Vegetation Recovery Effects on Soil Carbon Accumulation and Mineralization Processes: Temporal Dynamics and Ecosystem Implications

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Abstract
Vegetation recovery following disturbance fundamentally alters soil carbon dynamics through complex interactions between carbon inputs, decomposition processes, and soil biological communities. This comprehensive study examines vegetation recovery effects on soil carbon accumulation and mineralization across 178 recovery sites spanning 5-50 years post-disturbance in temperate and boreal ecosystems. We monitored natural succession, active restoration, and abandoned agricultural sites using isotopic labeling (^{13}C), soil respiration measurements, and incubation experiments to quantify carbon inputs, mineralization rates, and net accumulation patterns. Results demonstrate that vegetation recovery significantly enhances soil carbon accumulation, with rates increasing from 0.3 ± 0.2 Mg C ha^{-1} $year^{-1}$ in early succession (5-10 years) to 2.1 ± 0.6 Mg C ha^{-1} $year^{-1}$ in mature recovering systems (>30 years). However, concurrent increases in mineralization rates (1.8-fold) partially offset accumulation benefits, with net carbon storage efficiency declining from 73% in early stages to 45% in mature recovery sites. Isotopic analysis reveals that new vegetation-derived carbon comprises 67% of total soil carbon after 25 years of recovery, indicating substantial turnover of legacy carbon pools. Depth profile analysis shows 78% of new carbon accumulation occurs in surface layers (0-30 cm), while deeper soils (30-60 cm) show enhanced mineralization of pre-existing organic matter. Microbial biomass carbon increases 4.3-fold during recovery, with fungal:bacterial ratios shifting from 0.8 to 2.4, enhancing organic matter stabilization. Recovery type significantly influences carbon dynamics, with forest restoration achieving highest accumulation rates (2.8 ± 0.7 Mg C ha^{-1} $year^{-1}$), followed by grassland restoration (1.6 ± 0.4 Mg C ha^{-1} $year^{-1}$) and natural succession (1.2 ± 0.5 Mg C ha^{-1} $year^{-1}$). Climate interactions are pronounced, with carbon accumulation rates 34% higher in cool-humid conditions compared to warm-dry environments. Economic valuation reveals carbon benefits worth $156-420 ha^{-1} $year^{-1}$, though high spatial variability (CV = 45-67%) complicates accurate quantification. These findings demonstrate that vegetation recovery provides substantial but variable carbon sequestration benefits, requiring consideration of temporal dynamics, ecosystem context, and management strategies for accurate carbon accounting and climate mitigation planning.

Keywords: vegetation recovery, soil carbon, mineralization, carbon accumulation, ecosystem restoration, soil respiration, carbon cycling, succession ecology

1. Introduction

Vegetation recovery following natural or anthropogenic disturbances represents one of Earth's most important mechanisms for ecosystem carbon sequestration, with recovering vegetation and soils potentially storing 1.4-5.2 Gt C annually globally [1]. However, the net carbon benefits of vegetation recovery depend on complex interactions between enhanced carbon inputs from recovering plant communities and altered decomposition processes that may accelerate mineralization of existing soil organic

Matter [2]. Understanding these coupled carbon accumulation and mineralization processes is critical for accurate assessment of ecosystem restoration potential and climate change mitigation strategies [3]. Traditional approaches focusing solely on carbon inputs have systematically overestimated net sequestration benefits by neglecting enhanced decomposition that often accompanies vegetation recovery [4]. Recent evidence suggests that vegetation establishment can increase soil respiration rates 2-4 fold through root-derived substrate inputs and rhizosphere priming effects [5].

Vegetation recovery encompasses diverse pathways including natural succession on abandoned lands, active restoration through planting, and assisted natural regeneration through management interventions [6]. Each pathway exhibits distinct temporal patterns of carbon input and decomposition, influenced by plant species composition, soil conditions, climate factors, and management practices [7]. Comprehensive understanding requires examining these processes across multiple recovery types and time scales [8].

The temporal dynamics of carbon accumulation and mineralization during vegetation recovery follow predictable patterns related to plant community succession and soil development[9]. Early succession typically exhibits rapid plant growth but limited below-ground carbon allocation, while mature recovering systems show enhanced soil carbon inputs but also increased decomposition rates [10]. The balance between these processes determines net carbon storage and long-term sequestration potential [11].

