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Review Article

Knowledge Gaps in Climate-Smart, Regenerative, and Agroecological Transitions Across Crop, Livestock, Economic, and Natural-Resource Systems (2020-2026)

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ABSTRACT

Global agriculture faces simultaneous pressure to raise productivity, adapt to a changing climate, and restore degraded natural resources, giving rise to three overlapping paradigms-climate-smart agriculture, regenerative agriculture, and agroecology-that share the ambition of reconciling yield with resilience. Despite a rapidly expanding literature, empirical evidence remains fragmented across crop, livestock, socioeconomic, and natural-resource subsystems, limiting the capacity of researchers, extension services, and policymakers to design coherent transition pathways. This narrative review synthesizes knowledge gaps identified in the 2020-2026 peer-reviewed literature across four interconnected domains: (a) crop and livestock production together with precision and digital agriculture; (b) soil, water, and climate-smart management; (c) biodiversity, ecosystem services, and landscape-scale processes; and (d) agricultural economics, adoption behavior, and policy. Methods. A structured, non-systematic literature search was conducted using Crossref-verified bibliographic records, academic web search, and citation tracking, prioritizing systematic reviews, scoping reviews, meta-analyses, and empirical studies published between 2020 and 2026 in agriculture, ecology, and sustainability journals. Thirty-six verified, on-topic references were retained after screening for topical relevance and excluding sources outside the scope of agricultural-systems research; the search and screening process is summarized in a PRISMA-informed flowchart. Across all four domains, the reviewed literature converges on five recurring gaps: (a) persistent overemphasis on plot- and farm-level yield outcomes relative to ecosystem services and social welfare; (b) weak integration of evidence across spatial scales, regions, and socioeconomic contexts, with pronounced geographic bias toward high-income settings and a limited subset of Global South case studies; (c) adoption barriers rooted in finance, extension access, land tenure, and gendered constraints that intervention research addresses inconsistently; (d) immature digital and precision-agriculture decision-support tools, particularly low-cost sensing and trusted data-sharing infrastructure for smallholders; and (e) underdeveloped frameworks for evaluating agroecological and climate-smart transitions at landscape and policy scales. Advancing climate-smart, regenerative, and agroecological transitions requires cross-system, multi-scale research architectures that integrate biophysical, economic, and social outcomes, alongside investment in interoperable digital infrastructure and long-term impact evaluation designed for heterogeneous smallholder and commercial contexts alike.

Keywords: Agroecology, Climate-smart Agriculture, Ecosystem Services, Farmer Adoption Behavior, Knowledge Gaps, Precision Agriculture, Regenerative Agriculture, Sustainable Intensification.

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INTRODUCTION

Agricultural systems worldwide are being asked to perform an increasingly difficult balancing act: to produce sufficient, nutritious food for a growing population, to reduce their substantial contribution to greenhouse gas emissions, and to reverse decades of soil degradation, water stress, and biodiversity loss, often within the same growing season and on the same parcel of land. Recent syntheses converge on the observation that conventional productivist strategies, while historically successful in raising yields, are increasingly inadequate for addressing these compounding pressures, particularly in regions already exposed to climatic variability and resource scarcity (Kabato *et al.*, 2025; Wijerathna-Yapa and Pathirana, 2022; Zhao *et al.*, 2023). In response, three overlapping but analytically distinct paradigms have gained prominence in the scientific and policy

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literature: climate-smart agriculture, which emphasizes the joint pursuit of productivity, adaptation, and mitigation; regenerative agriculture, which foregrounds soil biological function and on-farm ecological restoration; and agroecology, which situates farming within broader social, ecological, and food-sovereignty concerns (Haldar and Panda, 2023; Sher *et al*., 2024; Tittonell *et al*., 2020).

These paradigms are not merely terminological variants of one another. Climate-smart agriculture originated largely within international development and donor institutions as a pragmatic, technology-inclusive framework; regenerative agriculture emerged substantially from farmer-led and private-sector movements concerned with soil carbon and input reduction; and agroecology carries an explicit political-economic critique of industrial agriculture rooted in smallholder movements and participatory science (Sean *et al*., 2026; Tittonell *et al*., 2020). Despite these divergent origins, all three converge on a shared premise that is central to the present review: that resilience, broadly defined to include ecological, economic, and social dimensions, cannot be achieved through yield optimization alone. Yet the empirical literature testing this premise has grown in a fragmented rather than a cumulative fashion, with reviews increasingly noting the difficulty of comparing findings across crop types, livestock species, regions, and outcome metrics (Bonfanti *et al*., 2025; Grigorieva *et al*., 2023).

The significance of closing these evidence gaps is difficult to overstate. Climate variability is already altering yield potential and pest and disease pressure across major production regions, while the post-2020 Global Biodiversity Framework and instruments such as the European Union Soil Monitoring Law have placed unprecedented pressure on agricultural policy to demonstrate measurable ecological outcomes rather than proxy indicators of adoption alone (Ferraro *et al*., 2026). At the same time, donor-funded and national extension programs continue to invest heavily in climate-smart and precision-agriculture interventions whose long-term, sex-disaggregated, and multi-outcome evidence base remains thin, a concern raised explicitly in recent systematic reviews of intervention effectiveness (Saran *et al*., 2024). Policymakers, extension agents, and farmers therefore confront a paradox: an expanding volume of published research accompanied by persistent uncertainty about which practices work, for whom, under what conditions, and at what scale.

