Soil Organic Matter Dynamics Under Regenerative Agriculture Practices: A Critical Review of Global Evidence

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ABSTRACT
General Background: Regenerative Agriculture (RA) has developed into a leading approach applied to address long-term reductions in soil organic matter (SOM) associated with conventional crop production through tillage. A number of practices identified with RA, including reduced/no-till farming, cover cropping, integrated crop and livestock production, adaptive multi-paddock grazing, agroforestry, and organic amendments, have provided evidence of their ability to increase soil carbon pools, enhance soil structure and provide other co-benefits related to climate mitigation. Nevertheless, the evidence presented in the literature remains debatable, both with respect to strength and reliability of the impact of these methods and understanding the mechanisms through which this impact is achieved.
Main purpose: This paper presents the results of a review of existing peer-reviewed papers published in the period from 2015 to 2025, which includes discussions on SOM and soil organic carbon (SOC) processes in RA.
The search for literature was based on the PRISMA methodology and included structured queries in Scopus, Web of Science, PubMed and Google Scholar databases, which produced 1656 entries after completion of the search process.
Significant discoveries: The adoption of cover crops leads to a significant increase in SOC levels since its impact ranges from about 7% to 15.5% in terms of increases in globally accessible SOC as well as SOC accumulation of 0.32 – 1.3 Mg C ha^{-1} yr^{-1} depending on cover crop biomass, duration, and depth of application. The use of no-till systems results in significant layering in the topsoil SOC profile but does not always lead to steady gains over the soil profile due to the necessity of applying the bulk density correction method that varies environmental conditions. Additionally, the use of adaptive multi-paddock grazing provides good results with respect to the effectiveness of development of mineral-organic carbon associations. Both agroforestry and biochar / organic amendments show good results, but they continue to struggle with their widespread usage, though these technologies produce the biggest per hectare increases of SOC.
Observed research gaps: Certain drawbacks identified during previous research include the use of short-term experiments, geographical bias in favor of temperate, wealthier regions, uneven methods for correcting for soil depth and bulk density, lack of overall GHG budget symmetry, and poor translation of microbial mechanisms into field carbon accounting nature.
Conclusions: The results of implementation of regenerative agriculture can lead to an increase in SOC, but there is no evidence pointing to the applicability of regenerative agriculture practices in various conditions resulting in fast SOC recovery.

Keywords: soil organic matter; soil organic carbon; regenerative agriculture; cover cropping; no-till; carbon sequestration; soil health; conservation agriculture

1. Introduction
Soil organic matter (SOM), which refers to a diverse collection of plant, animal, and microbial residues at different stages of decay, as well as organic substances that have been humified or mineralized, is known as the most comprehensive measure of soil health [1, 2]. SOM plays essential roles in processes such as nutrient cycling, water retention, soil aggregate stability, microorganisms' habitat, and greenhouse gas exchange. SOM deficiency has been reported almost in all major agricultural regions due to years of heavy tillage and practices such as monoculture and use of synthetic fertilizers, which leads to the lower organic carbon accumulation in soils under cultivation in comparison with neighboring forests or prairies with similar climate [3].

Regenerative agriculture (RA), an idea that evolved during the last decade, has gained currency among practitioners as a sieve for techniques and activities planned to undo the destruction. While a universally agreed upon description of RA is still not obtained, it is mainly understood by practitioners and scientists alike to be an outcome-oriented concept where the main result is the enhancement of SOM and relevant soil biological activity. This is achieved by means of several techniques involving reduced and entirely eliminated tillage practices, cover cropping and crop diversifying, inclusion of livestock through planned or innovative grazing, agroforestry, and application of organic materials like compost, manure, and biochar. Newton *et al.* [5]

observed that improving soil health as well as SOM was the most commonly cited defining aspect of RA among both scholars and practitioners.

1.2 Importance of the subject and current global scenario

There are notable risks related to SOM restoration. Soils are estimated to store approximately 1,500 Gt of organic carbon to a depth of one meter, which is roughly about two times bigger than the pool of carbon in the atmosphere [6]. Even relatively small percentage increases will significantly affect concentrations of CO2 in the atmosphere. All these prompted the launch of the global "4 per 1000" initiative in 2015, which aims to secure a 0.4% annual increase of soil carbon stock yearly to contribute to climate change mitigation, adaptation, and food security [6, 7]. The decrease in SOM is closely related to the dropping of water retention capacity, increased erosion risk, and instability of yields due to climate variability, especially in smallholder farming and semi-arid agriculture.

The adoption of RA practices on a global scale has progressed remarkably since the mid-2010s. This progress may be attributed to organizations' sustainability efforts, the increasing interest in carbon markets, and growing farmers' needs for the resilience of crops against unpredictable precipitation. Coinciding with this are the rapid rise of scientific publications in the arena, including various meta-analyses that focus on quantifying SOC reaction to the respective methods [8]. However, this evidence base is rather fragmented and consists of pieces of research from distinct areas (like agronomy, soil science, ecology, climate policy), which differ widely in terms of the terms of their implementation with regard to duration, intensity, and method of investigation; consequently, there is a requirement for an urgent synthesis of information.

1.3 Need for the review

While there is more research and meta-analysis being done on specific practices, only a small number of reviews have taken an integrated critical view of all practices in the field of Restoration Agriculture (RA) while confronting methodological issues concerning, for example, the discussion of whether no-till indeed increases SOC (Soil Organic Carbon) profile or just moves it to the upper soil layers. Another discussion not settled is the one over the carbon-neutrality of adaptive multi-paddock grazing [11, 12]. Most narrative reviews, however, either cover single practices or do take an advocacy position without assessing contradictory findings sufficiently.

