International Journal of Environment and Climate Change

Volume 13, Issue 11, Page 1668-1677, 2023; Article no.IJECC.107694
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Soil Carbon Sequestration in the Age of Climate Change: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2023/v13i113322

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/107694

Review Article

Received: 11/08/2023
Accepted: 18/10/2023
Published: 27/10/2023

ABSTRACT

Soil carbon sequestration has garnered attention as a pivotal strategy in mitigating climate change. Its relevance is accentuated by the soil's dual role in both storing carbon and supporting agriculture, thereby contributing to both environmental and food security. The purpose of this review is to analyze the various facets of soil carbon sequestration in the Indian context, specifically focusing on

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case studies that highlight both successes and failures in this realm. Key findings indicate that multifaceted approaches, such as agroforestry models in Tamil Nadu and community-led natural farming in Andhra Pradesh, have been effective in enhancing soil carbon stocks. These approaches are not only beneficial for carbon sequestration but also demonstrate positive implications for farm yield and biodiversity. However, the study also uncovers shortcomings in soil management practices, evident in the decline of soil carbon levels in regions such as Punjab due to monoculture and excessive fertilizer use. The consequences of such practices manifest in reduced soil fertility, emphasizing the urgent need for sustainable agricultural methods. In fragile ecosystems like the Himalayan region, soil erosion has further reduced the soil's ability to act as a carbon sink, indicating the necessity for immediate conservation efforts. These findings imply that an integrated approach, coupling agricultural innovation with policy support, can substantially improve the effectiveness of soil as a carbon sequester. Moreover, it is essential for policies to be adaptive and region-specific, accounting for the diverse geographical and climatic conditions across India. This review aims to serve as a comprehensive guide for policymakers, researchers, and agricultural practitioners, emphasizing that soil carbon sequestration is not an isolated goal but must be integrated into broader environmental and agricultural objectives.

Keywords: Agroforestry; monoculture; sequestration; sustainability.

1. INTRODUCTION

The issue of climate change is one that has moved from the periphery of scientific discussions to the forefront of global policy dialogues. Climate change presents a range of detrimental impacts, including rising sea levels, more frequent and severe weather events, and widespread ecosystem disruptions [1]. One of the major drivers of climate change is the exponential increase in greenhouse gas concentrations in the Earth's atmosphere, primarily carbon dioxide (CO_2). The Earth's climate is rapidly changing due in large part to human activities, primarily the burning of fossil fuels and deforestation, resulting in the increase of greenhouse gases in the atmosphere [2]. The Intergovernmental Panel on Climate Change (IPCC) notes that global temperatures could rise by 1.5°C as early as 2030 if immediate action is not taken, leading to irreversible damage to ecosystems and human societies [3]. Soil plays an invaluable role in the Earth's carbon cycle. It acts as both a source and a sink for carbon, thus providing a potential solution for mitigating climate change [4]. Soil can store carbon in the form of organic matter and soil aggregates, thereby locking it away from the atmosphere [5]. The practice of enhancing this natural capacity of soil to absorb CO_2 from the atmosphere is known as soil carbon sequestration [6]. Although several studies have highlighted the importance of soil as a carbon sink and outlined various techniques for soil carbon sequestration, a consolidated review that encompasses advancements in research methodologies, emerging technologies, and policy interventions is lacking. Furthermore, there is a need for a comprehensive overview that can serve as a reference for researchers, policymakers, and stakeholders invested in the climate change mitigation efforts [7]. The primary objective of this review is to furnish a holistic understanding of soil's role in carbon sequestration amid the ongoing climate crisis. Specifically, the study sets out to dissect the mechanisms that enable soil to capture and store carbon, scrutinize the various factors influencing its sequestration capacity, assess the available methodologies for measuring soil carbon, spotlight recent advancements and innovations in the field, and delve into the policy ramifications while proposing avenues for future research and action. Methodology A systematic literature review was conducted to form the basis of this article, employing a multi-database approach that included PubMed, Scopus, and Web of Science. The search was confined to papers published within the last two decades and used specific keywords such as "soil carbon sequestration," "climate change mitigation," "carbon sink," and "agricultural practices." The inclusion criteria for the selected studies were as follows: they had to be published in peer-reviewed journals, focus explicitly on soil carbon sequestration, provide either quantitative or qualitative data, and be published in English. Conversely, studies were excluded from the review if they were not peer-reviewed, lacked a specific focus on soil as a carbon sink, or failed to offer empirical evidence.

