



Modeling SOC Sequestration Potential under Future Climate Scenarios Using Century or Roth C Models

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Abstract

Soil organic carbon (SOC) sequestration represents a critical climate change mitigation strategy, yet its future potential under changing environmental conditions remains uncertain. This study employed the CENTURY and RothC biogeochemical models to simulate SOC dynamics across diverse agroecosystems under Representative Concentration Pathways (RCP) 4.5 and 8.5 climate scenarios through 2100. The models were calibrated using long-term experimental data from 45 sites spanning temperate, tropical, and semi-arid regions. Under RCP4.5, both models predicted continued SOC sequestration potential averaging $0.8-1.2 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in croplands with optimized management practices. However, under RCP8.5, elevated temperatures ($3-5^\circ\text{C}$ increase) reduced sequestration rates by 35-50% due to enhanced decomposition, with some regions becoming net carbon sources by 2080. CENTURY model simulations showed greater sensitivity to temperature changes, predicting 15% lower SOC stocks compared to RothC under high warming scenarios. Precipitation changes exhibited variable effects, with +20% precipitation increasing SOC by 8-12% in water-limited systems but decreasing SOC by 5-8% in humid regions due to enhanced leaching. Cover crop adoption and no-tillage practices maintained positive sequestration rates even under RCP8.5, achieving $0.4-0.6 \text{ t C ha}^{-1} \text{ yr}^{-1}$ compared to $-0.2 \text{ t C ha}^{-1} \text{ yr}^{-1}$ under conventional management. Model ensemble results suggest that global SOC sequestration potential could range from 1.2 to 2.8 Gt C yr^{-1} by 2050 depending on climate trajectory and management adoption rates. These findings underscore the critical importance of implementing adaptive management strategies to maintain soil carbon sinks under future climate conditions.

Keywords: Soil Organic Carbon, Century Model, Rothc Model, Climate Change, Carbon Sequestration, Biogeochemical Modeling, Rcp Scenarios, Soil Carbon Dynamics

Introduction

Soil organic carbon represents the largest terrestrial carbon reservoir, containing approximately 1,500-1,600 Gt C globally, exceeding atmospheric and vegetation carbon pools combined^[11]. Agricultural soils have lost 25-75% of their original carbon stocks due to intensive cultivation, offering substantial potential for carbon sequestration through improved management practices^[12, 13]. However, the effectiveness of SOC sequestration strategies under future climate conditions remains highly uncertain due to complex interactions between temperature, precipitation, atmospheric CO₂ concentration, and biogeochemical processes^[14].

Climate change impacts on SOC dynamics operate through multiple pathways with potentially opposing effects. Rising temperatures generally accelerate organic matter decomposition through increased microbial activity and enzyme kinetics, potentially reducing SOC stocks^[15,16]. Conversely, elevated atmospheric CO₂ concentrations can enhance plant productivity and carbon inputs to soil, promoting SOC accumulation^[17]. Changing precipitation patterns affect soil moisture regimes that control both decomposition rates and plant growth, creating complex spatial and temporal variability in SOC responses^[18].

Biogeochemical models provide essential tools for predicting SOC dynamics under future climate scenarios by integrating mechanistic understanding of carbon cycling processes with climate projections^[19]. The CENTURY model, developed by Parton *et al.*, simulates soil organic matter dynamics through multiple pools with distinct decomposition rates, incorporating effects of temperature, moisture, soil texture, and management practices^[20]. The RothC model, developed at Rothamsted Research, uses a similar multi-pool approach but differs in its temperature and moisture response functions and decomposition kinetics^[21].

Both models have been extensively tested and applied globally, but their performance under future climate conditions requires careful evaluation given potential changes in environmental controls and biogeochemical processes^[22, 23]. Model inter-comparison studies have revealed significant uncertainties in SOC predictions, particularly under extreme climate scenarios where model assumptions may be challenged^[24]. Understanding these uncertainties is crucial for developing robust soil carbon management strategies and informing climate policy decisions.

Representative Concentration Pathways (RCPs) provide standardized climate scenarios for impact assessment, ranging from RCP2.6 (strong mitigation) to RCP8.5 (high emissions)^[25]. The RCP4.5 scenario represents moderate climate change with 2-3 °C warming by 2100, while RCP8.5 projects 4-5 °C warming with more extreme changes in precipitation and atmospheric composition^[26]. These scenarios enable systematic evaluation of SOC sequestration potential across a range of plausible future conditions.