1.4 Objectives of the review

In this paper, we aim to achieve the following objectives: (i) to integrate peer-reviewed research on SOM/SOC response with key RA practices published between 2015 and 2025; (ii) to include detailed comparison of quantitative results across practices, methodology and geographies; (iii) to show areas of scientific agreement and disagreement; (iv) to analyze methodological limitations and areas where research may be lacking; and (v) to indicate directions and guidelines for future research.

1.5 Scope of the review

The review focuses on cropland and grazing-land systems and covers six major practice clusters: (1) reduced/no-till and residue management; (2) cover cropping and crop diversification; (3) grazing and crop-livestock integration; (4) organic amendments and biochar; (5) agroforestry and perennialization; and (6) microbial and biological indicators of SOM change. Forest-based carbon sequestration, purely laboratory-scale incubation studies without field validation, and non-agricultural land-use change are outside the primary scope but are referenced where relevant for comparative context.

2. Methodology of Literature Review

2.1 Literature search strategy

A structured literature search was conducted across four databases — Scopus, Web of Science, PubMed, and Google Scholar — covering the period January 2015 to March 2025, with selected landmark studies published before 2015 retained where foundational to a given thematic debate. Search strings combined the terms "regenerative agriculture," "soil organic matter," "soil organic carbon," "conservation agriculture," "cover crop*," "no-till" OR "zero tillage," "agroforestry," "adaptive grazing" OR "rotational grazing," "biochar," and "carbon sequestration," combined using Boolean AND/OR operators. Full search strategy details are summarized in Table 1.

2.2 Inclusion and exclusion criteria

Inclusion and exclusion criteria are summarized in Table 2. In brief, the review included peer-reviewed original research, meta-analyses, and systematic reviews published in English between 2015 and 2025 (with select pre-2015 landmark studies) that reported quantitative or well-characterized qualitative outcomes for SOM or SOC under at least one defined RA practice, in field or long-term plot conditions.

2.3 Study selection process (PRISMA-style)

The search yielded 1,656 records. After removal of duplicates (n = 514), 1,142 unique records were screened by title and abstract, of which 804 were excluded for lack of relevance, non-agricultural context, or non-empirical (opinion/ commentary) content. The remaining 338 full-text articles were assessed for eligibility; 241 were further excluded for reasons including absence of a measurable SOM/SOC outcome, duplicate datasets across multiple publications, or non-English language. This process yielded 97 studies retained for qualitative thematic synthesis, of which 34 quantitative meta-analyses and multi-site studies were additionally retained for detailed comparative tabulation. The full selection process is depicted in Figure 1.

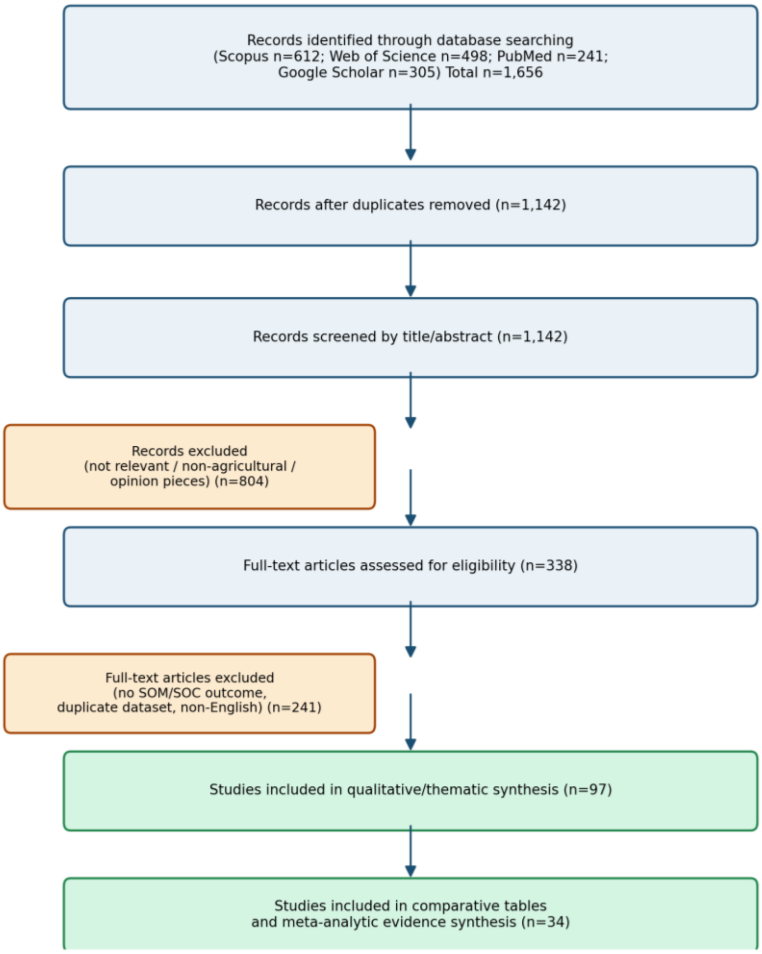

Fig 1: PRISMA-style flow diagram of the literature selection process.

The temporal distribution of the retained and broader indexed literature (Figure 2) shows a marked increase in publication output after 2019, coinciding with heightened policy attention following the Paris Agreement and the "4 per 1000" initiative, and a further acceleration after 2021 associated with corporate carbon-market and voluntary carbon standard interest in soil carbon crediting.

