and scaling integrated practice bundles, and identifies research gaps. The review is organised as follows: Section 2 outlines methods; Section 3 presents the conceptual framework; Sections 4 to 7 examine soil, nutrient, water, pest, diversification, and precision components; Section 8 synthesises outcomes and trade-offs; Section 9 addresses adoption, institutions, and scaling; and Section 10 concludes with research priorities.

A central argument runs through the review. Soil is the foundation on which climate resilience and productivity are built. Practices that protect and feed the soil, keep it covered, minimise disturbance, diversify roots and residues, and balance nutrients tend to improve soil structure, biological activity, and water storage. Those soil improvements, in turn, buffer crops against drought, heat, and heavy rainfall, improve nutrient uptake, and stabilise yields over time (Lal, 2015; Lehmann et al., 2020; Poeplau and Don, 2015). Technology does not replace this ecological foundation; it makes its management more precise, timely, and observable. Likewise, agronomy does not replace institutions; secure tenure, extension, credit, markets, and climate services determine whether farmers can adopt, adapt, and sustain new practices (Lipper et al., 2014; Campbell et al., 2014).

2. Review Methods

This article is a narrative and evidence-synthesis review. Literature was identified through systematic searches of peer-reviewed journals, books, and authoritative institutional reports using combinations of terms including climate-smart agriculture, sustainable intensification, conservation agriculture, soil health, soil organic carbon, agroforestry, cover crops, integrated nutrient management, integrated pest management, precision agriculture, remote sensing, deficit irrigation, and food security. Priority was given to meta-analyses, systematic reviews, long-term field experiments exceeding five years, multi-location trials, and large programme evaluations, because these designs provide stronger evidence on persistence, variability, and context dependence than single-season, single-site studies. Foundational works were included to trace conceptual development, and recent studies were included to capture advances in sensing, modelling, and digital advisory services.

Studies were included if they reported at least one outcome related to crop productivity, soil properties, water use, nutrient-use efficiency, pest or disease pressure, greenhouse gas fluxes, farm income, labour, or resilience, and if the agroecological context, soil type, and management history were sufficiently described to allow interpretation. Studies were excluded if methods were not described, if results could not be attributed to a defined practice, or if they reported only modelling without empirical calibration. Evidence was organised by practice family and outcome domain, and cross-checked across regions to avoid overgeneralisation from a single environment. Where meta-analyses reported divergent results, the review examines the sources of heterogeneity, including climate, soil texture, duration of the experiment, residue management, fertiliser rate, and crop type (Pittelkow et al., 2015; Poeplau and Don, 2015; Kaye and Quemada, 2017).

The synthesis does not claim to estimate a single global effect size for a bundled package, because bundles differ and contexts matter. Instead, it uses tables and figures to summarise directional patterns, typical magnitudes reported in the literature, and the conditions under which benefits are larger, smaller, or reversed. This approach is consistent with recent reviews that emphasise context specificity and the need for locally adapted recommendations (Giller et al., 2015; Rosenstock et al., 2016; Totin et al., 2018). Limitations are discussed explicitly in Section 10.

3. Conceptual Framework: From Practices to Resilient Systems

Climate-smart agriculture is best understood as an outcome-oriented approach rather than a fixed technology list (FAO, 2013; Lipper et al., 2014). A practice is climate-smart only if, in a given context, it contributes to productivity, adaptation, or mitigation without undermining the other pillars. For example, nitrogen fertiliser can raise productivity but increase nitrous oxide emissions if applied in excess or at the wrong time; the same fertiliser, applied at the right rate, source, time, and place, can raise nutrient-use efficiency and reduce emissions per unit of grain (Snyder et al., 2009; Zhang et al., 2015). Similarly, irrigation can buffer drought but increase energy use and water depletion if inefficient; deficit irrigation and scheduling can improve water productivity while reducing withdrawals (Fereres and Soriano, 2007; Geerts and Raes, 2009). Context therefore determines whether a practice is climate-smart.

Soil health provides the integrative mechanism that links many climate-smart practices to outcomes. Soil health is commonly defined as the continued capacity of soil to function as a living ecosystem that sustains plants, animals, and humans (Lehmann et al., 2020; Doran and Zeiss, 2000). It encompasses physical properties such as aggregation and porosity, chemical properties such as pH, nutrient availability, and cation exchange capacity, and biological properties such as microbial biomass, diversity, enzyme activity, and soil fauna. Soil organic carbon is a master variable because it influences aggregation, water retention, nutrient supply, and biological activity, while also representing a carbon stock relevant to mitigation (Lal, 2004; Lal, 2015; Paustian et al., 2016). Management that increases carbon inputs through roots, residues, cover crops, compost, and trees, and reduces carbon losses through erosion and excessive disturbance, tends to improve multiple soil functions simultaneously.

Sustainable intensification requires attention to efficiency, substitution, and redesign. Efficiency means producing more with the same or fewer inputs, for example through precision nutrient placement. Substitution means replacing a harmful input or process with a less harmful one, for example replacing broad-spectrum insecticide with biological control or resistant varieties. Redesign means reconfiguring the farming system, for example introducing rotations, intercrops, agroforestry, or crop-livestock integration so that ecological interactions perform functions previously provided by external inputs (Pretty et al., 2011; Gliessman, 2015). The largest and most durable gains often arise from redesign, but redesign also demands more knowledge, labour organisation, and coordination. This explains why simple input subsidies or single-technology promotion often produce modest or short-lived effects, whereas integrated packages supported by learning and institutions produce more sustained change.