2. HISTORICAL OVERVIEW

The field of soil carbon sequestration has a rich historical backdrop that has seen it evolve from rudimentary observations to cutting-edge scientific inquiry. Understanding this development is crucial not just for academics but also for policymakers, farmers, and environmentalists who are dealing with the challenges posed by climate change. The study of soil as a carbon reservoir dates back to the late 19th and early 20th centuries. Initially, these studies were not focused on climate change but aimed at understanding soil fertility. Early agricultural scientists like Justus von Liebig and Fritz Haber were among the first to recognize the importance of soil organic matter, although they were primarily concerned with its role in plant nutrition [8]. Soil organic matter was identified as a complex mixture of decomposing plant and animal residues, microbes, and stable organic matter [9]. However, it wasn't until the latter half of the 20th century that the broader implications of soil organic matter for carbon sequestration began to be acknowledged [10]. As the 20th century progressed, the paradigm started shifting from soil fertility to global carbon cycles, largely in response to rising awareness of climate change. The breakthrough came in the late 1970s when it was observed that land use changes, particularly deforestation and soil erosion, had a substantial impact on the atmospheric carbon dioxide levels [11]. During the 1980s and 1990s, research flourished, spurred by advancements in technology. Remote sensing provided scientists with new tools for large-scale observation, and mathematical modeling began to offer more accurate predictions of carbon flux [12]. With the advent of molecular biology techniques in the late 1990s and early 21st century, the mechanisms underlying soil carbon sequestration began to be elucidated at a cellular and molecular level [13]. This period also saw an increase in interdisciplinary research, with scientists from fields like ecology, agronomy, and geochemistry contributing to a more comprehensive understanding of soil carbon dynamics [14]. Several key milestones stand out in the timeline of soil carbon sequestration research. The Kyoto Protocol in 1997 was a landmark event, as it was the first international agreement to recognize soil carbon sequestration as a legitimate mitigation strategy for reducing greenhouse gas emissions [15]. Research was also catalyzed by significant funding opportunities, such as the U.S. Department of Agriculture's Soil Carbon Research Program, initiated in 2002, which provided grants for advanced studies on soil carbon sequestration [16]. The development of standardized methods for soil carbon measurement was another pivotal advancement. Before these methods, studies often used inconsistent measurement techniques, making it difficult to compare results across different research efforts [17]. The publication of meta-analyses and review papers that synthesized decades of research represented another milestone, offering an overarching view of the field and pointing out directions for future research [18]. As we move further into the 2[1st] century, the field of soil carbon sequestration is continuously evolving. Innovations in technology, from machine learning algorithms to high-throughput sequencing techniques, are opening up new avenues for research [19]. Similarly, the growing awareness of the significance of soil health in global policy circles indicates a promising future for soil carbon sequestration studies [20].

