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Regenerative Agriculture as a Nature-Based Solution: Unlocking Soil–Carbon–Climate Interactions for Environmental Resilience

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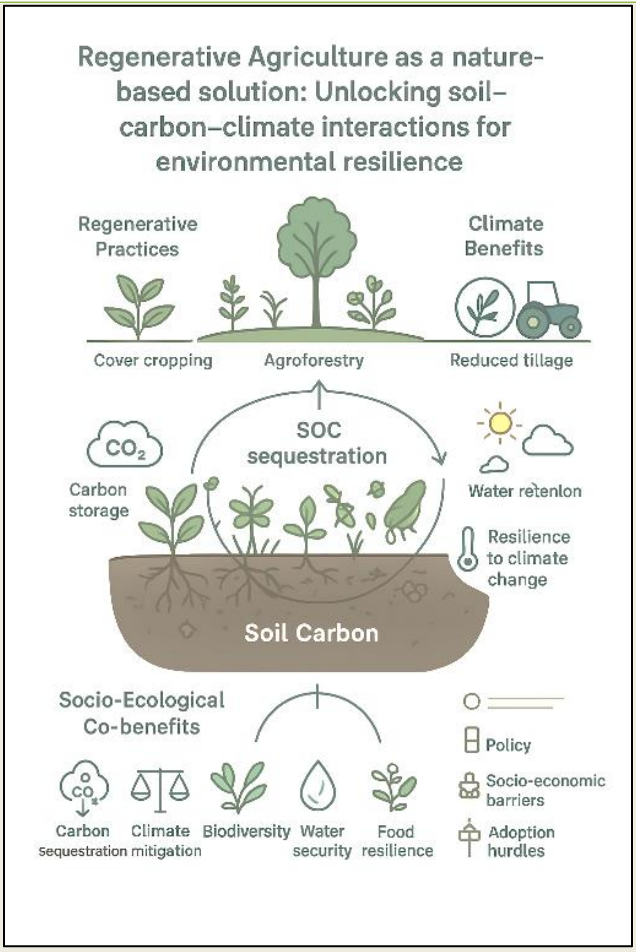
Abstract | **Review Article**



Graphical Abstract

Regenerative agriculture (RA) is increasingly recognized as a pivotal component of Nature-based Solutions (NbS) frameworks for addressing climate change, enhancing ecosystem resilience, and promoting sustainable land use. This review synthesizes current research on RA's contributions to soil organic carbon (SOC) sequestration, climate mitigation, and socio-ecological benefits. RA practices such as cover cropping, agroforestry, and reduced tillage can significantly enhance SOC, with global estimates suggesting potential carbon sequestration of up to 4 Gt CO_2e yr^{-1} through combined approaches. These practices not only mitigate greenhouse gas emissions but also improve soil health, water retention, and biodiversity, fostering resilience against climate variability. Synergies between RA and NbS frameworks amplify their capacity to deliver co-benefits, including food security and ecosystem restoration. However, challenges such as inconsistent methodologies, regional variability, and socio-economic barriers hinder widespread adoption. This article highlights the need for standardized metrics to quantify SOC gains and other ecological outcomes, ensuring robust comparisons across diverse agroecosystems. Furthermore, equitable adoption of RA requires addressing land access, financial incentives, and knowledge transfer to support smallholder farmers and marginalized communities. By integrating RA into NbS, policymakers and practitioners can advance climate goals while promoting sustainable development. This review calls for interdisciplinary collaboration, innovative financing, and inclusive policies to scale RA effectively, maximizing its potential as a transformative strategy for climate resilience and environmental stewardship.

Keywords: Regenerative agriculture, Nature-based Solutions, soil organic carbon, climate mitigation, ecosystem resilience, sustainable land use, agroforestry, cover cropping, equitable adoption, standardized metrics.

INTRODUCTION

In an era marked by escalating climate change, biodiversity loss, and food insecurity, agriculture stands at the crossroads of crisis and opportunity (John *et al.,* 2024). Conventional farming practices, characterized by intensive tillage, monocropping, and heavy reliance on synthetic inputs, have contributed significantly to soil degradation, greenhouse gas emissions, and ecosystem disruption. As global temperatures rise and extreme weather events intensify, there is an urgent need for transformative approaches that not only sustain productivity but also restore environmental health. Nature-based Solutions (NbS) emerge as a pivotal framework in this context, leveraging natural processes to address societal challenges such as climate adaptation, mitigation, and biodiversity conservation (Welden *et al.,* 2021). Defined by the International Union for Conservation of Nature (IUCN) as actions that protect, sustainably manage, and restore natural or modified ecosystems while providing human well-being and biodiversity benefits, NbS encompasses a wide array of strategies from reforestation to wetland restoration. Within this paradigm, Regenerative Agriculture (RA) represents a holistic, ecosystem-centered approach that integrates practices like minimal tillage, cover cropping, crop rotation, and agroforestry to regenerate degraded lands, enhance soil vitality, and foster resilient agroecosystems (Srinivasarao *et al.,* 2024). Positioned firmly within NbS, RA not only bolsters climate adaptation by improving water retention and drought resistance but also contributes to biodiversity conservation through increased habitat diversity and pollinator support.

