Multi-Scale Assessment of Climate-Smart Agriculture Interventions: A Systematic Review of Evidence, Frameworks, and Research Gaps

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ABSTRACT
Background: Climate-smart agriculture (CSA) is a leading approach to reconcile some of the most pressing concerns of today, namely enhancing agricultural production, improving resilience to unpredictable climate changes, and curbing the GHG emissions from food systems. While CSA combines different scales of approaches — from agricultural fields, farms, and landscapes to public policies and institutions — most of the studies on CSA are focused on one of the scales (mainly on farm or field) and don't assess the impact of CSA measures across the scales.
Objective: The objective of this paper is to analyze existing research on multi-scale assessment of CSA intervention and compare different assessment frameworks of CSA across all the relevant scales.
Sources of literature: A reviewer has conducted a systematic review including a search in Scopus, Web of Science, PubMed, Google Scholar, AGRIS, and grey literature from the FAO, World Bank, IPCC, and CGIAR from 2012 to 2026.
Notable results: From the evidence investigated, it is visible that the use of CSA practices like conservation tillage, integrated soil-fertility management, agroforestry, water-efficient irrigation, and climate-smart advisory services leads to positive results in terms of productivity, adaptability, and mutual benefits, but the level of adoption is rather low and varies in different places due to various factors such as land tenure, access to credit, gender priorities, extension contact, and market access. Different methods and approaches for assessing institutions and landscapes have been created to analyze the trade-offs between productivity, egalitarianism, and ecosystem services. Nowadays, digital technologies (remote sensing, unmanned aerial vehicles, IoT, and AI) are widely employed in monitoring but differ in availability.
Research Gaps: Existing gaps include the insufficiency of longitudinal and multi-scale impact studies, ambiguity in definitions of terms, lack of cooperation between biophysical and socio-economic indicators, minimal focus on gender-sensitive and intersectional effects, and insufficient methods to harmonise benefits at farm level with trade-offs at landscape level.
Conclusion: To advance CSA science, it is necessary to implement harmonised monitoring, reporting, and verification systems that combine data on biophysical field conditions with indicators about household welfare and approach to governance in the landscape, which can be achieved through application of standardised indicators, extended monitoring periods, and equal distribution of climate financing for small farms.

Keywords: Climate-smart agriculture, multi-scale assessment, systematic review, adoption determinants, landscape governance, greenhouse gas mitigation, food security, digital agriculture

1. Introduction
Agriculture also occupies a central role in the climate crisis: it is among the most vulnerable sectors subject to climate change effects, while at the same time being one of the largest contributors to greenhouse gas (GHG) emissions causing climate change. Climate-smart agriculture (CSA) was defined by the Food and Agriculture Organization of the United Nations (FAO) as an integrated strategy for transforming agricultural practices and institutions necessary for food security under climate change, constructed around three pillars: raising agricultural output and profit sustainably, adapting to and learning to live with climate change, and mitigating GHG emissions to some extent [1]. The term gained prominence in the scientific literature later, where it turned from a collection of practices into a framework where certain technological, institutional and investment options are determined based on the local bio-physical and socio-economic situation [2].
The significance of CSA arises from its addressing a serious challenge on a large scale. Agrifood systems are responsible for around a third of the global greenhouse gas emissions from human activity; however, they receive a very small portion of the world's climate financing (2). This financing is often not directed to small producers who are responsible for producing the food consumed around the world (2). At the same time, climate scenario projections show more warming and more extreme climate events occurring in the tropics and subtropics [3]—regions where people only rely on rain-fed agriculture (3). Without a good adaptation strategy, agricultural output in vulnerable regions may decrease dramatically by 2050 [4].
An important but insufficiently studied characteristic of Climate-Smart Agriculture (CSA) is the multiplicity of scales present in this phenomenon. The implementation of CSA encompasses activities that are conducted at different levels of intervention

process, such as the level of the field (e.g. conservation tillage, management of crop residues), the farm, where CSA is encompassed under the term of conserving agriculture practices (e.g. crop-livestock integration, income diversification), and at the level of policy (e.g. climate finance instruments, technology extensions, carbon markets). Some of the actions that may appear positive and beneficial at one level may not translate benefits to another scale: the increase of production on the individual level does not necessarily lead to an increase in biodiversity at the landscape level or the improvement of the institutional policy on paper does not guarantee its implementation at the farm level due to many barriers to adoption (6,7). Nonetheless, empirical research in the field of CSA remains mostly confined to a small scale of the farm. At the same time, the studies that examine CSA from the perspective of the landscape or policy scale are highly scarce (7,8).

The present global situation presents both the possibilities and the shortcomings of CSA as a concept. International organizations, such as the World Bank, FAO, and the Global Alliance for Climate-Smart Agriculture, have strongly advocated for CSA investment programs across Africa, Asia, and Latin America (3,9). The concept of CSA has already become a frequent reference point in Nationally Determined Contributions and national adaptation strategies. At the same time, independent systematic reviews indicate that the use of CSA practices by smallholder farmers is low and distributed differently in geographic regions, with the rates of implementation varying from below 20% to more than 70% depending on the practice, region, and gender of farmers (8,10,11). In addition, critics argue that in its implementation, CSA has prioritized narratives on productivity and mitigation instead of proving it pays attention to equity principles, voices of smallholder farmers, and cost-benefit distribution (10).

In light of the impressive pace of programmatic expansions against a backdrop of ongoing adoption gaps and unresolved scale-related dilemmas, there arises an evident need for a synthesis review that integrates evidence collected at different spatial and institutional scales instead of treating the literatures on field CSA, farm CSA, landscape CSA, and policy-related CSA research as separate bodies. The objectives of this review are to (i) synthesis of literature and institutional evidence regarding the outcomes of assessments of CSA interventions done at field, farm/household and policy/institutional levels; (ii) comparing the assessment frameworks and indicators used at all levels, discussing their strength and limitations; (iii) assessing the drivers and obstacles of CSA adoption and effectiveness at different levels; (iv) identifying emerging digital and data-based technologies that provide assistance in multi-scale monitoring of CSA; and (v) spotting research and methodological gaps in understanding the effectiveness of CSA comprehensively and from multiple levels of analysis. The review is international in scope but is more based on data obtained from sub-Saharan Africa and South Asia because the literature on the empirics of CSA is concentrated in these areas. It involves crop, livestock, and mixed systems with a specific reference to gender differences, digital agriculture, agriculture related soil carbon and greenhouse gas emissions.

