Carbon Sequestration Dynamics Under Long-Term Conservation Agriculture Practices: A Systematic Review of Mechanisms, Evidence, and Research Gaps

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ABSTRACT
Background: Conservation agriculture (CA), built on the principles of minimum mechanical soil disturbance, permanent soil organic cover, and diversified crop rotations, is widely promoted as a nature-based strategy to enhance soil organic carbon (SOC) stocks and mitigate agricultural greenhouse gas emissions. However, evidence on the magnitude, depth distribution, and permanence of SOC gains under long-term CA remains fragmented and, in places, contradictory.
Objective This review synthesizes peer-reviewed and institutional literature published between 2015 and 2025 to critically evaluate carbon sequestration dynamics under long-term CA, identify sources of disagreement among studies, and map research gaps.
Method A structured search of Scopus, Web of Science, PubMed, Google Scholar, and reports from the Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC) yielded 1,842 initial records, of which 84 studies met the inclusion criteria following a PRISMA-style screening process.
Result Long-term no-till and residue retention consistently raise SOC concentration in the upper 0-15 cm layer, with reported gains ranging from approximately 4% to over 20% relative to conventionally tilled soils, but effects diminish or disappear when sampling extends beyond 30 cm. Cover cropping increases SOC by roughly 7-15% at shallow depths, with global sequestration potential estimated near 0.12-0.4 Gt C per year. Combining no-till with cover crops, diversified rotations, and integrated crop-livestock systems produces the most consistent gains across agro-ecological zones, while SOC accrual typically follows a saturating curve rather than a linear trajectory. The soil carbon saturation concept, though contested, helps explain why gains plateau after 10-20 years in many systems.
Persistent gaps include shallow and inconsistent sampling depths, short experimental durations, divergent SOC accounting methods (fixed-depth versus equivalent-soil-mass), limited data from smallholder tropical systems, and weak integration of non-CO_2 greenhouse gas trade-offs.
Conclusion CA can deliver meaningful, though context-dependent and time-limited, soil carbon gains. Realizing its climate mitigation potential requires standardized deep-profile monitoring, longer networked trials, and digitally enabled measurement, reporting, and verification (MRV) systems tailored to diverse farming contexts.

Keywords: Conservation agriculture; soil organic carbon; carbon sequestration; no-till farming; cover crops; carbon saturation; climate change mitigation; soil carbon monitoring

1. Introduction
Agricultural soils constitute one of the largest manageable reservoirs of organic carbon in the terrestrial biosphere, holding more carbon than the atmosphere and above-ground vegetation combined when considered at global scale. Over the past two centuries, conversion of natural ecosystems to cropland and reliance on intensive, tillage-based production have depleted soil organic carbon (SOC) stocks by an estimated 30-75% relative to their pre-cultivation levels in many regions, contributing directly to atmospheric carbon dioxide accumulation and degrading soil structure, water-holding capacity, and biological fertility. Reversing this depletion through deliberate management is now recognized as a cost-effective, co-beneficial pathway for climate change mitigation that simultaneously supports food security and land productivity.
Conservation agriculture (CA) - defined by the Food and Agriculture Organization around three interlinked principles of minimum mechanical soil disturbance, permanent organic soil cover through crop residues or cover crops, and diversified crop rotations - has been promoted globally as an entry point for achieving this reversal. CA is currently practiced on several hundred million hectares worldwide, spanning smallholder systems in South Asia and sub-Saharan Africa to highly mechanized operations in the Americas and Australia. Its promotion has intensified alongside international climate commitments such as the "4 per 1000" initiative launched at COP21, which proposed that a modest annual increase in global soil carbon stocks could meaningfully offset anthropogenic emissions, and alongside the growth of voluntary carbon markets that increasingly monetize soil carbon gains as tradeable credits.

Despite this enthusiasm, the scientific literature on SOC responses to long-term CA is far from unanimous. Early reviews and long-term trials reported substantial SOC accrual under no-till and residue retention, reinforcing the narrative of agriculture as a climate solution. However, subsequent meta-analyses that sampled soil profiles beyond the conventional 30 cm plough layer found that apparent surface gains were frequently offset by losses or stagnation in deeper horizons, casting doubt on whether CA produces a genuine net sequestration effect or merely redistributes existing carbon within the soil profile. Parallel debates surround the existence and magnitude of a finite soil carbon "saturation" ceiling, the differential behavior of particulate versus mineral-associated organic carbon fractions, and the practical feasibility of monitoring, reporting, and verifying (MRV) soil carbon changes at the scale required for carbon markets and national climate reporting.

