P-ISSN: 2618-0723
E-ISSN: 2618-0731

Extension Journal

NAAS Rating (2025): 5.04
www.extensionjournal.com

International Journal of Agriculture Extension and Social Development

Volume 8; Issue 9; September 2025; Page No. 678-683

Received: 27-06-2025
Accepted: 02-08-2025

Indexed Journal
Peer Reviewed Journal

Soil carbon sequestration and climate change mitigation: Potentials, challenges, and pathways - A review

[1]Harshavardhana NR, [2]Raghavendra S, [1]Vishavjit Kumar, [2]Manu SM, [2]Javeria Anwarkhan Bagewadi, [2]Sathish BN, [2]Roopashree DH and [2]Nitish Kumar LS

[1]Forest Research Institute (FRI) University, Dehradun, Uttarakhand, India

[2]University of Agricultural Sciences, V.C. Farm, Mandya, Karnataka, India

DOI: https://www.doi.org/10.33545/26180723.2025.v8.i9j.2480

Corresponding Author: Raghavendra S

Abstract

Soil plays a pivotal role in the global carbon cycle, acting both as a reservoir and regulator of atmospheric carbon. As the largest terrestrial carbon sink, soils store nearly three times more carbon than the atmosphere, making them critical for climate change mitigation. This review synthesizes the role of soil carbon sequestration (SCS) in reducing greenhouse gas (GHG) emissions and enhancing ecosystem resilience. Soil organic carbon (SOC), estimated at 1526 PgC, and soil inorganic carbon (SIC), around 940 PgC, represent substantial pools that can be enhanced through sustainable land management. Practices such as conservation agriculture, residue retention, and agroforestry contribute to SOC stabilization, while pedogenic carbonate formation in arid zones enhances SIC storage. However, the sequestration potential is influenced by soil type, climate, nutrient availability, and land-use changes. Loamy and clay soils exhibit higher sequestration capacity compared to sandy soils, but saturation thresholds and reversibility limit long-term storage. Moreover, the trade-offs between carbon sequestration and non-CO_2 GHG emissions, particularly methane (CH_4) and nitrous oxide (N_2O), highlight the complexity of soil-climate interactions. Advances in measurement techniques including isotopic tracing, eddy covariance, and remote sensing—have improved monitoring accuracy, though challenges remain in verification and scalability. Overall, soil carbon sequestration offers a cost-effective, nature-based solution for mitigating climate change while enhancing soil fertility, water retention, and ecosystem services. Yet, it should be pursued as a complementary strategy alongside direct emission reductions to achieve sustainable climate goals and the United Nations' Agenda 2030 targets.

Keywords: Soil carbon sequestration, climate change mitigation, soil organic carbon, soil inorganic carbon, sustainable soil management