2. Methodology of Literature Review

2.1 Literature search strategy

A structured, though not fully systematic in the Cochrane sense, literature search was conducted between March and June 2026 across Scopus, Web of Science, PubMed, Google Scholar, and the AGRIS database maintained by FAO. Grey literature was additionally retrieved from the websites of FAO, the World Bank, the IPCC, CGIAR (including the CGIAR Research Program on Climate Change, Agriculture and Food Security), and the Global Alliance for Climate-Smart Agriculture. Search strings combined the core term "climate-smart agriculture" with scale-related and thematic qualifiers, including "multi-scale," "landscape," "farm-level," "adoption," "greenhouse gas mitigation," "remote sensing," "precision agriculture," "smallholder," and "policy framework," using Boolean operators (AND/OR) and truncation. The search period was restricted to January 2012 to June 2026, capturing the period following the formal articulation of the CSA concept, with a small number of foundational works published before 2012 retained where they were repeatedly cited as landmark contributions by the retrieved literature. Full details of the search strategy are summarised in Table 1.

Table 1: Literature search strategy across databases, showing representative search strings and approximate numbers of records retrieved prior to de-duplication and screening.

Database/Source	Field searched	Representative search string	Records retrieved (approx.)
Scopus	Title-Abstract-Keywords	"climate-smart agriculture" AND ("multi-scale" OR "landscape" OR "adoption")	1,840
Web of Science	Topic	"climate-smart agriculture" AND ("assessment framework" OR "impact evaluation")	1,510
PubMed	Title/Abstract	"climate-smart agriculture" AND ("food security" OR "greenhouse gas")	260
Google Scholar	All fields (first 200 results screened)	"climate-smart agriculture" "multi-scale assessment"	600 (screened subset)
AGRIS / FAO, World Bank, IPCC, CGIAR	Institutional repositories	"climate-smart agriculture" sourcebook / impact assessment	95 grey-literature items

2.2 Inclusion and exclusion criteria

Studies were included if they (i) were published in English between January 2012 and June 2026; (ii) addressed climate-smart agriculture, or a closely related construct such as climate-resilient or sustainable intensification agriculture, at an explicit spatial or institutional scale (field, farm/household, landscape, or policy); (iii) were peer-reviewed journal articles, systematic reviews, meta-analyses, or authoritative institutional reports; and (iv) reported empirical findings, a conceptual/assessment framework, or a synthesis of primary studies relevant to CSA outcomes, adoption, or measurement. Studies were excluded if they (i) were duplicate records across databases; (ii) were non-academic, opinion pieces, or trade publications without a transparent methodology; (iii) addressed climate change adaptation in agriculture without any reference to CSA-type interventions or frameworks; or (iv) were conference abstracts without accompanying full text. These criteria are summarised in Table 2.

Table 2: Inclusion and exclusion criteria applied during study selection.

Inclusion criteria	Exclusion criteria
Peer-reviewed articles, systematic reviews, or institutional reports (FAO, World Bank, IPCC, CGIAR)	Duplicate records across databases
Published in English, January 2012 to June 2026	Non-academic or trade press sources without transparent methods
Explicit focus on CSA (or closely related constructs) at a defined scale	Studies on climate adaptation with no reference to CSA-type interventions or frameworks
Reports empirical findings, an assessment framework, or a synthesis of primary evidence	Conference abstracts lacking accessible full text
Full text available for data extraction	Studies focused solely on climate projections/modelling with no agricultural intervention component

2.3 Study selection process

Study selection followed a PRISMA-style, three-stage process. In the identification stage, the combined database and grey-literature searches yielded 4,305 records; after removing 612 duplicates, 3,693 unique records remained. In the screening stage, titles and abstracts were reviewed against the inclusion and exclusion criteria, excluding 3,102 records that did not address CSA at an identifiable scale or lacked empirical or conceptual substance, leaving 591 records for full-text assessment. In the eligibility stage, full texts were examined for methodological transparency, scale specification, and relevance to at least one of the review's five objectives; a further 487 records were excluded at this stage, most commonly for insufficient scale specificity or duplication of findings already captured by an included systematic review. This process yielded 104 records included in the qualitative synthesis underpinning this review, comprising systematic reviews and meta-analyses (n = 22), primary empirical studies (n = 46), conceptual/framework papers (n = 19), and institutional or grey-literature reports (n = 17). A subset of these, selected for their direct relevance and methodological detail, are cited and tabulated explicitly in this manuscript; the remainder informed the narrative synthesis without individual citation.

3. Literature Review and Thematic Analysis

The included literature clusters around five recurring themes: (i) field- and farm-scale practices and their productivity, resilience, and mitigation outcomes; (ii) landscape-scale frameworks and cross-scale trade-offs; (iii) determinants and barriers to adoption; (iv) digital and remote-sensing tools for cross-scale monitoring; and (v) soil carbon, GHG mitigation, and climate finance at the policy/institutional scale. Each theme is examined below with attention to convergence, contradiction, and methodological quality across studies.

3.1 Field- and farm-scale CSA practices: productivity, resilience, and quality outcomes

At the field and farm scale, the most extensively studied CSA practices are conservation agriculture (minimum tillage, residue retention, crop rotation), integrated soil fertility management, drought-tolerant and early-maturing crop varieties, water harvesting and small-scale irrigation, agroforestry, and integrated pest management. A large systematic review of 50 peer-reviewed studies on smallholder maize systems in sub-Saharan Africa (2003 to 2023) found that conservation agriculture improved water-use efficiency by 18 to 38 percent and reduced erosion by 45 to 60 percent, while drought-tolerant varieties produced 83 to 137 percent higher yields than conventional varieties under severe moisture stress (12). Complementary evidence from Zambia indicates that combining multiple CSA practices, rather than adopting a single practice in isolation, produced roughly 33 percent higher yields during below-average rainfall seasons, suggesting that synergistic practice bundles outperform stand-alone interventions (13).