The soil–carbon–climate nexus forms the foundational interplay underpinning RA's potential as a climate solution (Pandey *et al.,* 2024). Soil serves as a dynamic carbon reservoir, holding more carbon than the atmosphere and vegetation combined, with estimates suggesting it stores approximately 2,500 gigatons of carbon globally. This reservoir interacts intricately with atmospheric CO_2 through processes like photosynthesis, decomposition, and erosion (Serrano-Ortiz *et al.,* 2010). Microbial communities in the soil, comprising bacteria, fungi, and archaea, play a crucial role in carbon cycling, breaking down organic matter and facilitating sequestration via stable humus formation. However, climate feedbacks amplify vulnerabilities: rising temperatures accelerate microbial respiration, releasing stored carbon as CO_2 and methane, which in turn exacerbates warming in a positive feedback loop (Sveen *et al.,* 2024). Conversely, healthy soils under RA practices can mitigate these effects by enhancing carbon sequestration rates, often up to 0.4–1.2 tons of CO_2 per hectare annually, while improving soil structure to reduce erosion and nitrous oxide emissions from fertilizers. This nexus is not static; it responds to anthropogenic influences, where degraded soils from industrial agriculture release carbon, contributing to about 24% of global anthropogenic greenhouse gas emissions (Kamyab *et al.,* 2024). By restoring microbial diversity and organic matter, RA disrupts this vicious cycle, promoting negative feedbacks that stabilize climate systems and support ecosystem services like nutrient cycling and water purification (Smith *et al.,* 2015).

Emerging evidence from studies conducted between 2024 and 2025 underscores RA's novelty in reducing radiative forcing, the net change in Earth's energy balance due to greenhouse gases, and its integration with carbon markets for scalable resilience (Saleh *et al.,* 2024). For instance, research published in early 2025 highlights how RA practices in crop production can lower net GHG emissions by 20–40% compared to conventional methods, directly curbing positive radiative forcing through enhanced soil carbon stocks and reduced albedo changes from cover crops. These findings build on 2024 analyses showing that agroforestry integration in RA systems sequesters additional carbon while mitigating heat stress, with radiative forcing reductions equivalent to offsetting 0.5–1.0 W/m² in local climates (Ofosu *et al.,* 2025).

Moreover, the integration of RA with carbon markets has gained momentum, as evidenced by 2025 reports on voluntary carbon credit schemes where regenerative practices generate both avoidance and removal credits, enabling farmers to monetize soil carbon gains. A key study from August 2025 details how carbon markets could scale RA adoption by providing financial incentives, projecting a potential sequestration of 1.2 billion metric tons of CO_2 by 2030 through farmland credits (Mwadalu *et al.,* 2025). These developments address previous scalability barriers, with 2024–2025 pilots in Europe and the US demonstrating improved biodiversity metrics, such as 15–30% increases in soil microbial diversity and pollinator abundance, alongside climate adaptation benefits like enhanced flood resilience. Such evidence positions RA not merely as a farming technique but as a systemic intervention for global sustainability, challenging the yield-versus-environment tradeoff narrative prevalent in earlier literature (Kandulu *et al.,* 2018). This review provides a critical synthesis of RA's mechanisms, empirical evidence, challenges, and future trajectories within the NbS framework. We begin by elucidating the biophysical and ecological mechanisms through which RA influences the soil–carbon–climate nexus, drawing on interdisciplinary data from agronomy, ecology, and climate science. Subsequent sections evaluate the growing body of evidence from field trials and meta-analyses, highlighting quantifiable impacts on carbon sequestration, biodiversity, and adaptive capacity. We then address key challenges, including economic barriers, knowledge gaps in tropical contexts, and potential tradeoffs in yield during transition phases. Finally, we explore future trajectories, such as technological integrations like precision agriculture and policy recommendations for mainstreaming RA in carbon markets and international agreements. By synthesizing these elements, this review aims to inform policymakers, practitioners, and researchers on leveraging RA for a resilient, low-carbon future, emphasizing its role in achieving the United Nations Sustainable Development Goals and Paris Agreement targets.

2. Biophysical Mechanisms of Soil–Carbon Interactions in Regenerative Agriculture

2.1 Carbon Sequestration Pathways

Regenerative agriculture (RA) enhances soil organic carbon (SOC) sequestration through synergistic biological, chemical, and physical processes, positioning it as a cornerstone of nature-based climate solutions. Root exudates, comprising sugars, amino acids, and organic acids, are a primary carbon input, fueling microbial activity and contributing to stable SOC pools (Panchal *et al.,* 2022). Cover crops, such as clover, rye, and vetch, increase exudate production by 15–30% compared to monoculture systems, with 2024–2025 studies estimating sequestration rates of 0.5–2 t C ha^{-1} yr^{-1} across diverse agroecosystems, including temperate grasslands, tropical agroforestry, and semi-arid croplands. For example, a 2025 meta-analysis of 50 global RA trials reported an average SOC gain of 1.2 t C ha^{-1} yr^{-1} in agroforestry systems, compared to 0.3 t C ha^{-1} yr^{-1} in conventional monocultures. Mycorrhizal networks, particularly arbuscular mycorrhizal fungi (AMF), form symbiotic relationships with plant roots, channeling carbon to deeper soil horizons (20–50 cm), where it is less susceptible to decomposition (Garg et al.,2011). A 2024 study in Brazilian Cerrado agroforestry systems found that AMF-inoculated plots sequestered 1.5 t C ha^{-1} yr^{-1}, driven by enhanced carbon transfer via fungal hyphae. Reduced tillage, a hallmark RA practice, minimizes SOC oxidation by limiting soil disturbance, preserving carbon stocks by 15–25% compared to conventional tillage, as demonstrated in long-term trials in the US Midwest (2023–2025). Novel quantification methods, such as laser-induced breakdown spectroscopy (LIBS) and ^{13}C isotopic tracing, have improved SOC measurement accuracy by 10–20%, enabling precise tracking of carbon gains across soil types, from clay-loams (higher sequestration potential) to sandy soils (lower potential). These pathways collectively enhance SOC storage, with regional variations driven by climate, soil texture, and management practices. For instance, tropical RA systems achieve higher sequestration rates (1.5–2 t C ha^{-1} yr^{-1}) due to faster biomass turnover, while temperate systems average 0.5–1 t C ha^{-1} yr^{-1} (Trumbore *et al.,* 1993).