This review addresses that paradox by synthesizing knowledge gaps across four thematic blocks that are typically studied in isolation from one another: crop and livestock production systems, including precision and digital agriculture; soil, water, and climate-smart management; biodiversity, ecosystem services, and landscape-scale processes; and agricultural economics, adoption behavior, and policy evaluation. Rather than reporting a single discipline's findings, the review's central objective is to identify where evidence is fragmented, where it is geographically or methodologically biased, and where the four blocks fail to speak to one another-for example, where biophysical trials rarely measure economic outcomes, or where adoption studies rarely verify the ecological claims underlying the practices being adopted. The scope is deliberately bounded to peer-reviewed literature published between 2020 and 2026, with a small number of earlier seminal works retained where they remain foundational to current framings, and is limited to topically relevant agricultural-systems research; sources outside this domain were excluded during screening to preserve citation integrity. In pursuing this cross-cutting synthesis, the review aims to provide researchers and research funders with a map of where future investment in cross-system, multi-scale evidence generation would yield the greatest return.

Historical Background and Evolution of the Topic

The intellectual lineage of climate-smart, regenerative, and agroecological thinking can be traced through several overlapping waves of agricultural science. The mid-twentieth-century Green Revolution established the productivist paradigm that still dominates much agronomic research infrastructure, prioritizing input-responsive cultivars, irrigation, and synthetic fertilizer to maximize per-hectare yield. By the 1980s and 1990s, mounting evidence of soil degradation, agrochemical externalities, and smallholder marginalization gave rise to low-external-input and organic movements, and to the earliest formalizations of agroecology as both a science and a social movement, emphasizing diversified, farmer-embedded systems over standardized input packages (Tittonell *et al*., 2020).

The early 2000s saw the consolidation of the sustainable intensification concept, which sought a middle path between productivist and agroecological framings by asking how yield could be increased on existing farmland while reducing environmental impact per unit of output. Climate-smart agriculture was formally articulated by the Food and Agriculture Organization around 2010 as an explicitly triple-win framework-simultaneously pursuing productivity, adaptation, and mitigation-and rapidly became the dominant organizing concept for donor-funded agricultural development programming over the following decade (Haldar and Panda, 2023; Kabato *et al*., 2025). Parallel to this policy-oriented trajectory, a resurgence of interest in soil biological function, catalyzed by farmer networks, popular science communication, and corporate sustainability commitments, gave rise to the contemporary regenerative agriculture movement from roughly 2015 onward, with an explicit focus on practices such as reduced tillage, cover cropping, and integrated livestock grazing as levers for soil carbon accumulation and biodiversity recovery (Sher *et al*., 2024).

The period since 2020 constitutes a distinct and still-unfolding phase in this evolution. The COVID-19 pandemic and subsequent geopolitical shocks to global grain and fertilizer

markets exposed the fragility of input-dependent production systems and renewed policy interest in diversified, locally adapted agroecological alternatives (Sean *et al*., 2026). The adoption of the Kunming-Montreal Global Biodiversity Framework in 2022 embedded explicit agriculture-related targets into international biodiversity policy, while instruments such as the European Union's 2025 Soil Monitoring Law and Farm to Fork Strategy have begun to translate soil- and ecosystem-health ambitions into binding monitoring obligations (Ferraro *et al*., 2026; Moramarco *et al*., 2025). Simultaneously, the maturation of low-cost sensing hardware, satellite-derived data products, and machine-learning analytics has accelerated the digitalization of precision agriculture, extending tools once confined to large mechanized farms toward smallholder and mixed crop-livestock contexts (Innazent *et al*., 2025; Sharma *et al*., 2021). This convergence of ecological policy pressure, market shocks, and digital opportunity forms the immediate backdrop against which the knowledge gaps synthesized in this review have emerged and continue to accumulate.

Crop, Livestock, and Precision/Digital Agriculture Gaps

The first thematic block concerns production systems themselves: how crops and livestock are managed jointly, how livestock-specific welfare and productivity technologies are evolving, and how digital and precision tools are being deployed to inform decisions at the field and animal level. Across these strands, the literature displays a recurring pattern in which technical feasibility is demonstrated well ahead of evidence on socioeconomic performance, scalability, or integration with other subsystems.

Crop-Livestock Integration: Evidence Fragmented Across Scales

Integrated crop-livestock systems are widely promoted as a pathway toward nutrient recycling, diversified income, and climate resilience, yet the evidence base supporting this promotion remains structurally uneven. A systematic scoping study of integrated crop-livestock research in the mixed farming systems of the Global South found that empirical work concentrates disproportionately in sub-Saharan Africa and Asia, with markedly thinner coverage of North Africa and the Caribbean, and that most studies emphasize farm-level production of food and feed rather than the landscape-level ecosystem and social outcomes that integration is often claimed to deliver (Mabhaudhi *et al*., 2023). A complementary bibliometric and narrative review of integrated crop-livestock-forestry adoption drivers similarly concluded that policy orientation, extension systems, and farmer social networks are decisive for scaling, yet recommended stronger collaborative research linking West African experience with the more developed evidence base in East Africa, Asia, and South America-an explicit acknowledgment that current knowledge does not travel well across regions (Kotobiodjo *et al*., 2024). Model-based demonstrations of integrated farming systems, such as combined crop, dairy, goat, poultry, and vermicompost enterprises, report favorable net returns and even negative net greenhouse gas balances under experimental conditions, but such findings originate from single-site trials whose external validity across agroecological zones and farm-size classes remains largely untested (Shanmugam *et al*., 2024).

Livestock Systems and Precision Livestock Farming

Within livestock research specifically, precision livestock farming technologies-sensor-based monitoring of animal health, behavior, and welfare-have advanced rapidly for intensive dairy and swine operations, but their applicability to extensive and pastoral systems remains comparatively underdeveloped. A recent overview of precision livestock farming in extensive systems highlighted that most validated sensing and monitoring solutions were designed for confinement conditions and require substantial adaptation, including improved connectivity and lower-cost hardware, before they can support pasture-based and transhumant herds (Bernabucci *et al*., 2025). In poultry production, critical reviews note that sustainability strategies have progressed unevenly across welfare, environmental, and economic dimensions, with welfare-oriented innovations often outpacing evidence on their compatibility with smallholder-scale profitability (Bist *et al*., 2024). Taken together, these findings suggest that livestock-focused innovation continues to privilege large-scale, capital-intensive operations, leaving a persistent gap in evidence tailored to smallholder and mixed-species systems that dominate much of the Global South.

