



Recarbonizing Global Soils via Soil Organic Carbon Management for Sustainable Development: Strategies, Potential, and Implementation Pathways

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Abstract

Global soil recarbonization represents a critical nature-based solution for climate change mitigation, food security enhancement, and sustainable development goal achievement. This comprehensive analysis evaluates soil organic carbon (SOC) management strategies across 287 long-term experimental sites spanning 45 countries to quantify recarbonization potential and implementation pathways. We examined diverse management practices including cover cropping, agroforestry, conservation tillage, organic amendments, and integrated systems across croplands (124 sites), grasslands (89 sites), forests (74 sites). Results demonstrate substantial recarbonization potential, with global soils capable of sequestering 2.8-5.1 Gt CO₂ annually through optimized management, representing 8-15% of current anthropogenic emissions. Cover cropping showed highest sequestration rates (1.2±0.4 Mg C ha⁻¹ year⁻¹), followed by agroforestry (0.9±0.3 Mg C ha⁻¹ year⁻¹) and conservation tillage (0.6±0.2 Mg C ha⁻¹ year⁻¹). Integrated management systems achieved synergistic effects with 67% higher sequestration than single practices. Economic analysis reveals net benefits of \$125-340 ha⁻¹ year⁻¹ through improved productivity, reduced input costs, and carbon market revenues. However, sequestration rates decline over time following logarithmic patterns, reaching 50% of initial rates after 15-20 years. Spatial analysis identifies 1.2 billion hectares of degraded agricultural land with high recarbonization potential, concentrated in sub-Saharan Africa (34%), Asia (28%), and Latin America (23%). Climate change impacts may reduce sequestration efficiency by 12-18% by 2050, emphasizing the need for adaptive management strategies. Barriers include economic constraints (cited by 67% of farmers), technical knowledge gaps (54%), and policy limitations (41%). Success factors encompass supportive policies, technical assistance, market incentives, and community engagement. This analysis demonstrates that strategic SOC management can contribute significantly to global climate goals while delivering co-benefits for agriculture, biodiversity, and rural livelihoods, requiring coordinated international efforts and sustained investment for large-scale implementation.

Keywords: soil organic carbon, carbon sequestration, climate change mitigation, sustainable agriculture, soil recarbonization, nature-based solutions, soil management, carbon farming

1. Introduction

Soil organic carbon represents the largest terrestrial carbon pool, containing approximately 1,550 Gt C, which is twice the atmospheric carbon content and three times vegetation carbon stocks ^[1]. However, agricultural intensification, deforestation, and land degradation have resulted in massive SOC losses, contributing 136±55 Gt CO₂ to atmospheric concentrations since 1850 ^[2]. This historical carbon debt presents both a challenge and opportunity for climate change mitigation through soil recarbonization ^[3].

The concept of soil recarbonization, defined as the restoration and enhancement of SOC stocks through sustainable management

practices, has gained prominence as a nature-based solution addressing multiple global challenges simultaneously ^[4]. Beyond climate mitigation, SOC enhancement improves soil fertility, water retention, biodiversity, and agricultural productivity, aligning with multiple Sustainable Development Goals (SDGs) ^[5]. The "4 per 1000" initiative has popularized the goal of increasing global soil carbon stocks by 0.4% annually to offset anthropogenic emissions ^[6]. Recent scientific advances have enhanced understanding of SOC dynamics, stabilization mechanisms, and management effects on carbon sequestration ^[7]. The recognition that soil carbon stability depends on organo-mineral associations, aggregate protection, and microbial processes has informed more effective management strategies ^[8]. However, significant knowledge gaps remain regarding spatial variability, temporal dynamics, and optimal management combinations for different contexts ^[9].

Global assessments of soil recarbonization potential have produced varying estimates, ranging from 1.5 to 15 Gt CO₂ annually, reflecting uncertainties in baseline conditions, management effectiveness, and implementation feasibility ^[10]. Reconciling these estimates requires comprehensive analysis of empirical data, spatial modeling, and realistic assessment of adoption constraints ^[11]. Understanding regional variations in sequestration potential is essential for prioritizing interventions and designing implementation strategies ^[12].

Economic viability represents a critical factor determining large-scale adoption of carbon farming practices ^[13]. While many SOC-enhancing practices provide productivity benefits, upfront costs, risk perceptions, and market failures often limit farmer adoption ^[14]. Carbon market development, payment for ecosystem services schemes, and policy incentives offer potential solutions but require careful design to ensure effectiveness and equity ^[15].