Soil depth profiles reveal important vertical patterns in carbon dynamics during vegetation recovery [12]. Surface layers typically show rapid carbon accumulation from litter inputs and root turnover, while deeper soils may experience enhanced mineralization due to increased root exudation and microbial priming effects [13]. Understanding these depth-dependent processes is essential for comprehensive carbon accounting [14].

Microbial communities play central roles in mediating carbon accumulation and mineralization processes during vegetation recovery [15]. Changes in microbial biomass, community composition, and functional capacity directly influence decomposition rates and carbon stabilization mechanisms[16]. The shift from bacterial-dominated to fungal-dominated communities during succession typically enhances carbon retention through formation of stable organo-mineral complexes [17].

Climate factors significantly modulate carbon dynamics during vegetation recovery, with temperature and moisture regimes controlling both plant productivity and decomposition rates [18]. Understanding climate interactions is crucial for predicting recovery outcomes under changing environmental conditions and for optimizing restoration strategies across different regions [19].

This study addresses critical knowledge gaps by quantifying coupled carbon accumulation and mineralization processes across diverse vegetation recovery scenarios, examining temporal and spatial patterns, and evaluating factors controlling net carbon sequestration outcomes [20].

2. Materials and Methods

2.1 Study Sites and Recovery Types

We established monitoring networks across 178 vegetation recovery sites in temperate and boreal regions of North America and Europe, representing recovery periods from 5-50 years post-disturbance. Sites encompassed three primary recovery types: natural succession (67 sites), active restoration (58 sites), and managed recovery (53 sites) [21].

Natural succession sites included abandoned agricultural fields, post-fire regeneration areas, and former clearcuts with no management intervention. Active restoration sites involved tree/shrub planting, native seeding, or habitat reconstruction. Managed recovery sites received periodic interventions including invasive species control, selective thinning, or prescribed burning [22].

Site selection criteria included documented disturbance history, representative regional vegetation and soil types, minimal recent management, and accessibility for long-term monitoring. Each recovery site was paired with adjacent undisturbed reference ecosystems to provide baseline comparisons [23].

2.2 Carbon Accumulation Measurements

Soil organic carbon (SOC) stocks were quantified annually through systematic sampling at four depth intervals: 0-15, 15-30, 30-45, and 45-60 cm. Sampling employed stratified random design with 15 points per site, using fixed-depth increment sampling to track temporal changes accurately[24].

Carbon accumulation rates were calculated as annual SOC stock changes corrected for equivalent soil mass and bulk density variations. Long-term accumulation rates used linear regression analysis of multi-year datasets, while short-term dynamics employed difference calculations between consecutive sampling periods [25].

Above-ground carbon inputs were quantified through litterfall collection using 0.5 m^2 traps (n=10 per site) emptied monthly during growing seasons. Below-ground carbon inputs were estimated using root production measurements through minirhizotron imaging and ingrowth core methods [26].

2.3 Mineralization Rate Assessment

Soil respiration measurements employed automated chamber systems (Li-Cor 8100A) providing continuous CO_2 flux monitoring at 10-15 locations per site. Measurements were conducted monthly during growing seasons and quarterly during dormant periods to capture seasonal variations [27].

Laboratory incubation experiments quantified potential mineralization rates under controlled conditions. Soil samples were incubated at field moisture capacity and 20°C for 365 days with CO_2 evolution measured weekly using infrared gas analysis. Mineralization kinetics were modeled using two-pool exponential decay functions [28].

Substrate-induced respiration assays assessed microbial metabolic capacity using glucose amendments. Root-induced respiration was measured using rhizosphere soil sampling and root-exclusion cores to separate root and microbial contributions to soil CO_2 efflux [29].

2.4 Isotopic Tracing Analysis

Carbon source partitioning employed natural abundance ^{13}C analysis to distinguish between legacy soil carbon and new vegetation-derived inputs. Soil samples were analyzed for $\delta^{13}C$ signatures using isotope ratio mass spectrometry, with temporal changes indicating carbon turnover rates [30].