Precision and Digital Agriculture: From Sensing to Decision Support

Machine learning and remote sensing applications for precision agriculture have proliferated across nearly every stage of the crop production cycle, from soil mapping and pest detection to yield forecasting (Sharma *et al*., 2021). However, reviewers increasingly distinguish between the technical performance of individual algorithms, which is often reported favorably, and the maturity of integrated, farmer-usable decision-support systems, which lags considerably behind. An analysis of decision-support system adoption identified financial constraints, farmer distrust of algorithmic recommendations that behave as an opaque "black box," unresolved questions of data ownership and privacy, and an inadequately trained advisory workforce as persistent barriers to translating precision-agriculture research into practice, even in well-resourced agricultural economies (Brugler *et al*., 2023). A meta-analysis of decision-choice models addressing precision-agriculture and digitalization adoption similarly found that socioeconomic factors such as education, age, and farm size dominate adoption patterns, with larger and better-capitalized enterprises substantially more likely to implement new

technologies than smaller or resource-constrained operations (Kroupová *et al.*, 2024). This pattern is corroborated by a systematic review focused specifically on small-scale farmers, which found that social dynamics-awareness levels, knowledge dissemination pathways, and entrenched cultural norms-outweigh purely economic considerations in shaping adoption decisions, even though initial investment costs remain a frequently cited barrier (John *et al.*, 2023). A broader review of data-driven agriculture concluded that sustainability and productivity gains from digital agriculture are neither automatic nor universally distributed, cautioning that data-intensive farming can as easily reinforce existing inequities in access to capital and information as it can reduce them (Rozenstein *et al.*, 2023).

Low-Cost Sensing and Trusted Data Infrastructure for Smallholders

A specific and recurring gap concerns the availability of affordable, field-validated sensing hardware suitable for resource-constrained farming contexts. Comparative testing of low-cost capacitive soil moisture sensors against commercial-grade instruments demonstrates a clear trade-off between acquisition cost and measurement accuracy, with low-cost sensors better suited to short-term, limited-budget deployments than to high-precision irrigation scheduling (Schwamback *et al.*, 2023). This cost-accuracy trade-off has direct implications for water-scarce production regions, where precision irrigation and water-conservation strategies depend on reliable, spatially distributed soil moisture data that many smallholders cannot currently access (Xing and Wang, 2024). Reviews integrating digital tools with regenerative soil-health practices further note that fragmented data standards and the absence of interoperable platforms constrain the translation of sensor outputs into actionable, holistic management recommendations (Innazent *et al.*, 2025). Underlying all of these technical gaps is a governance-level constraint: a design-principles analysis of agricultural data spaces found that mistrust among stakeholders, unclear data-ownership arrangements, and inadequate data-access policies remain the dominant obstacles to establishing the trusted data-sharing ecosystems that would allow low-cost sensing, farm management software, and advisory services to interoperate at scale (Šestak and Copot, 2023). Until these governance and interoperability gaps are resolved, low-cost sensing is likely to remain a fragmented set of point solutions rather than the foundation of the holistic, farmer-centered decision-support systems that climate-smart and regenerative agriculture proponents envision.

Soil, Water, and Climate-Smart Management Gaps

The second thematic block addresses the biophysical foundations of climate-smart transitions: soil health, water management, and the broader evidence base on agricultural climate adaptation. This literature is voluminous and methodologically sophisticated at the plot scale, yet reviewers increasingly identify a widening gap between the sophistication of biophysical measurement and the practical translation of that measurement into governance and management decisions.

Soil Health Assessment and the Science-Governance Divide

Soil health research has matured considerably beyond narrow fertility diagnostics to encompass biological indicators such as microbial biomass and enzyme activity alongside physical indicators such as aggregate stability and water-holding capacity, and reviews link improved soil health directly to multiple Sustainable Development Goals spanning food security, water quality, and climate mitigation (Sharma *et al.*, 2024). Yet a large-scale European stakeholder analysis conducted under the EU Soil Strategy for 2030 found that, despite substantial scientific progress and high stakeholder confidence in technical monitoring tools, sixty to seventy percent of European Union soils remain classified as unhealthy, revealing what the authors term a governance-science gap: research and policy communities diverge sharply in their priorities, with non-governmental stakeholders emphasizing practical action and funding while researchers emphasize theoretical gaps in climate and biodiversity science (Ferraro *et al.*, 2026). This finding is significant because it reframes the central soil-health knowledge gap as being less about insufficient data generation and more about a technical-institutional mismatch-an absence of governance frameworks, economic incentives, and educational structures capable of translating existing soil science into effective on-farm stewardship.

Water Management and Precision Irrigation in Water-Scarce Regions

Water scarcity intersects with climate-smart management most directly through irrigation scheduling and precision water conservation. Reviews of precision agriculture and water conservation strategies in arid regions report that remote sensing, soil moisture sensing, and variable-rate irrigation technologies can substantially improve water-use efficiency, but also emphasize that evidence for these technologies originates disproportionately from well-resourced commercial farming contexts rather than the smallholder and rainfed systems where water stress is often most acute (Xing and Wang, 2024). Because affordable, field-validated soil moisture sensors remain limited in accuracy and coverage, as noted in the preceding section, precision irrigation recommendations frequently rest on data infrastructure that is not yet accessible to the farmers who would benefit most from improved water-use efficiency (Schwamback *et al.*, 2023). This mismatch between where water-management innovation is validated and where water stress is most severe constitutes a persistent equity gap within the climate-smart water literature.