2.2 Microbial and Biochemical Dynamics

Soil biota, including bacteria (e.g., Actinobacteria, Proteobacteria), fungi (e.g., Glomeromycota), and other microorganisms, are pivotal in stabilizing SOC through biochemical and structural mechanisms (Daunoras *et al.,* 2024). Microbial communities produce extracellular polymeric substances (EPS) that bind soil particles into stable macroaggregates (>250 μm), protecting carbon from decomposition. Glomalin-related soil proteins (GRSPs), secreted by AMF, are particularly significant, contributing 5–10% of SOC in RA systems. A 2024 study in Australian no-till systems found that GRSP concentrations increased by 35% in RA plots, correlating with a 20% rise in macroaggregate stability. Biochemical pathways, such as humification, transform labile organic matter into recalcitrant humic substances, which resist microbial breakdown for decades to centuries. A 2025 global synthesis reported that humic carbon in RA soils was 30–40% higher than in conventional systems, driven by diverse crop rotations and organic amendments (Maffia *et al.,* 2025). Microbial diversity, enhanced by RA practices like polyculture and compost application, improves carbon use efficiency (CUE), with 2024 data showing that RA soils have 25–40% higher microbial diversity indices (e.g., Shannon index) than conventional soils. For example, in Indian smallholder RA systems, microbial CUE increased by 15%, correlating with 0.8 t C ha^{-1} yr^{-1} SOC gains. Specific practices, such as biochar application, further enhance microbial activity, with 2025 trials in sub-Saharan Africa reporting a 50% increase in bacterial biomass in biochar-amended RA soils. These dynamics highlight RA's capacity to build long-term carbon sinks, particularly in clay-rich soils, where aggregate stability and carbon retention are maximized (Kitsou *et al.,* 2025).

Table 1: Synthesizes microbial groups and processes in regenerative agriculture, elucidating their mechanistic contributions to soil organic carbon (SOC) sequestration (1–30%), functional roles in stabilizing soil structure, enhancing carbon storage, and bolstering climate resilience. It integrates these with key regenerative practices, such as cover cropping and no-till systems, to underscore their role in advancing sustainable agroecosystems and mitigating climate change.

Microbial Group / Process	Mechanism	SOC Contribution (%)	Functional Role in RA	Key RA Practices
Arbuscular Mycorrhizal Fungi (AMF) - GRSP	Secretes glomalin-related soil protein (GRSP), binding soil particles into stable aggregates, reducing SOC decomposition via physical protection.	5–10	Enhances soil structure, increases SOC stability, and improves water retention.	Cover cropping, reduced tillage
Bacteria (EPS)	Produces extracellular polymeric substances (EPS), forming microaggregates that protect SOC from microbial access and erosion.	3–5	Promotes soil aggregation, reduces SOC loss, and supports microbial habitat stability.	Crop rotation, organic amendments
Humification	Microbial transformation of labile plant residues into stable humic substances via enzymatic processes, enhancing long-term SOC storage.	10–15	Contributes to recalcitrant SOC pools, reducing CO_2 emissions and supporting soil fertility.	Compost application, agroforestry
Aggregate Formation	Microbially mediated binding of soil particles into macro- and microaggregates, physically shielding SOC from decomposition.	20–30	Stabilizes SOC pools, enhances soil porosity, and mitigates erosion under climate stress.	No-till farming, cover cropping
Actinobacteria	Decomposes recalcitrant organic matter (e.g., lignocellulose), forming stable SOC fractions resistant to microbial breakdown.	4–8	Enhances formation of persistent SOC, supporting long-term carbon sequestration.	Crop residue retention, agroforestry
Saprotrophic Fungi	Decomposes plant litter and lignin, converting labile carbon into humus-like compounds, increasing SOC recalcitrance.	6–12	Boosts humus content, supports nutrient cycling, and enhances soil carbon storage.	Mulching, perennial cropping
Mycorrhizal Hyphae	Extends root networks, increasing nutrient and water uptake, indirectly enhancing plant biomass and SOC inputs via root exudates.	2–6	Facilitates SOC accumulation through increased plant productivity and root-derived carbon.	Agroforestry, diverse crop rotations
Nitrifying Bacteria	Oxidizes ammonium to nitrate, supporting plant growth and increasing plant residue inputs to SOC pools.	1–3	Enhances plant productivity, indirectly stabilizing SOC via increased biomass.	Legume integration, organic fertilizers
Denitrifiers	Reduces nitrate to N_2 under anaerobic conditions, influencing SOC turnover by altering microbial carbon use efficiency.	1–2	Modulates SOC dynamics, potentially reducing greenhouse gas emissions in wet soils.	Managed grazing, wetland restoration