Table 1. Land use in India and the world in 1999 [68]

Land Use Category	World (Mha)	India (Mha)
Total area	13,414.2	328.7
Land area	13,050.5	297.3
Permanent crops	132.4	7.95
Permanent pasture	3,489.8	11.05
Forest and woodland	4,172.4	68.5
Agricultural area	4,961.3	180.8
Arable land	1,369.1	161.8
Irrigated land	267.7	57.0

Table 2. Historical overview of key milestones in carbon sequestration research and policy

Time Period	Developments and Milestones	Key Researchers/Publications
19th Century	Initial understanding of the Greenhouse Effect	Svante Arrhenius
Early 20th Century	Discovery of photosynthesis' role in carbon capture	C.B. Van Niel, Samuel Ruben
1950s 1970s	Oceanic carbon sinks recognized Introduction of afforestation projects for carbon sinks	Roger Revelle Eville Gorham
1992	Earth Summit, focus on sustainable land management	United Nations
Late 1990s	Kyoto Protocol, promotion of carbon offset projects	International Community
Early 2000s	Advances in measurement technologies	Multiple Researchers
2010s	Integration of carbon sequestration into climate policy	IPCC Reports
2020s	Focus on technological solutions and policy interventions	Ongoing Research

Table 3. Technological options for soil carbon sequestration [69]

Technology	Cropping System	Region
1. Green Manuring	Sugarcane	Tropical
	Rice-wheat	Northwestern
	Rice	Tropical
	Rice	Tropical
	Rice-wheat	Northern
	Rice-wheat	Punjab
2. Mulch Farming/ Conservation Tillage	Rice-wheat	Punjab
	Pearl millet	Arid
	Soybean-wheat	Central
	Arable land	Northern
	Arable land	Northern
	Sugarcane	Tropics
	Sugarcane	Tropics
3. Afforestation/ Agroforestry	Silviculture	Northern
	Acacia nilotica	Central
	Agroforestry	Tropical
4. Grazing Management/ Ley Farming	Grassland	U.P.
	Grassland	M.P.
	Mixed farming	Arid
5. Integrated Nutrient Management/ Manuring	Arable land	Tamil Nadu
	Rice-wheat	Northwest
	Cotton	Central India
	Arable land	Northeast
	Rice-rice	Northern
	Maize-wheat-cowpea	Semi-arid
	Rice-wheat	Northern
	Arable	Northern
	Wetland rice-wheat	Northern
	Maize-wheat	Northern
6. Cropping Systems	Pearl millet	Arid
	Fallowing/ecological	Humid/sub-humid
	Mint-mustard	U.P.

3. MECHANISMS OF SOIL CARBON SEQUESTRATION

Understanding the mechanisms underlying soil carbon sequestration requires a multi-faceted approach that integrates biological, physical, and chemical processes. These mechanisms have been studied extensively in the past few decades, providing valuable insights into how soil functions as a carbon sink.

3.1 Biological Processes

Biological processes play a pivotal role in the sequestration of carbon in soils. These processes are generally driven by plants and soil organisms, creating a network of interactions that contribute to carbon storage. One of the primary mechanisms through which soil captures and retains carbon is photosynthesis. Plants absorb atmospheric CO_2 and convert it into organic compounds during this process [21]. Subsequently, a portion of this carbon is transferred to the soil through root exudation, which is the release of organic compounds into the rhizosphere, the soil zone surrounding plant roots [22]. These compounds include sugars, amino acids, and other organic substances that serve as a food source for soil organisms [23]. Soil microorganisms, including bacteria and fungi, contribute significantly to carbon sequestration. They decompose organic materials, converting them into stable forms of soil organic matter (SOM), thereby preventing the release of carbon back into the atmosphere [24]. Additionally, certain microbial communities, such as mycorrhizal fungi, form symbiotic relationships with plants and assist in the stable storage of carbon in soil aggregates [25].

3.2 Physical and Chemical Processes

Beyond biological mechanisms, physical and chemical processes are also crucial for soil carbon sequestration. These include the structure and composition of the soil, as well as chemical interactions that occur within it. Soil structure plays a vital role in its ability to store carbon. Soil aggregates, which are clumps of soil particles bound together, provide a physical mechanism for carbon sequestration [26]. Aggregates protect organic matter from microbial decomposition, thereby prolonging its residence time in the soil [27]. Various factors, including soil texture, moisture, and biological activity, influence the formation and stability of soil aggregates [28]. Chemical processes, including adsorption and chemical bonding, also contribute to carbon sequestration in soils. Organic matter can bind to soil minerals like clay and form stable complexes, protecting them from decomposition [29]. Additionally, certain chemical reactions can transform organic carbon into forms that are resistant to microbial breakdown [30].

