

Soil Health Restoration through Regenerative Agriculture: Implications for Sustainable Food Security

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Abstract

Soil degradation, climate change, and declining resource-use efficiency threaten global agricultural sustainability and food security. Regenerative agriculture (RA) offers a systems-based approach emphasizing soil organic carbon restoration, biodiversity revitalization, and biologically regulated nutrient cycling. Long-term evidence demonstrates that regenerative systems consistently enhance soil organic carbon stocks (+22%), microbial biomass (+100%), and nutrient retention compared to conventional systems, strengthening ecosystem services including water regulation, carbon storage, and nutrient-use efficiency. These improvements reduce greenhouse gas emissions through enhanced carbon sequestration and lower nitrous oxide losses, positioning RA as a viable climate mitigation pathway. While crop productivity remains context-dependent with potential short-term yield variability, reduced input costs, improved stability, and enhanced nutritional quality offset these trade-offs. Adoption is constrained by knowledge gaps, risk perception, and policy frameworks favouring conventional systems. Strengthening soil health through regenerative pathways offers a scientifically grounded route toward resilient, climate-smart food systems.

Keywords: Agriculture; Biodiversity; Carbon; Climate change and Sustainable.

1. Introduction

Global agriculture faces a critical nexus of food security, environmental sustainability, and climate resilience challenges. Food demand is projected to increase by nearly 60% by 2060, while soil quality continues to decline due to long-term degradation of soil biological and physical functions (Foley *et al.*, 2005; Heijden *et al.*, 2023). Approximately one billion hectares worldwide are affected by soil degradation, threatening agricultural productivity, ecosystem services, and rural livelihoods across both developed and developing regions (Meena *et al.*, 2023; TAAS, 2021).

Much of this degradation has been driven by intensive tillage, monocropping, residue removal, and excessive dependence on synthetic fertilizers and pesticides, practices that weaken soil structure, reduce organic matter, and disrupt microbial communities. These processes accelerate erosion, nutrient loss, and declining water-holding capacity, ultimately reducing system

resilience to climatic variability and production shocks (Bender *et al.*, 2016; Foley *et al.*, 2005). In response to these challenges, regenerative agriculture (RA) has emerged as a restorative production paradigm that prioritizes ecological processes, biological regulation, and soil system recovery rather than input-intensive yield maximization.

Long-term comparative studies increasingly demonstrate that regenerative management can substantially enhance soil organic carbon stocks, total nitrogen availability, and microbial biomass, thereby improving nutrient retention, soil structure, and overall ecosystem functioning (Colombi *et al.*, 2025). However, despite its growing scientific and policy prominence, regenerative agriculture remains conceptually diverse and unevenly evaluated across agro-ecological zones, with limited multi-site, long-term assessments examining how combined regenerative practices perform under varying climatic and socio-economic conditions.

Beyond production concerns, modern agriculture also faces declining resource-use efficiency and rising environmental externalities. Intensive cultivation systems frequently contribute to groundwater depletion, nutrient runoff, and landscape-level ecological degradation, creating production systems that may be highly productive in the short term yet environmentally fragile over time. As climate variability increases the frequency of droughts, floods, and heat stress events, farming systems heavily dependent on external inputs encounter growing economic and environmental risks. Regenerative agriculture is therefore being explored not only as a soil restoration strategy but also as an approach capable of stabilizing agroecosystem performance under increasingly unpredictable climatic conditions (Foley *et al.*, 2005; Lal, 2020).

Another emerging dimension is the growing recognition that soil health directly influences crop nutritional quality, plant stress tolerance, and ecosystem resilience. Soils rich in organic matter and microbial diversity improve nutrient availability and support beneficial plant-soil interactions, reducing dependency on agrochemicals while enhancing crop health and stability. Increasing attention is thus being directed toward farming systems capable of delivering multiple outcomes simultaneously—productivity, environmental restoration, and improved food quality—rather than focusing solely on

yield maximization. Regenerative agriculture aligns with this broader systems perspective by emphasizing ecological interactions and soil biological processes as the foundation of sustainable agricultural production (Heijden *et al.*, 2023; Bender *et al.*, 2016).