Precision agriculture and agroecology are often presented as opposites, one high-technology and one low-input, but in practice they can be complementary. Precision tools can help farmers observe soil variability, detect nutrient deficiency or pest pressure early, schedule irrigation, and document outcomes, while agroecological principles guide what to observe, which diversity to introduce, and how to interpret feedback from the system (Mulla, 2013; Gebbers and Adamchuk, 2010; Wezel et al., 2020). A smallholder using a mobile phone advisory service, a leaf colour chart, and a diversified rotation is practising precision in an appropriate form, just as a large farm using satellite imagery and variable-rate applicators is. The relevant question is not whether technology is used, but whether it increases the farmer's ability to match management to local conditions, reduce waste, and learn from outcomes.

4. Soil Health and Conservation Agriculture

Conservation agriculture is built on three principles: minimum mechanical soil disturbance, permanent soil cover with crop residues or living mulches, and diversification through rotations or associations (FAO, 2013; Kassam et al., 2009; Hobbs et al., 2008). Each principle affects soil processes. Minimum disturbance preserves soil aggregates, fungal networks, and pore continuity, reduces oxidation of organic matter, and maintains habitat for earthworms and other fauna. Permanent cover protects the surface from raindrop impact, reduces evaporation, moderates soil temperature, suppresses weeds, and provides a continuous supply of organic material. Diversification introduces roots of different depths, architectures, and exudate profiles, supports diverse microbial communities, breaks pest and disease cycles, and improves nutrient cycling through legumes and deep-rooted species.

Evidence from long-term experiments and meta-analyses shows that conservation agriculture often increases soil organic carbon in the topsoil, improves aggregation, infiltration, and water retention, and reduces erosion, although the magnitude and depth distribution depend on climate, soil texture, residue quantity, and duration (Poeplau and Don, 2015; Pittelkow et al., 2015; Blanco-Canqui and Ruis, 2018). In many tropical and subtropical soils, where organic matter decomposes rapidly, the benefit of no-till alone is modest unless it is combined with residue retention and cover crops. Where residues are removed for fodder, fuel, or construction, or where they are burned, the soil-cover principle is compromised and benefits decline sharply. This is a central reason why conservation agriculture has succeeded in some regions and struggled in others (Giller et al., 2015; Thierfelder et al., 2013). Successful adaptation therefore requires negotiating residue trade-offs, for example through dual-purpose crops, improved fodder, or community agreements on grazing.

Cover crops are a powerful complement to conservation agriculture. Legume cover crops fix atmospheric nitrogen, non-legume cover crops scavenge residual nutrients, and mixtures combine these functions while providing continuous ground cover (Kaye and Quemada, 2017; Blanco-Canqui et al., 2015). Meta-analyses report that cover crops increase soil organic carbon, improve soil structure, reduce nitrate leaching, and suppress weeds, with benefits increasing over time and with biomass production. Yield effects on the following cash crop vary: they are often positive after several years, neutral in the short term, and occasionally negative if the cover crop depletes soil water, immobilises nitrogen, or is terminated too late. Management details, including species choice, sowing date, termination method, and timing relative to the main crop, therefore matter greatly. In water-limited environments, farmers may favour drought-tolerant, short-duration, or relay-planted cover crops, or may prioritise residue retention over a separate cover crop.

Soil biology mediates many of these effects. Arbuscular mycorrhizal fungi improve phosphorus uptake and aggregation; free-living nitrogen fixers and rhizobia contribute nitrogen; decomposers recycle residues; and predators and pathogens regulate soil food webs (Bender et al., 2016; Lehmann et al., 2020). Practices that reduce disturbance, maintain living roots for longer periods, and supply diverse organic substrates tend to support richer and more active soil communities. In turn, healthier soil biology improves nutrient mineralisation, disease suppression, and soil structure, creating positive feedbacks. These biological processes are not instantaneous; they build over seasons and years, which is why short-term evaluations may understate the benefits of soil-health practices, and why farmers need support

during the transition period when costs may be incurred before benefits are fully realised (Lal, 2015; Paustian et al., 2016).

Table 1. Core conservation agriculture practices, mechanisms, and expected soil outcomes

Practice	Main mechanism	Soil outcome	Key condition
Minimum tillage / no-till	Preserves aggregates and fungal networks	Higher topsoil carbon, better structure	Residue retained; traffic controlled
Permanent soil cover	Protects surface, feeds soil biota	Less erosion, more moisture	Residue not removed or burned
Crop rotation / diversification	Diverse roots and residues	Better nutrient cycling, fewer pests	Legume included where feasible
Cover crops	Living roots, biomass input	More carbon, less leaching	Species matched to water and season
Compost / manure	Direct organic matter addition	Higher fertility, water retention	Quality feedstock, correct rate

Source: Synthesis based on Poeplau and Don (2015), Kaye and Quemada (2017), Blanco-Canqui and Ruis (2018), and Lal (2015).