Soil fertility management, particularly the integration of organic and inorganic fertilisation with legume intercropping, has been repeatedly associated with yield gains of 25 to 60 percent alongside improvements in soil organic matter, with especially strong effects documented in the East African highlands (12). A widely cited meta-analysis of 94 studies on woody-legume intercropping in maize systems found yield increases of 1.3 to 1.6 tonnes per hectare together with improved soil fertility and system resilience (12), illustrating how agroforestry-based practices can simultaneously advance the productivity and resilience pillars of CSA. Diversified cropping systems, including maize-legume intercropping, have also been shown to reduce the probability of complete crop failure by around 30 percent and to lower income variability during extreme weather events by up to 45 percent relative to mono-cropping (12).

A systematic review focused specifically on small-scale farms across diverse global contexts similarly concluded that the effectiveness of CSA practices is highly case- and site-specific, reflecting the heterogeneity of small-scale farming systems, and cautioned that the length of the payback period is a decisive factor in farmers' willingness to adopt any given practice, given that small-scale agriculture is characterised by high production risk and thin margins (14). This heterogeneity is a recurring theme across the field-scale literature: while aggregate statistics point to consistent average benefits, the magnitude, and even the direction, of effects varies substantially with agro-ecological zone, crop type, and farm resource endowment, meaning that field-scale results from one setting cannot be assumed to generalise to another without local validation (14,15).

3.2 Landscape-scale frameworks and cross-scale trade-offs

A smaller but conceptually important body of literature has extended CSA thinking beyond the individual field or farm to the landscape scale. A landmark contribution reframed CSA as "climate-smart landscapes," arguing that three features characterise a climate-smart landscape: climate-smart practices operating at the field and farm scale, diversity of land use across the landscape to confer resilience, and deliberate management of land-use interactions at the landscape scale to secure social, economic, and ecological outcomes (5). Achieving these features, the authors argue, requires institutional mechanisms that are largely absent from farm-level CSA programming, including multi-stakeholder planning platforms, supportive landscape governance and resource-tenure arrangements, spatially targeted investment, and monitoring systems capable of tracking whether social and climate goals are being met simultaneously across scales (5).

This landscape perspective exposes trade-offs that remain invisible in farm-level studies. For instance, a review of assessment tools for the three CSA pillars, drawing on data from 800 farm households in Ethiopia, found that most existing CSA assessment frameworks (including several major sustainable-intensification tools) capture biophysical productivity metrics well but are considerably weaker at capturing the socio-economic and equity dimensions of CSA at farm and community level, and rarely link farm-level indicators to landscape-level ecosystem-service outcomes (6). The authors further note that a synthesis of studies on agricultural intensification generally found that intensification is "rarely found to lead to simultaneous positive ecosystem-service and well-being outcomes," particularly once ecosystem services beyond food provisioning are considered (6), a finding that directly challenges an implicit assumption in much farm-scale CSA research that productivity gains are unambiguously positive at broader scales.

A separate strand of the literature has developed generic frameworks for targeting, out-scaling, and prioritising CSA interventions across recommendation domains, explicitly treating CSA planning as a multi-stakeholder, multi-scale, and multi-objective decision process. Applying such a framework to livestock systems in sub-Saharan Africa, researchers demonstrated an iterative sequence of diagnosis, characterisation of intervention options, identification of recommendation domains and out-scaling potential, and ex-ante assessment of impacts across different groups of stakeholders, arguing that this staged approach helps reconcile the heterogeneous, and sometimes conflicting, impacts of CSA interventions across spatial and social scales (7). This targeting logic is echoed in FAO's own guidance for CSA investment appraisal, which recommends combining household-level socio-economic surveys, economy-wide models, biophysical or structural models, and scientific trial data within a single investment-assessment exercise rather than relying on any single data source (9).