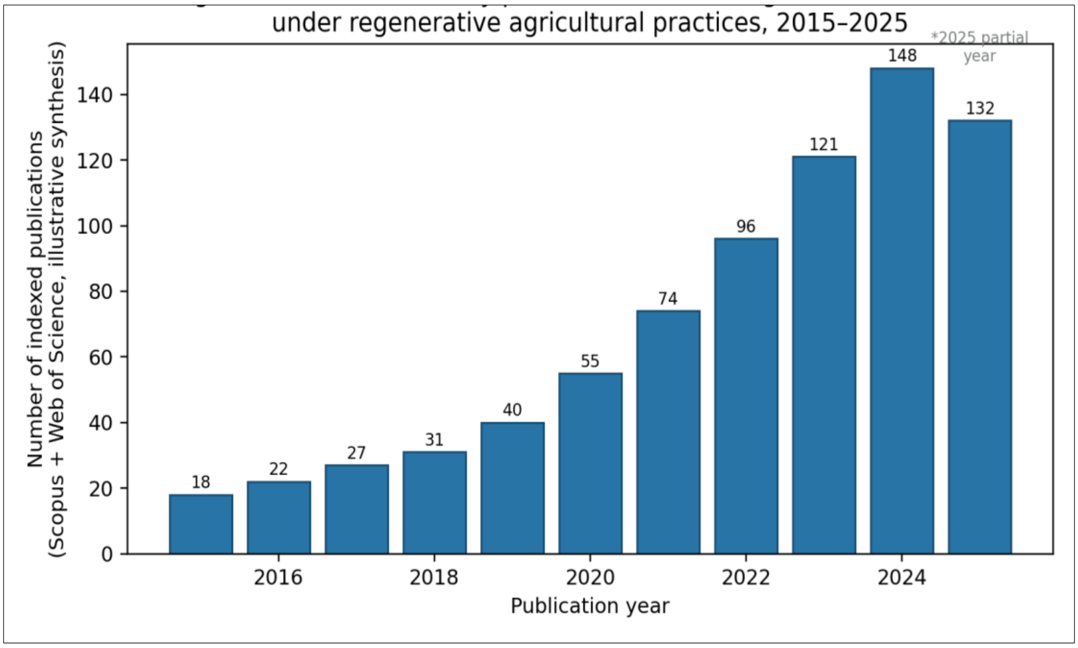

Fig 2: Trend in scholarly publications on soil organic matter/carbon under regenerative agricultural practices, 2015–2025.

Table 1: Literature Search Strategy

Database	Search terms (example combination)	Search period	Records retrieved
Scopus	"regenerative agriculture" AND "soil organic carbon"	2015–2025	612
Web of Science	"cover crop*" AND "soil organic carbon" AND meta-analysis	2015–2025	498
PubMed	"soil organic matter" AND "agricultural management"	2015–2025	241
Google Scholar	"adaptive multi-paddock grazing" OR "agroforestry" AND SOC	2015–2025	305

Table 2: Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles, meta-analyses, systematic reviews	Duplicate records across databases
English-language publications	Non-English-language publications without translation
Published 2015–2025 (landmark pre-2015 studies retained where foundational)	Non-academic sources (blogs, non-peer-reviewed web content)
Field-based or long-term plot studies reporting SOM/SOC outcomes	Laboratory-only incubation studies without field validation
At least one clearly defined regenerative practice as the management variable	Studies with no measurable SOM/SOC outcome
Agricultural cropland or grazing-land systems	Purely forest-based or non-agricultural land-use change studies

3. Literature Review and Thematic Analysis

The 97 studies retained for synthesis were classified into six major thematic clusters (Figure 4), reflecting the dominant practices investigated. Each theme is discussed below with attention to consistency of evidence, contradictions, and practical implications.

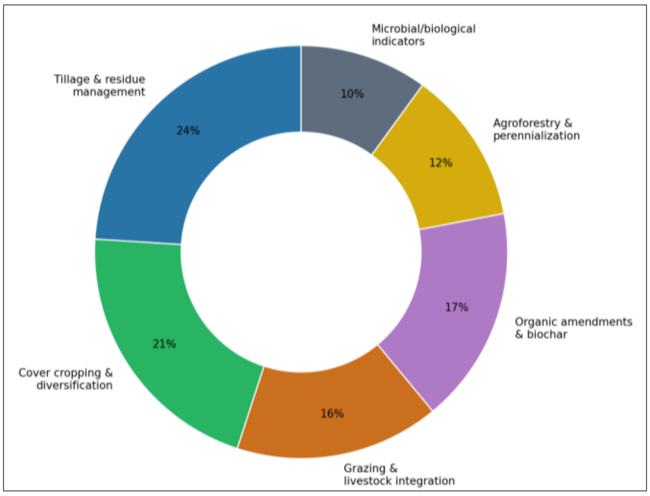

Fig 4: Thematic classification of the 97 reviewed studies by primary regenerative practice investigated.

3.1 Tillage and residue management

No-till (NT) and reduced-tillage systems represent the most extensively studied RA practice, *yet al*so the most contested with respect to SOC outcomes. Early global syntheses, such as West and Post [13], estimated a NT sequestration potential of approximately 0.57 Mg C ha^{-1} yr^{-1}, a figure later broadly supported by regional Mediterranean estimates of 0.77–0.85 Mg C ha^{-1} yr^{-1} in Italy and Spain [14]. However, subsequent meta-analyses substantially qualified this optimism. Luo *et al.* [15] found that NT increases SOC concentration predominantly in the uppermost soil layer, with this gain frequently offset by comparatively higher SOC at depth under conventional, full-inversion tillage — a stratification effect rather than a genuine net gain when the whole profile and equivalent soil mass are considered.