At a global scale, the transition toward regenerative practices is also being influenced by market and policy developments, including consumer demand for environmentally responsible food production and increasing interest in climate-smart agriculture. Governments and development agencies increasingly recognize soil carbon management as a mechanism for achieving climate mitigation targets while strengthening rural livelihoods and restoring degraded lands. Consequently, regenerative agriculture is gaining importance not only as a technical farming approach but also as part of a broader transformation toward climate-resilient and environmentally sustainable food systems capable of reversing long-term land degradation trends (Lal, 2020; Montgomery, 2017).

2. Conceptual Framework of Soil Health

2.1 Soil Health as a Systems Property

Soil health represents an emergent property arising from interactions among soil structure, nutrient availability, organic carbon pools, and soil biota. International frameworks define it as soil's ability to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health (Doran *et al.*, 2014; ITPS, 2020). In regenerative systems, soil health is measured by functional indicators including aggregation, infiltration capacity, microbial activity, nutrient cycling efficiency, and stress resilience (Colombi *et al.*, 2025).

2.2 Centrality of Soil Organic Matter

Soil organic matter (SOM), particularly soil organic carbon (SOC), occupies a central position in regenerative soil health frameworks. SOC acts as a biophysical nexus, simultaneously influencing soil structure, water retention, nutrient availability, and microbial habitat. RA prioritizes SOC accumulation through enhanced carbon inputs (cover crops, crop residues, composts, manures, root biomass) while minimizing losses from intensive tillage and erosion (Meena *et al.*, 2023). Evidence shows regenerative systems consistently increase SOC stocks, with mean increases of 22% under regenerative organic agriculture (Colombi *et al.*, 2025).

2.3 Soil Biodiversity and Biological Regulation

A defining feature of regenerative frameworks is restoring soil biodiversity as a functional ecosystem service driver. Soils host extraordinary organism

diversity—bacteria, fungi, protozoa, nematodes, arthropods, earthworms—collectively regulating decomposition, nutrient mineralization, disease suppression, and structure formation. Nearly 59% of global biodiversity is linked to soil ecosystems (van der Heijden *et al.*, 2023). Regenerative practices foster biodiversity by reducing chemical stressors, increasing organic substrates, and maintaining living roots, improving nutrient-use efficiency and strengthening plant–soil feedbacks (Bender *et al.*, 2016, 2023).

2.4 Physical Structure and Soil Resilience

Soil physical properties constitute another critical dimension of soil health, directly influencing water movement, aeration, and root development. Practices such as maintaining continuous soil cover, minimizing mechanical disturbance, and enhancing organic matter inputs promote the formation of stable soil aggregates, which improve porosity, infiltration rates, and root penetration while simultaneously reducing erosion risk and compaction (Meena *et al.*, 2023). Enhanced aggregation reduces erosion risk and increases water-holding capacity, building resilience to droughts and extreme rainfall. Regenerative systems improve hydrological regulation by enhancing infiltration and reducing runoff, contributing to groundwater recharge and improved water-use efficiency (TAAS, 2021).

2.5 Ecosystem Services Integration

The regenerative soil health framework is ecosystem service-oriented. Healthy soils simultaneously support provisioning services (food and fiber), regulating services (carbon sequestration, climate regulation, water filtration), supporting services (nutrient cycling, soil formation), and cultural services (Colombi *et al.*, 2025). RA reframes productivity not as short-term yield maximization but as long-term functional performance integrating soil health, environmental integrity, and socio-ecological resilience (Gulaiya *et al.*, 2024).

3. Mechanistic Pathways: SOC–Microbiome–Nutrient Cycling

The mechanistic foundation of RA rests on tight coupling between soil organic carbon, soil microbial communities, and nutrient cycling. These three components form a self-reinforcing system where improvements in one domain amplify gains in others (Meena *et al.*, 2023; Gulaiya *et al.*, 2024).

3.1 Soil Organic Carbon as Primary Driver

SOC functions as the central energy and structural backbone of soil systems. RA promotes SOC accumulation through continuous carbon inputs from crop residues, cover crops, organic amendments, root

exudates, and integrated livestock systems (TAAS, 2021). Unlike conventional systems where tillage and residue removal accelerate carbon oxidation, regenerative practices shift soils toward positive carbon balance. Empirical evidence shows 22% average SOC concentration increases, reflecting improved carbon retention (Colombi *et al.*, 2025). Increased SOC enhances aggregation through organo-mineral complex formation, physically protecting carbon while improving structure and porosity. SOC also serves as a nutrient reservoir, gradually releasing nitrogen, phosphorus, and micronutrients through microbial mineralization (Meena *et al.*, 2023).