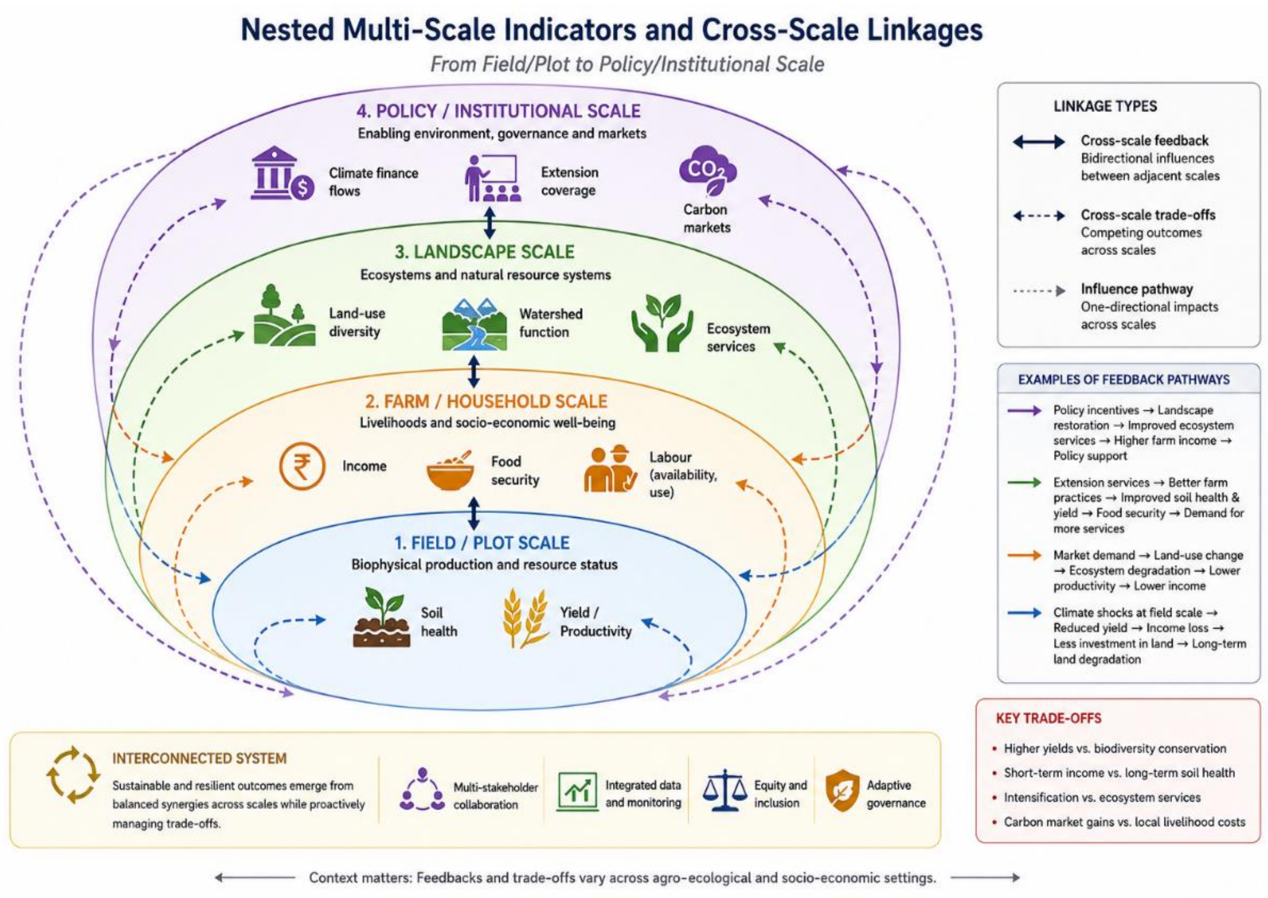

Fig 1: Conceptual framework linking field, farm, landscape, and policy scales of climate-smart agriculture assessment

3.3 Determinants and barriers to CSA adoption across scales

A substantial share of the reviewed literature is devoted to identifying the determinants of, and barriers to, CSA adoption at farm and household level, an area now mature enough to support several systematic reviews. A systematic review synthesising more than 40 factors influencing CSA adoption among African farmers grouped these into personal, farm-related, financial, environmental, and informational categories, and noted that the same factor (for example, farm size or off-farm income) could exert a positive, negative, or mixed effect on adoption depending on the specific CSA practice and context under study (10). The same review highlighted normative critiques of the CSA framework itself, noting that some scholars argue CSA has insufficiently addressed social and equity concerns, describing this as a failure to respect a "do no significant harm" principle, and raising concerns that CSA framing has sometimes been used to favour agro-industrial expansion at the expense of smallholder voice (10).

A large-scale systematic review of 190 studies published between 2013 and 2023 organised CSA adoption determinants into four categories: socio-demographic factors (age, gender, education), institutional factors (social groups, credit access, crop insurance, land tenure), resource-endowment factors (labour, machinery, land size), and socio-economic factors (income and wealth) (11). This review found that most individual-level factors exert a dual, context-dependent effect on adoption, whereas institutional variables, including secure land tenure, access to extension services, agricultural training, membership of farmer organisations, and non-governmental organisation support, consistently and positively predict adoption across studies, suggesting that institutional strengthening may be a more reliable adoption lever than attempts to alter individual farmer characteristics (11).

Regional systematic reviews reinforce and refine these findings. A review of climate-smart maize systems in sub-Saharan Africa (50 studies, 2003 to 2023) found pronounced regional variation in adoption, with rates of 56.7 percent in Eastern Africa compared with 38.9 percent in Western Africa, and documented that access to extension services increased the likelihood of successful adoption by a factor of 2.8, while secure land tenure improved long-term investment in CSA practices by around 60 percent (12). The same review identified a marked gender gap, with female farmers exhibiting adoption rates of 40 to 55 percent compared with 55 to 70 percent among male farmers, a gap attributed principally to differential resource access, including secure land tenure (only 15 percent of women farmers compared with 45 percent of men), rather than to differences in underlying willingness to adopt (12). A systematic review focused specifically on West Africa similarly found that limited user-friendliness of practices, high labour and input costs, weak extension services, and constrained access to credit were the most frequently reported barriers, while access to credit, secure tenure, and market linkages were the most consistently reported enablers (15). A further systematic review addressing CSA adoption and food security outcomes across sub-Saharan Africa concluded that while an extensive literature documents CSA practices in the region, evidence directly linking adoption to measured household food-security outcomes remains comparatively limited, constituting an evidence gap distinct from the adoption-determinants literature itself (16).

Two theoretical frameworks recur across these adoption studies: Diffusion of Innovations Theory, which frames adoption as a staged process of knowledge acquisition, persuasion, decision, implementation, and confirmation, and the Sustainable Livelihoods Framework, which explains adoption through farmers' differential access to human, social, natural, physical, and financial capital (12). While these frameworks provide useful organising structures, their application across the reviewed studies is largely retrospective and correlational; few studies test the frameworks' predictive validity prospectively, and fewer still connect individual-level adoption theory to the landscape- or institutional-scale frameworks discussed in section 3.2, representing a conceptual disconnect that section 5 of this review returns to.

3.4 Digital and remote-sensing tools for cross-scale monitoring

A rapidly growing literature addresses the role of digital technologies, remote sensing, and artificial intelligence (AI) in enabling CSA planning and monitoring across scales. Geospatial technologies, including Geographic Information Systems, remote sensing, and Global Navigation Satellite Systems, have been reviewed as tools for climate risk assessment, crop modelling, and precision agriculture in South Asia, with the authors emphasising that spatial data infrastructures and volunteered geographic information can help bridge farm-level data collection with landscape- and national-scale planning (17). Complementary reviews of smart sensors and the Internet of Things (IoT) in precision agriculture describe how networks of soil-moisture, temperature, and nutrient sensors, combined with cloud-based farm-management systems and AI-driven analytics, can support real-time, field-level decision-making while aggregating into landscape-level datasets useful for planners (18,19).

Reviews integrating unmanned aerial vehicles (UAVs), satellite remote sensing, and machine learning describe a shift from localised, discrete-parameter monitoring toward integrated ecosystem management driven by continuous data streams, reporting, for example, that multi-source remote-sensing recommendation algorithms have achieved measurable improvements in adaptive resource-allocation accuracy in controlled evaluations (20). Complementary evidence indicates that combining IoT sensing with machine-learning-based irrigation scheduling has achieved high simulation accuracy for yield prediction alongside meaningful reductions in irrigation costs in reported case studies (20). Reviews of AI and remote sensing applied specifically to CSA further emphasise applications in pest and disease detection, yield forecasting, and precision-input management, arguing that these tools can reduce input waste while improving both productivity and mitigation outcomes simultaneously (21).