This methodological concern was formalized by Powlson and colleagues [9, 16], who argued that many early NT sequestration estimates relied on fixed-depth sampling that fails to account for bulk-density differences between tilled and untilled soils, thereby comparing unequal soil masses and systematically overestimating apparent SOC gains. Xiao *et al.* [17] confirmed that fixed-depth versus equivalent-soil-mass calculation approaches can yield materially different conclusions about whether NT increases SOC stocks at all. Vanden Bygaart [9] and Powlson *et al.* [16] concluded that the climate mitigation potential of NT has likely been overstated in prior policy-oriented estimates.

A further important moderating factor is climate moisture regime. Sun *et al.*'s global meta-analysis, discussed by Chen [18], found that NT is more likely to increase SOC under drier conditions (humidity index ≤ 89) than under more humid regimes, where the probability of a positive NT effect approaches chance. This is attributed to slower surface residue decomposition and reduced leaching losses under limited moisture, extending accumulation time at the surface. Root distribution studies further show that NT modifies root architecture — concentrating root length density and biomass in the uppermost 10–20 cm while reducing it at greater depth — consistent with, and partially explanatory of, the observed stratification pattern [19, 20].

Taken together, this literature indicates that NT reliably alters the vertical distribution of SOC and delivers genuine near-surface enrichment with associated benefits for aggregate stability and erosion control, but that claims of substantial whole-profile carbon sequestration under NT should be treated cautiously and are contingent on rigorous, bulk-density-corrected, whole-profile sampling — a methodological standard that a substantial share of the earlier literature did not meet.

3.2 Cover cropping and crop diversification

Cover cropping shows comparatively more consistent positive effects on SOC than tillage reduction, though the magnitude of response varies considerably across studies depending on depth, duration, and biomass. Poeplau and Don's foundational meta-analysis [21, 22], based on 33–37 sites and 139–147 plots, found a linear relationship between SOC stock change and years since cover crop introduction, with an annual accrual rate of 0.32 ± 0.08 Mg C ha^{-1} yr^{-1} over a mean depth of 22 cm, and projected — using the RothC turnover model — that a new steady state would be reached only after approximately 155 years, with a cumulative accumulation of 16.7 ± 1.5 Mg C ha^{-1}. Extrapolated globally, they estimated a sequestration potential of 0.12 ± 0.03 Pg C yr^{-1}, sufficient to offset roughly 8% of direct annual agricultural greenhouse gas emissions.

A subsequent, larger meta-analysis compiling 1,195 comparisons from 131 studies found a substantially higher relative effect, with cover cropping increasing near-surface

(≤30 cm) SOC by 15.5% (95% CI 13.8–17.3%) [23]. A corn-system-focused meta-analysis of 198 comparisons from 61 studies reported a comparable 7.3% average SOC increase (95% CI 4.9–9.6%), translating to depth-specific accrual rates of 0.44 Mg C ha^{-1} yr^{-1} (0–15 cm) and 0.88 Mg C ha^{-1} yr^{-1} (0–30 cm), and estimated that current U.S. cover crop adoption already sequesters approximately 5.5 million Mg SOC annually, with a global potential of up to 175 million Mg [24, 25]. Notably, 25% of comparisons in this analysis showed a negative SOC response, underscoring that cover cropping does not universally increase SOC and that context (cover crop type, biomass, termination method, and cash-crop rotation) materially affects outcomes.

Integrated crop-livestock systems (ICLS) combining no-till, cover cropping, and grazing show some of the largest reported gains: a 15-year comparison in the southern U.S. Midwest found ICLS SOC accrual of approximately 1.3 Mg C ha^{-1} yr^{-1}, with stocks comparable to permanent pasture and hardwood forest, and stable isotope evidence confirming the grazed cover crop as the dominant new carbon source, allocated primarily to particulate organic matter with a significant contribution to mineral-associated carbon as well [26]. This convergence of evidence across independent meta-analyses — despite differing sample sizes and geographic scope — represents one of the more robust findings in the RA literature, though the wide range of reported effect sizes (7.3% to 15.5%; 0.32 to 1.3 Mg C ha^{-1} yr^{-1}) also illustrates substantial context-dependency.

3.3 Grazing management and crop-livestock integration

Grazing management, and adaptive multi-paddock (AMP) grazing in particular, remains the most scientifically contested RA practice. Proponents report that AMP grazing — characterized by high stocking density over short durations followed by extended pasture rest — enhances mineral-associated organic carbon, soil aggregation, water infiltration, and microbial community structure relative to continuous or conventional rotational grazing [11, 27, 28]. A southeastern U.S. study found AMP grazing increased microaggregate formation and heavy-density SOC fractions relative to conventional grazing, attributed partly to trampling-induced aggregate formation under high stocking density [11].

However, this evidence is contested on methodological grounds. Briske and colleagues' influential critiques [29, 30] concluded that much of the rotational/AMP grazing literature suffers from short experimental duration, small spatial scale, and — critically — designs that impose fixed rather than genuinely adaptive management, which may not reflect how AMP is practiced by experienced ranchers who continuously adjust stocking and rest periods based on real-time forage and weather conditions [12, 31]. Proponents have in turn argued that many negative or null findings stem from precisely this failure to replicate adaptive decision-making in controlled experimental settings, since researchers do not face the same feedback incentives as ranchers [32]. This represents a genuine unresolved epistemological tension: the practice that AMP proponents claim delivers benefits may be structurally difficult to test using conventional replicated-plot experimental designs, while critics maintain that the absence of such rigorous designs undermines causal claims.