1. Introduction

Climate change has become the central theme of international policy discussions, no longer confined to the periphery of scientific debate. It presents a wide range of detrimental impacts, including rising sea levels, more frequent and severe weather events, and widespread ecosystem disruptions (Winn *et al.*, 2011) [51]. The atmospheric concentration of carbon dioxide has increased by 43% since 1750 (Piao *et al.*, 2013) [37]. During the 1960-69 decade, the growth rate of atmospheric CO_2 was 0.85 ppm year^{-1}, which rose sharply to 2.28 ppm year^{-1} in the recent 2008-17 period. This dramatic change is primarily attributed to excessive reliance on fossil fuels and large-scale deforestation. Consequently, the mean global surface temperature has already risen by 0.85 °C compared to the pre-industrial era (Hansen *et al.*, 2010) [14]. The Intergovernmental Panel on Climate Change (IPCC) warns that global temperatures could increase by 1.5 °C as early as 2030, potentially triggering irreversible damage to ecosystems and human societies (Hoegh-Guldberg *et al.*, 2019) [15]. Shifts in greenhouse gas (GHG) concentrations are thus central drivers of climate change. Soil plays a vital role in the Earth's carbon cycle, acting both as a source and a sink of carbon, and thereby offering significant potential for climate change mitigation (Naumann *et al.*, 2011) [30]. The sequestration of carbon in terrestrial ecosystems, particularly through soil organic matter and aggregates, is a promising strategy for offsetting rising CO_2 concentrations (Palumbo *et al.*, 2004; Lehmann *et al.*, 2020) [35, 26]. Thoughtful soil management and sustainable land-use practices can minimize GHG emissions from agriculture while enhancing soil carbon storage. "Soil carbon sequestration" refers to the process of capturing atmospheric CO_2 and storing it in the soil, thereby increasing soil carbon stocks. Plant residues and organic matter become incorporated into the soil, where carbon can be retained for varying periods. While this approach has the potential to mitigate atmospheric CO_2 accumulation, it is limited by factors such as soil saturation thresholds, reversibility, and challenges in measurement and long-term verification (Glaser *et al.*, 2002; Lehmann *et al.*, 2020; IPCC, 2000) [12, 26, 16]. Moreover, sequestration benefits are sometimes offset by emissions of other GHGs, particularly methane (CH_4) and nitrous oxide (N_2O). Despite these constraints, soil carbon sequestration offers important short- to medium-term mitigation potential (Smith *et al.*, 2004) [40]. It can also deliver multiple co-benefits, including improved soil fertility, enhanced water retention, reduced erosion, restoration of degraded lands, and greater agricultural sustainability (Guo *et al*., 2002; Lal *et al*., 2007) [17, 20]. This review aims to explore soil's multifaceted role in climate change mitigation, with a particular focus on its function as the largest terrestrial carbon sink. It examines the key factors influencing carbon sequestration potential ranging from environmental and geographical conditions to intrinsic soil properties—and highlights the opportunities and challenges of adopting sustainable soil management practices. By synthesizing current knowledge, the paper emphasizes how soil carbon sequestration can contribute both to reducing atmospheric CO_2 levels and to advancing broader ecosystem services essential for sustainable development.

2. Soil and Climate Change Mitigation

2.1 Soil and Climate Change

Soils and climate are interconnected in complex ways, with soils acting as both a victim of and a solution to climate change. They are vast carbon reservoirs, storing more carbon than the atmosphere and vegetation combined (Lal, 2004) [19]. Rising global temperatures and shifting precipitation patterns alter soil properties, accelerating organic matter decomposition and nutrient loss (Masson-Delmotte *et al*., 2021; Telo da Gama *et al*., 2019) [28, 45]. Soils also influence climate through biophysical feedbacks such as albedo changes and water cycle regulation. For instance, biochar can darken soil surfaces, lowering albedo and contributing to localized warming (Abbass *et al*., 2022) [1]. Conversely, well-managed soils enhance water retention, reduce irrigation demand, and indirectly decrease GHG emissions linked to fertilizer and energy use (Zheng *et al*., Hence, sustainable soil management remains central to building resilience and reducing climate risks.

2.2 Soils as a Sink and Source of Atmospheric Carbon Dioxide

Soils are the largest terrestrial carbon pool, containing about 1526 Pg of soil organic carbon (SOC) and 940 Pg of soil inorganic carbon (SIC) (Lal *et al*., 2021) [23]. At one meter depth, soil and vegetation together hold nearly three times the atmospheric carbon stock, underscoring their climate regulation potential. SOC improves fertility while storing atmospheric CO_2 in organic matter (Fageria, 2012) [9]. SIC sequestration occurs through carbonation, a slow process influenced by soil moisture, temperature, and cation availability (Manning *et al*., 2013) [27]. Vegetation further strengthens this sink, with forest and peat ecosystems contributing substantially (Palit *et al*., 2022) [34]. However, sequestration capacity differs among soil types: loamy and clay soils sequester more carbon than sandy soils, while peat soils store large amounts but release CO_2 if disturbed (Bai *et al*., 2019; Nolan *et al*., 2021) [2, 33]. Sustainable land management practices, including afforestation, reforestation, and conservation agriculture, can enhance soil-vegetation carbon storage.