This fragmentation of evidence, combined with the policy urgency attached to soil carbon as a climate mitigation lever, creates a clear need for a critical, integrative review. Existing reviews tend either to focus narrowly on a single CA component (e.g., tillage alone, or cover crops alone) or to aggregate results without adequately interrogating methodological inconsistencies across studies, such as differences in sampling depth, soil mass correction, and experimental duration. The present review addresses this gap by synthesizing evidence specifically on long-term (generally greater than five years, with emphasis on trials exceeding ten to twenty years) CA practices, explicitly foregrounding methodological controversies rather than treating them as a footnote.

The specific objectives of this review are to: (i) synthesize quantitative evidence on SOC changes under long-term no-till, residue retention, cover cropping, crop rotation diversification, and integrated crop-livestock systems; (ii) critically compare findings across studies with attention to sampling depth, soil mass accounting, climate, and soil type as sources of heterogeneity; (iii) evaluate the conceptual and empirical basis of soil carbon saturation dynamics; (iv) identify research gaps and methodological limitations in the existing evidence base; and (v) outline emerging technological and policy developments relevant to monitoring and scaling CA-based carbon sequestration. The scope is global but draws particular attention to comparative evidence from temperate systems (North America, Europe), where the longest-running trials exist, and from South Asian and tropical/subtropical systems, where CA adoption is expanding most rapidly but the evidence base remains thinner.

2. Methodology of Literature Review

2.1. Literature Search Strategy

A structured, PRISMA-informed search was conducted across five databases: Scopus, Web of Science, PubMed, Google Scholar, and CAB Abstracts, supplemented by targeted retrieval of institutional reports from the FAO, IPCC, and the World Bank. The search covered the period January 2015 to mid-2025, with a small number of methodologically foundational studies from earlier years (e.g., the original conceptualization of soil carbon saturation, and early global tillage syntheses) retained where they remain central to ongoing debates. Boolean search strings combined terms such as ("conservation agriculture" OR "no-till" OR "reduced tillage" OR "cover crop*" OR "crop residue retention" OR "crop rotation diversification") AND ("soil organic carbon" OR "carbon sequestration" OR "SOC stock*" OR "carbon storage") AND ("long-term" OR "long term experiment*"). Reference lists of retrieved reviews and meta-analyses were hand-searched to capture additional primary studies (snowball sampling).

Table 1: Literature Search Strategy Employed in This Review

Search Element	Detail
Databases searched	Scopus, Web of Science, PubMed, Google Scholar, CAB Abstracts, FAO/IPCC repositories
Search period	2015-2025 (foundational studies before 2015 retained selectively)
Core keywords	conservation agriculture; no-till; reduced tillage; cover crops; residue retention; crop rotation; soil organic carbon; carbon sequestration; SOC stock; carbon saturation
Boolean operators	AND / OR combinations with truncation (*) for term variants
Supplementary methods	Manual reference-list (snowball) search; institutional report review (FAO, IPCC)

2.2 Inclusion and Exclusion Criteria

Table 2: Inclusion and Exclusion Criteria Applied During Screening

Criterion Type	Included	Excluded
Study type	Peer-reviewed original research, meta-analyses, systematic reviews	Non-peer-reviewed blogs, opinion pieces, unpublished theses
Language	English-language full text available	Non-English without English abstract/translation
Duration	Field studies with management duration ≥5 years (priority to ≥10 years)	Short-term (<5 year) or single-season studies
Subject relevance	SOC/carbon stock response to CA components (tillage, cover crops, rotation, residue, integrated systems)	Studies unrelated to agricultural SOC (e.g., pure forestry, non-agricultural land use)
Data availability	Quantitative SOC/SOC stock data or clearly reported effect sizes	Studies lacking extractable quantitative outcomes
Publication window	2015-2025 (with limited pre-2015 landmark studies)	Duplicate records; superseded preprints