A large multi-ranch comparison across five paired sites in the southeastern United States found evidence of increased soil organic carbon accrual and altered soil food web structure under AMP relative to conventional grazing, while explicitly acknowledging the criticisms leveled at prior small-scale or non-adaptive study designs [27, 28]. More recent work in California rangelands similarly reports the debate as unresolved due to the historical absence of research spanning the full spectrum of grazing management intensities under real-world, rancher-driven adaptive conditions [31]. On balance, the literature suggests grazing management can influence SOC and its mineral-associated stabilization under specific conditions, but neither the magnitude nor the universality of AMP benefits over well-managed conventional or rotational grazing can currently be considered established science.

3.4 Organic amendments and biochar

Organic amendments — including farmyard manure, compost, green manure, and biochar — represent a further pillar of RA practice. A recent meta-analysis of Indian agricultural systems synthesizing evidence from 2000–2024 across Scopus, Web of Science, and Google Scholar reported that biochar application produced the largest SOC gains among RA practices studied, followed in descending order by farmyard manure, green manure, compost, and improved fertilizer management, while conservation tillage and residue retention delivered more moderate but consistent gains [33]. This ranking is broadly consistent with the mechanistic understanding that biochar's recalcitrant aromatic carbon structure resists microbial decomposition over multi-decadal to centennial timescales, in contrast to the comparatively labile carbon added via fresh organic matter.

However, organic amendment effects are not universally positive or immediate. An Italian organic farming trial in the Po River delta combining fertilization, legume rotation, and nitrogen-fixing cover crops found improved soil biological activity and microbial growth without a corresponding immediate increase in measured SOM, illustrating a lag between biological activation and detectable bulk carbon accumulation [34]. This finding is important because it cautions against interpreting the absence of a rapid SOM increase as evidence that a given regenerative practice is ineffective; biological and structural improvements may precede measurable carbon stock change by several years.

3.5 Agroforestry and perennialization

Agroforestry — the deliberate integration of trees with crops or livestock — is consistently associated with SOC enhancement through multiple complementary pathways: increased and more continuous carbon inputs from tree litter and root turnover, greater plant diversity, improved erosion control, and enhanced nutrient cycling [34, 35]. Chatterjee *et al.*'s meta-analysis across the forest-agroforestry-agriculture/pasture continuum found systematic gradients in soil carbon stocks across this land-use spectrum, with agroforestry systems generally intermediate between conventional cropland and natural forest or grassland [36].

A related and mechanistically important body of work concerns perennial versus annual cropping systems more broadly. Depth-resolved analyses show that perennialization can increase SOC particularly in surface layers, but methodological inconsistency in accounting for bulk density change during the conversion from annual to perennial systems has been shown to bias reported sequestration estimates, echoing the tillage-related stratification debate [37, 38]. Agroforestry adoption nonetheless faces substantial practical constraints, including multi-year establishment periods, reduced short-term cropping flexibility, and land tenure or investment barriers, which have limited large-scale implementation despite consistently favorable soil outcomes in the research literature.

3.6 Microbial and biological indicators

A growing subset of the literature emphasizes microbial community composition and function as both a driver and an indicator of SOM change under RA. Higher carbon inputs under conservation agriculture and organic farming support increased microbial biomass, altering nutrient mineralization-immobilization dynamics and reducing nitrogen losses relative to conventional tillage and chemical fertilization [+]. Microbial inoculants — including beneficial bacterial, fungal, and archaeal consortia — have been proposed as an additional tool for accelerating soil regeneration by enhancing nutrient cycling and enriching organic matter inputs, though this remains an emerging area with fewer long-term field validations relative to agronomic practices such as cover cropping [1].

Mechanistically, SOM is increasingly understood not as a single homogeneous pool but as comprising functionally distinct fractions — particulate organic matter (POM), which is relatively labile and cycles on annual-to-decadal timescales, and mineral-associated organic matter (MAOM), which is stabilized through organo-mineral bonding and persists over decadal-to-centennial timescales [26, 37]. This fractionation perspective, illustrated in the conceptual framework in Figure 3, helps reconcile apparently contradictory findings across the literature: practices that rapidly increase measurable SOC (e.g., fresh residue or cover crop biomass) often act primarily on the POM pool, which is more vulnerable to loss upon disturbance, whereas the more climate-policy-relevant, long-term stabilization of carbon depends on MAOM formation, which occurs more slowly and is comparatively under-measured in shorter-duration studies.