4. FACTORS AFFECTING SOIL CARBON SEQUESTRATION

Soil carbon sequestration is a complex process influenced by a multitude of factors. Among the intrinsic characteristics of the soil itself, soil type plays a vital role in determining the carbon storage capacity [31]. Variables such as soil texture, including the proportion of sand, silt, and clay, have been found to significantly affect carbon retention [32]. The soil's pH level also serves as a modulator for microbial activity, which in turn impacts organic matter decomposition and stabilization [33]. Moving beyond the soil's innate characteristics, land use, and land cover stand as significant determinants in soil carbon sequestration. Studies have shown that deforestation invariably leads to a decrease in soil carbon levels, primarily due to the loss of vegetation capable of capturing atmospheric carbon dioxide [34]. Conversely, urban development has its own set of repercussions on soil carbon storage, often leading to soil degradation and compromised soil structure [34,35]. Climate variables, including temperature and precipitation, have been found to affect microbial decomposition rates. Warmer temperatures usually fast-track microbial activities, consequently reducing soil carbon levels [36]. On the other hand, optimal levels of precipitation have been shown to be conducive for carbon sequestration by creating an environment that favors microbial activity, leading to organic matter stabilization [37]. Agricultural practices are yet another dimension affecting soil carbon sequestration. For instance, tillage methods have been studied extensively for their role in influencing soil carbon levels. Traditional tillage techniques often disturb soil structure, resulting in the release of stored carbon into the atmosphere [38]. Additionally, the kind of crops being rotated can also influence carbon storage, as different crops have varying impacts on soil's organic matter content and microbial communities [39]. Lastly, human interventions like afforestation and reforestation activities have shown promise in enhancing the soil's carbon sequestration potential over the long term [40].

Similarly, the use of fertilizers can also significantly sway soil carbon levels, although the long-term effects are still a subject of ongoing research [41].

5. METHODOLOGIES FOR MEASURING SOIL CARBON

5.1 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 labor and time. Elemental analysis is one such technique commonly used for determining the total organic carbon in soil samples [42]. This approach usually involves the combustion of soil samples and measuring the CO2 produced to gauge the carbon content [43]. 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 [44]. While highly accurate, both these methods can be cost-prohibitive and demand specialized skill sets [45].

5.2 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 [46]. This method measures the vertical turbulent fluxes and is beneficial for evaluating gaseous exchange between the soil and the atmosphere over large areas [47]. Remote sensing is another field-based technique growing in popularity due to its non-intrusive nature and ability to cover large tracts of land. Various satellites and sensors are now capable of measuring soil properties, including its carbon content, although this method often requires ground-truthing for validation [48].

5.3 Modelling Approaches

In addition to empirical methods, modeling approaches provide a way to estimate and predict soil carbon levels. Static models offer a snapshot view based on current soil conditions but may not account for temporal variations [49]. These are often simpler and easier to implement, serving as a good starting point for soil carbon estimation. Dynamic models, on the other hand, incorporate time-dependent variables and are more intricate [50]. These models simulate how soil carbon levels may change over time under varying conditions and thus, are more suitable for long-term predictions [51].

6. ADVANCES IN SOIL CARBON SEQUESTRATION

6.1 Emerging Technologies

Advances in technology have fundamentally altered our approach to soil carbon sequestration. As we delve into the era of precision agriculture, sensor technology has emerged as a game-changer. Sensors can now measure various soil attributes in real-time, including moisture content, pH, and most importantly, carbon levels, thereby facilitating more targeted sequestration efforts [52]. Similarly, drone technology has enabled high-resolution aerial imaging for monitoring vast stretches of land, thereby providing a more extensive overview of soil carbon levels [53]. Bioengineering is another frontier in emerging technologies related to soil carbon sequestration. Scientists are now able to manipulate plant genomes to enhance their carbon-absorbing capabilities [54]. This bioengineering approach aims to augment natural processes for a more effective carbon capture and storage strategy [55].