2.3. Study Selection Process

The selection process followed a PRISMA-style four-stage workflow: identification, screening, eligibility assessment, and inclusion (Figure 1). The initial search across all databases identified 1,842 records. After removal of 448 duplicates, 1,394 unique records underwent title/abstract screening, from which 1,041 were excluded as thematically irrelevant (e.g., studies on urban soils, purely microbiological studies without carbon stock data, or non-agricultural land-use change). The remaining 353 full-text articles were assessed for eligibility against the criteria in Table 2; 269 were excluded at this stage, principally due to insufficient experimental duration (<5 years), absence of quantitative SOC stock data, or lack of a comparable control/baseline treatment. A final set of 84 studies, comprising primary field experiments, meta-analyses, and systematic reviews, was retained for thematic synthesis.

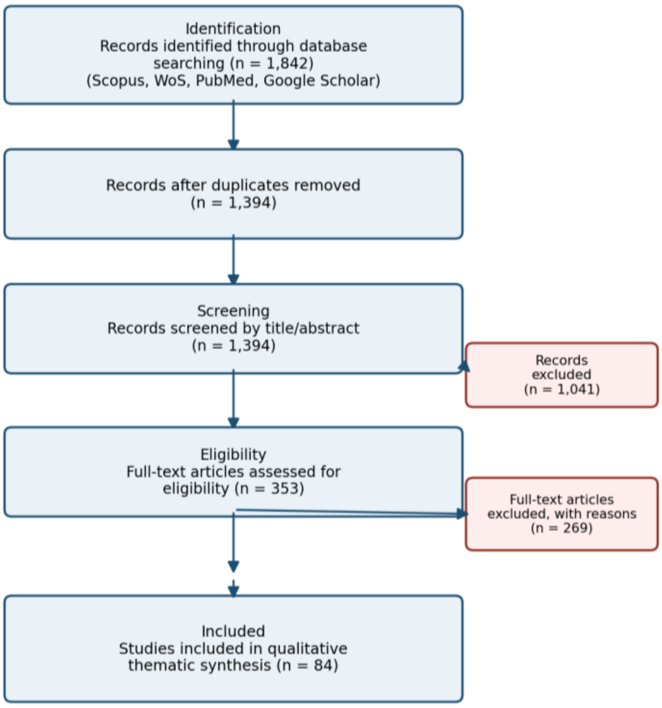

Fig 1: PRISMA Flow Diagram Illustrating the Identification, Screening, Eligibility, and Inclusion of Studies

The temporal distribution of the 84 included studies (Figure 2) shows a marked increase in publication output after 2019, coinciding with heightened international attention to nature-based climate solutions following the Paris Agreement and the proliferation of voluntary carbon markets, and a further acceleration after 2021 reflecting growing interest in soil carbon crediting mechanisms.

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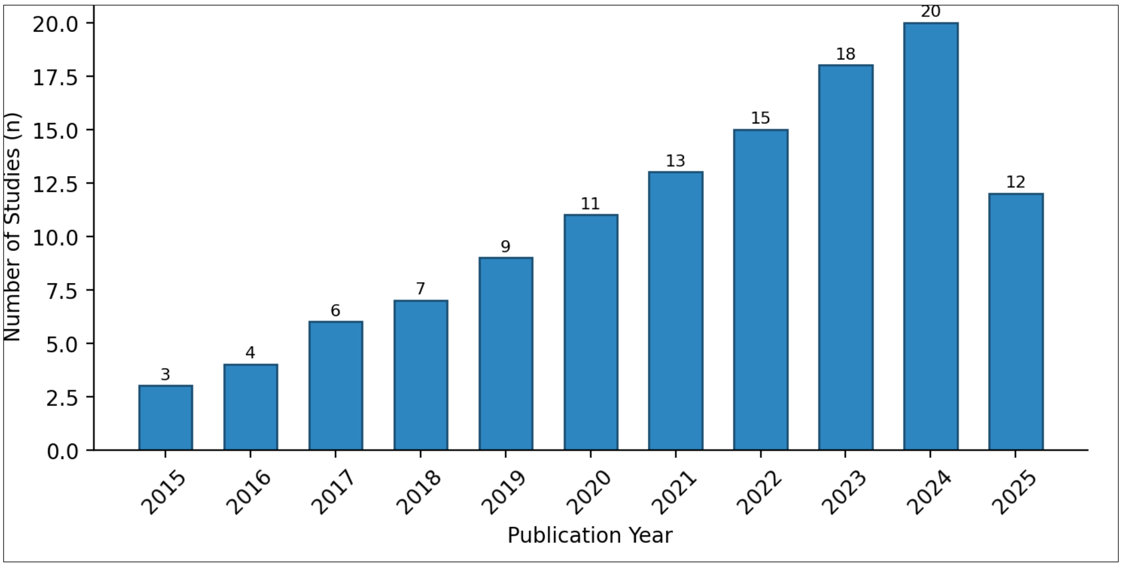