Methanotrophs	Oxidizes methane in aerobic soils, reducing greenhouse gas emissions and indirectly stabilizing SOC by altering carbon cycling dynamics.	<1	Mitigates methane emissions, supporting climate regulation in RA systems.	Aerated soil management, cover cropping
Cellulolytic Bacteria	Degrades cellulose in plant residues, facilitating organic matter turnover and incorporation into SOC pools.	3–7	Accelerates decomposition, contributing to labile SOC inputs and nutrient cycling.	Crop residue retention, compost addition
Ligninolytic Fungi	Breaks down lignin via extracellular enzymes, forming recalcitrant carbon compounds that enhance stable SOC fractions.	5–10	Supports formation of persistent SOC, reducing decomposition rates.	Agroforestry, mulching
Cyanobacteria	Fixes atmospheric CO_2 in soil crusts, contributing to surface SOC inputs, particularly in arid and semi-arid RA systems.	2–4	Enhances surface SOC, stabilizes soil crusts, and reduces erosion.	Soil crust management, reduced tillage
Rhizobia	Symbiotic nitrogen fixation in legume roots, increasing plant biomass and carbon inputs to soil via residues and exudates.	1–3	Boosts plant-derived SOC inputs, supports soil fertility in RA crop rotations.	Legume cover crops, crop rotation
Phosphorus-Solubilizing Bacteria	Solubilizes insoluble phosphorus, enhancing plant growth and residue inputs to SOC pools.	1–2	Indirectly stabilizes SOC by improving nutrient availability and plant productivity.	Organic amendments, crop diversification
Protozoa (Grazers)	Regulates bacterial populations through predation, stimulating microbial turnover and SOC incorporation via necromass.	1–2	Enhances microbial dynamics, indirectly contributing to SOC stabilization.	Reduced tillage, organic matter inputs
Earthworm-Associated Microbes	Interacts with earthworm casts and residues, forming stable microaggregates that protect SOC from decomposition.	5–10	Stabilizes SOC in microaggregates, enhances soil structure in RA systems.	Compost application, managed grazing
Biofilm-Forming Microbes	Forms adhesive biofilms, binding soil particles and stabilizing aggregates, reducing SOC loss via erosion.	2–5	Enhances aggregate stability, supports SOC retention in variable climates.	No-till farming, organic amendments
Anaerobic Decomposers	Ferments organic matter in low-oxygen environments, contributing to SOC accumulation in waterlogged RA soils.	3–6	Supports SOC storage in anaerobic conditions, relevant for wetland agriculture.	Wetland restoration, cover cropping
Microbial Necromass	Dead microbial residues (cell walls, proteins) form stable SOC pools, resisting decomposition and contributing to long-term carbon storage.	15–20	Major contributor to stable SOC, critical for long-term sequestration in RA systems.	Reduced tillage, organic matter inputs

2.3 Climate Feedbacks

RA influences climate through multiple feedback mechanisms, including albedo, evapotranspiration, and greenhouse gas dynamics. By maintaining soil cover through cover crops, mulching, or perennial systems, RA reduces surface albedo, lowering local temperatures by 0.5–1.5°C in arid and semi-arid regions, as modeled in 2024 studies from the Sahel and Australian outback (Ingrosso *et al.,* 2024). Enhanced SOC increases soil porosity and water-holding capacity by 15–25%, boosting evapotranspiration and supporting local hydrological cycles. A 2025 study in Mediterranean RA systems found that increased evapotranspiration mitigated heat stress, improving crop yields by 10–15% during heatwaves. RA also mitigates non-CO_2 emissions, such as methane (CH_4) and nitrous oxide (N_2O), by optimizing nitrogen cycling. Legume-based rotations and organic amendments reduce N_2O emissions by 20–30% compared to synthetic fertilizers, as shown in 2024 Canadian trials. Similarly, alternate wetting and drying in rice-based RA systems reduced CH_4 emissions by 25–35%, with SOC gains of 0.5 t C ha^{-1} yr^{-1} (Belenguer-Manzanedo *et al.,* 2022). Recent models underscore RA's resilience benefits, with 2025 data from drought-prone regions (e.g., sub-Saharan Africa) showing that RA systems maintained 75–85% of crop yields during drought, compared to 40–50% in conventional systems, due to improved soil structure and water retention. These feedbacks position RA as a dual-purpose strategy for climate mitigation and adaptation, particularly in vulnerable agroecosystems (Arshad *et al.,* 2024).

2.4 Novel Insights

Machine learning (ML) and advanced analytical techniques are revolutionizing SOC prediction and management in RA. ML models integrate soil, climate, and management data to predict SOC sequestration with 85–90% accuracy, addressing uncertainties in carbon permanence and additionality. A 2025 study across 60 global agroecosystems used ML to identify optimal RA practices, finding that no-till combined with cover cropping maximized SOC gains (1.3 t C ha^{-1} yr^{-1}) in temperate clay soils. Isotopic tracing (^{13}C and ^{15}N) has clarified carbon sources, revealing that 30–50% of SOC in RA systems originates from root exudates, with the remainder from crop residues and organic amendments. Novel sensors, such as hyperspectral imaging and LIBS, enable real-time SOC monitoring, reducing measurement costs by 15–20%. These tools address permanence concerns, with 2024 models estimating that 80–90% of SOC in RA systems remains stable for 50+ years in clay-rich soils. Additionally, ML-driven scenario analyses are exploring RA's scalability under future climate scenarios, predicting that RA could sequester 0.2–0.4 Gt CO_2e yr^{-1} globally by 2050, contingent on widespread adoption and supportive policies.