5. Integrated Nutrient and Water Management

Nutrient management is central to both productivity and environmental performance. Integrated nutrient management combines mineral fertilisers, organic amendments, biological nitrogen fixation, and improved timing and placement to match supply to crop demand (Snyder et al., 2009; Zhang et al., 2015; Vanlauwe et al., 2010). The 4R framework, right source, right rate, right time, and right place, provides a practical guide. Soil testing, leaf colour charts, chlorophyll meters, and remote sensing can improve the accuracy of rate and timing decisions, reducing both deficiency and excess. In many smallholder systems, the challenge is not only excess but also nutrient mining, where harvests remove more nutrients than are replaced, gradually depleting soil fertility. In high-input systems, the challenge is often surplus nitrogen and phosphorus, leading to nitrous oxide emissions, nitrate leaching, and eutrophication. Integrated management must therefore be calibrated to the starting point of the system.

Legumes play a strategic role in integrated nutrient management. Biological nitrogen fixation by grain and forage legumes can supply a substantial share of the nitrogen requirement of a rotation, reduce fertiliser costs, and improve soil organic matter and structure (Giller, 2001; Peoples et al., 2009). Intercropping cereals with legumes, relay planting, and including legume cover crops or green manures are well-established practices in Africa, Asia, and Latin America. Their success depends on effective rhizobial inoculation, phosphorus availability, soil pH, and variety adaptation. Phosphorus limitation is a common constraint in weathered tropical soils; combining organic amendments, phosphate-solubilising organisms, and modest mineral phosphorus can improve availability more sustainably than either source alone (Vanlauwe et al., 2010). Long-term trials in sub-Saharan Africa have shown that integrated soil fertility management, combining fertiliser, organic matter, and improved germplasm, outperforms fertiliser alone on degraded soils.

Water management interacts closely with nutrient management. Water stress reduces nutrient uptake even when nutrients are present, while excess water can leach nitrate and cause waterlogging. Water-smart practices include rainwater harvesting, mulching, conservation tillage, tied ridges, zai pits, and small-scale irrigation where feasible (Rockström et al., 2010; Geerts and Raes, 2009). Deficit irrigation, which applies less water than full crop demand during drought-tolerant growth stages, can improve water productivity, although it requires knowledge of crop sensitivity and reliable scheduling (Fereres and Soriano, 2007). Drip irrigation and alternate wetting and drying in rice can reduce water use and methane emissions while maintaining yields, but adoption depends on cost, water pricing, energy, and labour (Bouman et al., 2007; Carrijo et al., 2017). In rainfed systems, the highest return often comes from improving soil water storage through organic matter, cover, and structure, because stored soil water buffers dry spells between rainfall events.

Precision tools are increasingly useful for nutrient and water decisions. Satellite and drone imagery can detect spatial variability in canopy greenness, biomass, and stress, while soil sensors can monitor moisture and salinity in real time (Mulla, 2013; Gebbers and Adamchuk, 2010). Variable-rate application can target fertiliser to zones where response is highest, reducing waste in low-response zones. However, precision agriculture is not only about expensive equipment. Low-cost tools such as leaf colour charts, soil test kits, mobile advisories, and farmer field schools have improved nitrogen management in rice and maize systems in Asia and Africa, demonstrating that precision principles can be adapted to resource-constrained settings. The key is to combine sensing with agronomic interpretation and timely action, because data alone do not improve outcomes unless they change decisions.