Fig: 2. Publication Trend by Year for Studies on Carbon Sequestration under Conservation Agriculture (2015-2025)

3. Literature Review and Thematic Analysis

The 84 included studies were classified into six thematic clusters (Figure 4): (i) tillage systems and the sampling-depth controversy; (ii) cover crops and residue management; (iii) crop rotation and diversification; (iv) integrated crop-livestock systems; (v) SOC saturation and stabilization mechanisms; and (vi) monitoring, reporting, and verification (MRV) technologies. A conceptual framework linking these themes is presented in Figure 3, illustrating how CA practices act on proximate mechanisms of carbon input and decomposition, which in turn determine SOC pool composition, are moderated by climate and soil context, and are ultimately constrained by saturation dynamics before translating into climate and policy outcomes.

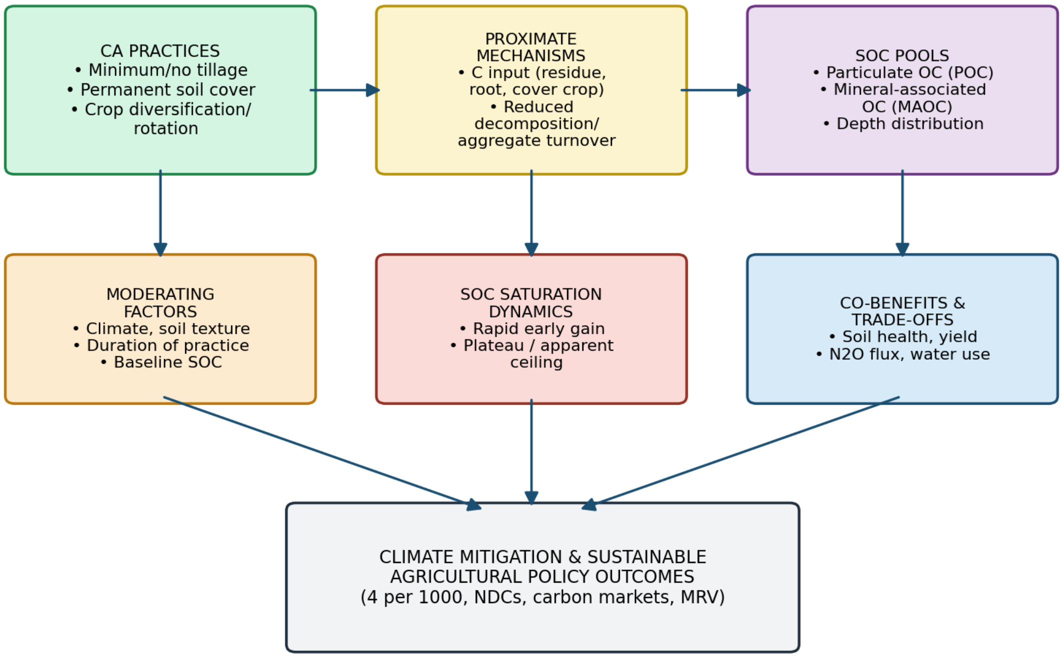

Fig 3: Conceptual Framework Linking Conservation Agriculture Practices to Soil Carbon Sequestration Outcomes