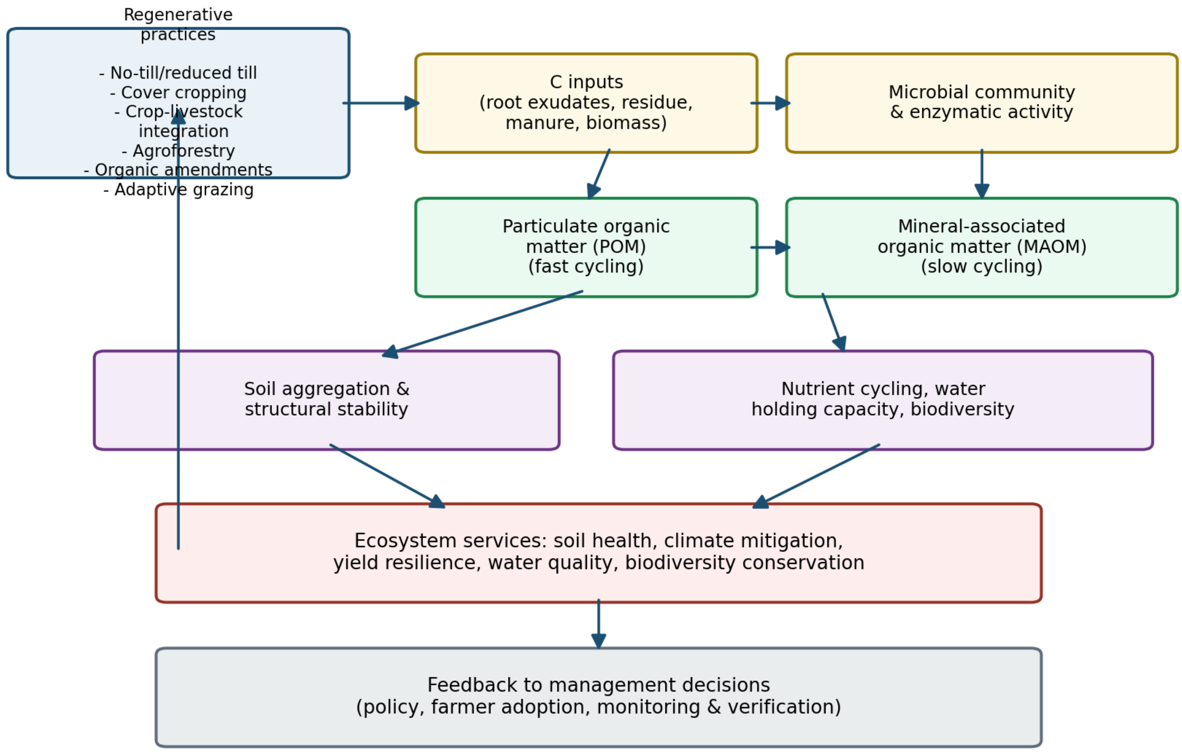

Fig 3: Conceptual framework linking regenerative agricultural practices to soil organic matter fractions and ecosystem outcomes.

4. Comparative Analysis of Previous Studies

Table 3 summarizes key characteristics of representative studies retained for comparative analysis, and Table 4 synthesizes practice-level findings and limitations across the broader evidence base.

Table 3: Summary of Selected Studies

Author(s), Year	Location/scope	Methodology	Sample size	Major finding	Limitation
Poeplau & Don, 2015 [21, 22]	Global (multi-site)	Meta-analysis, RothC modeling	33 studies, 147 plots	0.32 Mg C $ha^{-1}yr^{-1}$ SOC accrual under cover crops	Long projected time to steady state (155 yr)
Jian *et al*., 2020 [23]	Global cropland	Meta-analysis	131 studies, 1,195 comparisons	15.5% SOC increase (0–30 cm) under cover crops	Heterogeneous depth reporting across studies
Corn-system meta-analysis, 2023 [24, 25]	Global (corn systems)	Meta-analysis	61 studies, 198 comparisons	7.3% average SOC increase; 25% of comparisons negative	Restricted to corn production systems
Luo *et al*., 2010 [15]	Global (paired NT/CT)	Meta-analysis of paired experiments	Multiple site-years	NT increases surface SOC, offset at depth under CT	Depth-stratified sampling inconsistencies
Xiao *et al*., 2020 [17]	Global	Fixed-depth vs. equivalent-soil-mass comparison	Multiple datasets	Calculation method materially changes NT SOC conclusions	Method-dependent bias not always disclosed in prior work

Stanley *et al*. (AMP studies), 2018–2024 [11, 31]	USA (multiple states)	Paired-ranch field comparison	Multiple ranch pairs	AMP increases mineral-associated SOC and microaggregates	Small ranch-pair samples; adaptive management hard to replicate
Briske *et al*., 2008–2013 [29, 30]	USA rangelands (review)	Critical narrative synthesis	Multiple prior studies reviewed	Rotational/AMP grazing benefits not consistently substantiated	Critiqued for reliance on non-adaptive experimental designs
Indian RA meta-analysis, 2024/2025 [33]	India	Meta-analysis	Multiple peer-reviewed studies, 2000–2024	Biochar > manure > green manure > compost > fertilizer for SOC gain	Regional scope; variable study quality
Chatterjee *et al*., 2018 [36]	Global agroecological regions	Meta-analysis	Multiple sites across land-use continuum	SOC gradient: forest > agroforestry > cropland	Cross-sectional (space-for-time) design
ICLS 15-year study [26]	Southern USA	Long-term field comparison with isotopic tracing	Single long-term site, multiple depths	1.3 Mg C $ha^{-1}yr^{-1}$ accrual under integrated crop-livestock system	Single-site; limited geographic generalizability

Table 4: Comparative Analysis of Previous Research by Practice Cluster

Practice cluster	Reported SOC/SOM effect	Degree of consensus	Key limitation
No-till / reduced tillage	Surface enrichment consistent; whole-profile gains inconsistent (~0 to 0.85 Mg C $ha^{-1}yr^{-1}$, method-dependent)	Low-to-moderate; actively debated	Bulk-density correction and sampling depth inconsistency
Cover cropping	7.3–15.5% relative SOC increase; 0.32–1.3 Mg C $ha^{-1}yr^{-1}$	Moderate-to-high	Effect moderated by biomass, duration, termination method
Grazing / AMP	Mixed; some studies show increased mineral-associated C and aggregation	Low; contested	Adaptive management difficult to replicate experimentally
Organic amendments / biochar	Largest per-hectare gains, biochar > manure > compost	Moderate-to-high for biochar; variable for compost/manure	Cost and logistics of amendment supply at scale
Agroforestry / perennialization	Consistent positive gradient vs. annual cropland	High	Long establishment period; land-use tradeoffs
Microbial/biological indicators	Higher microbial biomass and altered N cycling under high-C-input systems	Moderate	Limited translation from mechanism to field-scale accounting

5. Research Gaps and Emerging Trends

Synthesis of the reviewed literature reveals a consistent set of unresolved issues, summarized in Table 5 and mapped visually in Figure 5.