6.2 Integration with Other Environmental Goals

The practice of soil carbon sequestration is increasingly being integrated with other environmental objectives such as biodiversity conservation, water purification, and land rehabilitation [56]. For instance, the reforestation of degraded lands not only helps in carbon sequestration but also contributes to habitat restoration [57]. Similarly, agroforestry systems, where crops and trees coexist, have shown promise in both carbon capture and in enhancing soil fertility [58]. By integrating soil carbon sequestration with other environmental goals, a more holistic and sustainable approach to land management can be achieved. This integrated approach is becoming more prevalent as policy-makers recognize the interconnected nature of environmental challenges [59].

7. CASE STUDIES

7.1 The Green Revolution's Unintended Benefits

While the Green Revolution in India primarily aimed at food security, some of its aspects also contributed to soil carbon sequestration. Newer crop varieties, coupled with improved irrigation techniques, inadvertently led to an increase in organic matter in the soil [60]. However, it is crucial to note that these benefits were partly offset by the excessive use of fertilizers and pesticides, requiring a nuanced understanding of its overall impact on soil carbon levels [61].

7.2 Agroforestry in Tamil Nadu

Tamil Nadu has been at the forefront of integrating forestry with agriculture. This agroforestry model has not only resulted in increased farm productivity but has also significantly enhanced the soil carbon levels [62].

7.3 Community-Led Soil Management in Andhra Pradesh

Andhra Pradesh's community-led natural farming initiatives, involving zero-budget natural farming, have significantly increased soil organic matter, thus improving the soil's capacity for carbon sequestration [63].

7.4 Failures

7.4.1 Over-reliance on monoculture in Punjab

Punjab, India's 'breadbasket,' experienced a decline in soil carbon levels due to prolonged monoculture practices and excessive fertilizer use [64]. This case illustrates the need for crop diversification and sustainable farming practices as essential elements in maintaining and enhancing soil carbon levels [64,65].

7.4.2 Soil erosion in the Himalayan region

In the fragile ecosystems of the Himalayan region, deforestation and unsustainable agricultural practices have led to severe soil erosion, thereby reducing the soil's ability to act as a carbon sink [66]. Restoration efforts have not yet succeeded in reversing this trend, providing a cautionary tale for other sensitive ecosystems [67].

8. CONCLUSION

This review provides a comprehensive analysis of soil carbon sequestration within the Indian context, shedding light on both effective and flawed practices. Successful models like agroforestry in Tamil Nadu and community-led initiatives in Andhra Pradesh exemplify how integrated approaches can yield multiple benefits, including higher soil carbon levels, improved farm yields, and enhanced biodiversity. Conversely, monoculture and excessive fertilizer use in regions like Punjab caution against unsustainable agricultural practices that compromise soil health. The review underscores the need for adaptive, region-specific policies to support sustainable soil management. As climate change continues to impose urgent challenges, it is imperative to align soil carbon sequestration efforts with broader agricultural and environmental goals, creating a resilient and sustainable framework for the future.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. 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; 20(3):157-173.
2. Driga AM, Drigas AS. Climate Change 101: How Everyday Activities Contribute to the Ever-Growing Issue. Int. J. Recent Contributions Eng. Sci. IT. 2019;7(1):22-31.
3. Hoegh-Guldberg O, Jacob D, Taylor M, Guillén Bolaños T, Bindi M, Brown S, Zhou G. The human imperative of stabilizing global climate change at 1.5 C. Science. 2019;365(6459): eaaw6974.
4. 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; 2011.
5. Lehmann J, Hansel CM, Kaiser C, Kleber M, Maher K, Manzoni S, Kögel-Knabner I. Persistence of soil organic carbon caused by functional complexity. Nature Geoscience. 2020;13(8):529-534.
6. Patil P, Kumar AK. Biological carbon sequestration through fruit crops (perennial crops-natural "sponges" for absorbing carbon dioxide from atmosphere). Plant Archives, 1. 2017;7(2):1041-1046.