Despite this technological promise, the digital-agriculture literature consistently flags an access and equity concern that echoes the adoption barriers identified in section 3.3: the same resource-poor, tenure-insecure smallholders who face the greatest barriers to conventional CSA practice adoption are also the least likely to have access to smartphones, connectivity, digital literacy, or the capital required to invest in sensor or drone-based systems (17,19). This suggests a risk that digital CSA tools could, if deployed without deliberate equity safeguards, widen rather than narrow the adoption gaps documented at the farm scale, an issue rarely addressed explicitly within the technical remote-sensing and precision-agriculture literature itself.

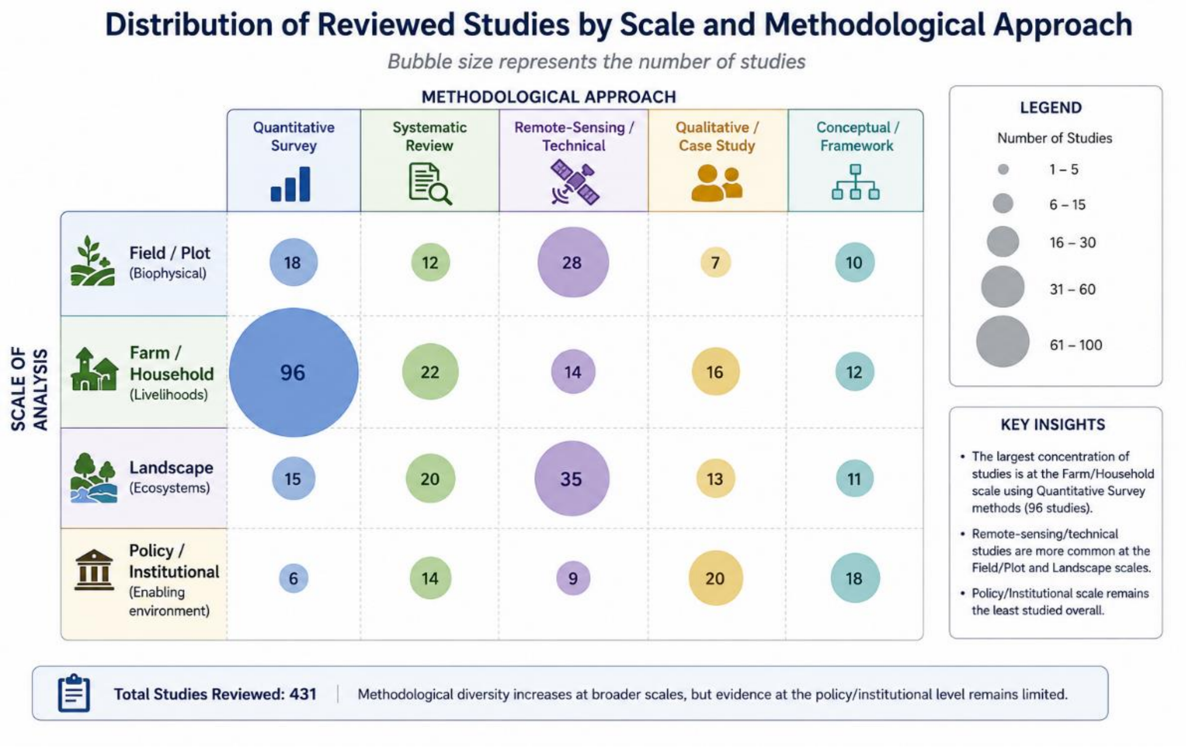

Fig 2: Thematic classification of the reviewed studies by CSA assessment scale and methodological approach

3.5 Soil carbon, GHG mitigation, and climate finance at the policy/institutional scale

At the policy and institutional scale, a substantial literature addresses soil carbon sequestration as a natural climate solution and the policy architecture required to operationalise it. A review of agricultural soil carbon sequestration organised the central scientific and policy debates around six recurring concepts, permanence, additionality, leakage, measurement uncertainty, transaction costs, and the differential heat-trapping ability of greenhouse gases, arguing that robust measurement, reporting, and verification (MRV) systems addressing all six are prerequisites for credible carbon-credit schemes in agriculture (22). Complementary work reviewing United States federal soil-carbon policy identifies similar structural challenges, including the difficulty of quantifying soil carbon changes at scale, ensuring that practice adoption is genuinely additional rather than business-as-usual, and preventing increases in non-carbon-dioxide GHG emissions, such as nitrous oxide, from offsetting soil carbon gains (23).

A recent review highlights that soil health indicators remain the "missing metric" in much CSA monitoring, noting that although agricultural soils constitute the largest terrestrial carbon reservoir after the oceans and underpin more than 95 percent of global food production, systematic soil-monitoring infrastructure capable of supporting performance-based climate finance remains weak in most developing-country contexts (24). This gap has direct policy consequences: the World Bank has reported that although agrifood systems are responsible for roughly one-third of global GHG emissions, they receive only about 4 percent of global climate finance, with just a fifth of that finance reaching smallholder producers directly (3), a mismatch that several reviewed sources attribute in part to the absence of credible, scalable MRV systems linking farm-level practice change to verifiable emissions outcomes (22,24).

Taken together, the policy-scale literature suggests that the effectiveness of CSA as a global mitigation strategy is currently constrained less by a shortage of viable field-level practices, several of which show robust productivity, resilience, and carbon co-benefits, than by the absence of institutional and financial architecture capable of verifying those practices at scale and channelling finance to the smallholders who would need to adopt them. This is consistent with the cross-scale disconnect identified throughout this review: strong field- and farm-scale evidence, weaker landscape-scale integration, and an under-resourced policy and finance layer.

4. Comparative Analysis of Previous Studies

Table 3 summarises a purposive set of key studies retrieved during the review, selected to represent the range of scales, geographies, and methodologies encountered in the wider literature set. Table 4 extends this comparison by contrasting methodological approaches and the principal limitations reported by the studies themselves or identified by subsequent reviewers.

Table 3: Comparative summary of selected studies included in the review, by author(s), year, study location/scope, assessment scale, methodology, sample size, and major findings. Numbers in parentheses refer to the reference list.