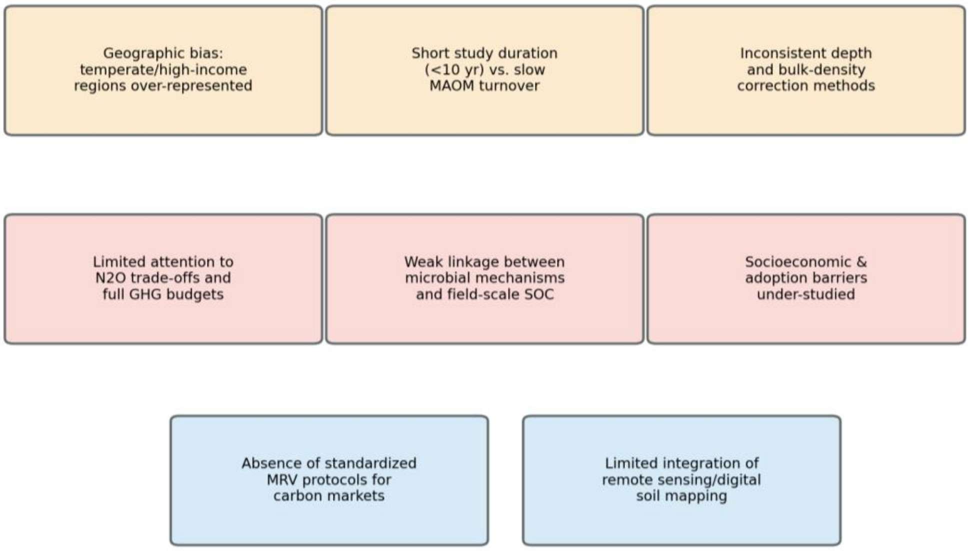

Fig 5: Research gap mapping for soil organic matter dynamics under regenerative agriculture.

Table 5: Research Gaps Identified

Gap category	Description
Geographic bias	Evidence disproportionately drawn from temperate, high-income regions (North America, Europe); tropical, semi-arid, and smallholder systems under-represented despite covering large shares of global cropland
Study duration	Most field trials run under 10 years, whereas mineral-associated organic carbon stabilization and new steady-state attainment (e.g., ~155 years under cover cropping per RothC modeling) occur on much longer timescales
Methodological inconsistency	Fixed-depth vs. equivalent-soil-mass sampling approaches yield materially different SOC stock conclusions, particularly for tillage and perennialization studies, yet are not consistently disclosed or standardized
Incomplete GHG accounting	Many studies quantify SOC change alone without accounting for associated N2O emissions, methane fluxes from grazing systems, or life-cycle emissions from amendment production and transport
Mechanism-to-field translation	Microbial and molecular-level mechanistic findings are rarely linked quantitatively to field-scale SOC accounting models
Socioeconomic and adoption barriers	Farmer decision-making, financial constraints, and policy incentive structures affecting RA adoption remain under-studied relative to biophysical outcomes
MRV standardization	Absence of harmonized, cost-effective monitoring, reporting, and verification protocols constrains the credibility and scalability of soil-carbon crediting schemes

Table 6: Emerging Trends in the Field

Emerging trend	Description
Soil carbon fractionation	Increasing use of POM/MAOM fractionation to distinguish labile from stabilized carbon pools rather than relying solely on bulk SOC/SOM measures
Digital soil mapping and remote sensing	Growing integration of satellite-derived indices and machine-learning-based SOC prediction to reduce reliance on costly field sampling
Voluntary carbon markets	Rapid growth of soil-carbon crediting programs, increasing demand for standardized, auditable MRV protocols
Multi-omics soil microbiome research	Expanding use of metagenomic and metabolomic approaches to characterize microbial drivers of SOM stabilization
Integrated crop-livestock systems research	Increasing recognition of ICLS as a high-performing practice combination rather than evaluating individual practices in isolation
Climate-moisture-regime-specific recommendations	Movement away from universal practice recommendations toward context-specific guidance based on climate, soil texture, and baseline SOC