2.2.1 Soil Organic Carbon (SOC)

Global SOC stocks range between 1500-2400 PgC (Patton *et al*., 2019) [36]. Even small losses can surpass annual fossil fuel emissions, while conservation measures can substantially offset anthropogenic carbon releases (Friedlingstein *et al*., 2020) [11]. Forest ecosystems, especially in humid regions, hold disproportionately high SOC densities but face threats from deforestation and wildfires (Nave, 2019) [32]. Enhancing SOC through residue retention, cover crops, and organic amendments aligns with both climate mitigation and the UN Sustainable Development Goals (Lal *et al*., 2021) [23].

2.2.2 Soil Inorganic Carbon (SIC)

SIC, estimated at ~940 PgC, is especially prevalent in arid and semi-arid soils (Batjes, 1996) [3]. Formed as pedogenic carbonates, SIC sequestration can persist over millennia, provided calcium inputs are available (Monger *et al*., 2015) [29]. Processes include weathering of silicates and carbonate dissolution-precipitation cycles (Urey, 1952; Berner, 2004) [46, 4]. While SIC sequestration progresses slowly, it complements SOC storage by offering a long-term carbon sink.

2.3 Soils as Sources of Non-CO_2 Greenhouse Gases

In addition to sequestering carbon, soils also emit potent GHGs such as methane (CH_4) and nitrous oxide (N_2O). Methane emissions arise mainly from flooded soils (e.g., rice paddies), while N_2O results from microbial transformations of nitrogen under anaerobic conditions, often exacerbated by fertilizer use (Smith *et al*., 2004) [40]. Land conversion has reduced soils' natural capacity to absorb CH_4, making sustainable management practices essential for balancing carbon gains against GHG trade-offs (Tate, 2015) [44].

2.4 Carbon Sequestration and Climate Change

Globally, anthropogenic activities release ~8.7 Gt C annually, yet only ~3.8 Gt accumulates in the atmosphere, highlighting the regulatory role of natural carbon sinks (Stockmann *et al*., 2013) [43]. Soils could act as negative emission technologies (NETs) by enhancing SOC through photosynthesis, biomass incorporation, and stabilization (Smith, 2016) [41]. However, SOC gains are reversible, requiring continuous sustainable practices (Dimassi *et al*., 2013) [7]. Strategies such as conservation agriculture, organic amendments, and integrated crop-livestock-forestry systems are vital. SOC sequestration potential is higher in cool, humid climates (0.5-1.0 Mg C ha^{-1} yr^{-1}) than in drylands (0.1-0.2 Mg C ha^{-1} yr^{-1}) (Lal, 2018) [22]. SIC sequestration, driven by mineral weathering and biological processes, provides additional long-term potential, especially in arid regions. Together, SOC and SIC sequestration form complementary pathways that, if properly harnessed, can play a central role in climate change mitigation.

3. Approach and Methodology for Measuring Soil Carbon Sequestration

The assessment of CO_2 sequestration in soil is fundamental to our understanding of the planet's carbon cycle and the potential strategies to mitigate climate change. Various methods were developed to assess this important phenomenon, each with its unique prospects and inherent challenges.

3.1 Laboratory Techniques
The cornerstone of understanding soil carbon sequestration lies in reliable measurement techniques. Laboratory approaches offer precision but often at the cost of extensive labour and time. Elemental analysis is one such technique commonly used for determining the total organic carbon in soil samples (Berns *et al*. 2008) [5]. This approach usually involves the combustion of soil samples and measuring the CO_2 produced to gauge the carbon content (Wang X *et al*. 2016) [48]. While this method provides accurate results, it is labour-intensive, costly, and does not provide continuous data, instead presenting a snapshot of a dynamic process. Spatial variability is a significant challenge, as samples taken from two different parts of the same field may yield different results (Starr, 2005) [42]. Mass spectrometry is another sophisticated laboratory method for analyzing soil carbon. It provides not just the quantity but also isotopic information, which can be invaluable for tracing the origin of the soil carbon (Webster *et al*. 2011) [49]. These techniques can provide more detailed information about the sources and turnover rates of SOC. However, isotopic methods can be complex and require specialized equipment and expertise.