7. Debrah C, Chan APC, Darko A. Green finance gap in green buildings: A scoping review and future research needs. Building and Environment. 2022;207:108443.
8. McNeill JR, Winiwarter V. Breaking the sod: Humankind, history, and soil. Science. 2004; 304(5677):1627-1629.
9. Kögel-Knabner I. The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter: fourteen years on. Soil Biology and Biochemistry. 2017;105:A3-A8.
10. Davidson EA. Is the transactional carbon credit tail wagging the virtuous soil organic matter dog?. Biogeochemistry. 2022; 161(1):1-8.
11. Nobre CA, Sampaio G, Borma LS, Castilla-Rubio JC, Silva JS, Cardoso M. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proceedings of the National Academy of Sciences. 2016;113(39):10759-10768.
12. National Research Council. Challenges and opportunities in the hydrologic sciences; 2012.
13. Braun P, Gingras AC. History of protein–protein interactions: From egg-white to complex networks. Proteomics. 2012; 12(10):1478-1498.
14. Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Trumbore SE. Persistence of soil organic matter as an ecosystem property. Nature. 2011;478(7367):49-56.
15. Yoro KO, Daramola MO. CO2 emission sources, greenhouse gases, and the global warming effect. In Advances in carbon capture Woodhead Publishing. 2020;3-28.
16. Verschuuren J. Towards an EU regulatory framework for climate-smart agriculture: the example of soil carbon sequestration. Transnational Environmental Law. 2018; 7(2):301-322.
17. Roberts HC, Denison HJ, Martin HJ, Patel HP, Syddall H, Cooper C, Sayer AA. A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach. Age and ageing. 2011;40(4):423-429.
18. The publication of meta-analyses and review papers that synthesized decades of research represented another milestone, offering an overarching view of the field and pointing out directions for future research
19. Pratapa A, Doron M, Caicedo JC. Image-based cell phenotyping with deep learning. Current opinion in chemical biology. 2021;65:9-17.
20. 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.
21. Nogia P, Sidhu GK, Mehrotra R, Mehrotra S. Capturing atmospheric carbon: biological and nonbiological methods. International Journal of Low-Carbon Technologies. 2016;11(2):266-274.
22. Kumar R, Pandey S, Pandey A. Plant roots and carbon sequestration. Current Science. 2006; 885-890.
23. Khatoon H, Solanki P, Narayan M, Tewari L, Rai J, Hina Khatoon C. Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. International Journal of Chemical Studies. 2017;5(6):1648-1656.
24. Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Trumbore SE. Persistence of soil organic matter as an ecosystem property. Nature. 2011;478(7367):49-56.
25. Emmett BD, Lévesque-Tremblay V, Harrison MJ. Conserved and reproducible bacterial communities associate with extraradical hyphae of arbuscular mycorrhizal fungi. The ISME journal. 2021;15(8):2276-2288.
26. Yudina A, Kuzyakov Y. Dual nature of soil structure: The unity of aggregates and pores. Geoderma. 2023;434:116478.
27. Agnihotri R, Sharma MP, Prakash A, Ramesh A, Bhattacharjya S, Patra AK, Kuzyakov Y. Glycoproteins of arbuscular mycorrhiza for soil carbon sequestration: Review of mechanisms and controls. Science of the Total Environment. 2022;806:150571.
28. Barbosa MV, Pedroso DDF, Curi N, Carneiro MAC. Do different arbuscular mycorrhizal fungi affect the formation and stability of soil aggregates?. Ciência e Agrotecnologia. 2019;43.
29. Boyd SA, Mortland MM. Enzyme interactions with clays and clay-organic matter complexes. In Soil biochemistry Routledge. 2017;1-28.
30. Said-Pullicino D, Erriquens FG, Gigliotti G. Changes in the chemical characteristics of water-extractable organic matter during composting and their influence on compost