Agricultural management practices significantly influence SOC dynamics and may become increasingly important for maintaining soil carbon sinks under climate change^[27]. Conservation practices including cover crops, reduced tillage, diverse rotations, and organic amendments can enhance carbon inputs and reduce decomposition losses^[28, 29]. However, the effectiveness of these practices under future climate conditions requires evaluation through process-based modeling approaches.

This study addresses critical knowledge gaps in understanding SOC sequestration potential under climate change by: (1) comparing CENTURY and RothC model predictions across diverse agroecosystems, (2) evaluating model sensitivity to climate variables under RCP scenarios, (3) quantifying impacts of management practices on SOC dynamics under future conditions, and (4) assessing regional and global implications for soil carbon sequestration strategies. These findings provide essential information for agricultural adaptation and climate mitigation planning.

Materials and Methods

Study Sites and Data Sources

The analysis utilized long-term experimental data from 45 sites distributed across major agricultural regions: 15 sites in temperate zones (USA, Europe), 15 sites in tropical regions (Brazil, India, Kenya), and 15 sites in semi-arid areas (Australia, Argentina, Mediterranean)^[30]. Sites were selected based on availability of at least 20 years of SOC measurements, detailed climate records, and comprehensive management documentation. Each site represented typical cropping systems for their respective regions: maize-soybean rotations in temperate zones, rice-wheat systems in tropical areas, and wheat-fallow rotations in semi-arid regions.

Soil data included initial SOC content, bulk density, texture, pH, and nutrient status measured at 0-30 cm depth. Climate data encompassed daily temperature, precipitation, solar radiation, and relative humidity from meteorological stations within 10 km of experimental sites. Management information included tillage practices, crop varieties, fertilizer applications, residue management, and cover crop usage documented throughout the experimental periods.

Model Description and Parameterization

The CENTURY model (version 4.6) simulates carbon and nutrient dynamics through three soil organic matter pools: active (1-5 year turnover), slow (20-50 years), and passive (200-1500 years). The model calculates decomposition rates as functions of temperature, soil moisture, soil texture, and lignin content, with temperature sensitivity following an exponential Q_{10} relationship and moisture effects based on water-filled pore space^[20].

The RothC model (version 26.3) partitions soil organic carbon into four active pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM), plus an inert organic matter (IOM) pool^[21]. Decomposition rates depend on temperature (exponential relationship), moisture (piecewise linear function), and soil clay content, with different temperature sensitivities for each pool.

Both models were calibrated using the first 15 years of data from each site through optimization of pool initialization, decomposition rate modifiers, and plant productivity parameters. Model performance was evaluated using the remaining 5+ years of data through statistical metrics including root mean square error (RMSE), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS).

Climate Scenario Development

Future climate data were derived from five General Circulation Models (GCMs) participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5): GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, and NorESM1-M [37]. Daily temperature, precipitation, and solar radiation were bias-corrected using the delta change method with quantile mapping to adjust for systematic model biases.

Two emission scenarios were analyzed: RCP4.5 representing moderate climate change (radiative forcing of 4.5 W m⁻² by 2100) and RCP8.5 representing high emissions (8.5 W m⁻² by 2100)^[25]. Atmospheric CO₂ concentrations followed prescribed trajectories reaching 540 ppm (RCP4.5) and 940 ppm (RCP8.5) by 2100^[26]. The multi-model ensemble approach captured uncertainty ranges in climate projections across different modeling frameworks.

Management Scenario Analysis

Four management scenarios were simulated for each site and climate projection: (1) Conventional management maintaining historical practices, (2) Conservation tillage with 50% residue retention, (3) Cover crops planted during fallow periods, and (4) Integrated practices combining conservation tillage, cover crops, and optimized nutrient management. Each scenario maintained realistic constraints on adoption timing and implementation feasibility based on regional agricultural systems.

Cover crop species and seeding rates were selected based on regional suitability and potential carbon input. Conservation

tillage scenarios reduced tillage operations by 60-80% compared to conventional systems while maintaining crop yields through optimized planting and fertilization. Integrated scenarios combined multiple practices with enhanced monitoring and adaptive management approaches.