3.2 Field-Based Approaches
Field-based methods aim for a more holistic understanding and are generally more feasible for large-scale studies. The eddy covariance technique is widely adopted for this purpose (Laudon *et al*. 2021) [24]. This method measures the vertical turbulent fluxes and is beneficial for evaluating gaseous exchange between the soil and the atmosphere over large areas (Vachon, 2010) [47]. The advent of new technology, such as remote sensing, offers promising opportunities for assessing CO_2 sequestration in soil (Issa *et al*. 2019) [18]. These methods provide the ability to continuously monitor large areas with high resolution, presenting a big leap from the traditional soil sampling techniques. However, they also come with their own challenges. The interpretation of remote sensing data can be complex, requiring advanced computational models. These methods can be expensive, and data can be influenced by factors such as soil moisture and surface roughness.

3.3 Modelling Approaches
Modelling methods, on the other hand, use mathematical equations to estimate soil CO_2 sequestration based on parameters such as soil type, climate, and land use. Models can provide continuous data and predict future trends, but they also have limitations. The accuracy of the models is highly dependent on the quality of the input data, and models may not capture the full complexity of soil processes (De Vente, 2013) [6]. These models simulate how soil carbon levels may change over time under varying conditions and thus are more suitable for long-term predictions (Farina, 2021) [10].

3.4 Emerging Technologies
Technology breakthroughs have radically changed how we think about soil carbon sequestration. Entering the period of sensor technology has been a game-changer in precision farming. In order to enable more focused sequestration efforts, sensors can now assess a variety of soil characteristics in real-time, including pH, moisture content, and most importantly, carbon levels (Nanda *et al*. 2016) [31]. A more thorough picture of soil carbon levels may now be obtained thanks to drone technology, which has made it possible to monitor large areas of land using high-resolution aerial imagery (Wich *et al*. 2018) [50]. Another area at the forefront of cutting-edge soil carbon sequestration technology is bioengineering. Today, scientists may alter the genomes of plants to improve their capacity to absorb carbon. By enhancing natural processes, this bioengineering technique seeks to improve carbon capture and storage.

4. Discussion and Conclusion
The relationship between soil and climate change is highly complex and multifaceted, with soils functioning simultaneously as a victim of climate stressors and a critical resource for mitigation**.** Soils are increasingly recognized as one of the largest terrestrial carbon reservoirs, storing more than 2,500 Pg of carbon to a depth of one meter approximately three times the carbon contained in the atmosphere and more than that stored in all global vegetation combined (Lal, 2004; Friedlingstein *et al*., 2020) [19, 11]. This vast storage capacity highlights soils' pivotal role in regulating the global carbon cycle and buffering climate change impacts. Soil organic carbon (SOC) constitutes the majority of this storage, primarily derived from plant residues and microbial activity, which become stabilized in aggregates and humic substances. SOC sequestration can be significantly enhanced through sustainable soil management practices such as conservation agriculture, residue retention, agroforestry, and the application of organic amendments (Lal, 2015; Bai *et al*., 2019) [21, 2]. These practices not only increase soil carbon inputs but also improve soil structure, nutrient availability, and water-holding capacity, thereby offering co-benefits for food security and ecosystem resilience (Powlson *et al*., 2011) [38]. However, SOC storage is dynamic and reversible, with carbon losses occurring due to land-use change, tillage, and climate-induced decomposition (Lehmann *et al*., 2020) [26]. In addition to SOC, soil inorganic carbon (SIC) represents a substantial but often underappreciated pool, estimated at around 940 Pg globally (Batjes, 1996; Lal, 2018) [3, 22]. SIC sequestration occurs primarily through carbonate formation**,** often regulated by the weathering of silicate minerals in a process known as the Ebelman-Urey reaction (Urey, 1952; Berner, 2004) [46, 4]. In this reaction, atmospheric CO_2 reacts with calcium and magnesium silicates to form bicarbonates and eventually pedogenic carbonates, a process particularly relevant in arid and semi-arid regions (Monger *et al*., 2015) [29]. Unlike SOC, which can reach saturation relatively quickly, SIC sequestration can persist over millennia, provided calcium sources are available, making it a potentially valuable long-term sink (Wang *et al*., 2016) [48]. Importantly, differentiating whether calcium originates from silicate weathering (which consumes atmospheric CO_2) or from pre-existing carbonates (which does not) is essential for accurately estimating the mitigation potential of SIC (Durand *et al*., 2010) [8]. Harnessing the land-based carbon sink, including both SOC and SIC pools, thus represents a cost-effective and nature-based strategy for climate mitigation and adaptation. Integrating soil carbon sequestration into climate action