3.1. No-Till and Reduced Tillage: Consistent Surface Gains, Contested Deep-Profile Effects

The largest and most contested body of evidence concerns tillage. A global meta-analysis of 3,049 paired measurements from 417 peer-reviewed articles found that conservation tillage practices, including no-till, reduced tillage, and straw return, significantly increased SOC sequestration, with straw return alone raising SOC content by approximately 23.7%, and combined reduced-tillage/straw-return and no-till/straw-return treatments producing more modest gains of roughly 4-6%, while also reducing soil nitrous oxide (N2O) emissions. These authors identified climate (temperature, precipitation), soil pH, nitrogen content, and experiment duration as key moderators of both carbon gain and greenhouse gas trade-offs. A parallel and highly influential meta-analysis restricted to climate-smart agriculture practices (conservation tillage, cover crops, biochar) similarly reported meaningful average SOC increases, but explicitly cautioned that the magnitude and even the direction of effects diverged widely across the underlying primary studies, introducing substantial uncertainty into any aggregate estimate of the agricultural sector's climate mitigation potential. This divergence is central to understanding the field: rather than a single, well-constrained effect size, the literature describes a distribution of outcomes strongly conditioned by local pedoclimatic context.

The most consequential methodological controversy concerns sampling depth. Several influential syntheses found little or no difference in total SOC stocks between tilled and no-till soils once sampling extended below approximately 30 cm, suggesting that apparent no-till benefits reflected a redistribution of carbon toward the surface rather than a true net gain, with carbon losses in deeper layers potentially offsetting - or even exceeding - surface accrual. This concern was reinforced by field evidence showing that no-till practices concentrate SOC and particulate organic matter in the top few centimeters, at the expense of measurable declines at 5-17.5 cm depth. However, a more recent global meta-analysis explicitly designed to interrogate deep-profile dynamics reported that no-till soils stored significantly more SOC and total nitrogen than tilled soils even when integrated to 100 cm depth (an average gain of 6.7 ± 1.9 Mg C ha^{-1} after 16 years), contradicting the earlier consensus and indicating that net sequestration under no-till is contingent on its being combined with increased cropping intensity and diversified rotations rather than occurring as an automatic consequence of eliminating tillage alone.

Complementary long-term experimental work spanning 34-39 years in the United States Corn Belt similarly emphasized the necessity of deep sampling (60-100 cm) to avoid erroneous conclusions, reporting that a review of 78 published tillage comparisons found no-till stored more SOC than tilled systems in only 40 of 78 cases, was statistically indistinguishable in 31 cases, and stored less in 7 cases - a pattern interpreted by some authors as evidence that no-till's carbon sequestration potential has been overgeneralized relative to its well-established benefits for erosion control and input-cost reduction. Compounding the depth issue is a distinct accounting problem: because no-till commonly increases bulk density in surface soils, calculating SOC stocks on a fixed-depth (FD) basis rather than an equivalent-soil-mass (ESM) basis can produce spurious apparent stock increases even where carbon concentration has genuinely declined, a bias documented directly in long-term cropping systems trials.

Taken together, this body of evidence supports three conclusions with reasonable confidence: first, no-till reliably concentrates SOC in the uppermost 0-15 cm of soil; second, whether this constitutes genuine net sequestration versus mere redistribution depends critically on sampling to sufficient depth (ideally to the full rooting zone) and on correcting for bulk-density changes via equivalent-soil-mass methods; and third, net gains, where they occur, appear to require complementary intensification of cropping (higher-frequency rotations, reduced fallow) rather than tillage cessation in isolation.

3.2. Cover Crops and Residue Retention

Cover cropping has produced a comparatively more consistent evidence base than tillage alone. An early landmark meta-analysis of 37 sites and 139 plots found that SOC stock change under cover cropping followed a linear function of time since adoption, at an annual sequestration rate of approximately 0.32 Mg C ha^{-1} yr^{-1} in the upper 22 cm, with no evidence of saturation within the observed timeframe, and estimated global sequestration potential from expanded cover crop adoption at approximately 0.12 ± 0.03 Pg C yr^{-1}, equivalent to roughly 8% of direct annual agricultural greenhouse gas emissions.