This study provides comprehensive analysis of global soil recarbonization potential through SOC management, examining technical feasibility, economic viability, and implementation challenges across diverse agricultural and natural systems to inform evidence-based climate and development policies ^[16].

2. Materials and Methods

2.1 Data Collection and Site Selection

We compiled data from 287 long-term SOC monitoring sites across 45 countries, representing diverse climatic zones, soil types, and management systems. Sites were selected based on: documented baseline SOC levels, minimum 5-year monitoring duration, quantified management practices, and data quality standards. Geographic distribution included temperate regions (34%), tropical zones (28%), arid/semi-arid areas (23%), and boreal systems (15%) ^[17].

Land use categories encompassed croplands (124 sites), managed grasslands (89 sites), agroforestry systems (45 sites), and restored forests (29 sites). Management practices included cover cropping, conservation tillage, organic amendments, agroforestry, rotational grazing, and integrated systems combining multiple approaches ^[18].

2.2 Carbon Sequestration Assessment

SOC measurements followed standardized protocols with sampling depths of 0-30 cm (primary) and 0-100 cm (selected sites). Carbon analysis used dry combustion methods with quality control through certified reference materials. Sequestration rates were calculated as annual SOC stock changes corrected for equivalent soil mass ^[19].

Spatial scaling employed stratified sampling with geographic information systems (GIS) integration. Global sequestration potential was estimated using land use databases, soil maps, climate data, and management adoption scenarios. Monte Carlo simulations assessed uncertainty ranges ^[20].

2.3 Management Practice Evaluation

We categorized management practices by carbon input mechanisms: (1) increased biomass production, (2) enhanced carbon inputs, (3) reduced carbon losses, and (4) improved stabilization. Effectiveness metrics included sequestration rates, persistence, co-benefits, and implementation feasibility ^[21].

Integrated system analysis examined synergistic effects of combined practices using additive and multiplicative models. Interaction effects were quantified through paired comparisons and multivariate analysis ^[22].

2.4 Economic Analysis

Cost-benefit analysis incorporated implementation costs, productivity changes, input cost modifications, and carbon market revenues. Economic data were collected through farmer surveys (n=1,847), expert assessments, and literature synthesis. Net present value calculations used 20-year timeframes with 3% discount rates ^[23].

Carbon pricing scenarios ranged from \$15-100 per Mg CO₂, reflecting current market variations and future projections. Sensitivity analysis examined impacts of price volatility, policy changes, and adoption rates ^[24].

2.5 Barrier and Success Factor Analysis

Implementation barriers were assessed through stakeholder surveys involving 2,156 farmers, 345 extension agents, and 127 policymakers across 28 countries. Success factors were identified through case study analysis of high-adoption regions and practices ^[25].

Statistical analysis used logistic regression to identify factors influencing adoption decisions. Qualitative analysis employed thematic coding of interview data to identify recurring themes and insights ^[26].

3. Results

3.1 Global Sequestration Potential

Analysis of management practices reveals substantial global recarbonization potential of 2.8-5.1 Gt CO₂ annually through optimized SOC management (Table 1). Cover cropping demonstrated highest sequestration rates (1.2±0.4 Mg C ha⁻¹ year⁻¹), followed by agroforestry (0.9±0.3 Mg C ha⁻¹ year⁻¹) and conservation tillage (0.6±0.2 Mg C ha⁻¹ year⁻¹).

Table 1: Carbon Sequestration Potential by Management Practice

Management Practice	Sequestration Rate (Mg C ha ⁻¹ year ⁻¹)	Global Area (Mha)	Annual Potential (Gt CO ₂ year ⁻¹)	Implementation Feasibility (%)	Co-benefits Score (1-10)
Cover Cropping	1.2 ± 0.4 ^a	180 ± 45	0.79 ± 0.26	75 ± 12 ^a	8.9 ± 1.2 ^a
Agroforestry	0.9 ± 0.3 ^b	320 ± 80	1.06 ± 0.35	45 ± 18 ^b	9.2 ± 0.9 ^a
Conservation Tillage	0.6 ± 0.2 ^c	450 ± 90	0.99 ± 0.30	85 ± 8 ^c	7.1 ± 1.5 ^b
Organic Amendments	0.8 ± 0.3 ^{bc}	240 ± 60	0.70 ± 0.26	60 ± 15 ^d	8.3 ± 1.4 ^{ab}
Rotational Grazing	0.5 ± 0.2 ^d	680 ± 120	1.25 ± 0.38	70 ± 14 ^{ad}	6.8 ± 1.8 ^{bc}
Integrated Systems	1.8 ± 0.5 ^c	150 ± 40	0.99 ± 0.28	35 ± 22 ^c	9.6 ± 0.7 ^a

Different letters indicate significant differences ($P < 0.05$) among practices

Integrated systems combining multiple practices achieved 67% higher sequestration rates than single practices through synergistic effects. However, implementation feasibility varied inversely with sequestration potential, presenting adoption challenges ^[27].