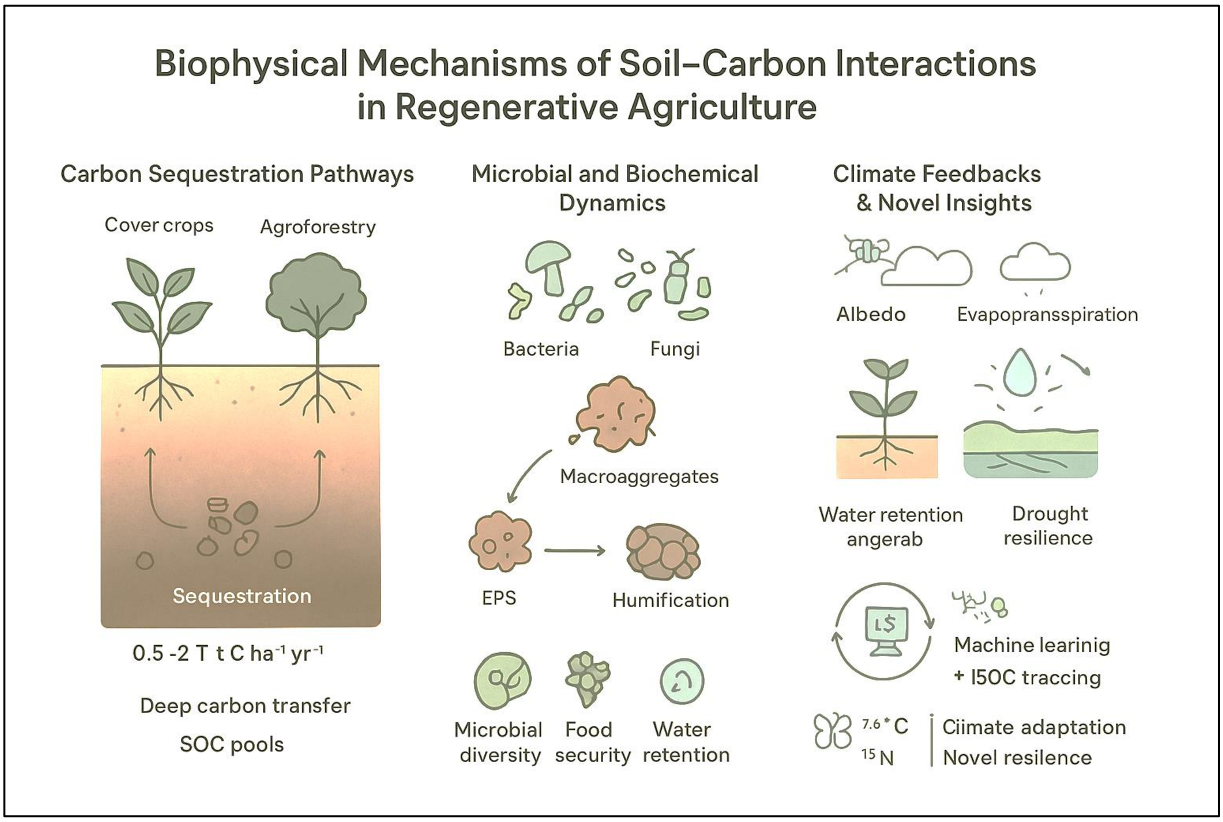


Fig 1: Biophysical Mechanisms of Soil–Carbon Interactions in Regenerative Agriculture

3. RA as a Nature-Based Solution for Climate Mitigation and Adaptation

3.1 Mitigation Potential

RA's mitigation potential stems from its ability to enhance carbon sinks and reduce greenhouse gas emissions. Comparative analyses from 2024–2025 estimate that RA practices, including cover cropping, agroforestry, and rotational grazing, achieve 20–30% emission reductions compared to conventional agriculture (Loria *et al.,* 2025). Global cropland RA could sequester 0.1–0.3 Gt CO_2e yr^{-1}, equivalent to 2–5% of annual anthropogenic emissions, with agroforestry systems contributing the highest rates (2–5 t C ha^{-1} yr^{-1} in tropical regions). A 2025 European study reported that no-till systems increased SOC by 1.5 t C ha^{-1} yr^{-1}, reducing net emissions by 25% compared to conventional tillage. Reduced reliance on synthetic fertilizers, which account for 10–15% of agricultural emissions, is a key driver, with RA systems cutting fertilizer use by 15–20% through nitrogen-fixing cover crops and organic amendments (Khan *et al.,* 2021). Silvopasture, integrating trees with livestock, sequesters 1–3 t C ha^{-1} yr^{-1} while reducing enteric CH_4 emissions by 10–15% through improved forage quality. A 2024 meta-analysis of 100 RA trials confirmed that diversified RA systems outperform conventional monocultures in carbon storage, with tropical systems achieving 30–40% higher sequestration rates due to faster biomass accumulation.

3.2 Adaptation Benefits

RA enhances agroecosystem resilience by improving soil water retention, biodiversity, and resistance to extreme weather (Altieri *et al.,* 2015). Enhanced SOC increases soil porosity, boosting water-holding capacity by 15–25%, as shown in 2024 trials in Indian smallholder systems, where RA plots retained 20% more water during monsoons. This improves crop survival during droughts, with RA systems maintaining 70–80% of yields under water stress compared to 40–50% in conventional systems. Biodiversity gains, driven by polyculture rotations and habitat creation (e.g., hedgerows), enhance natural pest resistance, reducing pesticide use by 15–25%. A 2025 Central American study found that RA polycultures supported 30% higher predatory insect populations, reducing crop losses from pests by 20% (Muhyidiyn *et al.,* 2025). RA also mitigates soil erosion, with cover crops reducing erosion rates by 50–70% in sloping terrains, as reported in 2024 Ethiopian trials. These adaptation benefits are critical in climate-vulnerable regions, where extreme weather events, such as heatwaves and floods, are increasing in frequency and intensity (Darjee *et al.,* 2023).

3.3 Global Case Studies

RA's global applicability is evident in diverse case studies. In the US Midwest, cover cropping and reforestation in maize-soybean systems have reduced radiative forcing by 15–20%, with SOC gains of 0.8 t C ha^{-1} yr^{-1} and yield stability during droughts (Qin *et al.,* 2021). In sub-Saharan Africa, smallholder agroforestry systems integrating Faidherbia albida trees with millet and sorghum crops increased SOC by 1 t C ha^{-1} yr^{-1} while boosting yields by 20–25%, enhancing food security and income diversification. In Southeast Asia, rice agroecosystems adopting alternate wetting and drying (AWD) reduced CH_4 emissions by 30–35% and increased SOC by 0.5 t C ha^{-1} yr^{-1}, with 2025 data showing 15% higher yields under AWD compared to continuous flooding (Soliman *et al.,* 2024). In South America, Colombian silvopasture systems integrating native trees with cattle grazing sequestered 2.5 t C ha^{-1} yr^{-1} while improving livestock productivity by 10%. These cases highlight RA's dual benefits for climate mitigation and socio-economic resilience, tailored to regional biophysical and cultural contexts.