Author(s), Year	Study location / scope	Scale	Methodology	Sample size	Major findings
Scherr *et al.*, 2012 (5)	Global (conceptual)	Landscape	Conceptual synthesis	N/A	Defined "climate-smart landscapes"; identified institutional mechanisms (multi-stakeholder planning, governance, tenure) needed to sustain CSA across scales
Notenbaert *et al.*, 2017 (7)	Sub-Saharan Africa (livestock)	Landscape/policy	Framework application, case examples	2 case studies	Generic targeting framework for prioritising CSA interventions; iterative diagnosis-to-impact process applicable across scales
van Wijk *et al.*, 2020 (6)	Ethiopia	Farm/landscape	Framework review + household survey data	800 households	Existing CSA assessment tools capture biophysical productivity well but weakly capture socio-economic and ecosystem-service dimensions
Mizik, 2021 (14)	Global (small-scale farms)	Field/farm	Systematic literature review	30 articles	CSA outcomes highly case- and site-specific; payback period is decisive for adoption on small farms
Silva *et al.*, 2024 (10)	Africa	Farm/household	Systematic review	Not stated (multi-study synthesis)	40+ adoption factors identified across personal, farm, financial, environmental, informational categories; equity critiques of CSA noted
Agyekum *et al.*, 2024 (15)	West Africa	Farm/household	Systematic review	Multi-study synthesis	User-unfriendliness, high costs, and weak extension are key barriers; credit and market access are key enablers
Li, Ma & Zhu, 2024 (11)	Global	Farm/household	Systematic literature review	190 studies (2013–2023)	Institutional variables (tenure, extension, training, NGO support) consistently positive predictors of adoption across contexts
Mnukwa, Mdoda & Mudhara, 2025 (12)	Sub-Saharan Africa (maize)	Farm/household	Systematic review, MMAT quality appraisal	50 studies (2003–2023)	Regional adoption variation (38.9–56.7%); extension access raises adoption 2.8×; secure tenure raises investment 60%; marked gender gap
Yiridomoh & Derbile, 2025 (16)	Sub-Saharan Africa	Farm/household	Systematic review	Multi-study synthesis	Extensive CSA-practice literature but limited direct evidence linking adoption to measured food-security outcomes
Sykes *et al.*, 2020 (22, cf. 23)	Global (policy synthesis)	Policy/institutional	Multidisciplinary review	N/A	Identified permanence, additionality, leakage, uncertainty, transaction costs, and GHG heat-trapping differentials as core soil-carbon policy challenges

Table 4: Comparative analysis of methodological clusters within the reviewed literature, showing predominant methods, typical scale of analysis, and commonly reported limitations.

Study cluster	Predominant methodology	Typical scale addressed	Common limitations reported
Field/farm agronomic trials and reviews (e.g., 12,13,14)	Quantitative surveys, on-farm trials, systematic review	Field, farm	Cross-sectional designs (approx. 75% of studies); short observation windows (2–3 seasons); inconsistent definition of "adoption"
Adoption-determinants reviews (e.g., 10,11,15,16)	Systematic review of correlational/econometric studies	Farm/household	Reliance on self-reported adoption data; limited triangulation; weak measurement of extension "quality" versus mere access
Landscape/targeting frameworks (e.g., 5,6,7)	Conceptual synthesis, framework application, case studies	Landscape, policy	Few frameworks are empirically validated across multiple landscapes; limited quantitative linkage to farm-level indicators
Digital/remote-sensing and precision agriculture (e.g., 17,18,19,20,21)	Technical review, engineering case studies	Field, farm (with landscape potential)	Limited testing in smallholder, resource-constrained contexts; equity and access implications rarely analysed
Soil carbon / GHG policy studies (e.g., 22,23,24)	Policy and scientific synthesis	Policy/institutional	MRV systems remain immature; limited empirical data on real-world programme performance versus modelled potential

5. Research Gaps and Emerging Trends

Synthesising across the thematic sections above, five categories of unresolved issues recur across the reviewed literature. First, there is a scarcity of longitudinal, multi-scale impact studies: the large majority of farm-level adoption studies are cross-sectional, and even the most rigorous systematic reviews note that long-term impact studies extending beyond two to three growing seasons remain rare

(12,16), making it difficult to distinguish transient from durable CSA outcomes or to assess landscape-level cumulative effects. Second, the operational definition of "adoption" and "climate-smartness" varies considerably across studies, with some researchers treating minimal, single-season implementation as adoption while others require sustained multi-season practice, a definitional inconsistency that complicates cross-study comparison and meta-analysis (11,25). Third, there is weak integration between biophysical and socio-economic indicators: most CSA assessment frameworks were originally designed to capture either productivity/biophysical outcomes or socio-economic outcomes, but rarely both in a unified, farm-to-landscape indicator architecture (6), leaving trade-off analysis (for example, between yield gains and biodiversity or water outcomes) largely absent from the empirical literature. Fourth, gender-differentiated and intersectional analysis remains underdeveloped relative to its demonstrated importance: although gender gaps in adoption are consistently documented (12), few studies examine how gender interacts with age, ethnicity, land-tenure status, or household structure to shape differential access to CSA benefits, and fewer still evaluate whether gender-targeted interventions durably close these gaps rather than producing short-term improvements. Fifth, and most centrally for the purposes of this review, there is a persistent methodological gap in reconciling farm-level benefits with landscape-level trade-offs: very few studies in the reviewed set attempt to model or empirically trace how aggregated farm-level CSA adoption decisions translate into landscape-scale outcomes for water availability, biodiversity, or downstream communities, despite the conceptual recognition that such trade-offs exist (5,6).

Table 5: Research gaps identified across the reviewed literature, with illustrative supporting sources.