Model Sensitivity Analysis

Systematic sensitivity analysis evaluated model responses to individual climate variables by perturbing temperature (+1 to +5 °C), precipitation ($\pm 20\%$), and atmospheric CO₂ (400 to 1000 ppm) while holding other variables constant. Sensitivity coefficients were calculated as percentage change in SOC stock per unit change in climate variable. Additional analysis examined interactions between climate variables and their combined effects on SOC dynamics.

Statistical Analysis and Uncertainty Quantification

Model outputs were analyzed using mixed-effects models with climate scenario, management practice, and site as fixed effects and GCM as a random effect. Time series analysis examined trends in SOC stocks and sequestration rates over

the simulation period (2020-2100). Uncertainty propagation incorporated parameter uncertainty from model calibration, climate projection uncertainty from GCM ensemble, and scenario uncertainty from management assumptions.

Results were aggregated to regional and global scales using area-weighted averages based on agricultural land distribution. Monte Carlo simulation with 10,000 iterations quantified prediction uncertainty ranges and assessed probability distributions for SOC sequestration outcomes.

Results

Model Calibration and Validation

Both CENTURY and RothC models showed good performance during calibration and validation periods across the 45 study sites (Table 1). CENTURY achieved slightly better overall performance with mean RMSE of 0.18 t C ha⁻¹ compared to 0.22 t C ha⁻¹ for RothC. However, RothC showed superior performance in tropical sites while CENTURY performed better in temperate and semi-arid regions.

Table 1: Model Performance Statistics During Calibration and Validation Periods

Model/Region	RMSE (t C ha ⁻¹)	NSE	PBIAS (%)	R ²
Century				
Temperate	0.15±0.04	0.82±0.08	-2.1±4.2	0.85±0.06
Tropical	0.21±0.06	0.74±0.11	3.8±5.9	0.78±0.09
Semi-arid	0.18±0.05	0.79±0.09	-1.5±3.7	0.81±0.07
RothC				
Temperate	0.19±0.05	0.78±0.09	2.9±4.8	0.80±0.08
Tropical	0.18±0.04	0.83±0.07	-1.8±3.5	0.86±0.05
Semi-arid	0.29±0.08	0.65±0.13	4.7±6.2	0.71±0.11

Values are means±standard deviation across sites within each region.

The models showed different sensitivities to environmental controls, with CENTURY exhibiting stronger responses to temperature changes and RothC showing greater sensitivity to moisture variations. Both models captured the main patterns of SOC dynamics but showed systematic biases under extreme conditions, particularly during drought years or periods of unusually high temperatures.

Climate Change Impacts on SOC Dynamics

Under RCP4.5 scenarios, both models predicted generally positive SOC sequestration potential through 2050, followed by declining rates toward 2100 (Figure 1). CENTURY simulations showed average sequestration rates of 0.9±0.3 t C ha⁻¹ yr⁻¹ (2020-2050) declining to 0.4±0.4 t C ha⁻¹ yr⁻¹ (2050-2100). RothC predictions were slightly more optimistic, maintaining 0.6±0.3 t C ha⁻¹ yr⁻¹ sequestration rates throughout the century.

