Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 3, 2026

REGENERATIVE AGRICULTURE AND CLIMATE-RESILIENT SOIL FERTILITY MANAGEMENT FOR SUSTAINABLE CROP PRODUCTIVITY, SOIL HEALTH, AND CARBON SEQUESTRATION

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DOI: https://doi.org/10.5281/zenodo.23828932

Keywords
Regenerative agriculture, soil organic carbon, carbon sequestration, soil health, crop productivity, ecosystem resilience, conservation tillage, cover cropping, climate change mitigation, sustainable agriculture

Article History
Received: 07 January 2026
Accepted: 17 March 2026
Published: 31 March 2026

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Abstract

Industrialized agriculture has achieved substantial yield gains but often at the cost of soil degradation, organic carbon depletion, and diminished ecosystem resilience. Regenerative agriculture (RA) has emerged as a holistic, outcome-driven paradigm aimed at restoring soil health through minimized disturbance, continuous living roots, diversified cropping, residue retention, and integrated livestock management. This review synthesizes current scientific evidence on the biogeochemical mechanisms, agronomic impacts, economic trade-offs, and policy frameworks associated with regenerative practices. We examine the stabilization of soil organic carbon (SOC) through particulate and mineral-associated organic matter pathways, emphasizing the central role of microbial processing of root exudates in forming persistent carbon pools. Quantitative evaluations of conservation tillage, cover cropping, organic amendments, biochar, agroforestry, and adaptive multi-paddock grazing reveal SOC sequestration rates ranging from 0.06 to 4.20 Mg C ha⁻¹ yr⁻¹, with the global technical potential estimated at 0.9 ± 0.3 Pg C yr⁻¹. While regenerative systems may experience temporary yield reductions of 5–29% during the initial transition, yields typically stabilize at parity with conventional baselines and demonstrate superior drought resilience. Financially, reduced input costs can yield 20–100% higher net profit margins despite lower absolute yields. Enhanced soil structure improves plant-available water capacity, microclimate buffering, and biotic resilience. However, scaling regenerative agriculture requires robust monitoring, reporting, and verification protocols, standardized carbon accounting, and supportive policy instruments including transition financing and restructured crop insurance. This review concludes that regenerative agriculture offers a viable pathway for simultaneously improving crop productivity, carbon storage, and ecosystem resilience, provided

that implementation is context-adapted and supported by rigorous science and enabling policies.

INTRODUCTION

Industrialized agricultural paradigms over the past century have driven unprecedented gains in global crop yield, yet these achievements have frequently come at the expense of fundamental ecological infrastructure. Intensive tillage, monocultural cropping, synthetic chemical fertilization, and continuous overgrazing have accelerated soil degradation, leading to widespread loss of soil organic carbon (SOC), erosion of topsoil structure, and impairment of ecosystem services (Khangura et al., 2023). Globally, cultivated mineral soils have suffered significant historical carbon depletions, with global topsoils estimated to have lost between 1.6 ± 3.4 and 2.5 ± 2.3 Mg C ha^{-1} under conventional management. This degradation depletes agricultural productivity, diminishes soil water-holding capacity, and amplifies the vulnerability of food production systems to extreme weather events (Sher et al., 2024).

Regenerative agriculture (RA) has emerged as a holistic, outcome-driven paradigm designed to reverse this trajectory by prioritizing the restoration and continuous improvement of soil health. Rather than viewing soil merely as an inert physical medium for chemical inputs, regenerative management conceptualizes soil as a dynamic living ecosystem powered by biological interactions (Rosier et al., 2025). The foundational principles of regenerative agriculture encompass minimizing chemical and physical soil disturbance, maintaining continuous living roots, maximizing biodiversity through crop rotations and multi-species swards, keeping the soil covered with plant residues, and re-integrating livestock into cropping landscapes (Joshi et al., 2026).

The terrestrial soil reservoir represents the largest active organic carbon pool on Earth, storing between 1,500 and 2,400 Petagrams of carbon (Pg C) to a depth of one meter more than the atmospheric (~860 Pg C) and biotic (~500–600 Pg C) pools combined. Consequently, small fractional increases in SOC can exert disproportionately large impacts on global atmospheric carbon dioxide (CO_2) trajectories (Biswas et al., 2024). The global technical potential for SOC sequestration through regenerative practices is estimated at 0.9 ± 0.3 Pg C yr^{-1}, an offset equivalent to roughly one-fourth of the annual net accumulation of atmospheric CO_2. Under initiatives such as the global "4 per 1000" campaign, an annual growth rate of 0.4% in topsoil organic carbon stocks is targeted to simultaneously stabilize climate systems and revitalize global land resources (Mishra et al., 2024).

