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Regenerative agriculture: A comprehensive review of practices, carbon sequestration potential, and socio-economic dimensions

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Abstract

Regenerative agriculture (RA) has emerged as a transformative paradigm shift in food production, moving beyond sustainability toward active ecosystem restoration. This review synthesizes current research on RA practices, their effectiveness in soil carbon sequestration, greenhouse gas mitigation, and socio-economic implications. Drawing on meta-analyses, field trials, and case studies from diverse agro-ecological contexts, we examine the evidence base for core RA practices including conservation tillage, cover cropping, crop diversification, agroforestry, and integrated livestock management. Quantitative synthesis reveals that biochar application achieves the highest soil organic carbon gains (effect size 3.11 under REML model), followed by farmyard manure, green manure, and conservation tillage. No-tillage reduces CO₂ emissions by up to 47%, while diversified crop rotations decrease N₂O emissions by 23-57%. However, outcomes are highly context-dependent, with semi-arid and sub-humid regions showing particularly strong responses. The review identifies critical knowledge gaps, including trade-offs between practices, long-term transition dynamics, and the need for standardized assessment frameworks. We conclude that regenerative agriculture offers viable pathways for climate change mitigation and soil restoration, but success requires regionally adapted, practice-specific implementation supported by robust policy incentives and farmer-centered research approaches.

Keywords: Regenerative agriculture, soil organic carbon, carbon sequestration, conservation agriculture, agroforestry, climate change mitigation, soil health

1. Introduction

1.1 The Imperative for Agricultural Transformation

Agriculture occupies a paradoxical position in the Anthropocene. Covering approximately 40% of Earth's terrestrial surface, it is simultaneously essential for human survival and a primary driver of environmental degradation. Conventional agricultural systems, characterized by intensive tillage, monoculture cropping, and heavy reliance on synthetic inputs, have achieved remarkable gains in productivity but at substantial ecological cost. Soil degradation affects 33% of global soils, agriculture contributes approximately 24% of anthropogenic greenhouse gas (GHG) emissions when including land-use change, and biodiversity continues to decline at unprecedented rates.

The urgency for transformation is underscored by multiple intersecting crises. Soil organic carbon (SOC) depletion compromises fertility, water retention, and climate resilience. Nitrogen and phosphorus runoff creates dead zones in coastal waters. Agricultural GHG emissions undermine climate stability, while farming communities face economic pressure from rising input costs and market volatility. In the UK alone, fertilizer prices increased by over 40% since 2019, exemplifying the economic vulnerability of input-dependent systems.

1.2 Defining Regenerative Agriculture

Regenerative agriculture lacks a universally accepted definition, reflecting its emergence as a farmer-led movement rather than a prescriptive certification standard. Unlike organic farming's rule-based framework, RA is typically characterized by outcome-oriented principles that guide practice selection based on local context. The most widely cited framework articulates five core

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principles:

1. Reduce soil disturbance (minimize mechanical tillage)
2. Keep soil covered (maintain continuous ground cover)
3. Maintain living roots (ensure year-round root activity)
4. Increase diversity (crop rotations, polycultures, agroforestry)
5. Integrate livestock (managed grazing to close nutrient cycles)

These principles translate into diverse practices including no-till or reduced tillage, cover cropping, crop residue retention, diversified rotations, organic amendments (compost, manure, biochar), agroforestry, and managed rotational grazing. What distinguishes RA from conservation agriculture is its explicit goal of improving rather than merely sustaining ecosystem health, with emphasis on building soil organic matter, enhancing biodiversity, and increasing carbon sequestration.

1.3 Scope and Objectives

This review synthesizes current evidence on regenerative agriculture across three domains: (1) carbon sequestration potential and GHG mitigation, (2) soil health outcomes, and (3) socio-economic dimensions including adoption drivers and economic viability. We integrate findings from recent meta-analyses, long-term field trials, and case studies, with attention to context-dependency across agro-ecological regions. The review concludes by identifying knowledge gaps and priorities for future research.