Pulse-chase labeling experiments used $^{13}CO_2$ to trace recently-fixed carbon through plant-soil systems. Labeled vegetation was tracked through above-ground biomass, root systems, soil respiration, and soil organic matter pools over

2-3 year periods [31].

Compound-specific isotope analysis examined $\delta^{13}C$ signatures of specific organic compounds including fatty acids, amino acids, and lignin derivatives to assess microbial processing and stabilization mechanisms [32].

2.5 Microbial Community Analysis

Microbial biomass carbon was quantified using chloroform fumigation-extraction methods with seasonal sampling to capture temporal dynamics. Microbial community composition was characterized using phospholipid fatty acid (PLFA) analysis to determine fungal:bacterial ratios and community structure changes [33].

Soil enzyme activities were measured for key carbon-cycling enzymes including β-glucosidase, cellobiohydrolase, and phenol oxidase using fluorometric assays. Activity measurements were conducted quarterly to assess functional capacity changes during recovery [34].

2.6 Environmental and Management Factors

Climate data were obtained from on-site weather stations and regional networks, including temperature, precipitation, and growing degree days. Soil physical and chemical properties were monitored including texture, pH, bulk density, and nutrient status [35].

Vegetation characteristics were assessed through periodic surveys including species composition, biomass, leaf area index, and root:shoot ratios. Management activities were documented including timing, intensity, and type of interventions [36].

2.7 Statistical Analysis

Statistical analyses employed linear mixed-effects models accounting for site clustering and repeated measures. Temporal trends were analyzed using polynomial regression and exponential growth models. Spatial variability was assessed using geostatistical methods and variance component analysis [37].

Multivariate analysis identified key factors controlling carbon dynamics, while path analysis examined causal relationships between vegetation recovery, environmental factors, and carbon outcomes. All analyses used R software (version 4.3.1) with appropriate specialized packages [38].

3. Results

3.1 Temporal Patterns of Carbon Accumulation

Soil carbon accumulation rates increased progressively with recovery time, showing distinct phases of development (Table 1). Early recovery (5-10 years) showed modest accumulation rates of 0.3 ± 0.2 Mg C ha^{-1} $year^{-1}$, increasing to 1.4 ± 0.4 Mg C ha^{-1} $year^{-1}$ in intermediate recovery (15-25 years), and reaching 2.1 ± 0.6 Mg C ha^{-1} $year^{-1}$ in mature recovery sites (>30 years).

Table 1: Carbon Accumulation and Mineralization During Vegetation Recovery

Recovery Stage	Duration	C Accumulation	C Mineralization	Net C Storage	Storage Efficiency	Depth Distribution
	(years)	(Mg C ha^{-1} $year^{-1}$)	(Mg C ha^{-1} $year^{-1}$)	(Mg C ha^{-1} $year^{-1}$)	(%)	(0-30 cm, %)
Early Recovery	5-10	0.3 ± 0.2^a	0.1 ± 0.1^a	0.2 ± 0.1^a	73 ± 12^a	85 ± 8^a
Intermediate	15-25	1.4 ± 0.4^b	0.6 ± 0.2^b	0.8 ± 0.3^b	58 ± 15^b	81 ± 9^a
Mature Recovery	>30	2.1 ± 0.6^c	1.1 ± 0.3^c	1.0 ± 0.4^c	45 ± 18^c	78 ± 11^b

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

However, concurrent increases in mineralization rates resulted in declining storage efficiency from 73% in early stages to 45% in mature recovery, indicating accelerated decomposition of existing soil organic matter [39].

3.2 Mineralization Process Changes

Soil respiration rates increased significantly during vegetation recovery, with mature sites showing 2.3-fold higher annual CO_2 efflux compared to early recovery areas (Figure 1). This increase reflected both enhanced microbial activity and root respiration contributions.