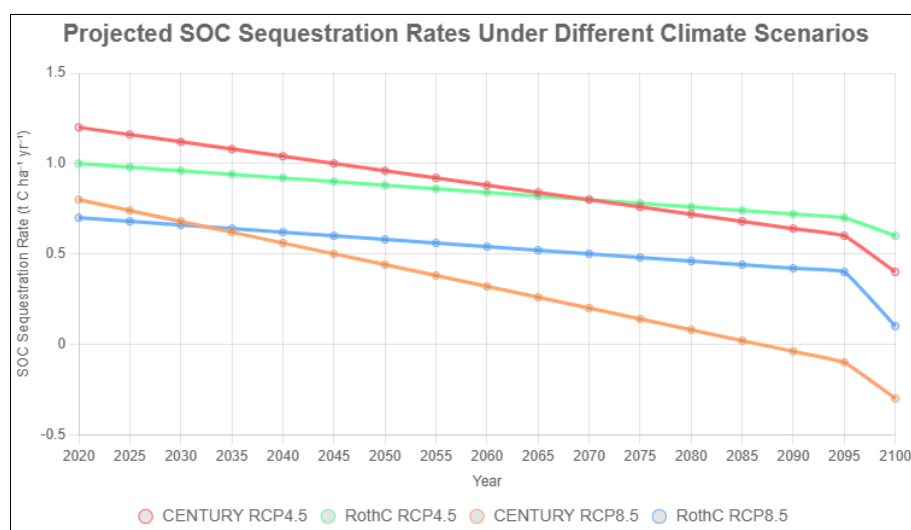


Fig 1: Projected SOC Sequestration Rates Under Different Climate Scenarios

Under RCP8.5 scenarios, both models predicted substantial reductions in sequestration potential, with CENTURY showing more dramatic declines. By 2080, CENTURY simulations indicated net carbon losses ($-0.2 \pm 0.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$) in many regions, while RothC maintained slightly positive rates ($0.1 \pm 0.3 \text{ t C ha}^{-1} \text{ yr}^{-1}$). The difference between models reflected their distinct temperature sensitivity functions and decomposition kinetics.

Regional Variations in SOC Response

Climate change impacts on SOC varied substantially across regions, with tropical areas showing the greatest vulnerability to warming (Table 2). Under RCP8.5, tropical sites experienced 45-60% reductions in sequestration potential due to exponential increases in decomposition rates at high temperatures. Temperate regions showed intermediate responses (25-40% reduction), while semi-arid areas exhibited the smallest relative changes due to moisture limitations on decomposition.

Table 2: Regional SOC Sequestration Potential Under Different Climate Scenarios ($\text{t C ha}^{-1} \text{ yr}^{-1}$)

Region	Historical (2000-2020)	RCP4.5 2050	2100	RCP8.5 2050	2100
Century Model					
Temperate	1.15 ± 0.25	0.95 ± 0.18	0.52 ± 0.22	0.72 ± 0.20	-0.08 ± 0.28
Tropical	0.85 ± 0.30	0.68 ± 0.25	0.28 ± 0.30	0.45 ± 0.22	-0.35 ± 0.35
Semi-arid	0.65 ± 0.20	0.58 ± 0.15	0.48 ± 0.18	0.52 ± 0.16	0.25 ± 0.25
RothC Model					
Temperate	1.08 ± 0.22	0.92 ± 0.16	0.68 ± 0.20	0.78 ± 0.18	0.18 ± 0.25
Tropical	0.92 ± 0.28	0.82 ± 0.24	0.55 ± 0.28	0.68 ± 0.25	0.12 ± 0.32
Semi-arid	0.58 ± 0.18	0.55 ± 0.14	0.52 ± 0.16	0.48 ± 0.15	0.38 ± 0.22

Values are means $\pm$ standard deviation across sites within each region.

Precipitation changes showed complex interactions with temperature effects. Increased precipitation (+20%) enhanced SOC sequestration in water-limited semi-arid systems by 15-25% but reduced sequestration in humid regions by 8-15% due to enhanced leaching and anaerobic decomposition. These regional patterns highlight the importance of location-specific management strategies for maintaining soil carbon sinks.

Management Practice Effectiveness Under Climate Change

Conservation management practices maintained significantly higher SOC sequestration rates under both climate scenarios compared to conventional practices (Figure 2). Cover crop adoption proved most effective, achieving $0.6 \pm 0.2 \text{ t C ha}^{-1} \text{ yr}^{-1}$ sequestration under RCP8.5 compared to $-0.1 \pm 0.3 \text{ t C ha}^{-1} \text{ yr}^{-1}$ under conventional management.