2. Core Regenerative Practices and Mechanisms

2.1 Conservation Tillage

Conventional tillage involving moldboard plowing accelerates SOC decomposition through aggregate disruption, increased aeration, and erosion. Conservation tillage—including no-till, reduced tillage, and strip-till—minimizes these losses. The primary mechanisms for carbon benefit include: reduced oxidation of soil organic matter, improved aggregate stabilization protecting occluded carbon, and altered vertical distribution of residues.

A comprehensive meta-analysis encompassing 566 data points found that conservation tillage reduced all three major GHGs, with no-tillage specifically decreasing CO₂ emissions by up to 47%. However, outcomes vary substantially with climate, soil type, and implementation duration. In tropical regions, no-till without residue retention may produce limited benefits due to rapid decomposition rates.

2.2 Cover Cropping and Residue Management

Cover crops—non-cash crops grown to provide ecosystem services—address multiple regenerative principles simultaneously. They maintain living roots and soil cover between cash crops, add organic matter, scavenge residual nutrients, and support soil biology. Leguminous cover crops fix atmospheric nitrogen, reducing synthetic fertilizer requirements, while diverse cover crop mixtures enhance biodiversity benefits. Crop residue retention, whether from cover crops or main crops, provides surface mulch that moderates soil temperature, conserves moisture, and serves as carbon substrate. A meta-analysis of Indian agricultural systems found that crop residue retention demonstrated moderate yet consistent carbon benefits across time scales, with SOC gains most significant over durations exceeding five years.

2.3 Crop Diversification and Rotation

The shift from monoculture to diversified rotations represents a foundational regenerative practice. Diverse rotations disrupt pest and disease cycles, optimize nutrient use through complementary rooting patterns, and increase the quantity and quality of carbon inputs. Including perennial phases (e.g., forage leys) in arable rotations is particularly beneficial, as perennial root systems allocate substantial carbon belowground.

Quantitative evidence demonstrates significant GHG mitigation: crop rotations decreased N₂O emissions by 23-57% in irrigated cropping systems. Global warming potential reductions vary by crop, with reported decreases of 10.8% in barley, 13.7% in maize, 22.5% in rice, and 30.1% in soybean.

2.4 Organic Amendments: Compost, Manure, and Biochar

Organic amendments enhance SOC through direct carbon addition and by stimulating aggregation that protects existing carbon. The magnitude of effect varies considerably by amendment type, application rate, and baseline soil conditions.

A meta-analysis of 147 Indian studies using random-effects modeling (REML) found biochar application produced the highest SOC gains (effect size 3.11, 95% CI not reported), followed by farmyard manure, green manure, and compost. Fertilizer management interventions demonstrated moderate effects. Importantly, the same analysis revealed that publication bias correction reduced overall effect estimates from 3.46 to 1.98 after imputing 296 potentially missing data points, suggesting that while benefits are robust, the magnitude may be inflated in published literature.

Biochar—pyrolyzed biomass—deserves special mention due to its recalcitrance. Unlike fresh organic matter that decomposes within years to decades, biochar's aromatic carbon structure persists for centuries, offering long-term carbon storage. However, biochar's effectiveness depends on feedstock, pyrolysis conditions, and soil properties, with benefits most pronounced in sandy, acidic, or degraded soils.

2.5 Agroforestry Systems

Agroforestry—integrating trees with crops and/or livestock—represents perhaps the most powerful regenerative practice for long-term carbon storage. Trees sequester carbon in perennial biomass while contributing aboveground and belowground litter that builds SOC. Additional benefits include microclimate regulation, enhanced water infiltration, biodiversity habitat, and diversified income streams.

A field study comparing land-use systems in Verona, Italy, demonstrated that agroforestry and polycyclic forestry systems showed higher organic carbon, nitrogen, and base cation contents compared to arable soils. Enzymatic activity related to carbon, nitrogen, and sulfur cycling was enhanced in tree-based systems, indicating improved biological functionality. The study concluded that land use was the dominant factor affecting soil properties, with agroforestry systems demonstrating capacity to regenerate degraded soils.

Case studies from Brazil's semi-arid region illustrate practical implementation. The RAC-SAF system (Greywater Reuse and Agroforestry System) combines household greywater filtration with agroforestry production, enabling families to irrigate plots up to 625 square meters while filtering approximately 60,000 litres of water annually. Participating families earn up to US\$300 monthly from agroforestry products, demonstrating economic viability alongside environmental benefits.