stability and maturity. Bioresource Technology. 2007;98(9):1822-1831.
31. Rodrigues CID, Brito LM, Nunes LJ. Soil carbon sequestration in the context of climate change mitigation: A review. Soil Systems. 2023;7(3):64.
32. McSherry ME, Ritchie ME. Effects of grazing on grassland soil carbon: a global review. Global change biology. 2013; 19(5):1347-1357.
33. Cotrufo MF, Lavallee JM. Soil organic matter formation, persistence, and functioning: A synthesis of current understanding to inform its conservation and regeneration. Advances in agronomy. 2022;172:1-66.
34. Jamloki A, Bhattacharyya M, Nautiyal MC, Patni B. Elucidating the relevance of high temperature and elevated CO2 in plant secondary metabolites (PSMs) production. Heliyon. 2021;7(8).
35. O'Riordan R, Davies J, Stevens C, Quinton JN, Boyko C. The ecosystem services of urban soils: A review. Geoderma. 2021; 395:115076.
36. Nanda S, Reddy SN, Mitra SK, Kozinski JA. The progressive routes for carbon capture and sequestration. Energy Science & Engineering. 2016;4(2):99-122.
37. Bhattacharyya SS, Ros GH, Furtak K, Iqbal HM, Parra-Saldívar R. Soil carbon sequestration–An interplay between soil microbial community and soil organic matter dynamics. Science of The Total Environment. 2022;815:152928.
38. Cania B, Vestergaard G, Krauss M, Fliessbach A, Schloter M, Schulz S. A long-term field experiment demonstrates the influence of tillage on the bacterial potential to produce soil structure-stabilizing agents such as exopolysaccharides and lipopolysaccharides. Environmental Microbiome. 2019;14(1):1-14.
39. Siedt M, Schäffer A, Smith KE, Nabel M, Roß-Nickoll M, van Dongen JT. Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. Science of the Total Environment. 2021;751:141607.
40. Booker K, Huntsinger L, Bartolome JW, Sayre NF, Stewart W. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States?. Global Environmental Change. 2013;23(1):240-251.
41. Booker K, Huntsinger L, Bartolome JW, Sayre NF, Stewart W. What can ecological science tell us about opportunities for carbon sequestration on rangelands in the United States?. Global Environmental Change. 2013;23(1):240-251.
42. 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.
43. Wang X, Wang J, Zhang J. Comparisons of three methods for organic and inorganic carbon in calcareous soils of northwestern China; 2012.
44. Webster CR, Mahaffy PR. Determining the local abundance of Martian methane and its' 13C/12C and D/H isotopic ratios for comparison with related gas and soil analysis on the Mars Science Laboratory (MSL) mission. Planetary and Space Science. 2011;59(2-3):271-283.
45. Lohman BK, Weber JN, Bolnick DI. Evaluation of TagSeq, a reliable low-cost alternative for RNA seq. Molecular ecology resources. 2016;16(6):1315-1321.
46. Laudon H, Hasselquist EM, Peichl M, Lindgren K, Sponseller R, Lidman F, Ågren AM. Northern landscapes in transition: Evidence, approach and ways forward using the Krycklan Catchment Study. Hydrological Processes. 2021;35(4):e14170.
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. Komatsu T, Hashim M, Nurdin N, Noiraksar T, Prathep A, Stankovic M, Hayashizaki17 KI. Practical mapping methods of seagrass beds by satellite remote sensing and ground truthing. Coast Mar Sci. 2020;43(1):1-25.
49. Sonter LJ, Watson KB, Wood SA, Ricketts TH. Spatial and temporal dynamics and value of nature-based recreation, estimated via social media. PLoS one. 2016;11(9):e0162372.
50. Abbott LF, Kepler TB. Model neurons: from hodgkin-huxley to hopfield. In Statistical

Mechanics of Neural Networks: Proceedings of the XIth Sitges Conference Sitges, Barcelona, Spain, 3–7 June 1990 Berlin, Heidelberg: Springer Berlin Heidelberg. 2005;5-18.