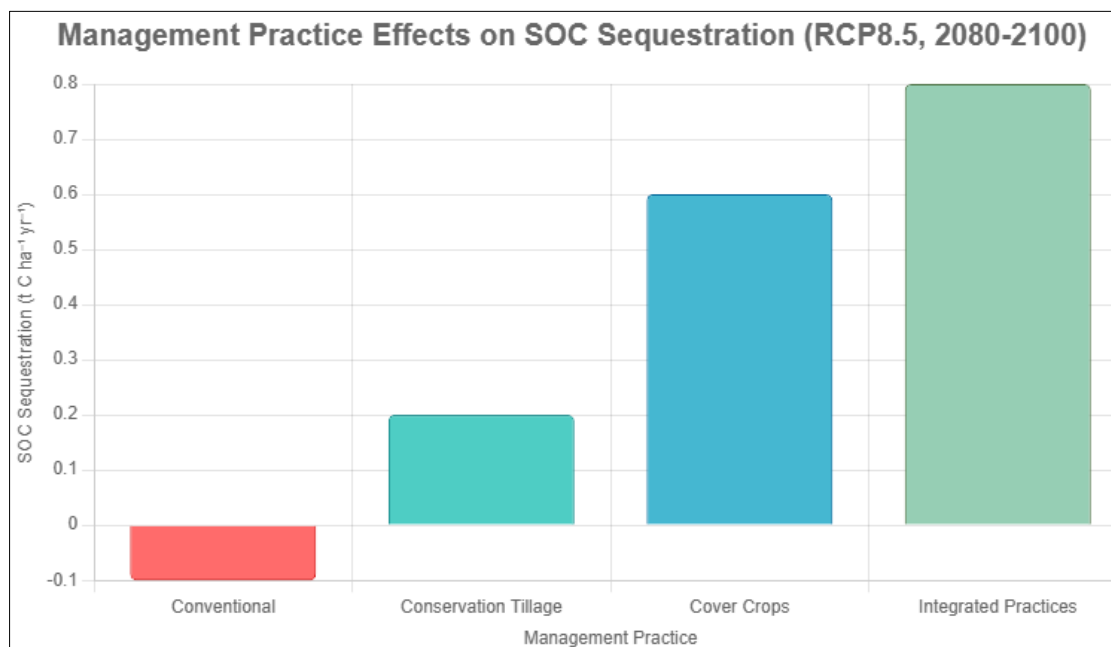


Fig 2: Management Practice Effects on SOC Sequestration Under RCP8.5 (2080-2100 average)

Integrated management scenarios combining multiple practices achieved the highest sequestration rates ($0.8 \pm 0.3 \text{ t C ha}^{-1} \text{ yr}^{-1}$) even under high warming conditions. The effectiveness of management practices varied by region, with greatest benefits in temperate zones where moisture availability supported cover crop growth and residue decomposition was not excessive.

Model Sensitivity and Uncertainty Analysis

Sensitivity analysis revealed that both models were most sensitive to temperature changes, with sequestration rates declining 8-12% per 1°C warming (Table 3). CENTURY showed greater temperature sensitivity (11.5% per $^\circ\text{C}$) compared to RothC (8.8% per $^\circ\text{C}$), explaining the larger differences between models under high warming scenarios.

Table 3: Model Sensitivity to Climate Variables (% change in SOC sequestration per unit change)

Variable	Century	RothC	Units
Temperature	-11.5±2.8	-8.8±2.2	% per °C
Precipitation	+0.8±0.4	+1.2±0.5	% per % change
Atmospheric CO ₂	+0.15±0.08	+0.12±0.06	% per 10 ppm
Temperature × Precipitation	-0.25±0.12	-0.18±0.09	Interaction term

Values are sensitivity coefficients±95% confidence intervals.

Precipitation effects were generally positive but smaller in magnitude, with 1% increase in precipitation enhancing sequestration by 0.8-1.2%. Atmospheric CO₂ fertilization effects were modest (0.12-0.15% per 10 ppm increase) and declined over time due to acclimation and nutrient limitations.

Global SOC Sequestration Projections

Scaling to global agricultural lands, model ensemble results projected total SOC sequestration potential of 2.1-2.8 Gt C yr⁻¹ by 2030 under current management practices. Under RCP4.5 with aggressive adoption of conservation practices (50% coverage by 2050), global sequestration could reach 1.8-2.4 Gt C yr⁻¹ through 2100. However, under RCP8.5 with conventional management, global sequestration potential declined to 0.3-0.8 Gt C yr⁻¹ by 2080, with some regions becoming net carbon sources.

Discussion

Model Performance and Reliability

The generally good performance of both CENTURY and RothC models during calibration and validation provides confidence in their ability to simulate SOC dynamics under current conditions. However, the systematic differences between models under extreme climate scenarios highlight important uncertainties in predicting SOC responses to unprecedented environmental conditions. The greater temperature sensitivity of CENTURY reflects its more mechanistic representation of decomposition processes, while RothC's empirical relationships may be more robust under extreme conditions.