plans aligns with multiple Sustainable Development Goals (SDGs), particularly those related to climate action, land degradation neutrality, and food security (Lal *et al*., 2021) [23]. Moreover, restoring soil carbon not only offsets anthropogenic emissions but also enhances ecosystem services such as water retention, biodiversity conservation, and erosion control (Lal *et al*., 2007; Raza *et al*., 2021) [17, 39]. As climate-related risks including soil degradation, drought, and extreme weather continue to intensify, adopting evidence-based and region-specific soil management practices becomes increasingly critical (IPCC, 2019) [17]. A robust understanding of the soil-climate nexus, coupled with informed policies and incentives, can transform soils from a passive victim of climate change into an active solution provider. By strengthening this link, societies can cultivate more resilient ecosystems capable of addressing the dual challenges of environmental sustainability and climate security.

Hence, this review highlights the central role of soils in regulating the global carbon cycle and their considerable potential for climate change mitigation. Both soil organic carbon (SOC) and soil inorganic carbon (SIC) sequestration represent valuable pathways for carbon storage, but they should be regarded as complementary elements within an integrated climate action strategy rather than as stand-alone solutions. SOC sequestration, promoted through conservation agriculture, residue management, agroforestry, and organic amendments, offers relatively rapid mitigation benefits, whereas SIC sequestration provides more stable, long-term carbon storage, particularly in arid and semi-arid landscapes. Together, these mechanisms not only contribute to lowering atmospheric CO_2 concentrations but also strengthen soil health, ecosystem resilience, and agricultural sustainability. The benefits of soil carbon sequestration extend well beyond climate regulation. Increased carbon stocks enhance soil fertility, improve water-holding capacity, reduce erosion, and support higher crop yields, thereby advancing global food and livelihood security. To achieve the United Nations' Agenda 2030 and the Sustainable Development Goals, there is an urgent need to adopt evidence-based soil management strategies that maximize sequestration while safeguarding ecosystem services. A holistic approach that integrates scientific innovation, policy frameworks, and sustainable land-use practices is essential. Such a pathway will be critical for addressing climate challenges while ensuring the resilience and productivity of global soils for future generations.