Beyond climate change mitigation, regenerative management seeks to solve the dual challenges of global food security and environmental resilience. Enhancing SOC stocks yields direct agronomic dividends: for every additional metric ton of soil carbon stored per hectare in degraded cropland soils, crop yields can increase by 20 to 40 kg ha^{-1} for wheat and 10 to 20 kg ha^{-1} for maize (Gulaiya et al., 2024). This synthesized review provides an exhaustive scientific evaluation of regenerative agricultural practices, examining their biogeochemical mechanisms of soil carbon stabilization, agronomic yield dynamics, hydrological benefits, economic trade-offs, and policy frameworks required for widespread adoption (Vamshi et al., 2024).

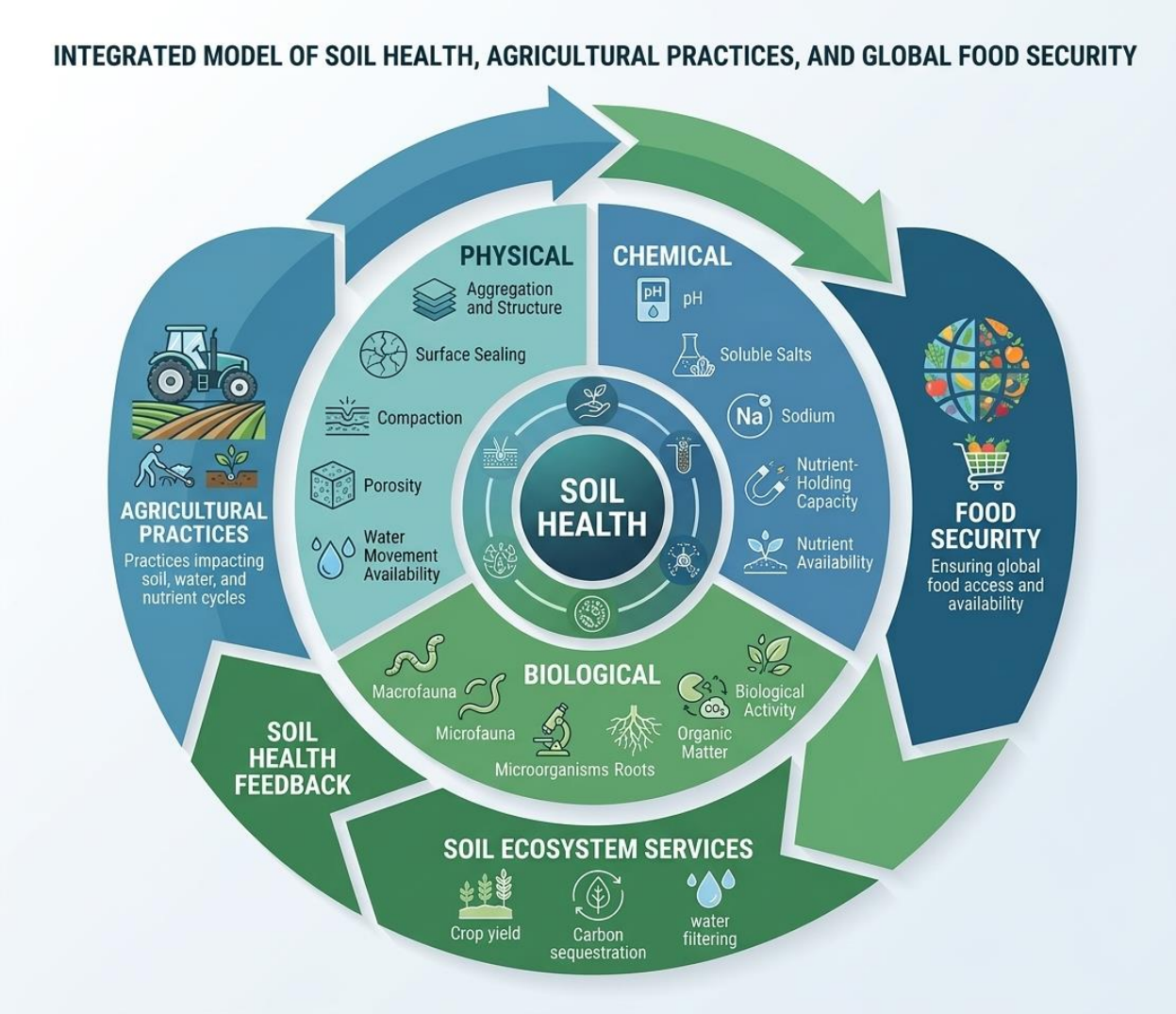


Figure 1: Conceptual framework linking agricultural practices, physical, chemical, and biological soil health indicators, ecosystem services, and global food security.