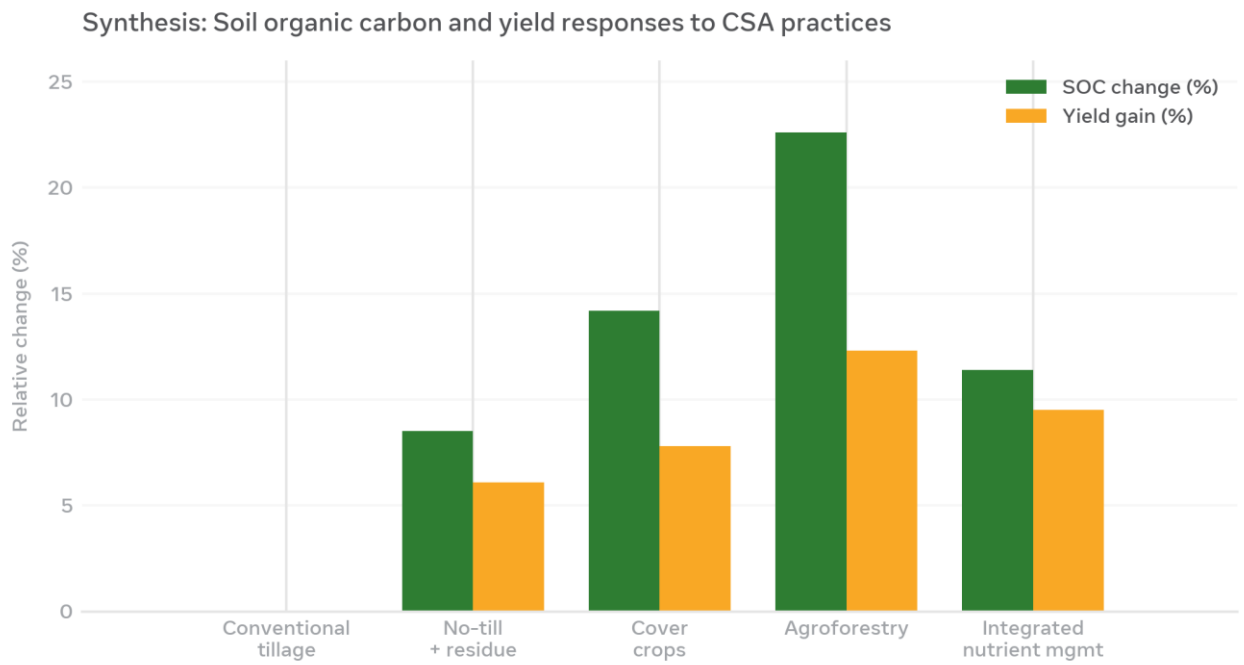


Figure 1. Synthesis of soil organic carbon and yield responses reported for climate-smart practices relative to conventional tillage. Values summarise directional patterns from meta-analyses cited in the text.

6. Agroforestry, Diversification, and Integrated Pest Management

Agroforestry integrates trees and shrubs into crop and livestock systems, providing shade, windbreaks, fodder, fruit, timber, and carbon storage, while improving soil fertility through litter, root turnover, and nitrogen fixation by leguminous trees (Nair, 1993; Jose, 2009; Garrity et al., 2010). Farmer-managed natural regeneration, parkland systems, alley cropping, silvopasture, and homegardens are diverse forms adapted to different climates and cultures. In the Sahel, for example, farmer-managed regeneration of Faidherbia albida and other native species has improved soil fertility, microclimate, and crop yields while providing fodder and fuelwood (Garrity et al., 2010; Reij et al., 2009). In Southeast Asia and Latin America, complex agroforestry systems support biodiversity, diversify income, and reduce risk from price or weather shocks. The benefits of trees accrue over years, so tenure security and long-term planning are essential for adoption.

Diversification beyond trees also strengthens resilience. Intercropping, relay cropping, rotation, and mixed crop-livestock systems spread risk across species with different sensitivities to drought, pests, and markets (Lin, 2011; Altieri, 1995). Diversified systems can improve resource-use complementarity, for example when a deep-rooted crop accesses water and nutrients below the root zone of a shallow-rooted companion, or when a legume supplies nitrogen to a cereal. They can also improve dietary diversity when they include vegetables, pulses, and fruits, linking agronomic diversification to nutrition outcomes (Sibhatu and Qaim, 2018). The management complexity of diversified systems is higher, and mechanisation, harvesting, and marketing may be more difficult, so diversification should be designed around labour availability, market demand, and processing options, not promoted as a uniform prescription.

Integrated pest management provides an ecological approach to crop protection that combines cultural, biological, mechanical, and, when necessary, chemical controls (Pretty and Bharucha, 2015; Barzman et al., 2015). Cultural controls include rotation, resistant varieties, adjusted planting dates, and sanitation. Biological controls include conservation of natural enemies, release of parasitoids and predators, and use of microbial biopesticides. Monitoring and thresholds ensure that interventions are applied only when pest populations exceed economic injury levels, reducing unnecessary pesticide use. Evidence from Asia and Africa shows that integrated pest management can maintain or increase yields while reducing pesticide applications and costs, with benefits for farmer health and the environment (Pretty and Bharucha, 2015; Gurr et al., 2016). Push-pull technology, which uses companion plants to repel pests and trap plants to attract them, is a well-documented example in maize systems in East Africa, combining pest control with fodder production and soil fertility benefits.

The interaction between diversification and pest management is important. Habitat diversity can support natural enemies, provide alternative hosts, and disrupt pest movement, but it can also harbour pests if not managed carefully. Landscape-level management, including field margins, hedgerows, and fallows, therefore complements field-level practices. Similarly, soil health influences plant health: well-nourished plants with balanced nutrition are often more tolerant of pest and disease pressure, while stressed plants are more vulnerable. This reinforces the value of integrated, systems-level management rather than isolated pest control. Future advances in pest forecasting, based on weather data, remote sensing, and artificial intelligence, may improve early warning, but they must be accessible, interpretable, and linked to locally available control options to be useful to farmers.

7. Precision Technologies, Digital Advisory, and Climate Services

Precision agriculture encompasses global positioning systems, geographic information systems, remote sensing, proximal sensors, variable-rate technology, and decision-support models (Gebbers and Adamchuk, 2010; Mulla, 2013). These tools can reveal within-field variability in soil properties, elevation, moisture, and crop vigour that is invisible to the naked eye or too labour-intensive to map manually. For example, satellite-derived vegetation indices can identify nitrogen-deficient zones, while soil electrical conductivity mapping can delineate management zones for variable seeding or fertilisation. Drones can provide high-resolution imagery for crop scouting, while yield monitors can map spatial patterns of productivity. When combined with agronomic models, these data can support site-specific recommendations that improve input-use efficiency and reduce environmental losses.