Research gap	Description	Illustrative supporting sources
Longitudinal, multi-scale impact evidence	Predominance of cross-sectional, single- to few-season studies; limited multi-year or multi-scale panel data	12, 16
Inconsistent operationalisation of "adoption" and "climate-smartness"	Minimal versus sustained implementation used interchangeably across studies, complicating comparison	11, 25
Weak biophysical–socio-economic indicator integration	Assessment tools capture productivity or welfare outcomes, rarely both in a unified framework	6
Underdeveloped gender and intersectional analysis	Gender gaps documented, but interaction with tenure, age, and household structure rarely modelled	12, 15
Farm-to-landscape trade-off modelling	Conceptually recognised trade-offs (water, biodiversity, downstream effects) rarely empirically traced	5, 6, 7
Immature measurement, reporting, and verification (MRV) systems	Soil-carbon and GHG-mitigation claims constrained by weak, costly, or unstandardised MRV	22, 23, 24

Alongside these gaps, several emerging trends are reshaping the field. Digital and remote-sensing technologies, including UAV- and satellite-based phenomics integrated with genomic, transcriptomic, and metabolomic data (a "pixels-to-proteins" paradigm), are enabling higher-resolution, near-real-time monitoring of crop stress and management outcomes that could, in principle, support genuinely cross-scale MRV if linked coherently from field sensors to landscape-level platforms (26). Artificial intelligence and machine-learning applications are increasingly used for yield forecasting, pest and disease detection, and adaptive resource allocation, with reported gains in prediction accuracy and resource-use efficiency in technical trials (20,21), although as noted in section 3.4, equitable access to these tools among smallholders remains a substantial unresolved concern. Institutional innovations, including performance-based climate finance, blended public-private investment vehicles, and landscape-governance platforms, are emerging as candidate mechanisms for bridging the policy-scale finance gap documented by the World Bank (3), though empirical evaluation of their effectiveness remains nascent. Finally, a growing body of work is beginning to interrogate CSA's political-economy and equity dimensions more directly, rather than treating adoption purely as a technical or informational problem, reflecting a maturing critical literature that complements the earlier, more technocratic framing of CSA (10).

Table 6: Emerging trends in climate-smart agriculture research and practice, with illustrative supporting sources.

Emerging trend	Description	Illustrative supporting sources
Multi-scale remote-sensing phenomics integrated with multi-omics	Combining UAV/satellite phenotyping with genomic and metabolomic data to link field signals to molecular stress-response pathways	26
AI-driven precision agriculture and adaptive resource allocation	Machine-learning models for yield prediction, pest detection, and irrigation scheduling with reported efficiency gains	20, 21
Performance-based and blended climate finance	Emerging mechanisms to channel climate finance toward verified smallholder practice change	3, 24
Critical/political-economy scholarship on CSA equity	Growing scrutiny of whose interests CSA framing serves and how benefits are distributed across scales	10
Landscape governance platforms	Multi-stakeholder planning and tenure arrangements intended to operationalise climate-smart landscapes	5, 7