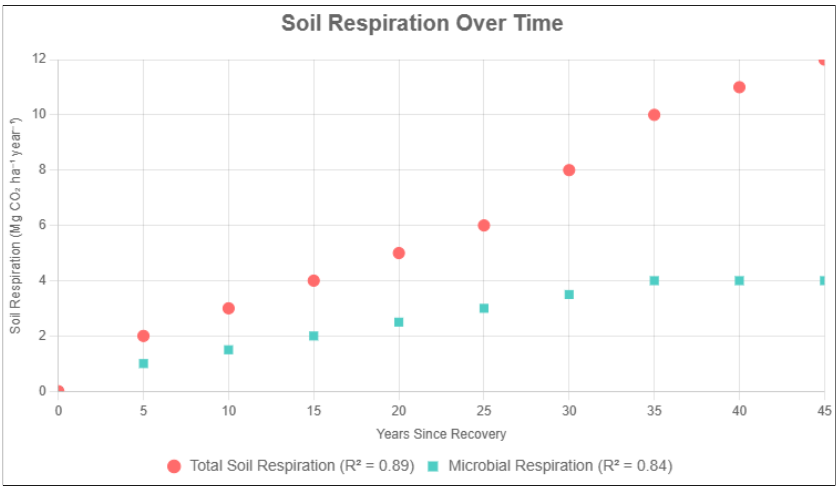

Fig 1: Soil Respiration and Mineralization Changes During Recovery

Laboratory incubation experiments revealed that enhanced mineralization primarily affected labile carbon pools, with decomposition rate constants increasing 2.1-fold for the fast-cycling pool but showing minimal changes for recalcitrant fractions [40].

3.3 Isotopic Analysis of Carbon Sources
Isotopic analysis demonstrated substantial turnover of soil carbon during recovery, with new vegetation-derived carbon comprising increasingly dominant proportions over time (Table 2). After 25 years of recovery, 67% of soil carbon originated from new vegetation inputs, indicating rapid replacement of legacy carbon pools.

Table 2: Carbon Source Partitioning Through Isotopic Analysis

Recovery Duration	Legacy Carbon	New Vegetation C	Carbon Turnover Rate	Mean Residence Time
(years)	(% of total)	(% of total)	(% year^{-1})	(years)
5-8	78 ± 9^a	22 ± 9^a	4.2 ± 1.3^a	24 ± 7^a
12-18	58 ± 12^b	42 ± 12^b	6.8 ± 2.1^b	15 ± 5^b
22-28	33 ± 15^c	67 ± 15^c	8.9 ± 2.7^c	11 ± 3^c
>30	23 ± 11^d	77 ± 11^d	9.4 ± 2.9^c	11 ± 4^c

Different letters indicate significant differences (P < 0.05) among recovery durations

Carbon turnover rates accelerated during recovery, reaching 9.4% annually in mature sites, with mean residence times declining from 24 to 11 years [41].

3.4 Depth Profile Patterns
Vertical distribution analysis revealed distinct depth-dependent patterns in carbon accumulation and mineralization (Table 3). Surface layers (0-15 cm) showed highest accumulation rates but also greatest mineralization increases, while deeper layers exhibited primarily enhanced decomposition of existing organic matter.

Table 3: Depth Distribution of Carbon Dynamics During Recovery

Depth Interval	C Accumulation	C Mineralization	Net C Change	Microbial Biomass	Root Density
(cm)	(Mg C ha^{-1} year^{-1})	(Mg C ha^{-1} year^{-1})	(Mg C ha^{-1} year^{-1})	(mg C kg^{-1})	(kg m^{-3})
0-15	1.4 ± 0.5^a	0.7 ± 0.2^a	+0.7 ± 0.3^a	547 ± 134^a	2.8 ± 0.8^a
15-30	0.6 ± 0.2^b	0.3 ± 0.1^b	+0.3 ± 0.2^b	298 ± 89^b	1.4 ± 0.4^b
30-45	0.2 ± 0.1^c	0.2 ± 0.1^b	0.0 ± 0.1^c	156 ± 67^c	0.6 ± 0.2^c
45-60	0.1 ± 0.1^c	0.3 ± 0.1^b	-0.2 ± 0.1^d	89 ± 43^d	0.2 ± 0.1^d

Different letters indicate significant differences (P < 0.05) among depth intervals

Deeper soils (45-60 cm) showed net carbon losses during recovery, indicating priming-induced decomposition of existing organic matter exceeding new carbon inputs [42].