Digital advisory services and climate services extend precision principles to farmers who do not own sensors or machinery. Mobile phone messages, interactive voice response, radio, and extension apps can deliver weather forecasts, planting advisories, pest alerts, and market prices (Campbell et al., 2014; Totin et al., 2018). Participatory approaches that co-produce advisories with farmers, integrating local knowledge and forecast information, tend to be more trusted and actionable than top-down messages. Climate services are particularly valuable when they are downscaled to local conditions, communicated in local languages, and linked to concrete management options, such as whether to plant early, choose a short-duration variety, or delay fertiliser application. Evidence shows that access to timely climate information can improve planting decisions, input use, and risk management, although benefits depend on literacy, gender, phone ownership, and social norms that affect who receives and can act on information.

Equity and access are central to the digital agenda. Technologies that require high capital, connectivity, or literacy can widen inequalities if they are accessible only to larger, wealthier, or male farmers. Inclusive design, including low-cost sensors, shared service models, women-focused extension, and offline functionality, can broaden access. Data governance also matters: farmers should understand how their data are used, retain rights over their information, and benefit from aggregated insights. Cooperatives, farmer organisations, and public extension can play a mediating role by aggregating demand, negotiating service provision, and ensuring that digital tools complement rather than replace human advisory relationships. The most successful digital programmes combine technology with social learning, demonstration, and feedback loops.

Table 2. Precision and digital tools: functions, suitability, and constraints

Tool	Function	Best suited for	Constraint
Satellite imagery	Canopy vigour, stress detection	Large areas, seasonal monitoring	Cloud cover, resolution
Drone imagery	High-resolution scouting	Field-level pest, nutrient checks	Cost, regulation, skill
Soil moisture sensors	Real-time water status	Irrigated and high-value crops	Maintenance, calibration
Leaf colour chart / SPAD	Nitrogen status	Rice, maize smallholders	Training, interpretation
Mobile advisories	Weather, planting, pest alerts	Smallholders with phones	Connectivity, language, trust
Variable-rate applicator	Site-specific fertiliser	Mechanised large farms	Capital, soil maps needed

Source: Synthesis based on Gebbers and Adamchuk (2010), Mulla (2013), and Campbell et al. (2014).

8. Outcomes, Trade-Offs, and Heterogeneity

Productivity outcomes from integrated climate-smart packages are generally positive but heterogeneous. Meta-analyses of conservation agriculture report yield effects that range from negative in the first one to two years to positive thereafter, with the transition period influenced by weed pressure, nitrogen immobilisation, and learning (Pittelkow et al., 2015; Thierfelder et al., 2013). In many studies, the yield advantage of conservation agriculture is largest in dry years or on degraded soils, where improved water retention and soil structure provide the greatest benefit. This pattern is important: the value of resilience practices is most evident under stress, not under optimal conditions. Evaluations conducted only in favourable years may therefore understate their contribution to stability and risk reduction, which matter greatly to farmers who prioritise avoiding catastrophic loss over maximising average yield.

Environmental outcomes are more consistently positive for soil and water, but mixed for greenhouse gases if practices are implemented incompletely. Increasing soil organic carbon, reducing erosion, and improving water infiltration are well-documented benefits of cover, residue retention, and agroforestry (Lal, 2004; Poeplau and Don, 2015). Nitrous oxide emissions can increase under no-till in wet soils or when nitrogen is applied in excess, offsetting some carbon gains, but can decrease when nitrogen is applied precisely and when legumes replace fertiliser (Snyder et al., 2009). Methane emissions from rice can be reduced by alternate wetting and drying, while agroforestry can sequester carbon in biomass and soil (Paustian et al., 2016; Nair, 1993). Life-cycle assessment is needed to evaluate net emissions, because focusing on a single gas or a single field can be misleading.

Economic and labour outcomes determine adoption. Integrated practices can reduce costs for tillage, fertiliser, and pesticides, increase yields and diversification income, and improve price stability, but they can also increase labour for weeding, residue management, tree planting, or composting (Giller et al., 2015; Pretty et al., 2011). Labour effects are gendered: women often bear additional labour for weeding, water fetching, and post-harvest processing, and practices that increase their burden without increasing their control over income are less likely to be sustained. Mechanisation, herbicide

management where appropriate and safe, and labour-sharing arrangements can mitigate labour constraints, but they raise questions about safety, equity, and environmental trade-offs that must be addressed explicitly. Economic evaluations should therefore report labour, gender, and distributional effects, not only average net returns.

Social and nutritional outcomes are increasingly recognised as core measures of success. Diversified systems that include legumes, vegetables, fruits, and animal-source foods can improve household dietary diversity and micronutrient intake, particularly when combined with nutrition education and women's empowerment (Sibhatu and Qaim, 2018; Wezel et al., 2020). Secure tenure, participation in farmer groups, and access to markets shape whether productivity gains translate into improved food security and income. Studies that track only grain yield may miss these broader benefits, while studies that track only environmental indicators may miss livelihood effects. A multi-dimensional evaluation framework, covering productivity, resilience, environment, economics, nutrition, and equity, provides a more complete picture of sustainable intensification.