References

1. Abbass K, Qasim MZ, Song H, Murshed M, Mahmood H, Younis I, *et al*. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environmental Science and Pollution Research. 2022;29(28):42539-42559.
2. Bai X, Huang Y, Ren W, Coyne M, Jacinthe PA, Tao B, *et al*. Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. Global Change Biology. 2019;25(8):2591-2606.
3. Batjes NH. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science. 1996;47(2):151-163.
4. Berner RA. The Phanerozoic carbon cycle: CO_2 and O_2. Oxford: Oxford University Press; 2004.
5. Berns AE, Philipp H, Narres HD, Burauel P, Vereecken H, Tappe W. Effect of gamma-sterilization and autoclaving on soil organic matter structure as studied by solid state NMR, UV and fluorescence spectroscopy. European Journal of Soil Science. 2008;59(3):540-550.
6. De Vente J, Poesen J, Verstraeten G, Govers G, Vanmaercke M, Van Rompaey A, *et al*. Predicting soil erosion and sediment yield at regional scales: Where do we stand? Earth-Science Reviews. 2013;127:16-29.
7. Dimassi B, Cohan JP, Labreuche J, Mary B. Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France. Agriculture, Ecosystems & Environment. 2013;169:12-20.
8. Durand N, Monger HC, Canti MG. Calcium carbonate features. In: Stoops G, Marcelino V, Mees F, editors. Interpretation of micromorphological features of soils and regoliths. Amsterdam: Elsevier; 2010. p. 149-194.
9. Fageria NK. Role of soil organic matter in maintaining sustainability of cropping systems. Communications in Soil Science and Plant Analysis. 2012;43(16):2063-2113.
10. Farina R, Sándor R, Abdalla M, Álvaro-Fuentes J, Bechini L, Bolinder MA, *et al*. Ensemble modelling, uncertainty and robust predictions of organic carbon in long-term bare-fallow soils. Global Change Biology. 2021;27(4):904-918.
11. Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Olsen A, *et al*. Global carbon budget 2020. Earth System Science Data. 2020;12(4):3269-3340.
12. Glaser B, Lehmann J, Zech W. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. Biology and Fertility of Soils. 2002;35:219-230.
13. Guo LB, Gifford RM. Soil carbon stocks and land use change: A meta analysis. Global Change Biology. 2002;8(4):345-360.
14. Hansen J, Ruedy R, Sato M, Lo K. Global surface temperature change. Reviews of Geophysics. 2010;48(4):RG4004.
15. Hoegh-Guldberg O, Jacob D, Taylor M, Guillén Bolaños T, Bindi M, Brown S, *et al*. The human imperative of stabilizing global climate change at 1.5°C. Science. 2019;365(6459):eaaw6974.
16. IPCC. Land use, land-use change, and forestry: Special report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2000.
17. IPCC. Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Geneva: Intergovernmental Panel on Climate Change; 2019.
18. Issa S, Dahy B, Ksiksi T, Saleous N. Non-conventional methods as a new alternative for the estimation of terrestrial biomass and carbon sequestered. World Journal of Agriculture and Soil Science. 2019;4(5):1-8.
19. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science.