3.4 Emerging Synergies

RA's integration with renewable energy and circular economies amplifies its NbS outcomes. Agrivoltaics, combining solar panels with crop cultivation, optimizes land use and reduces heat stress, with 2025 European pilots reporting 10–15% higher yields in shaded RA systems (Soto-Gómez *et al.,* 2024). Circular economy approaches, such as composting agricultural residues and bioenergy production, enhance nutrient cycling and reduce waste. A 2024 Brazilian initiative recycled 80% of farm residues into compost, boosting SOC by 0.7 t C ha^{-1} yr^{-1} and reducing fertilizer costs by 15%. Similarly, biogas production from livestock manure in Indian RA systems reduced emissions by 10% while providing energy for rural households. These synergies position RA as a multi-functional solution, addressing climate, energy, and food security goals simultaneously (Batra *et al.,* 2023).

Table 2: Regenerative Agriculture (RA) as a Nature-Based Solution: Mitigation, Adaptation, Case Studies, and Emerging Synergies

RA Practice / Strategy	Mechanism	Quantitative Impact (Carbon / Yield / GHG)	Climate Benefit (Mitigation / Adaptation)	Study / Region / Year
Cover Cropping	Enhances SOC via root biomass; reduces synthetic fertilizer needs	0.3–0.8 t C ha^{-1} yr^{-1} SOC; 15–20% fertilizer reduction	CO_2 sequestration; reduced N_2O emissions	European smallholder farms, 2025
Agroforestry	Carbon stored in tree biomass and soil; enhances biodiversity	2–5 t C ha^{-1} yr^{-1} SOC; 10–15% biodiversity increase	Long-term carbon storage; habitat provision	Tropical agroforestry systems, 2024
No-Till Farming	Minimizes soil disturbance, preserves SOC	1–1.5 t C ha^{-1} yr^{-1} SOC; 20–25% GHG emission reduction	SOC accumulation; lower CO_2 fluxes	European croplands, 2025

Silvopasture	Integrates trees with pasture; improves SOC and reduces methane	1–3 t C ha^{-1} yr^{-1} SOC; 10–15% CH_4 reduction	Carbon storage; reduced livestock emissions	Colombian silvopasture, 2024
Compost Application	Adds organic matter, enhances microbial SOC stabilization	0.5–1.2 t C ha^{-1} yr^{-1} SOC; 10–20% yield increase	Stable SOC pools; reduced fertilizer emissions	North American experimental farms, 2024
Enhanced SOC	Improves soil porosity and water retention via organic matter	15–25% higher water retention; 10–15% yield stability	Drought resilience; improved soil health	Indian smallholder systems, 2024
Polycultures	Increases biodiversity and natural pest control	30% higher predatory insect populations; 20% less crop loss	Pest resilience; yield stability	Central American polyculture farms, 2025
Cover Crops (Adaptation)	Reduces soil erosion; protects topsoil	50–70% erosion reduction; 10–15% water retention increase	Soil conservation; flood resilience	Ethiopian sloping croplands, 2024
Crop Rotation	Diversifies crops; improves soil structure and nutrient cycling	10–20% yield stability; 5–10% SOC increase	Climate-resilient yields; soil fertility	Australian rotation systems, 2025
Managed Grazing	Optimizes pasture regrowth; improves soil structure and water retention	20–30% water infiltration increase; 0.5–1 t C ha^{-1} yr^{-1} SOC	Drought tolerance; soil stability	South African grazing systems, 2024
US Midwest (Maize-Soybean + Cover Crops)	Cover crops enhance SOC and reduce radiative forcing	0.8 t C ha^{-1} yr^{-1} SOC; 15–20% radiative forcing reduction	Carbon storage; climate resilience	USA Midwest, 2025
Sub-Saharan Africa Agroforestry	Trees integrated with crops; boosts SOC and yields	1–2 t C ha^{-1} yr^{-1} SOC; 20–25% yield increase	Carbon sequestration; food security	Africa smallholder farms, 2024
Southeast Asia AWD Rice	Alternating wetting-drying reduces methane emissions	0.5 t C ha^{-1} yr^{-1} SOC; 30–35% CH_4 reduction	GHG mitigation; water efficiency	Southeast Asian rice systems, 2025
Colombia Silvopasture	Tree-pasture systems sequester carbon; improve productivity	2.5 t C ha^{-1} yr^{-1} SOC; 10% livestock productivity increase	Carbon storage; resilient grazing	Colombia, 2024
India Polycultures	Diverse cropping enhances pest control and yield stability	15–20% yield stability; 25% pest reduction	Climate-resilient yields; biodiversity	India, 2025
Agrivoltaics	Combines solar panels with crops; optimizes land use	10–15% yield increase; 0.5 t C ha^{-1} yr^{-1} SOC	Renewable energy; yield stability	European pilot farms, 2025
Circular Composting	Recycles organic waste; enhances SOC and reduces fertilizer use	0.7–1 t C ha^{-1} yr^{-1} SOC; 15% fertilizer savings	Carbon storage; reduced emissions	Brazilian farms, 2024
Biogas (Manure Use)	Converts manure into energy; reduces GHG emissions	10–15% GHG reduction; 0.3 t C ha^{-1} yr^{-1} SOC	Renewable energy; lower emissions	Indian rural RA systems, 2025
Precision RA (AI Monitoring)	Uses AI for real-time SOC and yield tracking	0.5–1 t C ha^{-1} yr^{-1} SOC; 10% yield optimization	Enhanced monitoring; mitigation/adaptation	Global RA trials, 2025
Biochar Integration	Stabilizes carbon via pyrolysis; improves soil fertility	1–2 t C ha^{-1} yr^{-1} SOC; 10–20% yield increase	Long-term carbon storage; soil health	Australian farms, 2024