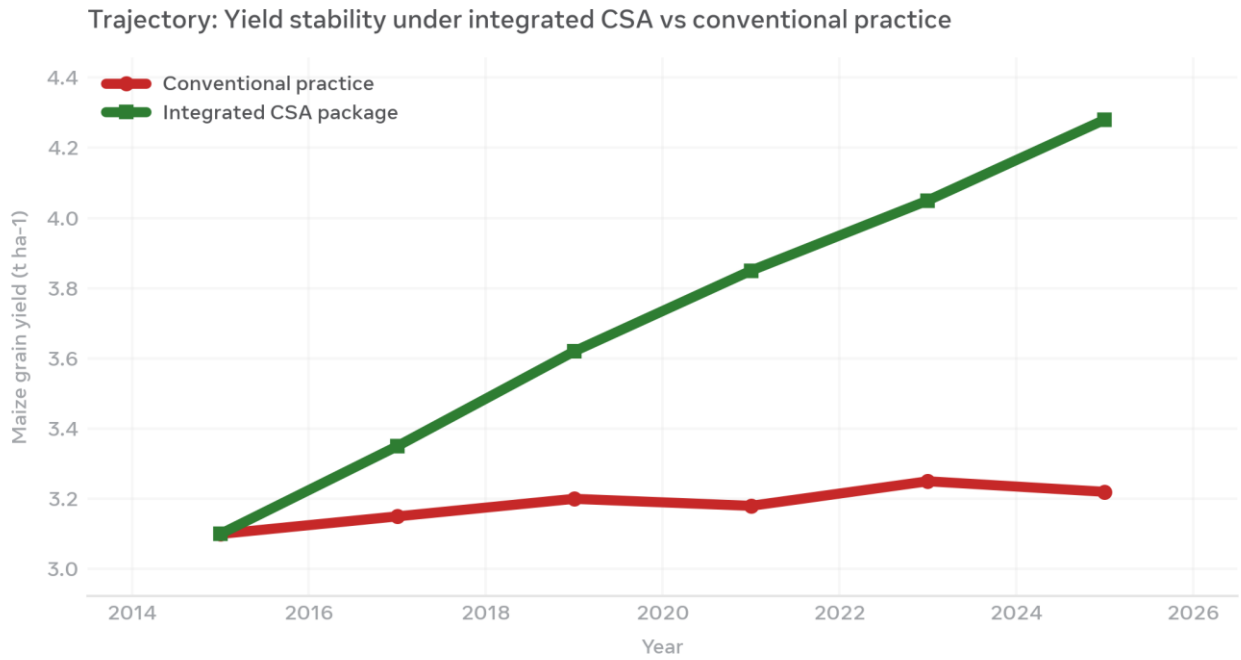


Figure 2. Trajectory of maize yield under an integrated climate-smart package compared with conventional practice, showing cumulative soil and management benefits over time.

9. Adoption, Institutions, and Scaling

Adoption is a process, not a one-time event. Farmers experiment, adapt, partially adopt, and sometimes disadopt practices as conditions change (Giller et al., 2015; Totin et al., 2018). Adoption is influenced by perceived benefits, risk, complexity, observability, trialability, and compatibility with existing systems, as well as by access to inputs, credit, extension, markets, and social networks. Practices that require long-term investment, such as agroforestry or soil carbon building, are less attractive when tenure is insecure or when farmers face high discount rates due to poverty and risk. Practices that provide rapid, visible benefits, such as improved varieties or pest control, are more readily adopted, and can serve as entry points for more complex system changes if they are bundled with soil and water practices.

Extension and learning approaches matter. Farmer field schools, demonstration plots, farmer-to-farmer exchange, and participatory trials have been more effective than lecture-based extension for complex, knowledge-intensive practices, because they allow farmers to observe, test, and adapt under local conditions (Pretty et al., 2011; Campbell et al., 2014). Innovation platforms that bring together farmers, researchers, input suppliers, traders, and policymakers can align incentives, resolve bottlenecks, and co-develop solutions. Gender-responsive extension, which addresses women's time constraints, mobility, and access to resources, is essential, because women are major agricultural producers in many regions yet are often underserved by advisory services. Youth engagement, including through digital tools and agribusiness opportunities, can also support scaling.

Policy and finance must create an enabling environment. Secure land tenure, including recognition of customary rights, encourages long-term soil investment (Lipper et al., 2014). Input subsidies can help if they are targeted, time-bound, and linked to soil testing and training, but they can distort markets and encourage unbalanced fertiliser use if they are untargeted or permanent. Crop insurance, weather-index insurance, and social protection can reduce risk and enable farmers to invest in new practices, although design and affordability remain challenges. Carbon finance and payments for ecosystem services have potential to reward soil carbon and tree planting, but they require credible measurement, verification, and benefit-sharing arrangements that do not exclude smallholders. Public investment in rural infrastructure, research, extension, and market access remains foundational.

Scaling should be understood as scaling of principles and learning processes, not only scaling of a fixed technology

package. Successful scaling involves adapting practices to new contexts, building local capacity, strengthening institutions, and monitoring outcomes and trade-offs. A decision framework can guide this process: diagnose soil, climate, farm, and market constraints; identify a shortlist of practices that address priority constraints; test bundles on-farm with farmer participation; evaluate multi-dimensional outcomes over multiple seasons; adapt and refine; and share learning through networks and platforms. Table 3 summarises such a framework. This iterative, learning-oriented approach is more demanding than mass distribution of a single input, but it is more likely to produce durable, equitable, and context-appropriate change.