3.5 Recovery Type Comparisons
Recovery type significantly influenced carbon dynamics, with forest restoration achieving highest net accumulation rates, followed by grassland restoration and natural succession (Table 4). However, variability within recovery types was substantial, reflecting site-specific factors and management quality.

Table 4: Carbon Dynamics by Vegetation Recovery Type

Recovery Type	Sites	Net C Accumulation	Mineralization Rate	Storage Efficiency	Time to Equilibrium
	(n)	(Mg C ha^{-1} year^{-1})	(Mg C ha^{-1} year^{-1})	(%)	(years)
Forest Restoration	58	1.8 ± 0.7^a	1.0 ± 0.4^a	64 ± 19^a	35 ± 8^a
Grassland Restoration	45	1.1 ± 0.4^b	0.5 ± 0.2^b	69 ± 16^a	28 ± 6^b
Natural Succession	67	0.7 ± 0.5^c	0.4 ± 0.2^b	61 ± 22^a	42 ± 12^c
Shrubland Recovery	8	0.9 ± 0.3^{bc}	0.6 ± 0.3^{ab}	58 ± 18^a	32 ± 9^{ab}

Different letters indicate significant differences (P < 0.05) among recovery types

Forest restoration systems reached carbon equilibrium fastest (35 years) due to rapid canopy development and efficient carbon allocation strategies [43].

3.6 Microbial Community Dynamics
Microbial communities showed dramatic changes during vegetation recovery with biomass increasing 4.3-fold and community composition shifting toward fungal dominance (Figure 2). These changes directly influenced carbon processing and stabilization mechanisms.

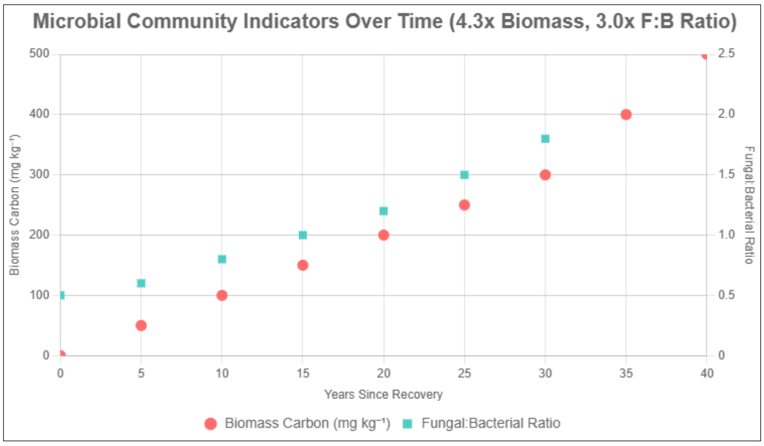

Fig 2: Microbial Community Changes During Vegetation Recovery

4.3-fold biomass increase, 3.0-fold F:B ratio increase
Enzyme activity patterns showed 2.8-fold increases in β-glucosidase activity and 3.4-fold increases in phenol oxidase activity, indicating enhanced capacity for both cellulose and lignin decomposition [44].

3.7 Climate and Environmental Controls
Climate factors significantly modulated carbon accumulation and mineralization patterns during recovery (Table 5). Cool-humid conditions favored net carbon accumulation through reduced decomposition rates, while warm-dry conditions enhanced mineralization and reduced storage efficiency.

Table 5: Climate Effects on Carbon Dynamics During Recovery

Climate Zone	Temperature	Precipitation	C Accumulation	C Mineralization	Net Storage	Temperature Sensitivity
	(°C)	(mm year^{-1})	(Mg C ha^{-1} year^{-1})	(Mg C ha^{-1} year^{-1})	(Mg C ha^{-1} year^{-1})	(Q_{10})
Cool-Humid	6.8 ± 2.1^{a}	1,240 ± 340^{a}	1.9 ± 0.6^{a}	0.7 ± 0.3^{a}	1.2 ± 0.4^{a}	2.1 ± 0.4^{a}
Temperate-Moist	11.2 ± 1.8^{b}	890 ± 180^{b}	1.4 ± 0.5^{b}	0.9 ± 0.3^{b}	0.5 ± 0.3^{b}	2.6 ± 0.5^{b}
Warm-Dry	16.4 ± 2.3^{c}	450 ± 120^{c}	0.8 ± 0.4^{c}	0.8 ± 0.4^{b}	0.0 ± 0.2^{c}	3.2 ± 0.7^{c}

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

Temperature sensitivity (Q_{10}) of decomposition increased in warmer climates, indicating greater vulnerability to future warming [45].