2. Mechanistic Pathways of Soil Organic Carbon Stabilization

2.1 Dynamics of Particulate vs. Mineral-Associated Organic Matter

Understanding soil carbon persistence requires moving away from traditional concepts of chemical recalcitrance toward a physical and chemical stabilization framework. Soil organic matter (SOM) is broadly divided into two major functional pools: Particulate Organic Matter (POM) and Mineral-Associated Organic Matter (MAOM). These pools differ fundamentally in their formation pathways, C:N stoichiometry, turnover rates, and susceptibility to environmental disturbance (Manzoni & Cotrufo, 2024).

Particulate Organic Matter comprises structural plant debris ranging in size from 63 to 2000 μm. It is characterized by high C:N ratios, a lower degree of microbial decomposition, and dependence on physical protection within soil macro- and micro-aggregates. Because POM relies heavily on structural aggregation for physical protection against microbial enzymatic cleavage, it is extremely vulnerable to destruction via mechanical tillage. Upon physical disturbance, macroaggregates rupture, exposing POM to rapid

oxidative mineralization and carbon loss as CO_2 (Wu et al., 2023).

Conversely, Mineral-Associated Organic Matter consists of fine organic fractions ($< 63\ \mu$m) chemically sorbed onto silt and clay mineral surfaces or physically protected within microaggregates. MAOM is characterized by low C:N ratios and is heavily enriched with microbially processed compounds and microbial necromass (Zhong et al., 2026). Because organo-mineral bonds require significant activation energy to disrupt, MAOM exhibits a long mean residence time spanning decades to centuries. Across diverse agricultural regimes, MAOM constitutes the dominant long-term carbon reservoir, typically accounting for 57.3% to 77.8% of the total SOC stock (Sun et al., 2023).

2.2 The Microbial Pathway of Soil Carbon Formation

A major paradigm shift in soil biogeochemistry underscores the centrality of the microbial pathway in building soil carbon. Historical models assumed that stable soil humus formed primarily through the slow, incomplete chemical decay of tough plant materials like lignin. Contemporary evidence demonstrates that low-molecular-weight root exudates and labile organic compounds processed efficiently by soil bacteria and fungi serve as the primary precursors for persistent MAOM (Liang et al., 2017).

Plants transfer up to 20–40% of their photosynthetically fixed carbon belowground through rhizodeposition, exuding simple sugars, amino acids, and organic acids into the rhizosphere. Soil microbes absorb these labile substrates with high carbon-use efficiency (CUE), building microbial biomass (Sokol & Bradford, 2019). As microbial cells undergo turnover, their cell wall fragments, proteins, and exudates (microbial necromass) form organo-mineral complexes with fine clay particles. Consequently, management practices that maximize continuous root exudation such as cover cropping, living mulches, and perennial swards drive higher rates of MAOM formation compared to practices that rely solely on surface crop residue retention (Cotrufo et al., 2015).

2.3 Mathematical Frameworks for SOC Quantification

Accurate measurement and standardization of SOC stocks are essential for carbon accounting, monitoring programs, and market credit verification. Soil organic carbon content is typically determined through dry combustion analysis of soil cores. To convert carbon concentrations into area-based stock values (Mg C ha^{-1}), physical soil properties including bulk density, layer depth, and coarse fragment volume must be incorporated (Coleman, 2017). The standard method proposed by the Food and Agriculture Organization (FAO) calculates the SOC stock for a specific soil layer i using the following formula:

$$SOC_{i_stock} = OC_i \times BD_{fine_i} \times (1 - vG_i) \times t_i \times 0.1$$

Where:

- SOC_{i_stock} is the soil organic carbon stock of layer i (Mg C ha^{-1}).
- OC_i is the mass concentration of organic carbon in the fine earth fraction (g C kg^{-1} dry soil or % mass equivalent).
- BD_{fine_i} is the dry bulk density of the fine earth fraction (< 2 mm) (g cm^{-3}) (Soon & Soon, 2026).
- vG_i is the volumetric fraction of gravel and coarse fragments (> 2 mm) (dimensionless, $0 \leq vG_i < 1$).
- t_i is the vertical thickness of the sampled soil layer (cm).
- 0.1 is the unit conversion factor (McLachlan, 1999).

Summing SOC_{i_stock} across sequential sampling horizons (e.g., 0–10 cm, 10–30 cm, and 30–100 cm) yields the cumulative profile stock down to one meter. Evaluating deeper soil layers is critical; evaluating topsoil (0–30 cm) alone can yield misleading results. For example, reduced tillage frequently concentrates organic carbon in the top 10 cm while causing subsoil carbon depletion, resulting in a neutral net effect when evaluated down to a full meter (Saltelli & Puy, 2023).