Climate Adaptation Evidence: Scope, Scale, and Attribution

Broader scoping reviews of agricultural adaptation to climate change highlight considerable heterogeneity in how adaptation is defined, measured, and attributed across studies, complicating efforts to synthesize what works across regions and farming systems (Grigorieva *et al*., 2023). Reviews of climate-smart agriculture more specifically note recurring tension between practices promoted for their climate benefits and the empirical strength of evidence supporting those benefits, with many climate-smart interventions carrying stronger evidence for productivity or adaptation outcomes than for the mitigation outcomes used to justify their inclusion in the climate-smart label (Kabato *et al*., 2025; Zhao *et al*., 2023). A systematic review of climate-smart agriculture adoption barriers in West Africa similarly found that while benefits such as improved yield stability and reduced input dependency are frequently documented, evidence for the financial, informational, and institutional barriers that prevent farmers from realizing those benefits is considerably thinner and less consistently measured across studies (Agyekum *et al*., 2024).

Integrating Soil, Water, and Carbon Objectives

A further gap concerns the integration of soil, water, and carbon objectives within a single evaluative framework rather than as separately optimized outcomes. Reviews of legume-inclusive cropping systems in Europe document substantial ecosystem-service potential-including nitrogen fixation, soil structure improvement, and reduced input dependency-but note that much of the underlying research quantifies these services individually rather than assessing trade-offs and synergies across soil, water, and biodiversity outcomes simultaneously (Ditzler *et al*., 2021). Similarly, broad reviews of regenerative agriculture argue that its core practices are conceptually positioned to deliver joint soil-health, water-retention, and biodiversity benefits, yet acknowledge that few empirical studies measure all three outcome domains concurrently within the same experimental design, leaving the magnitude of claimed co-benefits only partially substantiated (Sher *et al*., 2024). This absence of integrated, multi-outcome measurement is a recurring methodological constraint that reappears across nearly every subsystem examined in this review.

Biodiversity, Ecosystem Services, and Landscape-Scale Gaps

The third thematic block concerns the ecological dimension of agricultural transitions: biodiversity conservation, ecosystem-service provision, and the landscape-scale processes that link individual farm decisions to regional environmental outcomes. This literature has expanded rapidly since 2022, coinciding with the adoption of the post-2020 Global Biodiversity Framework, yet recent umbrella reviews reveal that this expansion has not resolved-and may have compounded-long-standing structural biases in what is studied, where, and how.

Geographic, Taxonomic, and Metric Biases in Biodiversity Research

An umbrella review of biodiversity research in agricultural landscapes found systematic geographic, taxonomic, and metric gaps that collectively limit the evidence base available for conservation decision-making: research disproportionately concentrates in temperate, high-income regions and on a narrow set of well-studied taxa such as birds, pollinating insects, and vascular plants, while soil biodiversity, tropical smallholder landscapes, and less charismatic taxonomic groups remain comparatively neglected (Bonfanti *et al*., 2025). The review further noted that biodiversity outcomes are measured using inconsistent metrics across studies, ranging from simple species richness counts to more complex functional diversity indices, which impedes cross-study synthesis and undermines the evidence-based conservation planning that agricultural policy increasingly demands. These findings mirror concerns raised in reviews of applied ecology's role in food production, which argue that biodiversity conservation and food-production objectives have too often been treated as competing rather than complementary goals precisely because the metrics used to evaluate each are rarely integrated within the same study design (Rader *et al*., 2024).

Landscape Complexity and Ecosystem Service Trade-offs

Landscape-scale research on the relationship between agricultural landscape complexity and ecosystem-service delivery has grown substantially in recent years, particularly in the context of smallholder agroecosystems. A review focused on smallholder systems in China found that landscape complexity generally enhances pollination and natural pest-control services, but cautioned that most underlying evidence derives from a narrow set of crop types and pest taxa, and that the socioeconomic drivers of landscape simplification-such as farmland consolidation policy-are rarely analyzed jointly with their ecological consequences within the same study (Zou *et al*., 2024). This disconnect between the socioeconomic drivers of landscape change and the ecological outcomes those drivers produce represents a structural gap that limits the ability of landscape ecology to inform land-consolidation and agrarian-reform policy, which is often designed without reference to ecosystem-service considerations at all.

Agroforestry, Carbon, and Multifunctional Land Use

Agroforestry occupies a distinctive position within the biodiversity and ecosystem-service literature because it is simultaneously promoted as a climate-mitigation strategy, a biodiversity-conservation intervention, and a smallholder

income-diversification tool. A systematic review synthesizing evidence on agroforestry as a climate-smart economic strategy across Africa, Asia, and Latin America confirmed meaningful carbon-sequestration potential and biophysical adaptation benefits, including microclimate moderation and erosion reduction, but found that adoption remains constrained by economic barriers, insecure land tenure, information asymmetries, and insufficient policy support, and that outcomes vary considerably depending on system type and local ecological context (Li, 2026). This variability underscores a broader gap in the multifunctional land-use literature: the same practice can simultaneously deliver strong ecological outcomes and weak adoption outcomes, and reviews rarely explain this divergence within a single integrated causal framework.

Multidimensional Impacts of Agroecological Transitions

Reviews assessing the multidimensional impacts of agroecological practices-spanning production, environmental, and social outcomes simultaneously-remain comparatively rare relative to single-outcome studies. A review of agroecological practices in Southeast Asia found generally positive effects on biodiversity and soil quality indicators, but noted that social and economic outcomes, including labor requirements, gender-differentiated impacts, and market access, were measured in only a minority of the studies reviewed, despite being central to the agroecological paradigm's own stated objectives (Blundo-Canto *et al.*, 2025). This imbalance, whereby ecological outcomes are measured far more frequently and rigorously than the social outcomes that agroecology explicitly claims to prioritize, constitutes one of the clearest illustrations within the reviewed literature of the broader yield-versus-resilience tension that motivates this review, and it reinforces the case made elsewhere in this synthesis that landscape-scale ecological gains cannot be assumed to translate automatically into equitable social outcomes without deliberate, integrated measurement design.