Table 3. Decision framework for selecting and scaling integrated climate-smart bundles

Step	Key question	Action
1. Diagnose	What limits productivity and resilience?	Soil test, climate risk, market and labour assessment
2. Prioritise	Which practices address priority limits?	Shortlist 2-4 complementary practices
3. Test	Do bundles work on local farms?	Participatory on-farm trials, 2+ seasons
4. Evaluate	What are multi-dimensional outcomes?	Yield, soil, water, income, labour, nutrition
5. Adapt	What needs changing?	Adjust species, timing, rates, labour organisation
6. Scale learning	How to reach more farmers equitably?	Demonstrations, networks, advisories, finance

10. Conclusions and Future Research Priorities

This review has shown that integrating climate-smart agriculture, soil health management, diversification, and precision technologies offers a promising pathway to sustainable intensification, but that success depends on context, bundling, sequencing, and institutional support. Soil health is the central mechanism linking many practices to resilience and productivity, while precision tools and climate services make management more timely and targeted. Diversification and agroforestry spread risk, improve nutrition, and enhance ecosystem services, while integrated nutrient, water, and pest management reduce waste and environmental harm. No single practice can deliver all objectives; bundles that are locally adapted, farmer-tested, and supported by extension, finance, tenure, and markets are more likely to succeed.

Future research should prioritise long-term, systems-level experiments that track soil, yield, emissions, water, labour, income, nutrition, and equity over a decade or more, rather than short-term, single-outcome trials. Research should also address the heterogeneity of effects across soil types, climates, farm sizes, and gender, and develop scalable methods for measuring soil health, carbon, and ecosystem services at low cost. Digital tools, including remote sensing, artificial intelligence, and citizen science, should be evaluated for accuracy, accessibility, and impact on decisions, not only for technical performance. Participatory research that co-develops solutions with farmers, including women and youth, and that integrates indigenous and local knowledge with formal science, will be essential for designing practices that are both effective and adoptable.

Finally, agricultural science must engage with policy and practice. Researchers, extension workers, farmers, private sector actors, and policymakers need shared frameworks, data, and learning platforms to translate evidence into action. If agronomic innovation is combined with secure tenure, inclusive finance, climate services, market access, and supportive policy, agriculture can contribute to food security, climate adaptation and mitigation, biodiversity, and rural livelihoods simultaneously. That integrated vision, grounded in soil health and farmer knowledge, is the core promise of climate-smart, sustainable intensification.

Acknowledgements

The authors thank farmers, extension workers, and researchers whose field experiments, trials, and practical knowledge inform this synthesis. No specific funding was received for this review.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed to conceptualisation, literature synthesis, writing, and revision. Amara Okafor coordinated the review and led the synthesis on soil health and climate-smart agriculture. Daniel Mwangi led the sections on conservation agriculture and water management. Priya Sharma led the sections on nutrient management and precision agriculture. Lucas Ferreira led the sections on agroforestry and diversification. Emily Carter led the sections on pest management and adoption. Yuki Tanaka led the sections on digital tools and scaling.

References

Altieri, M.A. (1995). Agroecology: The Science of Sustainable Agriculture. Westview Press, Boulder, CO, USA.

Barzman, M., Bàrberi, P., Birch, A.N.E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., Hommel, B., Jensen, J.E., Kiss, J., Kudsk, P., Lamichhane, J.R., Messéan, A., Moonen, A.C., Ratnadass, A., Rocque, P., Sattin, M. and Sutter, M. (2015). Eight principles of integrated pest management. Agronomy for Sustainable Development, 35, 1195-1215.

Bender, S.F., Wagg, C. and van der Heijden, M.G.A. (2016). An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends in Ecology and Evolution, 31(6), 440-452.

Blanco-Canqui, H. and Ruis, S.J. (2018). No-tillage and soil physical environment. Geoderma, 326, 164-200.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A. and Hergert, G.W. (2015). Cover crops and ecosystem services: insights from studies in temperate soils. Agronomy Journal, 107(6), 2449-2474.

Bouman, B.A.M., Lampayan, R.M. and Tuong, T.P. (2007). Water Management in Irrigated Rice: Coping with Water Scarcity. International Rice Research Institute, Los Baños, Philippines.

Campbell, B.M., Thornton, P., Zougmoré, R., van Asten, P. and Lipper, L. (2014). Sustainable intensification: what is its role

in climate-smart agriculture? Current Opinion in Environmental Sustainability, 8, 39-43.

Carrijo, D.R., Lundy, M.E. and Linquist, B.A. (2017). Rice yields and water use under alternate wetting and drying: a meta-analysis. Field Crops Research, 203, 173-180.

Doran, J.W. and Zeiss, M.R. (2000). Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology, 15(1), 3-11.

FAO (2013). Climate-Smart Agriculture Sourcebook. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fereres, E. and Soriano, M.A. (2007). Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany, 58(2), 147-159.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J. and Godfray, H.C.J. (2013). Sustainable intensification in agriculture: premises and policies. Science, 341(6141), 33-34.

Garrity, D.P., Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M. and Bayala, J. (2010). Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Security, 2, 197-214.

Gebbers, R. and Adamchuk, V.I. (2010). Precision agriculture and food security. Science, 327(5967), 828-831.