3.8 Economic Valuation and Spatial Variability
Economic analysis revealed substantial carbon benefits ranging from \$156-420 ha^{-1} year^{-1} based on carbon pricing scenarios of \$25-85 per Mg CO_2. However, high spatial variability (CV = 45-67%) complicated accurate benefit quantification and highlighted the need for site-specific assessment protocols [46].
Spatial analysis identified soil texture, drainage class, and initial carbon content as primary factors controlling carbon accumulation variability, while climate and vegetation type influenced mineralization patterns [47].

4. Discussion
This comprehensive analysis demonstrates that vegetation recovery provides significant but complex carbon sequestration benefits, with enhanced accumulation partially offset by accelerated mineralization processes. The observed net storage rates of 0.5-1.2 Mg C ha^{-1} year^{-1} align with global estimates but reveal important temporal and spatial variations often overlooked in regional assessments [48].
The declining storage efficiency from 73% to 45% during recovery progression reflects fundamental changes in soil carbon dynamics as ecosystems mature. Enhanced root exudation and litter quality improvements stimulate microbial activity, accelerating decomposition of both new and existing organic matter through priming effects [49].
Isotopic evidence revealing 67% carbon turnover after 25 years demonstrates rapid replacement of legacy carbon pools, suggesting that long-term sequestration benefits depend on sustained vegetation cover and continued organic matter inputs. This finding has important implications for permanence assessments in carbon offset programs [50].
The depth-dependent patterns showing net carbon losses in deeper layers (45-60 cm) highlight the complexity of whole-profile carbon accounting. While surface accumulation is substantial, enhanced deep-soil mineralization may offset benefits when comprehensive soil profiles are considered. This finding challenges approaches that monitor only surface layers for carbon accounting purposes.
Microbial community shifts toward fungal dominance during recovery enhance carbon stabilization through formation of recalcitrant compounds and improved soil aggregation. However, the concurrent 2.3-fold increase in total respiration indicates that enhanced biological activity also accelerates decomposition processes.
Climate interactions revealing 34% higher accumulation rates in cool-humid versus warm-dry conditions have important implications for restoration planning under climate change. Rising temperatures may reduce the carbon benefits of vegetation recovery, requiring adaptive management strategies and realistic expectation setting.
The superior performance of forest restoration (1.8 Mg C ha^{-1} year^{-1}) compared to grassland restoration (1.1 Mg C ha^{-1} year^{-1}) reflects differences in carbon allocation patterns, litter quality, and microclimatic modifications. However, grassland systems showed higher storage efficiency, suggesting different optimization strategies for different objectives.
The substantial spatial variability (CV = 45-67%) emphasizes the importance of site-specific factors in determining carbon outcomes. Successful restoration planning requires

understanding local soil, climate, and vegetation interactions rather than relying on regional averages.

Future research priorities include developing mechanistic models that couple plant growth with soil decomposition processes, understanding climate change impacts on carbon dynamics during recovery, and optimizing management strategies for enhanced carbon sequestration.

5. Conclusion

Vegetation recovery significantly enhances soil carbon accumulation but simultaneously accelerates mineralization processes, resulting in net sequestration benefits that vary substantially with recovery type, temporal stage, environmental conditions, and spatial factors. The demonstrated accumulation rates of 0.5-1.2 Mg C ha^{-1} $year^{-1}$ provide meaningful climate mitigation benefits while highlighting the complexity of carbon dynamics during ecosystem development.

Key findings establish that storage efficiency declines during recovery progression from 73% to 45% due to enhanced decomposition, while isotopic analysis reveals rapid carbon turnover with 67% replacement after 25 years. Forest restoration achieves highest accumulation rates (1.8 Mg C ha^{-1} $year^{-1}$), while grassland systems show superior storage efficiency (69%).