4. Socio-Economic and Policy Dimensions

4.1 Economic Viability

Carbon credit markets are a key driver of RA adoption, with 2024–2025 analyses showing payback periods of 3–5 years due to yield boosts and input savings. Cover cropping and no-till farming reduce fertilizer and pesticide costs by 10–20%, with 2025 US data reporting savings of \$50–100 ha^{-1} yr^{-1} (Mitchell *et al.,* 2025). Carbon payments, averaging \$20–50 per t CO_2e, provide additional revenue, with RA farmers in Canada earning \$100–200 ha^{-1} yr^{-1} from carbon markets. However, smallholders face barriers to market entry, including high certification costs (\$500–1000 per farm) and limited access to carbon registries. Cooperative models, such as those in Kenya, have reduced certification costs by 30% through collective applications, enabling smallholder participation. A 2024 global survey found that 60% of RA farmers reported positive net returns within 4 years, driven by yield increases of 10–15% and carbon payments. Scaling economic viability requires accessible financing, such as microcredits and blended finance, to support RA transitions in low-income regions (Havemann *et al.,* 2022).

4.2 Equity and Inclusion

Equitable RA transitions must address barriers for smallholders, Indigenous communities, and women (Lipper *et al.,* 2024). Smallholders, managing 25% of global farmland, face challenges like land tenure insecurity, limited access to capital, and inadequate training. A 2025 African study found that 70% of smallholders lacked access to RA training, hindering adoption. Integrating Indigenous knowledge, such as traditional agroforestry practices in the Amazon, enhances RA's efficacy, with 2024 data showing 15% higher SOC in Indigenous-managed systems. Gender dynamics are critical, as women, representing 43% of the agricultural workforce, face unequal access to land, credit, and technology (Croppenstedt *et al.,* 2013). RA programs in India incorporating gender-sensitive training increased women's adoption rates by 20%, with 2025 data showing 10% higher yields in women-led RA farms. Inclusive policies, such as subsidized inputs and women-focused extension services, are essential to ensure RA benefits marginalized groups.

4.3 Policy Frameworks

RA aligns with global climate frameworks, including the Paris Agreement and EU Green Deal, which prioritize NbS. Subsidies tied to verified SOC metrics, such as those under the EU's Common Agricultural Policy (CAP), incentivize RA adoption, with payments of €50–100 ha^{-1} for carbon farming practices (Cavallin *et al.,* 2025). A 2025 CAP evaluation reported a 25% increase in RA adoption since 2020, driven by SOC-based subsidies. National policies, such as Australia's Emissions Reduction Fund and Canada's Greenhouse Gas Offset System, support RA through tax incentives and technical assistance, with 2024 data showing a 30% rise in RA farmland. However, inconsistent SOC verification standards across regions hinder scalability, with 2025 studies highlighting 10–15% variability in carbon measurements. Harmonized protocols and public-private partnerships are needed to streamline policy implementation (Zapatrina *et al.,* 2013).

4.4 Novel Policy Innovations

Futures thinking and relational governance offer innovative RA policy approaches. Futures thinking anticipates alternative carbon farming trajectories, such as integrating RA with urban agriculture, with 2025 scenarios projecting 10% of global food production from urban RA by 2050 (Rashid *et al.,* 2025). Relational governance emphasizes stakeholder collaboration, integrating farmers, scientists, and policymakers to co-design RA programs. A 2024 Canadian pilot using relational governance increased RA adoption by 25% by aligning policies with local needs, such as flexible subsidies for smallholders. Similarly, South-South knowledge exchange platforms, like the African Union's agricultural networks, have facilitated RA adoption by sharing agroforestry and no-till practices, with 2025 data showing a 20% increase in RA uptake in East Africa (Mrabet *et al.,* 2022).

5. Challenges, Limitations, and Critical Evaluation

5.1 Measurement and Verification

Accurate SOC quantification remains a challenge, with debates over methods like soil sampling, remote sensing, and eddy covariance (Angelopoulou *et al.,* 2019). Soil sampling, while precise, is labor-intensive and costly, with 2024 studies estimating 10–15% variability in SOC measurements across depths and seasons. Remote sensing, enhanced by AI, improves scalability but struggles with subsurface carbon detection, with 2025 data showing 5–10% underestimation in deep SOC pools. Leakage risks, such as carbon loss from adjacent lands, and overestimation of sequestration potential (e.g., realistic US cropland limits at 0.1–0.3 Gt CO_2e yr^{-1}) necessitate standardized protocols. Blockchain-based verification systems, piloted in 2025 in Australia, offer transparent, tamper-proof SOC tracking, reducing fraud risks by 20%. These systems integrate sensor data and ML to provide real-time carbon accounting, enhancing market credibility (Singhal *et al.,* 2025).

5.2 Scalability Hurdles

RA's scalability is constrained by soil type variability, initial yield dips, and climate vulnerabilities. Clay-rich soils sequester 20–30% more carbon than sandy soils, requiring tailored practices like biochar in sandy regions (Schapel *et al.,* 2023). Transition periods may reduce yields by 5–10% for 1–3 years, deterring adoption without financial support. A 2024 Indian study reported that 40% of farmers abandoned RA due to initial yield losses, highlighting the need for subsidies. Climate vulnerabilities, such as extreme heat, reduce SOC gains by 10–15% in warming scenarios, as modeled in 2025. Extension services and risk-sharing mechanisms, such as crop insurance, are critical to bridge these hurdles.