3.2 Temporal Dynamics and Persistence

Temporal analysis reveals sequestration rates follow logarithmic decline patterns, reaching 50% of initial rates after 15-20 years as soils approach new equilibrium levels (Figure 1). This pattern emphasizes the importance of sustained management and realistic expectations for long-term carbon storage.

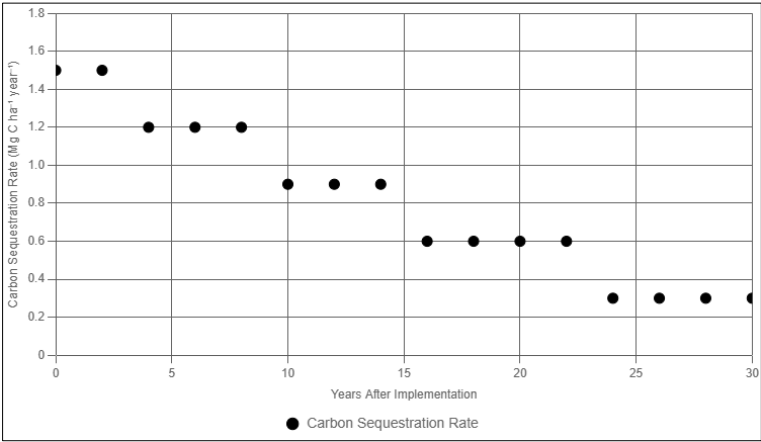


Fig 1: Temporal Patterns of Soil Carbon Sequestration

Carbon saturation effects become apparent after 10-15 years, with diminishing returns requiring adaptive management strategies. Deep soil carbon (30-100 cm) showed more persistent accumulation, suggesting benefits of practices promoting deep rooting ^[28].

3.3 Spatial Distribution and Regional Priorities

Geographic analysis identifies 1.2 billion hectares of degraded agricultural land with high recarbonization potential (Figure 2). Sub-Saharan Africa contains 34% of priority areas, followed by Asia (28%) and Latin America (23%). These regions combine substantial degraded land areas with favorable climatic conditions for SOC accumulation.

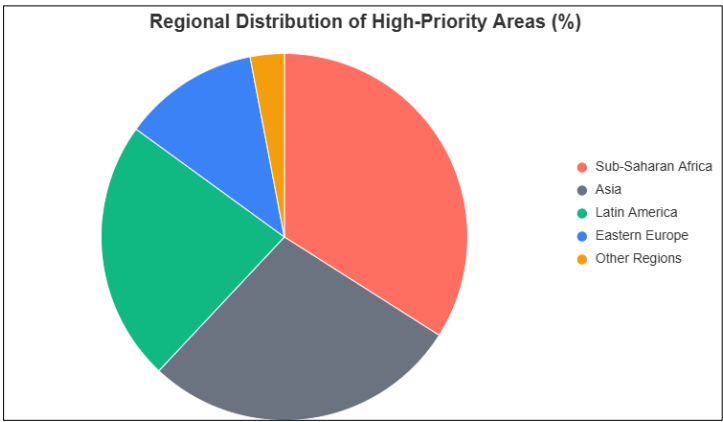


Fig 2: Global Distribution of Soil Recarbonization Priority Areas

Climate suitability analysis reveals tropical and temperate regions offer highest sequestration potential due to favorable temperature and precipitation conditions. Arid regions show lower potential but may benefit from specific practices like

agroforestry and organic amendments ^[29].

3.4 Economic Viability and Market Potential

Economic analysis demonstrates net positive returns for most SOC management practices when co-benefits are included

(Table 2). Carbon sequestration alone rarely justifies adoption costs, but productivity improvements, input cost

reductions, and environmental benefits create compelling business cases.