3.2 Microbiome Activation and Feedback Loops

The soil microbiome represents the biological engine transforming SOC into functional soil fertility. Regenerative practices create favorable conditions for microbial proliferation by supplying organic substrates, minimizing chemical stressors, and maintaining continuous living roots (van der Heijden *et al.*, 2023). A single gram of healthy soil harbors up to 10^{10} bacterial cells and thousands of microbial taxa. Increased microbial biomass and diversity strengthen plant–soil feedbacks, with root exudates stimulating microbial activity and microbes enhancing nutrient availability and plant stress tolerance. Studies report over 100% increases in microbial biomass carbon under regenerative organic management (Colombi *et al.*, 2025). Mycorrhizal fungi play particularly important roles, extending effective root systems, enhancing phosphorus and nitrogen uptake, improving aggregation through hyphal networks, and facilitating carbon transfer into stable pools (van der Heijden *et al.*, 2023).

3.3 Biological Nutrient Cycling

Nutrient cycling under RA shifts from externally driven input–output systems to biologically regulated internal cycling. Conventional agriculture supplies readily soluble nutrients often exceeding plant uptake capacity, causing leaching, volatilization, and environmental contamination. In contrast, regenerative systems rely on microbial-mediated transformations synchronizing nutrient release with plant demand (Meena *et al.*, 2023). Enhanced SOC and microbial diversity increase soil capacity to retain nutrients within organic and microbial pools, reducing nitrogen losses. Evidence indicates that regenerative systems consistently enhance soil carbon stocks relative to conventional management (Colombi *et al.*, 2025). Increased SOC improves aggregation and porosity while also serving as a reservoir for gradual nutrient release through microbial mineralization (Meena *et al.*, 2023).

3.4 Integrated Feedback Model

The mechanistic relationships among carbon inputs, microbial activity, and nutrient cycling can be conceptualized as a reinforcing feedback system in which improved carbon inputs stimulate microbial communities, enhancing nutrient availability and plant productivity, which in turn increases organic carbon return to soil (Gulaiya *et al.*, 2024; Colombi *et al.*, 2025).

3.5 System Resilience Implications

By simultaneously strengthening SOC pools, microbial networks, and nutrient cycling efficiency, RA enhances soil resilience to climatic and management stresses. Improved water-holding capacity, reduced nutrient losses, and increased biological regulation collectively increase system stability under droughts, extreme rainfall, and input constraints (Meena *et al.*, 2023). While transitional yield variability may occur, long-term evidence suggests regenerative systems stabilize productivity while delivering broader environmental benefits (Colombi *et al.*, 2025).

4. Long-Term Empirical Evidence

Long-term comparative studies (≥ 5 –10 years) provide robust evidence for evaluating RA impacts on soil health. Evidence from global meta-analyses, long-term farming system trials, and region-specific studies consistently indicates regenerative systems outperform conventional systems in key soil health indicators (Colombi *et al.*, 2025).

4.1 Soil Organic Carbon and Nutrient Stocks

SOC accumulation is the most consistently reported outcome. Comparative studies across temperate, tropical, and semi-arid regions show regenerative systems significantly increase SOC and associated nutrient pools. Key findings include:

- Global synthesis: +22% SOC, +28% soil total nitrogen (Colombi *et al.*, 2025)
- Rodale Farming Systems Trial (>40 years): +15–30% SOC, +20–40% nitrogen
- Mediterranean trials (10+ years): +18–25% SOC, +15–22% nitrogen
- Indian experiments (8–15 years): +10–20% SOC, +12–25% nitrogen

These SOC gains translate into improved nutrient retention and reduced losses. Increased organic matter enhances cation exchange capacity and nutrient buffering, allowing regenerative soils to retain nitrogen and phosphorus more effectively (Meena *et al.*, 2023; TAAS, 2021).

4.2 Soil Biological Properties

Long-term regenerative systems show pronounced improvements in biological indicators, particularly

microbial biomass carbon (MBC), enzymatic activity, and functional diversity. These indicators respond more rapidly than SOC during transition phases:

- Microbial biomass carbon: +80–133% (>100% in some studies)
- Enzyme activity (C & N cycling): +40–120%
- Mycorrhizal colonization: +30–70%
- Soil respiration stability: Improved resilience

Biologically diverse soils exhibit lower nitrogen losses and more efficient nutrient cycling, particularly under reduced input conditions (Colombi *et al.*, 2025; van der Heijden *et al.*, 2023).