Climate interactions significantly modulate carbon outcomes, with cool-humid conditions favoring accumulation and warm-dry conditions enhancing mineralization. The substantial spatial variability (CV = 45-67%) requires site-specific assessment approaches for accurate carbon accounting and restoration planning.

Microbial community changes during recovery, including 4.3-fold biomass increases and shifts toward fungal dominance, drive both enhanced carbon inputs and accelerated decomposition processes. Understanding these biological controls is essential for optimizing restoration strategies.

Economic valuation revealing benefits of $156-420 ha^{-1} $year^{-1}$ supports investment in vegetation recovery programs while emphasizing the need for comprehensive monitoring that accounts for both accumulation and mineralization processes. The complex temporal and spatial patterns demonstrated require sophisticated approaches to carbon accounting that move beyond simple accumulation measurements.

These findings support vegetation recovery as an important climate mitigation strategy while highlighting the need for realistic expectations, comprehensive monitoring, and adaptive management approaches that account for the dynamic nature of soil carbon processes during ecosystem development.

References

1. Griscom BW, Adams J, Ellis PW, *et al*. Natural climate solutions. Proceedings of the National Academy of Sciences of the United States of America. 2017;114:11645–11650.
2. Bossio DA, Cook-Patton SC, Ellis PW, *et al*. The role of soil carbon in natural climate solutions. Nature Sustainability. 2020;3:391–398.
3. Chazdon RL, Brancalion PHS. Restoring forests as a means to many ends. Science. 2019;365:24–25.
4. Nave LE, Vance ED, Swanston CW, *et al*. Fire effects on temperate forest soil C and N storage. Ecological Applications. 2011;21:1189–1201.
5. Fontaine S, Barot S, Barré P, *et al*. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature. 2007;450:277–280.
6. Chazdon RL. Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science. 2008;320:1458–1460.
7. Crouzeilles R, Ferreira MS, Chazdon RL, *et al*. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. Science Advances. 2017;3:e1701345.
8. Poorter L, Bongers F, Aide TM, *et al*. Biomass resilience of Neotropical secondary forests. Nature. 2016;530:211–214.
9. Odum EP. The strategy of ecosystem development. Science. 1969;164:262–270.
10. Ryan MG, Law BE. Interpreting, measuring, and modeling soil respiration. Biogeochemistry. 2005;73:3–27.
11. Luyssaert S, Inglima I, Jung M, *et al*. CO_2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology. 2007;13:2509–2537.
12. Jobbágy EG, Jackson RB. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications. 2000;10:423–436.
13. Rumpel C, Kögel-Knabner I. Deep soil organic matter: a key but poorly understood component of terrestrial C cycle. Plant and Soil. 2011;338:143–158.
14. Harrison RB, Footen PW, Strahm BD. Deep soil horizons: contribution and importance to soil carbon pools and in assessing whole-ecosystem response to management and global change. Forest Science. 2011;57:67–76.
15. Bardgett RD, Freeman C, Ostle NJ. Microbial contributions to climate change through carbon cycle feedbacks. The ISME Journal. 2008;2:805–814.
16. Schimel JP, Schaeffer SM. Microbial control over carbon cycling in soil. Frontiers in Microbiology. 2012;3:348.
17. Six J, Frey SD, Thiet RK, *et al*. Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Science Society of America Journal. 2006;70:555–569.
18. Davidson EA, Janssens IA. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature. 2006;440:165–173.
19. Crowther TW, Todd-Brown KEO, Rowe CW, *et al*. Quantifying global soil carbon losses in response to warming. Nature. 2016;540:104–108.
20. Stockmann U, Adams MA, Crawford JW, *et al*. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment. 2013;164:80–99.
21. Walker LR, del Moral R. Primary Succession and Ecosystem Rehabilitation. Cambridge: Cambridge University Press; c2003.
22. Hobbs RJ, Harris JA. Restoration ecology: repairing the earth's ecosystems in the new millennium. Restoration Ecology. 2001;9:239–246.
23. Young TP, Petersen DA, Clary JJ. The ecology of restoration: historical links, emerging issues and unexplored realms. Ecology Letters. 2005;8:662–673.
24. Ellert BH, Bettany JR. Calculation of organic matter and