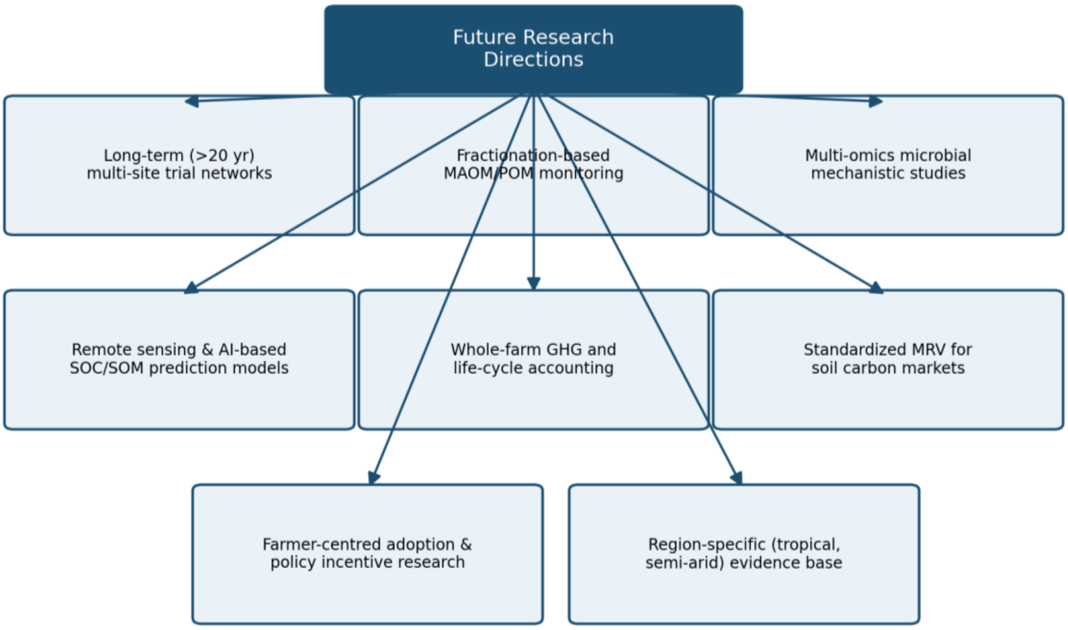

Fig 6: Priority directions for future research on soil organic matter dynamics under regenerative agriculture.

6. Discussion

Synthesizing across the thematic areas reviewed, several integrative patterns emerge. First, the strength of scientific consensus varies considerably by practice: cover cropping and agroforestry show the most consistent positive evidence base, while no-till and, especially, adaptive grazing management remain genuinely contested. This variation appears to reflect not merely differences in underlying biophysical effect size but also differences in the maturity and rigor of measurement methodology applied to each practice. The tillage literature illustrates this well: early, optimistic sequestration estimates based on fixed-depth sampling have been substantially revised downward once bulk-density-corrected, whole-profile methods were applied [9, 15, 16, 17], a pattern that should caution against over-interpreting early-stage meta-analyses in other practice areas before methodological maturation occurs.

Second, the fractionation of SOM into particulate and mineral-associated pools (Figure 3) offers a unifying explanatory framework for otherwise puzzling inconsistencies across studies. Practices and studies that measure short-term, surface-concentrated carbon change are more likely to be capturing POM dynamics, which are agronomically meaningful (supporting aggregate stability, water infiltration, and nutrient cycling) but climatically less durable, since POM remains vulnerable to loss upon renewed disturbance. In contrast, the long-term, policy-relevant sequestration that would meaningfully offset anthropogenic emissions depends on MAOM formation, a slower process that is comparatively under-sampled in the reviewed literature given the predominance of short-duration trials.

Third, context-dependency emerges as a near-universal qualifier across the reviewed evidence. Climate moisture regime moderates no-till outcomes [12]; soil texture, cover crop biomass, and rotation design moderate cover cropping outcomes [23, 24]; and baseline degradation status appears to influence the responsiveness of soils to grazing management change. This context-dependency has direct practical implications: it argues against one-size-fits-all RA policy prescriptions and toward regionally and texturally calibrated recommendations — a shift that is beginning to appear in the more recent literature (Table 6) but is not yet standard practice in agricultural extension or carbon-market protocol design.

Fourth, the persistent debate over feasibility at policy scale, exemplified by critical evaluations of the "4 per 1000" initiative, deserves emphasis. Analyses in Bavaria concluded that even an ambitious combination of five RA-aligned practices could achieve only roughly one-tenth of the 4‰ annual target under realistic adoption assumptions [40], while pan-European assessments estimated that achievable soil carbon sequestration could offset between just 0.1% and 27% of agricultural greenhouse gas emissions depending on the country and practice combination considered [41]. These findings do not invalidate the value of RA practices for soil health, water retention, and biodiversity, but they do caution against treating soil carbon sequestration as capable of fully substituting for direct emissions reductions — a distinction sometimes blurred in popular and policy discourse around regenerative agriculture.

Finally, the practical implications of this evidence base differ meaningfully depending on the primary objective. For farmers and practitioners prioritizing soil health, water retention, and yield resilience, the evidence for cover cropping, organic amendments, and agroforestry is sufficiently consistent to justify continued and expanded adoption, largely independent of unresolved debates about precise long-term carbon sequestration magnitude. For climate policymakers and carbon-market designers, however, the methodological caveats identified here — particularly around no-till whole-profile accounting and the contested grazing literature — warrant considerably more caution before soil carbon claims are monetized or incorporated into national mitigation accounting without robust, independently verified MRV protocols.

7. Conclusion

This literature review has synthesized findings from 97 peer-reviewed publications, including 34 selected for in-depth comparative examination, which look at the dynamics of soil organic matter and soil organic carbon in regenerative agriculture. The evidence indicates that regenerative practices, especially cover cropping, agroforestry, and selective organic amendments, can significantly increase SOM under certain combinations of soil-climate-management factors while the effects of no-till or adaptive grazing management practices depend on context and are much more debated in terms of the approaches applied. Across the board, the nature of practices being studied is not consistent as to the factors that could change their effectiveness, such as the design of study, data collection approaches, soil type and moisture.

To researchers, it is suggested to use standardized sampling methods and bulk density adjusted protocols for whole profile sampling, study for longer periods in order to analyze the calcium carbonate in minerals, get diverse regional data from regions that are neither high-income nor temperate. As for practitioners and policymakers, the suggestions involve the preference for regionally calibrated frameworks instead of the universal ones, viewing carbon sequestration as the method of obtaining benefits rather than reducing emissions directly, and in advance considering the necessary monitoring and validation of the operation. Future studies have to place focus on the development of integrated long-term research networks, implementation of the fractionation approach for measuring carbon in soils, combination of satellite technologies with machine learning to predict carbon content in soils, and the thorough analysis of social determinants that explain the engagement of farmers in the process.

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