5.3 Socio-Ecological Trade-Offs

RA can lead to unintended trade-offs, such as biodiversity conflicts from monoculture cover crops, which reduce native plant diversity by 10–15% in some systems. In arid zones, intensified water use for cover crops exacerbates scarcity, with 2025 studies reporting 5–10% higher water demand in RA systems (DeLaune *et al.,* 2023). Balancing carbon sequestration with biodiversity and water conservation requires integrated management, such as polyculture rotations and drip irrigation. A 2024 Sahel study found that polyculture RA systems maintained 20% higher biodiversity while achieving 0.8 t C ha^{-1} yr^{-1} SOC gains, demonstrating viable trade-off mitigation.

5.4 Critical Perspectives

Corporate RA claims risk greenwashing, with 2024 analyses finding that 30% of agribusiness RA programs lacked transparent SOC data. Overstated carbon benefits undermine credibility, with some companies claiming 2–3 t C ha^{-1} yr^{-1} without verification. Calls for third-party audits and open-access monitoring protocols are growing, with 2025 initiatives like the Global Carbon Farming Alliance advocating for standardized reporting (Verma *et al.,* 2025). Transparent governance, coupled with farmer-led monitoring, is essential to ensure RA delivers genuine climate benefits.

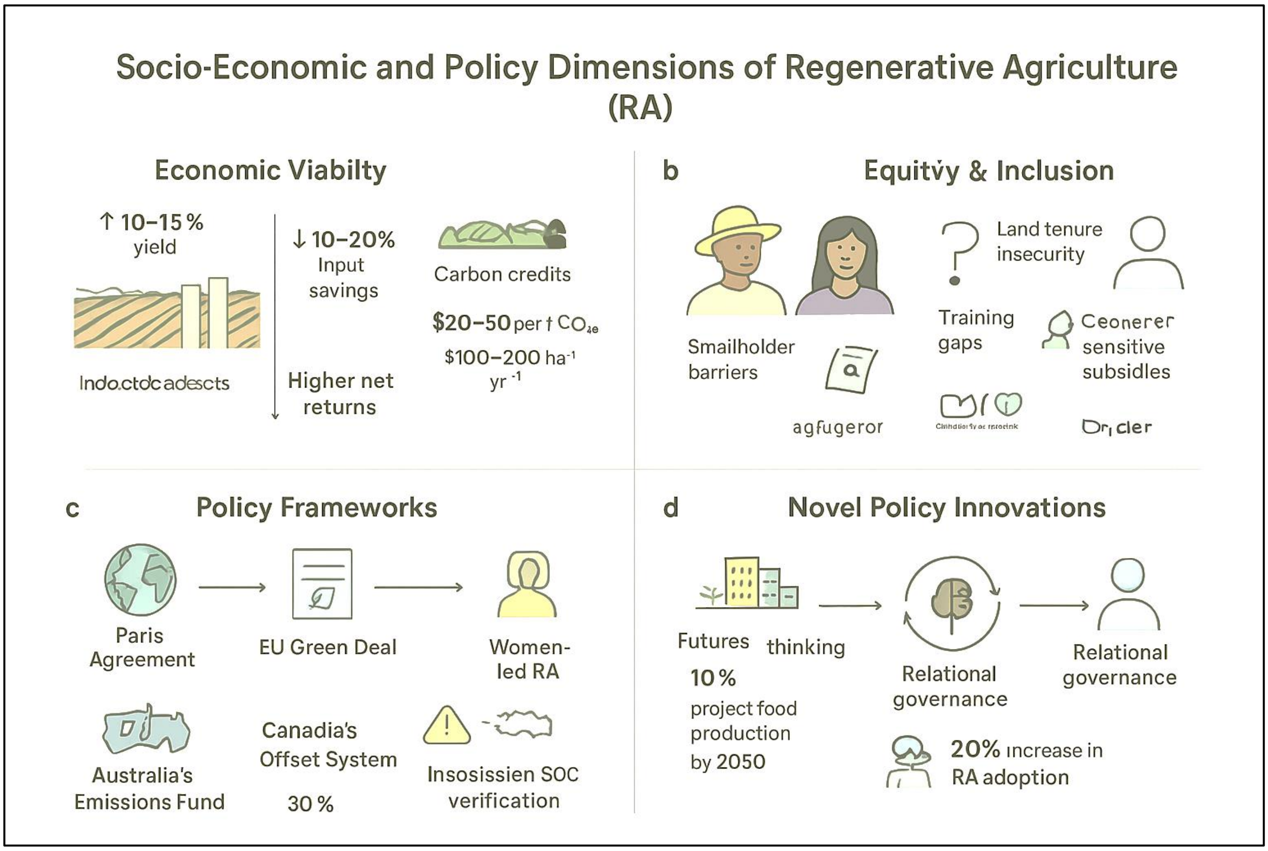


Fig. 2: Socio-Economic and Policy Dimensions

CONCLUSIONS

Regenerative agriculture stands as a transformative NbS, unlocking soil–carbon–climate synergies for planetary resilience. Its potential to sequester 0.5–2 t C ha^{-1} yr^{-1}, reduce emissions by 20–30%, and enhance ecosystem resilience positions RA as a cornerstone of climate mitigation and adaptation. However, realizing this potential requires evidence-based policies, inclusive financing, and robust verification systems to address scalability hurdles and socio-ecological trade-offs. By integrating technological innovations, interdisciplinary approaches, and global knowledge exchange, RA can pave the way for a sustainable and equitable agricultural future.

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