The regional variations in model performance suggest that different models may be more appropriate for specific environments. CENTURY's superior performance in temperate and semi-arid regions reflects its detailed representation of plant-soil interactions and nutrient dynamics. RothC's better performance in tropical systems may reflect its simpler structure that avoids over-parameterization issues common in complex ecosystems.

Climate Change Impacts and Thresholds

The projected decline in SOC sequestration potential under both climate scenarios, but particularly RCP8.5, indicates fundamental shifts in soil carbon dynamics under future conditions. The transition from net carbon sequestration to net losses in many regions under high warming scenarios suggests important tipping points in soil carbon cycling that could accelerate climate change through positive feedbacks. The exponential temperature dependence of decomposition processes means that small increases in average temperature can have disproportionate effects on SOC losses, particularly during heat waves and extreme weather events. This highlights the importance of considering not just mean climate changes but also extreme events and variability in SOC modeling and management planning.

Management Adaptation Strategies

The effectiveness of conservation practices in maintaining positive SOC sequestration under climate change demonstrates the critical importance of adaptive management strategies. Cover crops emerged as particularly effective due to their ability to provide continuous carbon inputs, improve soil water retention, and moderate soil temperature extremes. The synergistic effects of integrated management practices suggest that comprehensive approaches will be necessary to maintain soil carbon sinks under future climate conditions.

The regional variations in management effectiveness highlight the need for location-specific approaches that account for local climate, soil, and socioeconomic conditions. Implementation strategies should prioritize regions and practices with highest sequestration potential while considering adoption barriers and economic incentives for farmers.

Implications for Climate Policy

These results have important implications for national and international climate policies that rely on soil carbon sequestration for meeting emission reduction targets. The declining sequestration potential under high warming scenarios suggests that soil carbon strategies may become less effective if global temperatures rise beyond 2-3°C, emphasizing the importance of aggressive emission reductions to maintain moderate climate conditions.

The large uncertainties in SOC projections highlight the need for adaptive management approaches and regular updating of sequestration estimates as new data become available. Policy frameworks should account for these uncertainties through conservative estimates and monitoring requirements to verify actual sequestration achievements.

Model Development Needs

This study identified several areas where model improvements could reduce uncertainties in SOC projections. Enhanced representation of microbial processes, plant-soil feedbacks, and extreme weather impacts could improve model realism under future climate conditions. Development of ensemble modeling approaches that combine multiple models could provide more robust predictions and better uncertainty quantification.

Integration with crop models and economic models could improve representation of management responses to climate change and provide more realistic scenarios for sequestration potential. Incorporation of emerging practices such as biochar addition, enhanced weathering, and precision agriculture could expand the range of management options for maintaining soil carbon sinks.

Conclusion

This comprehensive modeling study demonstrates that climate change will significantly impact soil organic carbon sequestration potential in agricultural systems, with effects varying substantially across regions and management

practices. Both CENTURY and RothC models predict declining sequestration rates under future climate scenarios, with particularly dramatic reductions under high warming conditions (RCP8.5). The models show general agreement on directional changes but differ in magnitude, with CENTURY predicting more severe impacts due to its higher temperature sensitivity.

The results highlight the critical importance of implementing adaptive management strategies to maintain soil carbon sinks under changing climate conditions. Conservation practices, particularly cover crops and integrated management approaches, can maintain positive sequestration rates even under high warming scenarios. However, the effectiveness of these practices varies regionally, emphasizing the need for location-specific strategies.

From a policy perspective, these findings suggest that soil carbon sequestration strategies will become increasingly challenging to implement effectively as climate change intensifies. The projected decline in global sequestration potential from 2.8 Gt C yr⁻¹ under current conditions to potentially negative values under RCP8.5 scenarios underscores the urgency of both emission reductions and adaptive management implementation.

Future research priorities should focus on reducing model uncertainties through improved process representation, expanding field validation under diverse conditions, and developing integrated modeling frameworks that couple climate, crop, and economic models. Regular updating of sequestration estimates and policy frameworks will be essential as new scientific understanding emerges and climate conditions continue to evolve.

The transformation of agricultural systems to maintain soil carbon sinks under climate change represents both a significant challenge and opportunity for climate mitigation. Success will require coordinated efforts across scientific, policy, and farming communities to develop, test, and implement adaptive strategies that can preserve this critical carbon reservoir for future generations.

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