3. Evaluation and Quantification of Regenerative Practices

3.1 Conservation Tillage and Residue Management

Conservation tillage encompasses reduced-tillage (RT) and zero-tillage / no-till (NT) systems designed to minimize mechanical disturbance. Minimizing soil disturbance preserves macroaggregate structure, protects fungal hyphal networks, and reduces crop residue oxidation. Meta-analyses show that transitioning from conventional inversion tillage to no-till increases topsoil (0–20 cm) SOC stocks at rates ranging from 0.06 to 0.50 Mg C ha^{-1} yr^{-1} (Jones et al., 2024).

However, the long-term effectiveness of zero-tillage as a standalone strategy remains a subject of scientific debate. Long-term longitudinal studies reveal that carbon accumulation rates under no-till often slow down after 10 to 20 years as the topsoil reaches a new carbon steady-state or saturation limit (Shukla et al., 2025). Furthermore, if no-till systems are periodically interrupted by conventional tillage for weed management or compaction relief, previously accumulated macroaggregate-protected carbon can be rapidly oxidized, negating years of carbon gains. Sustainable SOC accumulation requires combining reduced tillage with organic inputs, such as crop residue retention and cover crops, to continually replenish the labile carbon pool (Saini et al., 2025).

3.2 Diversified Cover Cropping and Crop Rotations

Integrating cover crops into fallow periods between cash crops provides continuous living roots that supply exudates to soil microbes. A global meta-analysis evaluating 131 paired comparisons in temperate agricultural soils demonstrated that cover cropping increased SOC stocks at an average rate of +0.32 Mg C ha^{-1} yr^{-1} (Zou et al., 2024).

The magnitude of carbon sequestration driven by cover crops depends heavily on biomass yield, species diversity, and management. Multi-species cover crop mixes (combining brassicas, grasses, and legumes) generate diverse root exudate chemistry, stimulating a wider array of microbial functional groups than monocultural cover crops (Garbelini et al., 2022). Legume cover crops (e.g., hairy vetch, crimson clover) fix atmospheric nitrogen (N_2), lowering the C:N ratio of crop residues and facilitating the conversion of labile biomass into microbially derived MAOM. High-biomass grass cover crops (e.g., cereal rye) deposit substantial amounts of root-derived POM, improving aggregate stability and surface water infiltration (Sutton et al., 2025).

3.3 Organic Amendments and Biochar Integration

Exogenous organic additions such as farmyard manure (FYM), composted green waste, and biochar supply stable carbon directly to the soil system, bypassing the metabolic losses associated with in-situ crop residue decomposition (Ali et al., 2025). Meta-analyses evaluating organic management report topsoil SOC stock gains averaging 3.5 Mg C ha^{-1} across paired comparisons, with sustained sequestration rates of 0.45 Mg C ha^{-1} yr^{-1}. In long-term trials spanning 30 to 60 years, FYM applications maintained high effect sizes (> 30.0), demonstrating cumulative gains as organic matter built up over time (Sánchez-Monedero et al., 2019).

Biochar a carbon-rich, highly porous material produced through the pyrolysis of biomass under oxygen-limited conditions represents one of the most stable carbon amendments available. Because biochar contains a high proportion of condensed aromatic carbon structures, it resists microbial degradation, possessing an estimated soil half-life of centuries to millennia (Bonanomi et al., 2017). In field studies, biochar applications have produced high carbon sequestration rates. For example, a single application of 9.3 Mg ha^{-1} biochar (containing 7.25 Mg C ha^{-1}) yielded a cumulative SOC stock increase of +14.1 Mg C ha^{-1} over six years under no-till systems. When combined with regenerative practices (reduced tillage and cover crops), biochar acts as a catalytic habitat for soil microbes,

stimulating microbial biomass carbon (MBC) and accelerating the stabilization of native root exudates into MAOM (Liu et al., 2022).