4.3 Nutrient Cycling Efficiency

A critical advantage of regenerative systems is improved nutrient-use efficiency. Long-term trials demonstrate regenerative management reduces nitrogen leaching and gaseous losses while maintaining adequate nutrient supply. Key outcomes include:

- Nitrogen leaching: High (conventional) vs. Low (regenerative)
- Nitrous oxide emissions: Moderate–high (conventional) vs. Reduced (regenerative)
- Nutrient-use efficiency: Low–moderate (conventional) vs. High (regenerative)
- Synthetic fertilizer dependency: High (conventional) vs. Low–moderate (regenerative)

Cover crops and diversified rotations enhance internal nutrient recycling by capturing residual nutrients and redistributing them across soil profiles (Bender *et al.*, 2016; Meena *et al.*, 2023).

4.4 Crop Yield and Productivity

Yield outcomes are more variable than soil health indicators and depend on climate, crop type, and transition duration. Early transition phases may show yield penalties due to system adjustment, while medium to long-term studies often report yield stabilization approaching conventional systems.

Colombi *et al.* (2025) reported an average 24% reduction in yield under regenerative organic systems; however, these differences frequently narrow under stress conditions, and regenerative systems often demonstrate improved resilience and nutritional quality. Importantly, the mechanisms governing long-term yield stability under climate extremes remain insufficiently understood and represent a key research gap.

4.5 Integrated Synthesis

Long-term evidence indicates RA consistently delivers superior soil health outcomes relative to conventional

systems, particularly in SOC accumulation, biological activity, and nutrient cycling efficiency. While yield trade-offs may occur during early transition periods, regenerative systems demonstrate greater long-term stability, resilience, and ecosystem service delivery. From a systems perspective, RA replaces input-intensive productivity with biologically mediated efficiency, enhancing soil as natural capital rather than exploiting it as a consumable resource (Gulaiya *et al.*, 2024; Meena *et al.*, 2023).

5. Climate Change Mitigation and GHG Dynamics

Agriculture accounts for substantial global greenhouse gas (GHG) emissions through carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). RA is positioned as a climate-smart paradigm because it directly targets the soil–carbon–nitrogen nexus governing agricultural GHG fluxes (Meena *et al.*, 2023; Gulaiya *et al.*, 2024).

5.1 Soil Carbon Sequestration

The primary climate mitigation pathway is enhanced soil carbon sequestration. By increasing organic carbon inputs and reducing soil disturbance, regenerative systems slow carbon mineralization while promoting stabilization within aggregates and mineral-associated organic matter pools (Colombi *et al.*, 2025). Evidence demonstrates regenerative systems accumulate significantly higher SOC stocks, functioning as net carbon sinks. Global synthesis studies indicate SOC gains range from 0.2 to 1.0 Mg C ha⁻¹ yr⁻¹, depending on climate, soil type, and management intensity (Lal, 2020; Colombi *et al.*, 2025).

5.2 Nitrous Oxide Emissions

Nitrous oxide, with a global warming potential approximately 298 times greater than CO₂, is strongly influenced by nitrogen management. Conventional agriculture's high synthetic nitrogen inputs lead to elevated N₂O emissions. RA mitigates emissions by enhancing biological nitrogen cycling, improving nitrogen-use efficiency, and reducing surplus mineral nitrogen (Meena *et al.*, 2023). Studies show soils with higher microbial diversity and SOC exhibit lower N₂O emissions and reduced leaching, even under comparable nitrogen inputs (Bender *et al.*, 2016; van der Heijden *et al.*, 2023). Cover cropping, organic amendments, and diversified rotations synchronize nitrogen release with crop demand, minimizing emission hotspots.

5.3 Methane Dynamics

Methane emissions are context-dependent, particularly in livestock-integrated systems. While enteric methane remains challenging to mitigate, regenerative

grazing approaches such as Adaptive Multi-Paddock (AMP) grazing aim to improve pasture productivity, enhance soil carbon sequestration, and partially offset livestock emissions through improved ecosystem functioning (TAAS, 2021). In rice-based and flooded systems, regenerative residue and water management reduce anaerobic conditions favouring methanogenesis, thereby lowering CH₄ emissions (Meena *et al.*, 2023).