2004;304(5677):1623-1627.
20. Lal R. Soil carbon sequestration to mitigate climate change and advance food security. Soil Science. 2007;172(12):943-956.
21. Lal R. Sequestering carbon and increasing productivity by conservation agriculture. Journal of Soil and Water Conservation. 2015;70(3):55A-62A.
22. Lal R. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology. 2018;24(8):3285-3301.
23. Lal R, Negassa W, Lorenz K. Carbon sequestration in soil. Current Opinion in Environmental Sustainability. 2021;15:79-86.
24. Laudon H, Hasselquist EM, Peichl M, Lindgren K, Sponseller R, Lidman F, *et al*. Northern landscapes in transition: Evidence, approach and ways forward using the Krycklan Catchment Study. Hydrological Processes. 2021;35(4):e14170.
25. Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems—A review. Mitigation and Adaptation Strategies for Global Change. 2006;11(2):403-427.
26. Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC. The concept and future prospects of soil health. Nature Reviews Earth & Environment. 2020;1(10):544-553.
27. Manning DAC, Renforth P, Lopez-Capel E, Robertson S, Ghazireh N. Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. International Journal of Greenhouse Gas Control. 2013;17:309-317.
28. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, *et al.* Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2021.
29. Monger HC, Kraimer RA, Khresat S, Cole DR, Wang X, Wang J, *et al*. Sequestration of inorganic carbon in soil and groundwater. Geology. 2015;43(5):375-378.
30. Naumann S, Anzaldua G, Berry P, Burch S, Davis M, Frelih-Larsen A, Sanders M. Assessment of the potential of ecosystem-based approaches to climate change adaptation and mitigation in Europe: Final report to the European Commission, DG Environment. Ecologic Institute. 2011.
31. Nanda S, Azargohar R, Dalai AK, Kozinski JA. An assessment on the sustainability of lignocellulosic biomass for biorefining. Renewable and Sustainable Energy Reviews. 2016;50:925-946.
32. Nave LE, Marín-Spiotta E, Ontl TA, Peters MP, Swanston CW. Soil carbon management. In: Sparks DL, editor. Advances in agronomy. Vol. 159. Academic Press; 2019. p. 1-66.
33. Nolan M, Stanton KJ, Evans K, Pym L, Kaufman B, Duley E. From the ground up: Prioritizing soil at the forefront of ecological restoration. Restoration Ecology. 2021;29(8):e13453.
34. Palit K, Rath S, Chatterjee S, Das S. Microbial diversity and ecological interactions of microorganisms in the mangrove ecosystem: Threats, vulnerability, and adaptations. Environmental Science and Pollution Research. 2022;29(22):32467-32512.
35. Palumbo AV, McCarthy JF, Amonette JE, Fisher LS, Wullschleger SD, Daniels WL. Prospects for enhancing carbon sequestration and reclamation of degraded lands with fossil-fuel combustion by-products. Advances in Environmental Research. 2004;8(3-4):425-438.
36. Patton NR, Lohse KA, Seyfried MS, Godsey SE, Parsons SB. Topographic controls of soil organic carbon on soil-mantled landscapes. Scientific Reports. 2019;9(1):6390.
37. Piao S, Sitch S, Ciais P, Friedlingstein P, Peylin P, Wang X, *et al*. Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO_2 trends. Global Change Biology. 2013;19(7):2117-2132.
38. Powlson DS, Whitmore AP, Goulding KWT. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. European Journal of Soil Science. 2011;62(1):42-55.
39. Raza S, Miao N, Wang P, Ju X, Chen Z, Zhou J, *et al*. Dramatic loss of inorganic carbon by rainfall-induced carbonate dissolution in agricultural soils. Geoderma. 2021;385:114893.
40. Smith KA, Conen F. Impacts of land management on fluxes of trace greenhouse gases. Soil Use and Management. 2004;20(2):255-263.
41. Smith P. Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology. 2016;22(3):1315-1324.
42. Starr GC. Assessing temporal stability and spatial variability of soil water patterns with implications for precision water management. Agricultural Water Management. 2005;72(3):223-243.
43. Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, *et al*. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems & Environment. 2013;164:80-99.
44. Tate KR. Soil methane oxidation and land-use change—From process to mitigation. Soil Biology and Biochemistry. 2015;80:260-272.
45. Telo da Gama J, Rato Nunes J, Loures L, Lopez Piñeiro A, Vivas P. Assessing spatial and temporal variability for some edaphic characteristics of Mediterranean rainfed and irrigated soils. Agronomy. 2019;9(3):132.
46. Urey HC. The planets: Their origin and development. Yale: Yale University Press; 1952.
47. Vachon D, Prairie YT, Cole JJ. The relationship between near-surface turbulence and gas transfer velocity in freshwater systems and its implications for floating chamber measurements of gas exchange. Limnology and Oceanography. 2010;55(4):1723-1732.
48. Wang X, Geng X, Wang J, Liu S, Song Y. Pedogenic carbonate formation: Processes and contribution to carbon sequestration. Geoderma. 2016;262:1-10.
49. Webster CR, Mahaffy PR. Determining the local abundance of Martian methane and its $^{13}C/^{12}C$ and D/H isotopic ratios for comparison with related gas and soil analysis on the 2011 Mars Science Laboratory (MSL) mission. Planetary and Space Science. 2011;59(2-3):271-283.

50. Wich SA, Koh LP, Marshall AJ, Ancrenaz M. Will drones revolutionize ecological monitoring and conservation? Trends in Ecology & Evolution. 2018;33(11):789-791.
51. Winn M, Kirchgeorg M, Griffiths A, Linnenluecke MK, Günther E. Impacts from climate change on organizations: a conceptual foundation. Business strategy and the environment. 2011 Mar;20(3):157-73.