Geerts, S. and Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management, 96(9), 1275-1284.

Giller, K.E. (2001). Nitrogen Fixation in Tropical Cropping Systems. CABI Publishing, Wallingford, UK.

Giller, K.E., Andersson, J.A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O. and Vanlauwe, B. (2015). Beyond conservation agriculture. Frontiers in Plant Science, 6, 870.

Gliessman, S.R. (2015). Agroecology: The Ecology of Sustainable Food Systems. CRC Press, Boca Raton, FL, USA.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. and Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. Science, 327(5967), 812-818.

Gurr, G.M., Wratten, S.D., Landis, D.A. and You, M. (2016). Habitat management to suppress pest populations: progress and prospects. Annual Review of Entomology, 62, 91-109.

Hobbs, P.R., Sayre, K. and Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B, 363, 543-555.

IPCC (2019). Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. IPCC, Geneva, Switzerland.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Systems, 76, 1-10.

Kassam, A., Friedrich, T., Shaxson, F. and Pretty, J. (2009). The spread of conservation agriculture: justification, sustainability and uptake. International Journal of Agricultural Sustainability, 7(4), 292-320.

Kaye, J.P. and Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change: a review. Agronomy for Sustainable Development, 37, 4.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), 1623-1627.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. Sustainability, 7(5), 5875-5895.

Lehmann, J., Bossio, D.A., Kögel-Knabner, I. and Rillig, M.C. (2020). The concept and future prospects of soil health. Nature Reviews Earth and Environment, 1, 544-553.

Lin, B.B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience, 61(3), 183-193.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A. and Torquebiau, E.F. (2014). Climate-smart agriculture for food security. Nature Climate Change, 4, 1068-1072.

Mulla, D.J. (2013). Twenty-five years of remote sensing in precision agriculture: key advances and remaining knowledge gaps. Biosystems Engineering, 114(4), 358-371.

Nair, P.K.R. (1993). An Introduction to Agroforestry. Kluwer Academic Publishers, Dordrecht, Netherlands.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P. and Smith, P. (2016). Climate-smart soils. Nature, 532, 49-57.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H. and Jensen, E.S. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis, 48, 1-17.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T. and van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. Nature, 517, 365-368.

Poeplau, C. and Don, A. (2015). Carbon sequestration in soil under no-till: a meta-analysis. Global Change Biology, 21(2), 678-688.

Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. Philosophical Transactions of the Royal Society B, 363, 447-465.

Pretty, J. and Bharucha, Z.P. (2015). Integrated pest management for sustainable intensification of agriculture in Asia and Africa. Insects, 6(1), 152-182.

Pretty, J., Toulmin, C. and Williams, S. (2011). Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability, 9(1), 5-24.

Reij, C., Tappan, G. and Smale, M. (2009). Agroenvironmental transformation in the Sahel: another step toward sustainable intensification. IFPRI Discussion Paper 00914, International Food Policy Research Institute, Washington, DC, USA.

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J. and Qiang, Z. (2010). Managing water in rainfed agriculture: the need for a paradigm shift. Agricultural Water Management, 97(4), 543-550.

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L. and Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio, 46, 4-17.

Rosenstock, T.S., Lamanna, C., Chesterman, S., Bell, P., Arslan, A., Richards, M., Rioux, J., Akinleye, A.O., Champalle, C., Cheng, Z., Corner-Dolloff, C., Dohn, J., English, W., Eyring, J., Girvetz, E.H., Kerr, A., Koo, J., Mwongela, B., Ng, E., Nyasimi, M., Ouedraogo, M., Ouedraogo, M., Recha, J., Richards, M., Shepherd, K.D., Sileshi, G.W., van Asten, P., Vågen, T.G., van Wijk, M.T. and Wollenberg, E. (2016). The scientific basis of climate-smart agriculture: a systematic review. Springer, Cham, Switzerland.

Sibhatu, K.T. and Qaim, M. (2018). Farm production diversity and dietary quality: linkages and measurement issues. Food Security, 10, 47-59.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L. and Fixen, P.E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems and Environment, 133(3-4), 247-266.

Thierfelder, C., Chivenge, P., Cheesman, S., Mupangwa, W., Eash, N.S. and Rusinamhodzi, L. (2013). Conservation

agriculture in southern Africa: advances and challenges. In: Conservation Agriculture: Global Prospects and Challenges (Jat, R.A. et al., eds.), CABI, Wallingford, UK, pp. 155-175.

Tilman, D., Balzer, C., Hill, J. and Befort, B.L. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences USA, 108(50), 20260-20264.

Totin, E., Segnon, A.C., Schut, M., Affognon, H., Zougmoré, R.B., Rosenstock, T. and Thornton, P.K. (2018). Institutional perspectives on climate-smart agriculture: a systematic literature review. Sustainability, 10(6), 1990.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L. and Sanginga, N. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook on Agriculture, 39(1), 17-24.

Wezel, A., Herren, B.G., Kerr, R.B., Barrios, E., Gonçalves, A.L.R. and Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems: a review. Agronomy for Sustainable Development, 40, 40.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P. and Shen, Y. (2015). Managing nitrogen for sustainable development. Nature, 528, 51-59.