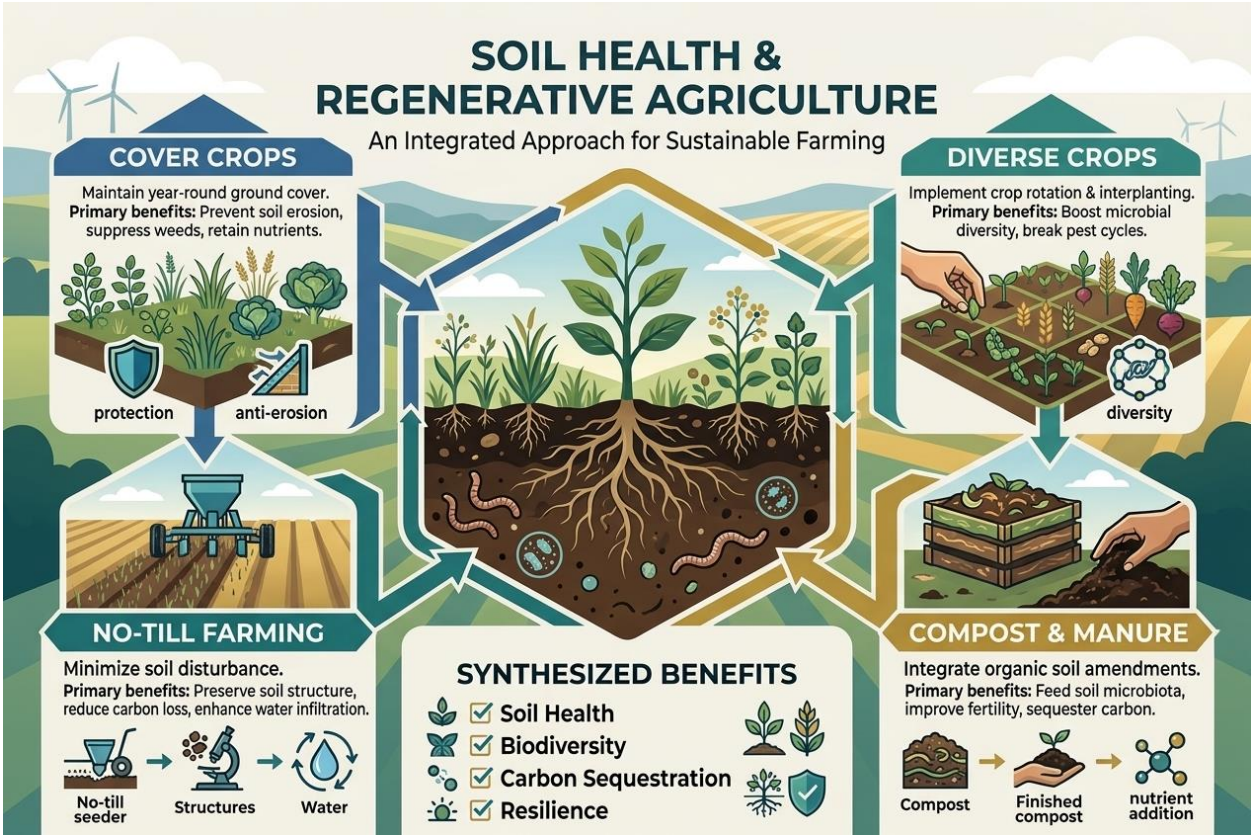


Figure 2: Integrated core practices of regenerative agriculture and their synthesized biological, carbon, and resilience outcomes.

3.4 Agroforestry and Perennial Integration

Agroforestry deliberately integrates woody perennials (trees or shrubs) with agricultural crops or livestock systems. These systems yield some of the highest combined biomass and soil carbon sequestration rates among temperate and tropical land management options. Deep-rooted tree species extract nutrients and water from subsoil layers while continually depositing root biomass and leaf litter across various depths (Fahad et al., 2022).

Systematic reviews demonstrate that agroforestry systems sequester carbon at rates ranging from 0.25 to 19.14 Mg C ha^{-1} yr^{-1} in tree woody biomass, alongside an additional 0.01 to 1.50 Mg C ha^{-1} yr^{-1} within the soil profile. Furthermore, diversified agroforestry systems hold on average 26.53 Mg C ha^{-1} more soil carbon than simplified single-species production systems, representing a 31% increase in SOC storage capacity (Comolli et al., 2025).

3.5 Adaptive Multi-Paddock (AMP) Grazing

Adaptive Multi-Paddock (AMP) grazing also termed holistic planned grazing or high-frequency rotational grazing utilizes high stocking densities of livestock for brief grazing durations, followed by extended recovery periods for pasture plant regeneration. This management emulates natural ungulate herd dynamics, preventing selective overgrazing and stimulating plant photosynthetic activity and root exudation (Mosier et al., 2021).

Empirical evaluations across North American grassland biomes indicate that AMP grazing can

sequester substantial quantities of soil carbon compared to conventional continuous grazing (CG). In southern Ontario pastures, AMP grazing achieved an annual sequestration rate of 0.957 Mg C ha^{-1} yr^{-1} compared to 0.507 Mg C ha^{-1} yr^{-1} under CG, reducing the net greenhouse gas intensity of beef production by 65% (Khatri-Chhetri et al., 2024). In the southeastern United States, AMP grazing increased total SOC stocks down to one meter by 13% (72.49 Mg C ha^{-1} under AMP versus 64.02 Mg C ha^{-1} under CG) and elevated standing crop biomass by more than 300%. Long-term pastured multi-species grazing implementations have documented sustained SOC sequestration rates of up to 2.29 Mg C ha^{-1} yr^{-1} over two decades (Johnson et al., 2022).