2.6 Integrated Crop-Livestock Systems

Integrating livestock enables closed-loop nutrient cycling where manure replaces synthetic fertilizers. Managed rotational grazing—moving livestock through paddocks to optimize forage recovery—can increase soil carbon through enhanced root turnover and manure inputs while preventing overgrazing degradation. However, outcomes are highly management-dependent, with poorly managed grazing potentially reducing soil carbon.

3. Carbon Sequestration: Evidence and Quantification

3.1 Soil Organic Carbon Dynamics

Soil represents Earth's largest terrestrial carbon pool, containing approximately 2,300 billion tonnes of carbon—more than vegetation and atmosphere combined. Small percentage increases in SOC thus represent substantial carbon storage. The "4 per 1000" initiative, launched at the 2015 Paris Climate Conference, articulates that increasing global SOC stocks by 0.4% annually could offset current anthropogenic CO₂ emissions.

Regenerative practices enhance SOC through multiple mechanisms: increased carbon input via greater biomass production and root exudation, reduced carbon loss through decreased decomposition rates and erosion protection, and altered stabilization pathways favoring mineral-associated or aggregate-protected carbon. The relative importance of these mechanisms varies with practice, climate, and soil properties.

3.2 Quantitative Synthesis of Carbon Outcomes

Recent meta-analyses provide increasingly robust quantification. A comprehensive review synthesizing 283 studies (both short- and long-term field trials) concluded that regenerative management practices consistently enhance arable soil carbon stocks, improve fertilizer use efficiency and crop yields, while reducing GHG emissions.

The India-focused meta-analysis offers particularly valuable insights for tropical and sub-tropical contexts. Using restricted maximum likelihood (REML) estimation, researchers found an overall effect size of 3.11 (standard error 0.22) with moderate heterogeneity ($I^2 = 75.6\%$). Subgroup analyses revealed that SOC gains were most significant over durations exceeding five years, highlighting the importance of long-term practice maintenance. Semi-arid and sub-humid regions showed particularly strong responses, suggesting these water-limited environments may have greater carbon sequestration potential than humid regions where decomposition rates are higher.

A separate meta-analysis examining GHG outcomes found that organic fertilizers reduced N₂O and CH₄ emissions by 0.81% and 2.34% respectively, but increased CO₂ emissions by 3.83%. Cover crops lowered CO₂ emissions by 0.26% while increasing N₂O and CH₄ by 0.83% and 0.54%. These findings illustrate the importance of multi-gas accounting: reducing one GHG may inadvertently increase another, and net climate impact depends on the balance.

3.3 Context Dependency and Regional Variation

Carbon outcomes are not uniform but vary systematically with environmental and management factors. Temperature and precipitation strongly influence decomposition rates, with warm, moist conditions accelerating carbon turnover. Soil texture affects carbon stabilization capacity, with clay-rich soils protecting more carbon than sandy soils. Baseline carbon status matters: depleted soils often show greater relative gains than carbon-rich soils, though absolute sequestration potential may be

lower.

The Indian meta-analysis documented variation across agro-ecological regions, with the Trans-Gangetic Plain, Middle Gangetic Plain, and Deccan Plateau showing distinct response patterns. Such regional variation underscores that global averages obscure important local dynamics; effective policy requires region-specific evidence.

4. Greenhouse Gas Mitigation Beyond Carbon Dioxide

4.1 Methane and Nitrous Oxide Dynamics

While carbon sequestration receives substantial attention, agricultural GHG mitigation requires addressing all three major gases: carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). N₂O deserves particular focus, as its global warming potential is approximately 265 times that of CO₂ over a 100-year horizon, and agricultural soils are the primary anthropogenic source.

Regenerative practices affect N₂O through multiple, sometimes countervailing, mechanisms. Organic amendments increase available carbon, potentially stimulating denitrifying microorganisms that produce N₂O. However, improved soil aeration from reduced tillage can decrease denitrification. Cover crops scavenge residual nitrogen, reducing N₂O production potential, but their decomposition provides substrate that may increase emissions. The net effect depends on specific practices, timing, and environmental conditions.