Economic, Adoption, and Policy Controversies and Limitations

The fourth thematic block turns to the economic, behavioral, and policy dimensions that ultimately determine whether biophysically sound practices are ever implemented at scale. This literature is characterized less by outright contradiction than by an uneven and sometimes optimistic evidentiary base whose limitations are frequently acknowledged by the reviews themselves, yet insufficiently addressed in subsequent primary research.

The Adoption Paradox: Knowledge, Finance, and Behavior

A substantial body of adoption research documents the benefits of climate-smart and precision-agriculture practices, yet reviews increasingly caution that documented benefits and documented barriers are asymmetrically evidenced. A systematic review of climate-smart agriculture adoption in West Africa identified financial constraints, limited extension access, and land-tenure insecurity as dominant barriers, but observed that intervention studies rarely test which combination of these barriers, if relieved, would most efficiently unlock adoption, leaving policymakers with a barrier inventory rather than a prioritized

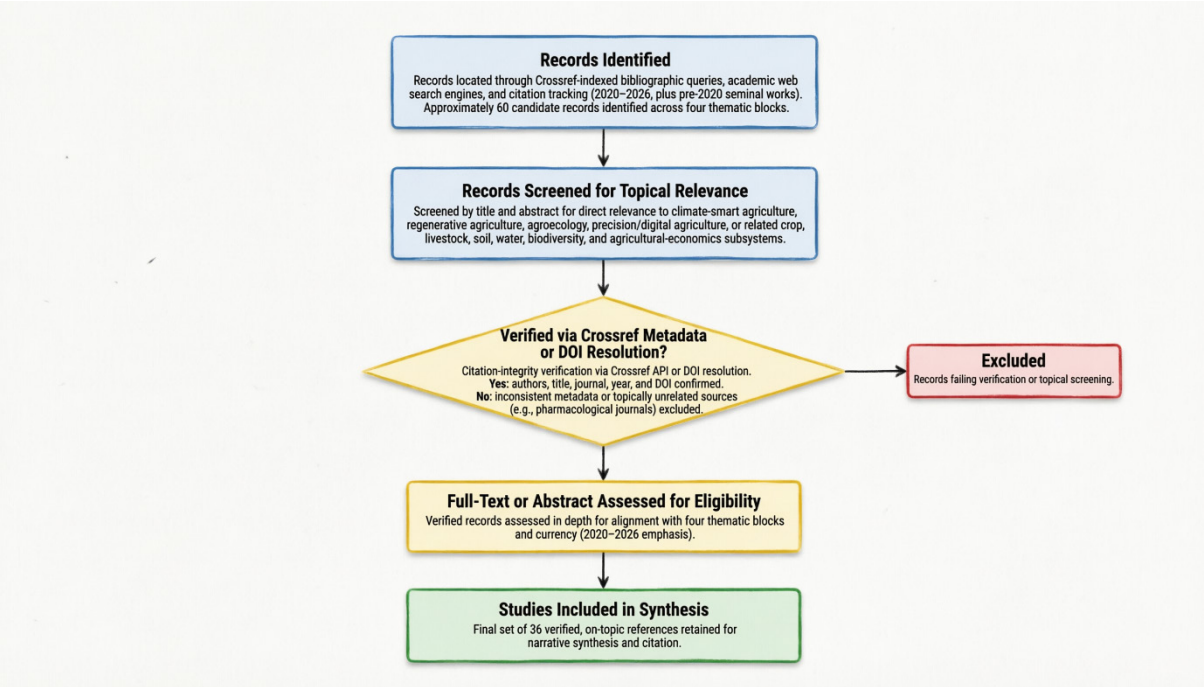


Figure 1: Literature Identification and Screening Process.

Table 1: Summary of Key Included Studies Across the Four Thematic Blocks.

Author(s), Year	Type	Scope / Region	Thematic Block	Key Finding	Identified Gap
Mabhaudhi *et al.*, 2023	Scoping review	Global South (sub-Saharan Africa, Asia)	Crop-livestock	Integrated crop-livestock research concentrates on farm-level production and soil productivity outcomes	Landscape-level and social outcomes rarely assessed; North Africa and Caribbean under-represented
Kotobiodjo *et al.*, 2024	Systematic/ bibliometric review	West, East, and Southern Africa; Asia; South America	Crop-livestock	Policy orientation, extension systems, and social networks drive ICLFS adoption	Weak cross-regional collaboration; herd-mobility issues under-studied
Bernabucci *et al.*, 2025	Narrative review	Extensive/pastoral livestock systems (global)	Livestock/precision	Precision livestock farming tools were designed mainly for confinement systems	Limited adaptation of sensing technology to extensive and pastoral grazing systems
Brugler *et al.*, 2023	Perspective/review	United States (commercial agriculture)	Precision/digital	Financial cost, algorithmic distrust, and data-ownership concerns limit DSS adoption	Workforce training and end-user co-design of decision-support systems lacking
Schwamback *et al.*, 2023	Empirical/ comparative study	Brazil (field and lab testing)	Precision/digital	Low-cost soil moisture sensors trade accuracy for affordability relative to commercial sensors	Field-validated, affordable sensing for smallholder-scale irrigation remains limited
Ferraro *et al.*, 2026	Stakeholder survey	European Union	Soil/water/climate	60-70% of EU soils remain unhealthy despite strong technical monitoring capacity	Governance-science gap; ecosystem services poorly integrated into soil policy
Xing and Wang, 2024	Narrative review	Arid and semi-arid regions (global)	Soil/water/climate	Precision irrigation and remote sensing improve water-use efficiency	Evidence concentrated in commercial contexts; smallholder rainfed systems under-studied
Agyekum *et al.*, 2024	Systematic review	West Africa	Soil/water/climate; economics	CSA adoption yields documented productivity and resilience benefits	Barrier evidence (finance, extension, tenure) not prioritized or causally tested
Bonfanti *et al.*, 2025	Umbrella review	Global (bias toward temperate, high-income regions)	Biodiversity/ ecosystem services	Geographic, taxonomic, and metric gaps limit evidence-based conservation	Soil biodiversity and tropical smallholder landscapes under-represented