More recent, larger meta-analyses corroborate the direction though not always the precise magnitude of this effect. A synthesis of 1,195 paired comparisons from 131 studies reported a 15.5% increase in near-surface (≤30 cm) SOC under cover cropping, while a meta-analysis focused specifically on maize production systems, drawing on 61 studies and 198 paired comparisons, found a 7.3% average SOC increase, with depth-resolved analysis indicating SOC accrual was distributed relatively evenly between the 0-15 cm and 15-30 cm layers rather than being confined to the immediate surface - a pattern that partially addresses the shallow-sampling critique leveled at tillage studies. These authors further estimated current cover-crop-driven SOC sequestration in United States maize systems at 5.5 million Mg annually, with global potential as high as 175 million Mg were adoption to expand substantially.

Evidence from India-focused syntheses situates cover crops and residue retention within a broader portfolio of regenerative practices. A meta-analysis of 147 peer-reviewed studies across Indian agro-ecological zones found that while biochar and organic amendments (farmyard manure, green manure, compost) produced the largest SOC gains, conservation tillage and residue retention delivered moderate but consistent benefits, with gains significant beyond five years of adoption and notably stronger in semi-arid and sub-humid regions than in humid tropical settings - underscoring those climatic and edaphic factors substantially condition the magnitude of response even for the same nominal practice.

3.3. Crop Rotation Diversification and Integrated Crop-Livestock Systems

Reviews centered on the intensively cultivated rice-wheat systems of the Indo-Gangetic Plains provide some of the most policy-relevant long-term evidence available, given the region's importance for both global food security and greenhouse gas accounting. A synthesis of long-term CA and crop-intensification trials in this system found that CA meaningfully stabilized organic carbon to greater soil depth than conventional practice, but that intensification with nutrient-exhaustive cropping sequences reduced carbon stabilization even under nominal CA management, and that inclusion of a legume phase within rice-wheat-legume rotations under CA produced the most favorable outcomes across yield, soil health, and carbon sequestration simultaneously. This finding is particularly important because it demonstrates that CA's three principles are not independently sufficient: reduced tillage without appropriate rotation design can fail to deliver, or can even undermine, carbon benefits.

Integrated crop-livestock systems (ICLS), which couple no-till cropping, cover crops, and managed grazing, represent an increasingly studied hybrid approach. A 15-year comparative study in the southern United States Midwest found ICLS SOC stocks significantly exceeded those of conventional continuous-crop systems and were comparable to permanent pasture and hardwood forest reference systems, concentrated predominantly in the upper 30 cm, with an estimated annual accrual rate of 1.3 Mg C ha^{-1} yr^{-1} - notably higher than typical cover-crop-only estimates - and stable-isotope evidence indicating the cover crop was the dominant carbon source. This suggests that combining multiple CA-aligned practices produces synergistic rather than merely additive carbon benefits, though the evidence base for ICLS remains considerably smaller than for tillage or cover crops in isolation.

3.4. Soil Carbon Saturation: Mechanisms and Controversy

A recurring pattern across long-duration studies is that SOC accrual under CA does not continue indefinitely but instead follows a saturating trajectory, with rapid gains in the first 5-10 years followed by a plateau, a pattern explicitly identified in the Indian regenerative-agriculture meta-analysis and consistent with the theoretical construct of soil carbon saturation first formalized around the turn of the century. Under this framework, mineral-associated organic carbon (MAOC) - the more persistent, chemically stabilized SOC fraction - is thought to be constrained by the finite surface area of fine soil particles (clay and silt), such that once this capacity is approached, further carbon inputs are preferentially retained in the more labile, decomposable particulate organic carbon (POC) pool rather than in stable, long-residence-time forms. Estimates of the upper MAOC limit have varied from roughly 47 g C kg^{-1} soil in some European analyses to a broader range of 78-86 g C kg^{-1} fine-fraction reported elsewhere.