6. Socio-economic Dimensions and Adoption Barriers

Regenerative agriculture holds particular relevance for farming systems located in fragile and erosion-prone landscapes worldwide. Practices that maintain continuous soil cover and enhance organic matter inputs help reduce soil erosion, improve water retention on sloping and degraded lands, and enhance resilience in nutrient-poor or structurally fragile soils. Such adaptive management approaches demonstrate how regenerative systems can address both global sustainability challenges and local agro-ecological constraints across diverse agricultural environments.

6.1 Economic Performance

RA often alters farming system economic structure by reducing reliance on external inputs. However, regenerative systems frequently demand higher management attention and labor inputs, requiring continuous observation, adaptive grazing or cropping decisions, and diversified crop planning. This increased management intensity can be a barrier, particularly for aging farming populations or regions facing labor shortages (TAAS, 2021).

6.2 Knowledge and Institutional Constraints

A significant adoption barrier is knowledge asymmetry. RA is management-intensive and context-specific, requiring farmers to understand soil biological processes, adaptive decision-making, and long-term planning. Limited access to extension services, demonstration trials, and region-specific data constrains adoption, particularly in developing countries (Meena *et al.*, 2023). Risk aversion further limits adoption, as farmers operating under narrow profit margins may be unwilling to experiment with practices perceived as uncertain. The absence of standardized soil health metrics and ecosystem service valuation complicates performance evaluation and credit access (Colombi *et al.*, 2025).

6.3 Policy and Market Barriers

Current agricultural policies in many regions favour input-intensive systems through subsidies for fertilizers, irrigation, and energy, reducing economic incentives for regenerative practices despite environmental benefits (TAAS, 2021). Moreover,

ecosystem services provided by regenerative systems—such as carbon sequestration and water regulation—are rarely monetized, limiting financial returns to farmers. Emerging mechanisms such as carbon markets, payments for ecosystem services (PES), and sustainability-linked supply chains offer potential pathways, but implementation remains uneven and institutionally complex.

7. Knowledge Gaps and Research Priorities

7.1 Critical Knowledge Gaps

Despite growing literature, several critical gaps remain:

- Long-term, multi-site experiments evaluating combined regenerative practices across agro-ecological zones are scarce
- Limited understanding of SOC sequestration thresholds and saturation points under regenerative management
- Interactions between regenerative practices and crop yield stability, nutritional quality, and climate extremes require investigation
- Socio-economic outcomes, particularly labor dynamics and gender impacts, remain underexplored (Colombi *et al.*, 2025; Gulaiya *et al.*, 2024)

7.2 Research Priorities

Future research should prioritize:

- Integrated soil–plant–microbiome–climate models to quantify system-level outcomes
- Long-term assessments of GHG balances, including trade-offs between CO₂, N₂O, and CH₄
- Development of standardized soil health indicators linked to ecosystem services
- Participatory research frameworks that co-produce knowledge with farmers

7.3 Policy Implications

Policy frameworks must shift from yield-centric metrics toward ecosystem-based performance indicators. Key policy actions include:

- Incentivizing SOC sequestration through carbon credits and soil health payments
- Reorienting subsidies to support regenerative transitions rather than input use
- Strengthening extension systems and institutional support for knowledge dissemination
- Aligning RA with Sustainable Development Goals (SDGs) related to climate action, food

security, and land degradation neutrality (TAAS, 2021)

8. Conclusion

Regenerative agriculture offers a scientifically grounded pathway toward resilient, climate-smart food systems capable of sustaining productivity while restoring environmental integrity. Long-term evidence demonstrates consistent improvements in soil organic carbon, microbial biomass, and nutrient cycling efficiency compared to conventional systems. Enhanced carbon sequestration and reduced greenhouse gas emissions position RA as a viable climate mitigation strategy. While context-dependent yield variability exists, particularly during transition phases, reduced input costs, improved system stability, and enhanced nutritional quality provide compelling economic and environmental rationales. Overcoming adoption barriers requires addressing knowledge gaps, risk perception, and policy structures that currently favor input-intensive agriculture. Strengthening institutional support, developing standardized soil health metrics, and creating financial incentives for ecosystem services are essential steps toward mainstreaming regenerative practices. As global agriculture confronts the interconnected challenges of food security, climate change, and resource degradation, regenerative agriculture represents not merely a farming technique but a fundamental reorientation toward ecological integrity and long-term sustainability.

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