Table 1: Comparative Analysis of Soil Organic Carbon (SOC) Sequestration Rates Across Regenerative Practices

Practice Category	Average SOC Sequestration Rate (Mg C ha−1 yr−1)	Dominant Stabilization Mechanism	Dominant Carbon Pool Target	Key References
Conservation / Zero Tillage	$0.06 - 0.50$	Macroaggregate occlusion; physical protection from oxidative decay	Topsoil POM (0–15 cm)	Jordon et al., McCoy, Poeplau & Don
Diversified Cover Cropping	0.32 ± 0.11	Microbial processing of root exudates; root necromass inputs	MAOM and labile POM	Poeplau & Don, Blanco-Canqui, Moukanni et al.
Organic Amendments (FYM / Compost)	$0.45 - 1.26$	Direct exogenous C inputs; microbial assimilation	Mineral-bound MAOM	Poeplau & Don, Basile-Doelsch, Kallenbach
Biochar Amendment	$1.00 - 4.20$	Pyrogenic chemical recalcitrance; aromatic structure resistance	Pyrogenic persistent C	Blanco-Canqui et al., Biochar Today, SOC Review
Agroforestry Systems	$0.25 - 1.50$ (Soil) $0.25 - 19.14$ (Biomass)	Deep root turnover; perennial litter deposition; structural shade	Deep-profile MAOM & POM	Lorenz et al., Mayer et al., Frontiers
Adaptive Multi-Paddock (AMP) Grazing	$0.40 - 3.59$	Pulsed rhizodeposition; litter trampling; root system turnover	Profile-wide MAOM & POM	Mehre et al., Mosier et al., Rowntree et al.

4. Impacts on Crop Yields, Nitrogen Dynamics, and Economics

4.1 Agronomic Yield Dynamics and Transition Trade-offs

A central question in agricultural research is whether regenerative practices can build soil health without causing reductions in crop yields. Comprehensive Bayesian meta-analyses evaluating paired observations across temperate arable systems reveal that adopting individual practices such as reduced tillage intensity or cover cropping does not cause statistically significant yield declines during cropping years. However, these practices rarely generate immediate yield increases

in the short term, challenging simplistic claims of immediate win-win productivity gains (Reckling et al., 2016).

During the initial 1 to 3 years of transitioning from conventional to regenerative systems, farms may experience temporary yield reductions ranging from 5% to 29%, particularly in nitrogen-demanding cereal crops like maize. This initial yield gap stems from temporal mismatches in nitrogen availability as soil microbial communities reorganize, as well as adjustments required for weed control without heavy tillage (Gai et al., 2026). However, as continuous carbon additions stimulate biologically active pools, soil nutrient cycling matures. By years 4 to 10, crop yields in regenerative systems typically stabilize at parity with conventional baselines, and frequently perform better during drought conditions due to superior soil moisture retention (Harter et al., 2026).

4.2 Nitrogen Cycling and Synthetic Input Reduction

Conventional crop production relies heavily on synthetic industrial nitrogen fertilizers synthesized via the Haber-Bosch process. Nitrogen fertilizer application often exceeds seasonal crop uptake demands, resulting in over 50% of applied nitrogen being lost to surrounding environments through nitrate (NO_3^-) leaching, surface runoff, and nitrous oxide (N_2O) emissions (Zhou et al., 2016).

Regenerative systems replace synthetic nitrogen inputs with biologically recycled nutrient sources (RNFs), legume nitrogen fixation, and integrated livestock manures. Leguminous cover crops convert atmospheric N_2 into organic nitrogen compounds that are gradually released as plant-available ammonium (NH_4^+) and nitrate (NO_3^-) through microbial mineralization (Vonk et al., 2025). Furthermore, because organic amendments yield a slow-release nitrogen profile, nitrogen availability aligns more closely with crop uptake curves, reducing peak nitrogen leaching losses. Empirical evaluations across European regenerative farms confirm that these integrated approaches allow producers to reduce synthetic nitrogen fertilizer use by an average of 61% and pesticide application by 75% without compromising long-term enterprise viability (Li et al., 2026).