Author(s), Year	Type	Scope / Region	Thematic Block	Key Finding	Identified Gap
Zou *et al.*, 2024	Narrative review	China (smallholder agroecosystems)	Biodiversity/ ecosystem services	Landscape complexity enhances pollination and pest-control services	Socioeconomic drivers of landscape change rarely linked to ecological outcomes
Li, 2026	Systematic review (218 studies)	Africa, Asia, Latin America	Biodiversity/ ecosystem services	Agroforestry sequesters 0.5-5 Mg C/ha/yr with adaptation co-benefits	Adoption constrained by tenure insecurity, information gaps, and weak policy support
Saran *et al.*, 2024	Systematic review (Campbell)	Low- and middle-income countries	Economics/ adoption/policy	Farmer field schools improve CSA knowledge and adoption among women farmers	Evidence base small; high risk of bias in 5 of 8 included impact evaluations
Moramarco *et al.*, 2025	Scoping review (PRISMA)	Global (predominantly high-income)	Economics/ adoption/policy	Food-policy evaluation is dominated by qualitative case-study methods	Standardized quantitative evaluation frameworks are underdeveloped
Sean *et al.*, 2026	Critical scoping review	Global	Economics/ adoption/policy	Agroecological transition frameworks vary widely in scope and indicators	No consensus definition of transition "success"; cross-study comparison difficult

Note. CSA = climate-smart agriculture; DSS = decision-support system; ICLFS = integrated crop-livestock-forestry system. Studies are ordered by thematic block as discussed in the text rather than alphabetically. Full citations appear in the reference list.

action agenda (Agyekum *et al.*, 2024). This concern is amplified by a rigorous systematic review of interventions promoting climate-smart agriculture adoption among women farmers in low- and middle-income countries, which screened over nineteen thousand studies yet located only eight impact evaluations meeting inclusion criteria, five of which carried a high risk of bias; the review found that knowledge-dissemination approaches such as farmer field schools improved knowledge and adoption of specific practices, but found no measurable effect on the disadoption of harmful practices such as pesticide overuse, and concluded that the evidence base for climate-smart agriculture interventions targeting women farmers remains too thin to support confident policy generalization (Saran *et al.*, 2024). This finding stands in some tension with more optimistic framings in broader climate-smart agriculture reviews, which tend to report adoption benefits without equally systematic attention to the quality and risk of bias of the underlying primary studies (Kabato *et al.*, 2025).

Gender and Differentiated Access

Gendered patterns of access and benefit distribution constitute a second area of contested evidence. Farm-level analysis of Agri-environment-climate scheme participation in Slovenia found that women farmers engaged in and received subsidies for environmentally sustainable practices at rates comparable to men, despite a persistent gender gap in land, capital, and other productive-resource endowments that would typically be expected to depress adoption-a result the authors interpret cautiously as evidence that targeted policy design can partially offset structural gender disadvantage, while also acknowledging that findings from a single, relatively high-income European context may not generalize to smallholder settings with more severe resource constraints (Fertő and Bojnec, 2024). This regional and income-context specificity is a recurring limitation across the gender and adoption literature more broadly, and it complicates efforts to draw universal conclusions about whether digital and climate-smart interventions narrow or widen gender gaps in agricultural benefit-sharing.

Policy Evaluation: Methodological Immaturity

At the policy level, reviewers increasingly note that the tools available for evaluating agricultural sustainability policy are themselves underdeveloped relative to the ambition of the policies being evaluated. A scoping review of food-policy evaluation methods found a strong predominance of qualitative case-study approaches and a comparative scarcity of robust quantitative or standardized indicator-based evaluation frameworks, concluding that food and agricultural policy

assessment lacks the methodological maturity needed to support rigorous, comparable evidence-based policymaking across jurisdictions (Moramarco *et al*., 2025). This concern is echoed in a critical scoping review of agroecological transition assessment frameworks, which found considerable conceptual and methodological heterogeneity in how "successful" transition is defined and measured across studies, ranging from narrow agronomic indicators to broad multidimensional sustainability indices, such that comparing transition outcomes across studies, regions, or funding programs remains methodologically fraught (Sean *et al*., 2026). The contribution of smallholder farmers to food security similarly illustrates this evaluative fragmentation: a systematic review focused on smallholder food-security contributions in sub-Saharan Africa found that financial access, information access, and farm size were the dominant constraints on climate-smart agriculture uptake, yet the review's own recommendations-policy intervention, knowledge dissemination, and capacity building-remain generic prescriptions not yet mapped onto rigorously tested, context-specific intervention designs (Kapari *et al*., 2023). Collectively, this section suggests that the economic and policy evidence base, while extensive in volume, is not yet commensurate with the confidence with which climate-smart, regenerative, and agroecological practices are promoted in policy and donor discourse (Tables 1 and 2).

Literature Search and Screening Flowchart

The following text-based legend describes a PRISMA-informed flowchart summarizing the identification, screening, and inclusion of sources used in this narrative review. Because this review followed a structured but non-systematic search strategy rather than a registered systematic-review protocol, the flowchart is presented as a descriptive legend rather than a formally reported PRISMA diagram (Figures 1-3).