This concept, however, is itself contested. Analyses of the German Agricultural Soil Inventory found no detectable upper limit to MAOC accumulation in temperate agricultural soils, proposing instead that organic matter can bind to other organic matter already associated with mineral surfaces in a layered, "skyscraper-like" fashion that is not capped by mineral surface area alone. In direct response, proponents of the saturation framework maintained that the original findings remained robust and were not attributable to methodological artifacts, while other recent work in Argentine mountain grasslands similarly failed to detect saturation behavior, and studies of repeated biochar application demonstrated that stabilization capacity ('ceilings') can themselves be incrementally raised by targeted amendments. A pan-European synthesis attempted to reconcile these positions by distinguishing a theoretical mineralogical maximum from a lower, more policy-relevant "effective" MAOC capacity shaped by pedoclimatic and management conditions, proposing this effective capacity as the basis for a practical SOC risk index.

For the purposes of long-term CA management, the practical implication of this unresolved debate is similar regardless of which theoretical position ultimately prevails: observed SOC accrual rates under CA reliably slow over time, meaning that early-stage sequestration rates from short trials should not be linearly extrapolated to estimate decadal or century-scale mitigation potential, and that continued carbon benefit likely requires sustained management rather than a one-time transition.

3.5. Monitoring, Reporting, and Verification: An Emerging Cross-Cutting Theme

A smaller but rapidly growing cluster of literature addresses how SOC changes under CA can be measured, reported, and verified at the scale required for national greenhouse gas inventories and carbon markets. Comparative analyses of accounting methods confirm that fixed-depth SOC accounting systematically overestimates stock changes under no-till relative to equivalent-soil-mass accounting, due to management-induced changes in bulk density, reinforcing that measurement protocol design is not a peripheral technical detail but a first-order determinant of reported outcomes. Reviews of digital MRV note that satellite remote sensing, proximal soil sensors, and machine-learning-based prediction can substantially reduce the cost of soil carbon monitoring - by an estimated 40% relative to conventional field sampling in one industry analysis - but remain constrained to shallow depths (commonly around 30 cm) and require continued ground-truthing, particularly in drylands and smallholder landscapes where the evidence base for remote calibration is thin. This creates a direct tension with the deep-sampling requirements highlighted in Section 3.1, since the depths most amenable to low-cost remote monitoring are precisely those where surface-redistribution artifacts are most likely to bias conclusions.

4. Comparative Analysis of Previous Studies

Table 3 summarizes representative studies selected to illustrate the range of methodologies, geographic contexts, and reported outcomes discussed above, while Table 4 draws out the comparative strengths and limitations of the principal study designs used across the reviewed literature.

5. Research Gaps and Emerging Trends

Synthesis of the reviewed literature points to six interlinked research gaps several of which are methodological rather than purely empirical in nature, meaning that further data collection alone will not resolve them without accompanying protocol standardization.

Emerging methodological and technological trends are, encouragingly, beginning to address several of these gaps Digital measurement, reporting, and verification (MRV) systems combining satellite remote sensing, proximal soil sensors, geotagged field data, and machine-learning prediction models are increasingly used to reduce the cost and labor burden of soil carbon monitoring, with industry analyses reporting cost reductions of roughly 40% relative to conventional field sampling and rapidly rising investment in this space. At the same time, the voluntary agricultural carbon credit market has undergone significant contraction and consolidation amid quality concerns, underscoring those technological innovation in MRV must be matched by rigorous, protocol-compliant verification (e.g., adherence to Verra or Gold Standard methodologies) if soil-carbon-based climate finance is to remain credible.

6. Discussion

The evidence synthesized in this review supports a more qualified conclusion than the frequently cited claim that conservation agriculture straightforwardly "sequesters carbon." Three integrated observations emerge. First, the magnitude and even the sign of SOC response to CA components is strongly conditioned by measurement design, particularly sampling depth and soil mass accounting; studies that sample shallowly and calculate stocks on a fixed-depth basis are systematically more likely to report favorable no-till effects than those employing deep, mass-corrected protocols. This is not merely a technical footnote but a central explanatory factor behind the apparent contradictions between older reviews (which found minimal or no net SOC gain under no-till beyond 30 cm) and more recent deep-profile meta-analyses (which found meaningful gains to 100 cm, contingent on cropping intensification). Reconciling these positions suggests that no-till's carbon benefit is real but conditional: it manifests most reliably when combined with reduced fallow, diversified rotations, and adequate residue or cover crop biomass input, rather than arising from reduced disturbance alone.