4.3 Enterprise Profitability and Risk Mitigation

Focusing exclusively on crop yields overlooks farm financial performance, which is determined by net profit margins rather than gross harvested biomass. Regenerative agriculture alters the farm cost structure by dramatically lowering expenditures on energy, machinery operation, synthetic fertilizers, and chemical pesticides (Pagach & Warr, 2015).

A comparative financial study of corn production systems in the Northern Great Plains revealed that conventional farms allocated 32% of their gross income to seed and fertilizer inputs. In contrast, regenerative farms allocated only 12% of gross income to these inputs (Aquino et al., 2022). Consequently, despite producing 29% lower absolute grain yields, the regenerative farms achieved 78% higher net profitability per hectare. Long-term research trials demonstrate that farm profit margins under regenerative management increase by 70% to over 120% after the 3-year transition period. (Buniarto et al., 2026)

Table 2: Agronomic, Environmental, and Economic Performance Metrics under Conventional and Regenerative Systems

System Performance Indicator	Conventional Agriculture Baseline	Regenerative Agriculture System	Net Impact / System Shift	Key Scientific References
Synthetic Nitrogen Input	High ($150-250$ kg N ha^{-1})	Reduced by 60–100% via legumes/manure	61% average global reduction	European Alliance, MDPI Agronomy
Synthetic Pesticide Use	High (routine calendar spraying)	Targeted / Integrated Pest Management	75% reduction in chemical applications	EARA Study, POSTnote
Gross Crop Yield (Short Term)	Optimized baseline (100%)	0% to −29% during transition	Temporary yield gap in early years	Jordon et al., ASPE Report
Gross Crop Yield (Long Term)	Vulnerable to weather extremes	Yield parity; higher drought resilience	Superior yield stability across climate shocks	ASPE Report, FASE Review
Input Cost Share (% Gross Revenue)	High (30% − 35% spent on inputs)	Low (10% − 15% spent on inputs)	Net operational expenditure cut by ~ 60%	Northern Plains Study, EARA
Net Farm Profitability	Lower net margins; high debt exposure	20% to > 100% higher profit margin	Enhanced financial resilience and lower risk	ASPE Report, EARA Study
Soil Carbon Sequestration Rate	Net negative (Loss: 0.245 Mg C ha^{-1} yr^{-1})	Net positive ($0.32-3.59$ Mg C ha^{-1} yr^{-1})	Reverses soil from C source to sink	Poeplau & Dechow, MDPI Carbon

5. Ecosystem Resilience and Hydrological Functions

5.1 Soil Structural Integrity and Available Water Capacity

Soil organic matter functions as a structural scaffold that dictates soil hydrological performance. As fungal hyphae, plant root mucilage, and microbial exopolysaccharides bind fine mineral particles into water-stable aggregates, soil pore structure transforms. Macroaggregates ($> 250\ \mu$m) form inter-aggregate pores that facilitate rapid surface water infiltration, while microaggregates ($< 250\ \mu$m) create intra-aggregate capillary pores that hold plant-available water (Bogunovic et al., 2025).

Quantifying this relationship reveals that for every 1.0% increase in soil organic matter (SOM) concentration in the topsoil profile, the plant-available water capacity (AWC) increases by up to 20,000 gallons per acre (equivalent to approximately 187,000 liters per hectare). This expanded water-holding capacity buffers crops against dry spells by extending the time plants can maintain transpiration before reaching their permanent wilting point (Napoletano et al., 2025). In field evaluations across regional soil health management networks, 97% of participating farmers confirmed that adopting regenerative practices increased their crop resilience to severe weather events, citing rapid water absorption

during heavy storm rainfall and sustained soil moisture retention during dry periods (Radulov et al., 2026).

5.2 Microclimate Buffering and Biotic Resilience

Regenerative practices alter surface microclimates and soil food web architecture. Maintaining continuous surface ground cover via plant residues or living covers lowers peak summer soil temperatures by up to 10°C, reducing direct soil evaporation losses and protecting temperature-sensitive microbial enzymes (Carnicer et al., 2021). In livestock grazing systems, switching to Adaptive Multi-Paddock management increases standing crop biomass by 46% to over 300%. This expanded photosynthetic surface canopy captures more solar radiation, channeling liquid carbon into the rhizosphere. Consequently, soil microbial biomass carbon (MBC) rises significantly, stimulating total fungal and bacterial respiration efficiency (De Frenne et al., 2021). Interestingly, while total photosynthetic C fixation increases under AMP grazing, specific basal soil CO_2 respiration rates per unit carbon stored drop by up to 19.5%. This efficiency shift demonstrates that microbially rich regenerative soils stabilize carbon more effectively, reducing carbon turnover losses back to the atmosphere (Lenoir et al., 2017).