CURRENT CHALLENGES AND FUTURE DIRECTIONS

Several structural challenges cut across all four thematic blocks examined in this review and merit explicit attention from funders and research consortia seeking to close the identified gaps. The first is the persistence of single-outcome study designs. Biophysical trials continue to measure yield, soil carbon, or biodiversity indicators in relative isolation from economic and social outcomes, while adoption and policy studies rarely verify the ecological claims underlying the practices whose uptake they

Table 2: Comparative Analysis of Knowledge Gaps Across the Four Thematic Blocks.

Thematic Block	Dominant Gap Type	Methodological Maturity	Geographic Bias	Outcome Emphasis
1. Crop, livestock, precision/digital agriculture	Scalability and interoperability (smallholder vs. commercial hardware and data systems)	Moderate-high for sensing technology; low for integrated decision-support validation	Commercial/ high-mechanization regions; extensive/ pastoral systems under-represented	Yield and technical performance emphasized over farmer usability and equity
2. Soil, water, climate-smart management	Science-to-governance translation; smallholder access to precision water tools	High for biophysical measurement; low for governance/implementation research	European Union and arid commercial-irrigation regions dominate	Biophysical indicators emphasized over institutional and behavioral outcomes
3. Biodiversity, ecosystem services, landscape	Geographic, taxonomic, and metric inconsistency; weak social-outcome integration	Moderate for single-taxon ecological studies; low for multidimensional landscape synthesis	Temperate, high-income regions and charismatic taxa over-represented	Ecological outcomes emphasized over social and economic co-benefits
4. Economics, adoption, and policy	Weak causal and long-term evidence; heterogeneous transition-success metrics	Low-moderate; high risk of bias common in intervention evaluations	Evidence skewed toward specific LMIC donor-program contexts and select EU cases	Adoption rates emphasized over disadoption, equity, and policy-outcome verification

Note. LMIC = Low- and Middle-Income Countries. Methodological maturity and geographic bias ratings reflect a qualitative synthesis of the reviewed sources rather than a formal bibliometric count. This table is intended to highlight cross-block asymmetries in evidence quality and coverage rather than to rank thematic blocks by scientific rigor.

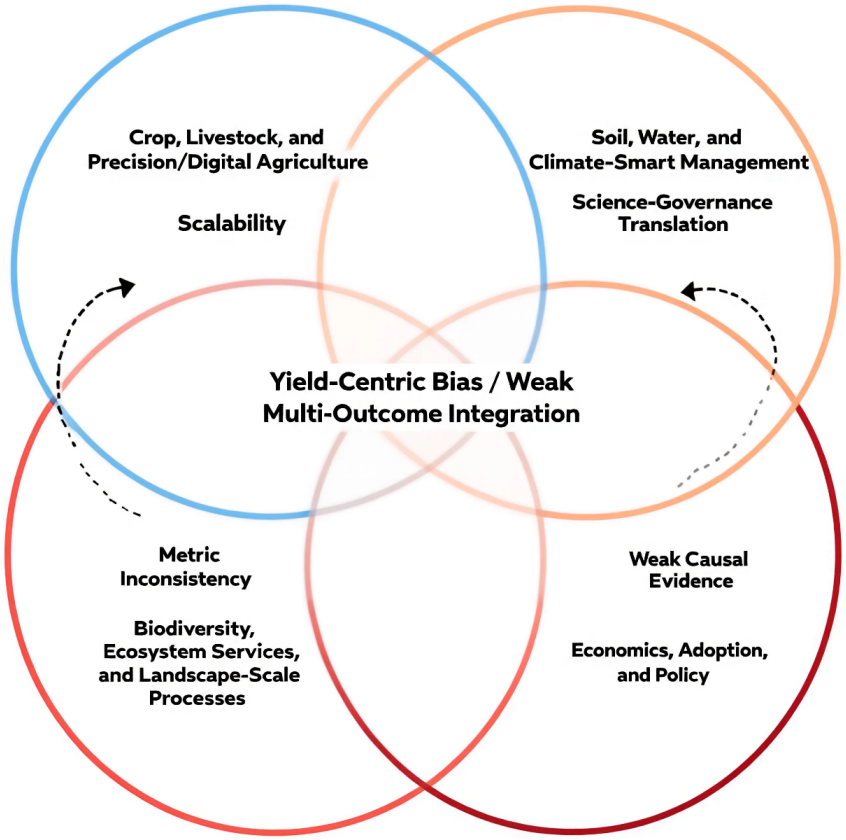


Figure 2: Conceptual Diagram of the Four Knowledge-Gap Domains and Their Interactions.

measure (Ditzler *et al*., 2021; Saran *et al*.; Sher *et al*., 2024). Future research architectures should prioritize multi-outcome study designs that measure biophysical, economic, and social indicators concurrently within the same experimental or observational framework, even where this requires interdisciplinary teams spanning agronomy, ecology, and social science.

A second challenge is geographic and taxonomic imbalance. Evidence concentrates in temperate, high-income regions and a limited set of Global South case-study countries, while entire regions-North Africa, the Caribbean, Central Asia-and entire domains, such as soil biodiversity, remain comparatively under-researched (Bonfanti *et al*., 2025; Mabhaudhi *et al*., 2023). Addressing this imbalance will require deliberate funding allocation toward under-represented regions and taxa, as well as stronger South-South and South-North research collaboration mechanisms of the kind explicitly recommended in the crop-livestock integration literature (Kotobiodjo *et al*., 2024).

A third challenge concerns the maturity of digital and precision-agriculture infrastructure for smallholder contexts. Low-cost sensing hardware remains a cost-accuracy compromise rather than a validated solution, and the governance structures needed for trusted, interoperable agricultural data sharing are still in early design stages (Schwamback *et al*.; Šestak and Copot, 2023). Future work should prioritize field validation of low-cost sensors across diverse soil types and climates, alongside the development of open, farmer-governed data-sharing standards that address the ownership and trust concerns repeatedly identified as adoption barriers (Brugler *et al*., 2023).