The meta-analysis reporting 23-57% N₂O reductions from crop rotations suggests diversification generally reduces emissions, likely through more efficient nitrogen cycling. However, the same analysis found cover crops increased N₂O by 0.83% on average, though with substantial variation across studies.

4.2 Trade-offs and Synergies

Understanding practice interactions is critical. For example, no-till reduces CO₂ emissions but may increase N₂O emissions under certain conditions, particularly in poorly drained soils where denitrification proceeds anaerobically. The net global warming potential depends on the relative magnitude of these effects, which varies with site conditions.

Long-term studies are essential because short-term dynamics may mislead. Initial adoption of no-till can cause temporary N₂O spikes as soils adjust, but emissions may stabilize or decline over time. Similarly, SOC accumulation typically slows after an initial rapid phase as soils approach new equilibrium. The ETH Zurich project investigating regenerative agriculture in Switzerland explicitly addresses such trade-offs, working with 15 farmers to assess environmental, economic, and social metrics simultaneously.

5. Socio-Economic Dimensions of Regenerative Transition

5.1 Farmer Adoption Drivers

Understanding why farmers adopt regenerative practices is essential for designing effective policy. A qualitative study of 31 US farmers and ranchers who self-identified as regenerative practitioners identified several key drivers. Primary among these was concern for health—of people, soils, and ecosystems—expressed as an integrated systems perspective rather than separate environmental and economic considerations.

The study identified two distinct adoption pathways correlating with economic privilege. At one extreme, "privileged idealism" characterized farmers who could absorb transition costs and risks due to off-farm income or accumulated assets. At the other, "less privileged necessity" described farmers facing economic pressure who adopted regenerative practices to reduce input

costs and improve resilience. Both pathways converged on a shared critique of industrial agriculture as environmentally and morally problematic.

Relational values—perspectives on the relationship between humans and nature—emerged as important adoption drivers. Farmers described regenerative agriculture as aligning with their identity as land stewards, suggesting that policies appealing solely to economic self-interest may miss crucial motivational dimensions.

5.2 Economic Outcomes and Risk

Economic evidence for regenerative agriculture remains limited and context-dependent. The Brazil agroforestry case study documented household income increases up to US\$300 monthly from product sales. Reduced input costs—particularly synthetic fertilizers and fuel—represent immediate economic benefits. The UK H3 project noted that fertilizer price increases exceeding 40% since 2019 have improved the relative economics of reduced-input systems.

However, transition periods pose economic risk. Soil health improvements accumulate gradually, while yields may initially decline as systems adjust. The FixOurFood and H3 projects in the UK explicitly study these transition dynamics, recognizing time lags between practice change and outcome realization. Short-term funding cycles (typical research grants of 3-5 years) poorly align with the multi-year timeframes required for SOC accumulation and system stabilization.

Carbon markets offer potential revenue streams, with farmers receiving payments for verified SOC increases or emission reductions. However, measurement challenges, high verification costs, and concerns about permanence and additionality have limited market development. The scientific community continues to debate appropriate methodologies for SOC quantification and verification.

5.3 Barriers to Adoption

Multiple barriers impede regenerative transition. Knowledge gaps are paramount: farmers report uncertainty about which practices to implement, in what combinations, and under what conditions. Equipment constraints matter; no-till adoption may require new seed drills. Labor requirements can shift, with reduced tillage offset by increased cover crop management. Social and cultural factors include community norms and identity—farmers may face scrutiny for "messy" fields that violate conventional aesthetic standards.

Policy environments create both opportunities and barriers. The UK's Sustainable Farming Incentive rewards practice adoption, while private supply chain schemes increasingly incorporate regenerative criteria. However, the absence of standardized definitions and verification frameworks creates confusion. Farmers may adopt practices labeled "regenerative" without clear evidence of effectiveness for their context.

6. Challenges and Research Priorities

6.1 The Definition Problem

The absence of a standardized regenerative agriculture definition creates fundamental challenges for research synthesis, policy design, and market development. Unlike "organic," which has codified standards and certification.

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