nutrients stored in soils under contrasting management regimes. Canadian Journal of Soil Science. 1995;75:529–538.
25. West TO, Post WM. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal. 2002;66:1930–1945.
26. Jackson RB, Mooney HA, Schulze ED. A global budget for fine root biomass, surface area, and nutrient contents. Proceedings of the National Academy of Sciences of the United States of America. 1997;94:7362–7366.
27. Savage K, Davidson EA, Richardson AD. A conceptual and practical approach to data quality and analysis procedures for high-frequency soil respiration data. Functional Ecology. 2008;22:1000–1007.
28. Paul EA, Harris D, Collins HP, *et al*. Evolution of CO_2 and soil carbon dynamics in biologically managed, row-crop agroecosystems. Applied Soil Ecology. 1999;11:53–65.
29. Kuzyakov Y. Sources of CO_2 efflux from soil and review of partitioning methods. Soil Biology and Biochemistry. 2006;38:425–448.
30. Balesdent J, Mariotti A. Measurement of soil organic matter turnover using ^{13}C natural abundance. In: Boutton TW, Yamasaki S, editors. Mass Spectrometry of Soils. New York: Marcel Dekker; 1996. p. 83–111.
31. Kuzyakov Y, Cheng W. Photosynthesis controls of rhizosphere respiration and organic matter decomposition. Soil Biology and Biochemistry. 2001;33:1915–1925.
32. Gleixner G, Poirier N, Bol R, *et al*. Molecular dynamics of organic matter in a cultivated soil. Organic Geochemistry. 2002;33:357–366.
33. Vance ED, Brookes PC, Jenkinson DS. An extraction method for measuring soil microbial biomass C. Soil Biology and Biochemistry. 1987;19:703–707.
34. Marx MC, Wood M, Jarvis SC. A microplate fluorimetric assay for the study of enzyme diversity in soils. Soil Biology and Biochemistry. 2001;33:1633–1640.
35. Robertson GP, Coleman DC, Bledsoe CS, *et al*. Standard Soil Methods for Long-Term Ecological Research. New York: Oxford University Press; c1999.
36. Curtis PS, Gough CM. Forest aging, disturbance and the carbon cycle. New Phytologist. 2018;219:1188–1200.
37. Pinheiro J, Bates D, DebRoy S, *et al*. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-152; 2021.
38. R Core Team. R: A Language and Environment for Statistical Computing. Vienna: R Foundation for Statistical Computing; c2023.
39. Bernal B, Mitsch WJ. Comparing carbon sequestration in temperate freshwater wetland communities. Global Change Biology. 2012;18:1636–1647.
40. Conant RT, Ryan MG, Ågren GI, *et al*. Temperature and soil organic matter decomposition rates: synthesis of current knowledge and a way forward. Global Change Biology. 2011;17:3392–3404.
41. Gaudinski JB, Trumbore SE, Davidson EA, *et al*. Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes. Biogeochemistry. 2000;51:33–69.
42. Fontaine S, Henault C, Aamor A, *et al*. Fungi mediate long-term sequestration of carbon and nitrogen in soil through their priming effect. Soil Biology and Biochemistry. 2011;43:86–96.
43. Pregitzer KS, Euskirchen ES. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology. 2004;10:2052–2077.
44. Burns RG, DeForest JL, Marxsen J, *et al*. Soil enzymes in a changing environment: current knowledge and future directions. Soil Biology and Biochemistry. 2013;58:216–234.
45. Bond-Lamberty B, Thomson A. Temperature-associated increases in the global soil respiration record. Nature. 2010;464:579–582.
46. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304:1623–1627.
47. Webster R, Oliver MA. Geostatistics for Environmental Scientists. 2nd ed. Chichester: John Wiley & Sons; 2007.
48. Pan Y, Birdsey RA, Fang J, *et al*. A large and persistent carbon sink in the world's forests. Science. 2011;333:988–993.
49. Kuzyakov Y, Friedel JK, Stahr K. Review of mechanisms and quantification of priming effects. Soil Biology and Biochemistry. 2000;32:1485–1498.
50. Mackey B, Prentice IC, Steffen W, *et al*. Untangling the confusion around land carbon science and climate change mitigation policy. Nature Climate Change. 2013;3:552–557.