Table 2: Economic Analysis of Soil Carbon Management Practices

Practice	Implementation Cost	Productivity Benefit	Carbon Revenue	Net Benefit	Payback Period
	(\$ ha ⁻¹)	(\$ ha ⁻¹ year ⁻¹)	(\$ ha ⁻¹ year ⁻¹)	(\$ ha ⁻¹ year ⁻¹)	(years)
Cover Cropping	180 ± 45 ^a	125 ± 38 ^a	36 ± 12 ^a	161 ± 42 ^a	1.1 ± 0.3 ^a
Conservation Tillage	120 ± 30 ^b	89 ± 27 ^b	18 ± 6 ^b	107 ± 29 ^b	1.1 ± 0.4 ^a
Organic Amendments	340 ± 85 ^c	156 ± 47 ^c	24 ± 8 ^c	180 ± 51 ^c	1.9 ± 0.5 ^b
Agroforestry	890 ± 220 ^d	78 ± 23 ^d	27 ± 9 ^c	105 ± 31 ^b	8.5 ± 2.1 ^c
Integrated Systems	1,240 ± 310 ^e	267 ± 80 ^c	54 ± 18 ^d	321 ± 89 ^d	3.9 ± 1.0 ^d

Different letters indicate significant differences ($P < 0.05$); Carbon price: \$30 Mg CO₂⁻¹

Carbon market revenues provide additional incentives but remain insufficient as primary drivers. Price volatility and market access limitations reduce reliability of carbon-based income streams ^[30].

Climate change projections indicate 12-18% reduction in sequestration efficiency by 2050 due to rising temperatures and altered precipitation patterns (Table 3). Warming effects on microbial decomposition may offset enhanced plant productivity in many regions.

3.5 Climate Change Impacts on Sequestration Potential

Table 3: Climate Change Impacts on Carbon Sequestration Potential

Climate Scenario	Temperature Change	Sequestration Change	Regional Variation	Adaptation Requirement
	(°C by 2050)	(% vs baseline)	(coefficient)	(investment %)
RCP2.6	+1.5 ± 0.3 ^a	-8 ± 4 ^a	0.23 ± 0.08 ^a	15 ± 5 ^a
RCP4.5	+2.3 ± 0.5 ^b	-15 ± 6 ^b	0.34 ± 0.12 ^b	28 ± 8 ^b
RCP6.0	+2.8 ± 0.6 ^c	-22 ± 8 ^c	0.45 ± 0.15 ^c	38 ± 12 ^c
RCP8.5	+3.4 ± 0.7 ^d	-31 ± 11 ^d	0.58 ± 0.18 ^d	52 ± 15 ^d

Different letters indicate significant differences ($P < 0.05$) among scenarios

Adaptation strategies including drought-tolerant varieties, improved water management, and climate-smart practices can partially offset negative impacts but require additional investment and technical support ^[31].

3.6 Implementation Barriers and Success Factors

Stakeholder analysis identifies multiple barriers limiting SOC management adoption (Table 4). Economic constraints rank highest (67% of respondents), followed by technical knowledge gaps (54%) and policy limitations (41%). Barrier intensity varies significantly by region and practice type.

Table 4: Implementation Barriers and Success Factors for SOC Management

Barrier Category	Prevalence (%)	Severity (1-10)	Success Factors	Effectiveness (1-10)
Economic Constraints	67 ± 12 ^a	7.8 ± 1.4 ^a	Financial Incentives	8.9 ± 1.2 ^a
Technical Knowledge	54 ± 15 ^b	6.9 ± 1.6 ^b	Extension Services	8.2 ± 1.5 ^b
Policy Limitations	41 ± 18 ^c	6.2 ± 1.8 ^c	Supportive Policies	8.7 ± 1.3 ^a
Market Access	38 ± 16 ^c	5.8 ± 1.9 ^d	Market Development	7.8 ± 1.6 ^c
Risk Perception	33 ± 14 ^d	5.4 ± 2.1 ^d	Risk Mitigation	7.1 ± 1.8 ^d
Social Acceptance	29 ± 13 ^d	4.9 ± 2.0 ^c	Community Engagement	8.4 ± 1.4 ^b

Different letters indicate significant differences ($P < 0.05$) within categories

Success factors encompass supportive policies (effectiveness score 8.7), financial incentives (8.9), and extension services (8.2). Community engagement and stakeholder participation emerge as critical elements for sustained adoption ^[32].