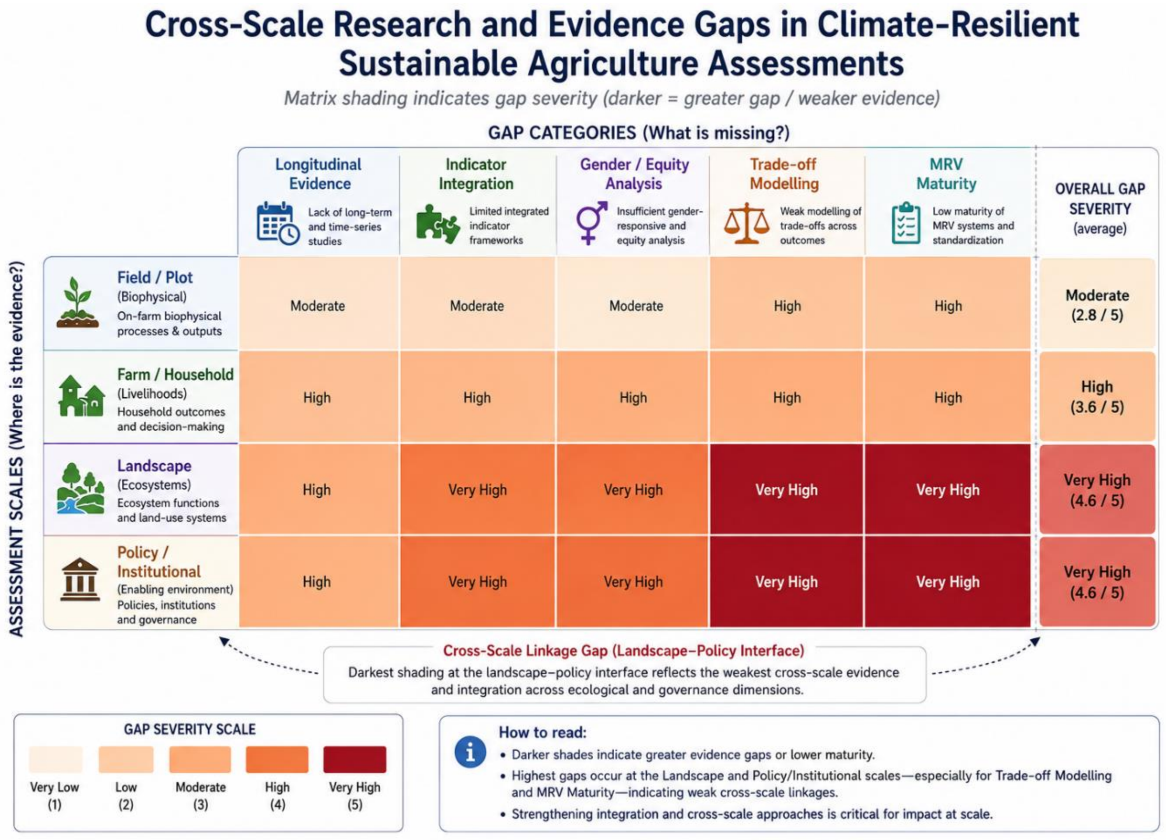

Fig 3: Research gap mapping across CSA assessment scales

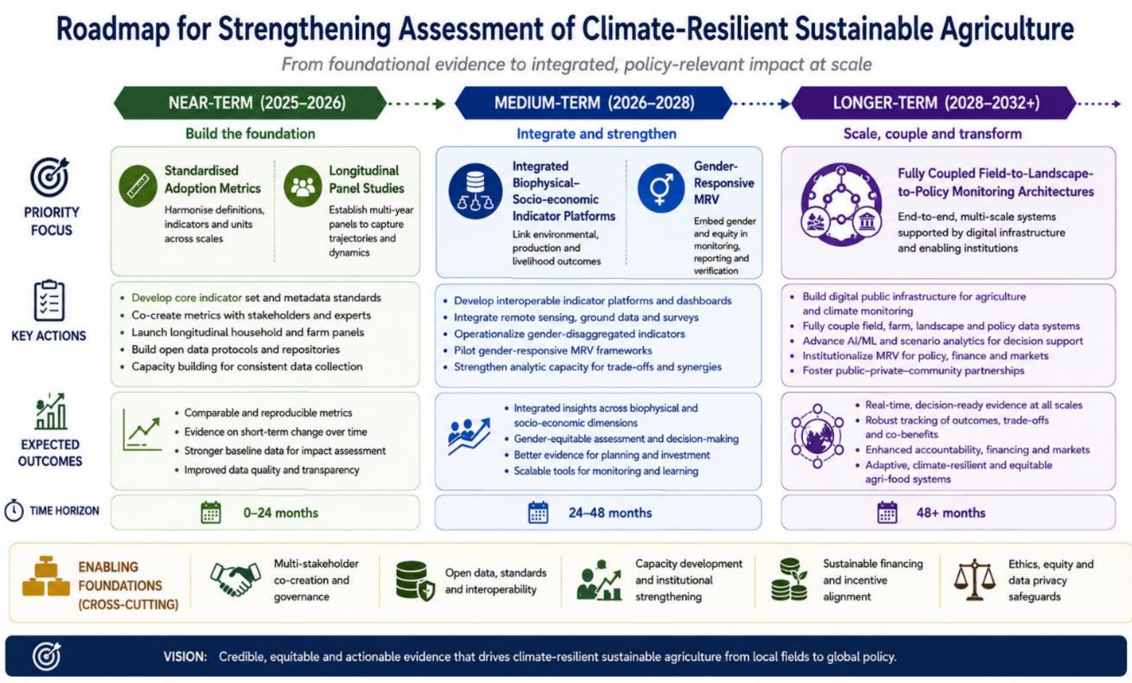

Fig 4: Priority future research directions for multi-scale CSA assessment

6. Discussion

The evidence synthesised in this review supports three integrated conclusions. First, the field- and farm-scale evidence base for CSA is comparatively mature and broadly consistent: across dozens of systematic reviews and hundreds of underlying primary studies, well-studied practices such as conservation agriculture, integrated soil fertility management, agroforestry, and drought-tolerant varieties show repeated, though heterogeneous, productivity, resilience, and, in some cases, carbon co-benefits (12,13,14). This consistency should not, however, be mistaken for uniformity: effect sizes vary substantially by agro-ecological zone, crop system, and socio-economic context, and the methodological reliance on cross-sectional, short-duration, self-reported data means that the durability of these benefits over longer time horizons is less well established than the volume of published studies might suggest (14,25).

Second, the landscape- and policy-scale evidence base is thinner, more conceptual, and less empirically validated than the farm-scale literature, yet it is precisely at these scales that some of the most consequential trade-offs, and the largest resource gaps, appear to reside. The observation that agricultural intensification is "rarely found" to generate simultaneous productivity and ecosystem-service benefits (6) directly complicates any straightforward extrapolation from favourable farm-level results to favourable landscape-level or societal outcomes. Similarly, the finding that agrifood systems receive a strikingly disproportionate share of global climate finance relative to their emissions footprint (3) suggests that the binding constraint on CSA's contribution to global climate goals may lie less in the availability of effective practices than in the financial and institutional architecture required to fund, verify, and scale them, an imbalance that is easy to overlook when the literature is read primarily through a farm-level, practice-adoption lens.

Third, the adoption-determinants literature and the digital-agriculture literature, when read together, point to a risk of a widening rather than narrowing implementation gap. The same structural constraints, insecure land tenure, limited credit access, weak extension coverage, and gender-based resource disparities, that have long been identified as barriers to conventional CSA practice adoption (10,11,12,15) also appear, on the evidence reviewed, to constrain access to the digital tools increasingly promoted as the next generation of CSA monitoring and decision-support infrastructure (17,19). Unless digital CSA investment is deliberately designed with equity safeguards, for example through shared community-level sensing infrastructure, subsidised access, or extension-mediated interpretation of digital outputs, there is a plausible risk that technological advancement in CSA monitoring could reinforce, rather than reduce, the very adoption disparities that the broader CSA agenda seeks to address.

These findings carry both theoretical and practical implications. Theoretically, they suggest that Diffusion of Innovations Theory and the Sustainable Livelihoods Framework, while useful for explaining individual farmer behaviour, are insufficient on their own to explain cross-scale CSA outcomes, since they do not incorporate landscape governance or climate-finance architecture as explanatory variables; a more integrated theoretical account would need to combine household-level behavioural theory with institutional and political-economy perspectives on landscape governance and climate finance. Practically, the findings imply that CSA programming would benefit from explicit multi-scale design from the outset, coupling farm-level extension and input-support programmes with landscape-level land-use planning and policy-level MRV and finance mechanisms, rather than treating these as sequential or separate programme components. This integrated framing is consistent with, and extends, recent developments in the field, including growing institutional interest in landscape-level climate finance instruments and the maturing critical scholarship on CSA equity (3,10).

7. Conclusion

This review provides evidence on climate-smart agriculture approaches examined at the field, farm, landscape, and legislative/institutional level. Studies show that the studied farming and agricultural practices provide good productivity, resilience, and mitigation benefits, but the evidence base is relatively weak at the landscape and policy levels. The challenges to adopting these practices are mainly related to the lack of security of land tenure, limited access to credit and extension services, and gender-related resource discrepancies. The main point of this synthesis is revealing an inconsistency that often remains implicit in CSA literature: strong and tall accumulative evidence on the farm level coexists with weak cross-scale integration and under-funded architecture of policies and finances so that except for the farm-level outcomes, it is impossible to find out the aggregate landscape and global mitigation effect of CSA. In this review, researchers are recommended to pay more attention to longitudinal multi-scale studies following the same farms, landscapes, and policy environment within several years as well as to the need to develop identical definitions of CSA “adoption” and “climate smartness” so as to make any meta-analysis. The article suggests that making investments in measurement, reporting and verification systems to link farmers' practices to large-scale outcomes must be on the agenda of both those who implement these practices and policymakers. It also recommends designing investments in digital agriculture in such a way that inequality is not exacerbated; for example, trying to match climate finance distribution with the size of smallholder investments and respective GHG emissions generated by agriculture. A further refinement of independent studies which would combine biophysical, social and economic processes is also needed.

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