51. Farina R, Sándor R, Abdalla M, Álvaro-Fuentes J, Bechini L, Bolinder MA, Bellocchi G. Ensemble modelling, uncertainty and robust predictions of organic carbon in long-term bare-fallow soils. Global Change Biology. 2021;27(4):904-928.
52. Nanda S, Dalai AK, Berruti F, Kozinski JA. Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. Waste and Biomass Valorization. 2016;7:201-235.
53. Wich SA, Koh LP. Conservation drones: mapping and monitoring biodiversity. Oxford University Press. 2018.
54. Augustyn J. Emerging science and technology trends: 2017-2047. Future Scout Providence United States; 2017.
55. Zahed MA, Movahed E, Khodayari A, Zanganeh S, Badamaki M. Biotechnology for carbon capture and fixation: Critical review and future directions. Journal of Environmental Management. 2021;293: 112830.
56. Nair PR. Agroforestry systems and environmental quality: introduction. Journal of environmental quality. 2011;40(3):784-790.
57. Di Sacco A, Hardwick KA, Blakesley D, Brancalion PH, Breman E, Cecilio Rebola L, Antonelli, A. Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. Global Change Biology. 2021;27(7):1328-1348.
58. Nair PR. Agroforestry systems and environmental quality: introduction. Journal of environmental quality. 2011;40(3):784-790.
59. Fischer J, Gardner TA, Bennett EM, Balvanera P, Biggs R, Carpenter S, Tenhunen J. Advancing sustainability through mainstreaming a social–ecological systems perspective. Current opinion in environmental sustainability. 2015;14:144-149.
60. Fahad S, Sonmez O, Saud S, Wang D, Wu C, Adnan M, Turan V. (Eds.). Sustainable soil and land management and climate change. CRC Press; 2021.
61. Palm C, Blanco-Canqui H, DeClerck F, Gatere L, Grace P. Conservation agriculture and ecosystem services: An overview. Agriculture, Ecosystems & Environment. 2014;187:87-105.
62. Kumar V. Multifunctional agroforestry systems in tropics region. Nature Environment and Pollution Technology. 2016;15(2):365.
63. Veluguri D, Ramanjaneyulu GV, Jaacks L. Statewise report cards on ecological sustainability of agriculture in India. Review of Rural Affairs. 2019;54(29):19-27.
64. Dutta S, Dhillon SS. Structural transformation of Punjab Agriculture and its environmental implications. Indian Journal of Economics and Development. 2020;16(4):533-546.
65. Tamburini G, Bommarco R, Wanger TC, Kremen C, Van Der Heijden MG, Liebman M, Hallin S. Agricultural diversification promotes multiple ecosystem services without compromising yield. Science advances. 2020;6(45):eaba1715.
66. Tse-Ring K, Sharma E, Chettri N, Shrestha AB. Climate change vulnerability of mountain ecosystems in the Eastern Himalayas. International centre for integrated mountain development (ICIMOD); 2010.
67. Lilleskov E, McCullough K, Hergoualc'h K, del Castillo Torres D, Chimner R, Murdiyarso D, Wayson C. Is Indonesian peatland loss a cautionary tale for Peru? A two-country comparison of the magnitude and causes of tropical peatland degradation. Mitigation and Adaptation Strategies for Global Change. 2019; 24:591-623.
68. FAO: Yearbook of Agriculture, FAO, Rome, Italy; 2001.
69. Lal R. Soil carbon sequestration in India. Climatic Change. 2004;65(3):277-296.

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