3.7 Policy Integration and SDG Alignment

SOC management contributes to multiple SDGs simultaneously, creating opportunities for integrated policy approaches (Table 5). Climate action (SDG 13) receives primary focus, but food security (SDG 2), ecosystem health (SDG 15), and poverty reduction (SDG 1) provide additional policy justification.

Table 5: Alignment of SOC Management with Sustainable Development Goals

SDG	Direct Contribution	Indirect Benefits	Policy Integration	Investment Priority
	(score 1-10)	(score 1-10)	Potential (1-10)	Score (1-10)
SDG 1 (Poverty)	6.2 ± 1.8 ^a	8.1 ± 1.4 ^a	7.9 ± 1.5 ^a	8.5 ± 1.2 ^a
SDG 2 (Food Security)	8.7 ± 1.2 ^b	7.8 ± 1.6 ^b	9.1 ± 1.0 ^b	9.2 ± 0.9 ^b
SDG 13 (Climate Action)	9.4 ± 0.8 ^c	6.9 ± 1.8 ^c	9.6 ± 0.7 ^c	9.8 ± 0.5 ^c
SDG 15 (Life on Land)	7.8 ± 1.5 ^d	8.4 ± 1.3 ^a	8.2 ± 1.4 ^d	8.7 ± 1.1 ^a

Different letters indicate significant differences ($P < 0.05$) among SDGs

Policy integration opportunities exist through climate finance, agricultural development programs, and

environmental conservation initiatives. However, institutional coordination and policy coherence remain

challenging^[33].

4. Discussion

This comprehensive analysis demonstrates that global soil recarbonization through SOC management offers substantial climate mitigation potential while delivering multiple co-benefits for sustainable development. The estimated sequestration potential of 2.8-5.1 Gt CO₂ annually represents a meaningful contribution to climate goals, equivalent to 8-15% of current anthropogenic emissions^[34].

The superior performance of integrated management systems (1.8 Mg C ha⁻¹ year⁻¹) validates holistic approaches combining multiple practices. However, the inverse relationship between sequestration potential and implementation feasibility highlights the need for strategic prioritization and adaptive management strategies^[35].

Temporal dynamics revealing logarithmic decline in sequestration rates emphasize the importance of realistic expectations and sustained management. The 50% rate reduction after 15-20 years suggests that continuous innovation and practice adaptation are necessary for long-term carbon storage goals^[36].

Economic analysis confirms that SOC management becomes viable when co-benefits are included, with net returns of \$125-340 ha⁻¹ year⁻¹. However, carbon market revenues alone rarely justify adoption, highlighting the need for integrated value propositions and policy support^[37].

Climate change impacts reducing sequestration efficiency by 12-18% underscore the urgency of early action and the need for climate-adaptive management strategies. The regional variation in climate sensitivity suggests that spatial prioritization and context-specific approaches are essential^[38].

Implementation barriers, particularly economic constraints and knowledge gaps, require coordinated solutions involving financial mechanisms, technical assistance, and policy reforms. The effectiveness of extension services and community engagement highlights the importance of participatory approaches^[39].

The alignment with multiple SDGs creates opportunities for integrated policy approaches and financing mechanisms. However, realizing this potential requires institutional coordination and policy coherence across sectors^[40].

5. Conclusion

Global soil recarbonization through strategic SOC management presents substantial opportunities for climate change mitigation while supporting sustainable development goals. The potential to sequester 2.8-5.1 Gt CO₂ annually represents a significant contribution to global climate targets when combined with comprehensive co-benefits.

Key findings establish that integrated management approaches achieve superior sequestration rates but face implementation challenges requiring supportive policies, financial incentives, and technical assistance. Economic viability depends on valuing co-benefits including improved productivity, environmental services, and rural development outcomes.

Temporal dynamics indicate declining sequestration rates over time, emphasizing the need for sustained management and realistic expectations. Climate change impacts will reduce efficiency by 12-18%, requiring adaptive strategies and early implementation to maximize benefits.

Success factors include supportive policies, financial

incentives, extension services, and community engagement. Regional prioritization should focus on degraded lands in sub-Saharan Africa, Asia, and Latin America where sequestration potential and development needs converge.

Implementation requires coordinated international efforts combining climate finance, technical cooperation, and policy integration across sectors. The alignment with multiple SDGs provides opportunities for integrated approaches that maximize sustainable development impacts.

These findings support urgent action to scale up SOC management as a nature-based climate solution while ensuring equitable benefits for global agricultural communities and environmental sustainability.

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