6. Monitoring, Reporting, Verification (MRV), and Policy Implementation

6.1 Challenges in Tracking Background SOC Fluxes

A major technical barrier to scaling carbon-farming initiatives and verifying carbon market offsets is detecting small annual SOC changes against large baseline background carbon stocks. Agricultural topsoils typically contain large background pools ranging from 30 to over 100 Mg C ha^{-1}. Annual SOC increases resulting from regenerative practices (0.32–0.95 Mg C ha^{-1} yr^{-1}) fall within the normal range of spatial baseline variability, making statistical verification challenging over short 1- to 3-year timescales (V'kovski et al., 2021). Furthermore, soil carbon stocks exhibit high vertical variability. Practices such as zero-tillage can concentrate organic carbon near the surface while causing subsoil carbon depletion, creating illusory surface carbon gains if sampling is limited to the upper 15 cm. Comprehensive Monitoring, Reporting, and Verification (MRV) protocols must mandate standardized core sampling down to a minimum depth of 30 cm and ideally to 100 cm using equivalent soil mass (ESM) calculations to correct for bulk density changes induced by management practices (Chen et al., 2010).

6.2 Advanced Quantification Frameworks

To overcome the economic costs of high-density physical soil sampling, modern MRV systems integrate direct soil core sampling with satellite remote sensing and process-based ecosystem models. Remote sensing platforms track surface ground cover, plant phenology, and tillage disturbance frequency across regional landscapes (Yazdinejad et al., 2025). High-resolution satellite observations feed directly into calibrated biogeochemical models such as RothC, Century, and COMET-Farm which simulate microclimates, carbon turnover rates, and nitrogen mineralization dynamics. Coupling direct, stratified soil core sampling with remote sensing and computational modeling reduces verification uncertainty, lowering transaction costs for carbon market participation while maintaining scientific rigor (Moreo et al., 2021).

6.3 Policy Mechanisms and Financial Instruments

Accelerating the global transition toward regenerative agriculture requires aligning policy frameworks, supply chains, and financial incentives. Traditional agricultural subsidy frameworks historically incentivized high-input monocultural production, penalizing complex crop rotations and multi-enterprise farming. Policy instruments are evolving toward rewarding public goods, providing direct financial compensation for verified soil carbon accumulation, biodiversity enhancement, and watershed restoration (Brown & Lee, 2018).

Transitioning successfully requires implementing targeted bridge financing to shield agricultural

producers from short-term financial exposure during the initial three-year adjustment period. Crop insurance programs can be restructured to offer lower premiums for farms utilizing cover crops and reduced tillage, reflecting their reduced risk of drought-induced crop failure (Rekkas, 2021). Concurrently, standardized carbon offset verification rules must enforce long-term permanence guarantees and baseline risk accounting to prevent double-counting. Finally, public funding must support peer-to-peer farmer knowledge networks and regional agronomic extension programs to ensure management decisions are adapted to local climatic and soil conditions (Tchamyou, 2021).

Conclusion

This review demonstrates that regenerative agriculture represents a scientifically grounded and practically viable strategy for addressing the intertwined challenges of soil degradation, climate change, and food security. The evidence synthesized here confirms that regenerative practices including conservation tillage, diversified cover cropping, organic amendments, biochar application, agroforestry, and adaptive multi-paddock grazing can significantly enhance soil organic carbon stocks, with sequestration rates varying by practice, climate, and management context. The mechanistic understanding of particulate versus mineral-associated organic matter dynamics, coupled with the microbial pathway of carbon stabilization, provides a robust theoretical foundation for predicting and optimizing carbon accrual. Agronomically, the transition to regenerative systems entails short-term yield trade-offs, particularly in nitrogen-demanding cereals, but long-term parity and enhanced climate resilience are consistently observed. Economically, reduced input costs and improved profit margins underscore the potential for regenerative agriculture to enhance farm viability, provided that transition financing and risk management tools are accessible. Hydrological and ecological benefits including improved water-holding capacity, microclimate buffering, and biodiversity support further reinforce the multifunctional value of regenerative management. Nevertheless, widespread adoption faces barriers related to monitoring and verification of soil carbon changes, policy inertia favoring conventional production, and knowledge gaps in region-specific practice optimization. Future research should prioritize long-term, multi-location field trials, standardized SOC quantification protocols, and integrated socio-economic analyses. Policy frameworks must evolve to reward ecosystem services, de-risk transition periods, and support farmer-led innovation networks. Ultimately, regenerative agriculture is not a universal prescription but a context-adaptive framework that, when rigorously implemented, can simultaneously advance crop productivity, carbon storage, and ecosystem resilience making it a cornerstone of sustainable food systems for the 21st century.

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