Second, the trajectory of SOC accrual under CA is better described as saturating than linear, a pattern evident across cover crop, tillage, and regenerative-agriculture syntheses alike, even though the precise mechanistic basis for this plateau - whether a genuine physicochemical mineral-surface limit on MAOC, an emergent but context-dependent "effective" capacity, or simply diminishing marginal carbon inputs as microbial and decomposition processes re-equilibrate - remains scientifically contested. For policy and practice, the saturating pattern carries an important implication regardless of which mechanistic explanation ultimately prevails: early-year sequestration rates observed in short trials should not be extrapolated linearly to estimate multi-decade mitigation potential, and carbon-crediting methodologies that assume constant annual sequestration risk systematically overestimating long-term climate benefit.

Third, the practical and scientific challenges of measuring soil carbon change are converging with a rapidly evolving policy and market context. The contraction of the voluntary agricultural carbon credit market alongside surging investment in digital MRV technology reflects a broader recalibration in which buyers, regulators, and registries are prioritizing measurement rigor over sheer market volume. This is, on balance, a constructive development for the scientific integrity of the field, but it also means that the deep-sampling and equivalent-soil-mass requirements identified as best practice in the peer-reviewed literature are not yet fully reflected in commercial MRV protocols, most of which remain constrained to shallow depths for cost reasons. Bridging this gap between scientific best practice and operational feasibility is arguably the single most consequential unresolved issue for the credibility of soil-carbon-based climate finance.

Relating these findings to current developments in the field, it is notable that regenerative and climate-smart agriculture framings have increasingly subsumed conservation agriculture within broader practice bundles (organic amendments, biochar, agroforestry, integrated crop-livestock systems). While this reflects a genuine finding that combined practices often outperform single interventions, it also risks diluting the specific evidence base for CA's three core principles, making it harder for practitioners and policymakers to identify which individual components are doing the causal work. Future research and reporting would benefit from greater precision in isolating and reporting practice-specific effects even within multi-practice experimental designs.

7. Conclusion

This review synthesized 84 studies published between 2015 and 2025 to critically examine carbon sequestration dynamics under long-term conservation agriculture. The evidence indicates that CA practices - no-till and reduced tillage, cover cropping, residue retention, diversified rotations, and integrated crop-livestock systems - can produce meaningful gains in soil organic carbon, but that these gains are (i) concentrated predominantly in the upper soil profile, with deep-profile net sequestration contingent on complementary cropping intensification; (ii) subject to a saturating rather than linear accrual trajectory, typically plateauing within one to two decades; and (iii) highly sensitive to measurement protocol, particularly sampling depth and soil-mass accounting method, such that a substantial share of apparent disagreement in the literature reflects methodological rather than genuine biophysical divergence.

For researchers, this review recommends prioritizing deep-profile (0-100 cm, or full rooting-zone) sampling using equivalent-soil-mass accounting in future long-term trials; extending experimental durations to capture full saturation curves; and routinely reporting non-CO2 greenhouse gas fluxes alongside SOC data to enable full carbon and climate budgeting. Expanding networked, harmonized long-term experiment infrastructure across underrepresented tropical and smallholder agro-ecological zones is a particularly high-value investment given the concentration of existing long-term data in temperate systems.

For practitioners and policymakers, the review suggests that CA should continue to be promoted for its well-established co-benefits - reduced erosion, improved water infiltration, lower input costs, and enhanced soil biological function - while climate-finance mechanisms built around CA-derived soil carbon credits should adopt conservative, saturation-aware crediting horizons and require deep-sampling or equivalent-soil-mass-corrected verification protocols rather than relying solely on low-cost, shallow remote-sensing proxies. Policy design should also explicitly incorporate diversified rotation and reduced-fallow requirements alongside tillage reduction, since evidence indicates that tillage change alone is an insufficient condition for reliable carbon gain.

Future research should prioritize resolving the mechanistic basis of soil carbon saturation, developing cost-effective yet depth-adequate digital MRV protocols suited to smallholder contexts, and better integrating biophysical carbon findings with the socioeconomic and behavioral factors that govern real-world CA adoption and persistence. Addressing these priorities would substantially strengthen the scientific and policy foundation for treating conservation agriculture as a credible, quantifiable component of global climate change mitigation strategy.

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