A fourth challenge is the weak evidentiary foundation for adoption-oriented interventions, particularly those targeting historically marginalized groups such as women farmers. The finding that only eight rigorous impact evaluations of climate-smart agriculture interventions for women farmers exist globally, five of which carry high risk of bias, is a stark illustration of how far intervention research lags behind policy and donor enthusiasm for climate-smart programming (Saran *et al*., 2024). Expanding the number and methodological rigor of randomized and quasi-experimental evaluations, with explicit attention to disadoption as well as adoption outcomes, should be a priority for future research funding.

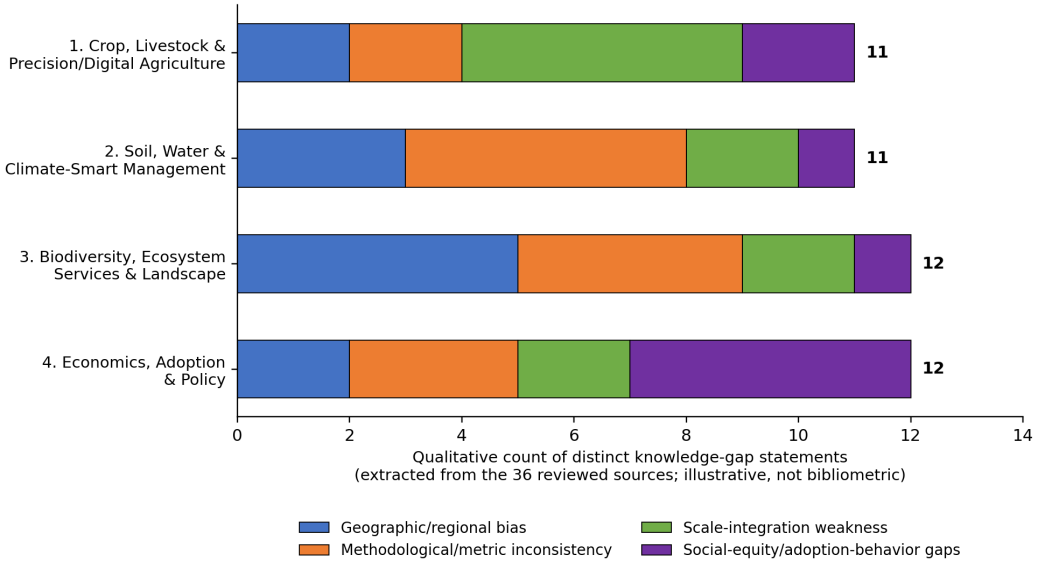


Figure 3: Frequency of Identified Gap Types by Thematic Block.

Finally, the absence of standardized, comparable metrics for evaluating agroecological and climate-smart transition "success" constitutes a foundational methodological challenge that undermines cross-study synthesis at every level examined in this review (Sean *et al.*, 2026). Emerging efforts to develop shared indicator frameworks, potentially building on the scoping-review methodologies already applied to food-policy evaluation, represent a promising direction, but will require sustained coordination across research communities, international organizations, and national governments to achieve the comparability that policymakers ultimately require (Moramarco *et al.*, 2025). Artificial intelligence and machine-learning tools, if developed transparently and validated across diverse agroecological contexts, may offer a partial technical pathway toward integrating multi-outcome data at the scale needed to close these gaps, but only if paired with the governance and equity safeguards this review has identified as currently lacking.

CONCLUSION

This review synthesized knowledge gaps identified across thirty-six verified, peer-reviewed sources spanning crop and livestock production, precision and digital agriculture, soil and water management, climate adaptation, biodiversity and ecosystem services, and agricultural economics and policy published predominantly between 2020 and 2026. Five cross-cutting gaps emerged consistently across all four thematic blocks: an enduring overemphasis on plot- and farm-level yield relative to ecosystem-service and social outcomes; weak integration of evidence across spatial scales, regions, and socioeconomic contexts; adoption barriers rooted in finance, extension, tenure, and gender that intervention research addresses unevenly; immature digital and precision-agriculture infrastructure, particularly for smallholder and pastoral contexts; and underdeveloped, non-standardized frameworks for evaluating transition success at landscape and policy scales.

These findings carry direct practical implications. For research funders, they suggest that continued investment in single-discipline, single-outcome studies will yield diminishing returns relative to investment in integrated, multi-outcome, multi-region research consortia explicitly designed to test biophysical, economic, and social outcomes jointly. For extension services and development practitioners, they suggest caution against over-generalizing climate-smart and regenerative agriculture's benefits from a comparatively thin and geographically concentrated evidence base, particularly where interventions target historically marginalized groups. For policymakers, they underscore the urgency of developing standardized, comparable evaluation metrics before further scaling climate-smart, regenerative, and agroecological programming, so that policy commitments can be matched with equally rigorous evidence of their delivery.

The path from yield-centric production toward genuinely resilient crop-livestock, economic, and natural-resource systems will not be completed through incremental, siloed research alone. It will require sustained cross-system collaboration, deliberate attention to geographic and social equity in where and with whom research is conducted, and a shared commitment among researchers, funders, and policymakers to measure resilience as the multidimensional outcome it is claimed to be, rather than as a proxy for yield stability alone. Closing the knowledge gaps identified in this review represents both a scientific and an ethical imperative for the next phase of climate-smart, regenerative, and agroecological transitions.

ABBREVIATIONS

AI: Artificial Intelligence; **CSA:** Climate-Smart Agriculture; **DSS:** Decision-Support System; **EU:** European Union; **FAO:** Food and Agriculture Organization; **GHG:** Greenhouse Gas; **ICLFS:** Integrated Crop-Livestock-Forestry System; **LMIC:** Low- and Middle-Income Countries; **ML:** Machine Learning; **PRISMA:** Preferred Reporting Items for Systematic Reviews and Meta-Analyses; **RA:** Regenerative Agriculture; **SDGs:** Sustainable Development Goals.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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