



Advancing carbon sequestration: Strategies in agricultural sector

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Abstract

Soil carbon sequestration is a pivotal process in the battle against global climate change, serving as a mechanism to extract CO₂ from the atmosphere and securely store it in terrestrial ecosystems. In India, with its diverse landscapes and extensive agricultural practices emerges as a promising candidate for effective carbon sequestration in soil. In this comprehensive review, we aim to consolidate the existing body of knowledge concerning carbon sequestration in Indian soils. This review commences by illuminating the critical role of soil carbon sequestration in the context of climate change mitigation specifically focusing on the distinctive challenges and opportunities prevailing in India. Within this review, we delve into an exploration of the myriad factors influencing soil carbon dynamics. These factors encompass land use patterns, soil types, climate conditions and the practices adopted for soil management. We also assess the consequences of these factors on the storage of carbon in the soil. Additionally, we investigate the contributions of India's varied ecosystems, spanning forests, grasslands, wetlands and croplands in the context of carbon sequestration. Furthermore, we consider the potential impact of afforestation and reforestation initiatives in the restoration of degraded lands, reinforcing efforts to store carbon. Furthermore, we emphasize the pivotal role of policy frameworks and incentives in promoting sustainable soil management practices, underlining the necessity for a holistic approach that effectively integrates scientific, socioeconomic, and environmental perspectives. Our review extends to the insights provided by ongoing research and projects dedicated to quantifying and monitoring soil carbon within the Indian context. Our review concludes by underscoring the paramount importance of advancing research, policy development, and collaborative endeavours which are keys to unlocking the full potential of Indian soils in sequestering carbon. This, in turn, contributes to the dual objectives of ensuring local food security and aiding in the achievement of global climate change mitigation goals.

Keywords: Global warming, green house gases, agriculture, food security, degraded lands

Introduction

Due to anthropogenic activities and greenhouse gas emissions, the temperature of the Earth has been rising every year and have been projected to reach more than 1.5 degrees Celsius (3.7 degrees Fahrenheit) by 2060 (Pachauri *et al.*, 2014)^[20]. Due to the effects of global warming, large-scale changes in climatic conditions may have an impact on the storage of C on land. Net primary production (NPP) C inputs to soils and soil C degradation rates are significantly influenced by changes in temperature, precipitation, and CO₂ concentrations. Changing climatic conditions may also speed up land-use changes and alter the terrestrial C fluxes (Zeng *et al.*, 2019)^[32]. However, agricultural intensification is an indicator of successful agricultural development. Continuous monoculture and large-scale farming practices, the lack of high-quality seed, inadequate crop rotation and a variety of environmental factors have caused soil degradation and other natural resources to deteriorate, which has a negative impact on global food security and livelihood opportunities for small family farmers (Vermeulen *et al.*, 2012)^[30]. Traditional tillage practices (including deep ploughing) are extremely damaging to agricultural soils and account for 24 per cent of global soil degradation (Bai *et al.*, 2008)^[11].

Agricultural soils are particularly vulnerable to erosion because most of the vegetation is removed in a traditional tillage system. Lal in 2000^[14], examined the yield levels under various erosion conditions and reported that accelerated soil erosion has decreased yield by 29 per cent in 25 years of under-fed agriculture (1995–2020). It is

estimated that around 30 per cent of all arable land is significantly degraded by soil-and wind erosion (Kendall & Pimentel, 1994) and 10 million hectares of arable land was lost annually due to accelerated soil erosion worldwide (Pimentel & Burgess, 2013)^[23]. Global warming driven by anthropogenic emissions of greenhouse gases (GHG's) has increased Earth's temperature and is likely to exceed 1.5 °C by the end of this century (Pachauri *et al.*, 2014^[20]; Baker *et al.*, 2018)^[2]. Due to global warming effect, large-scale shifts in weather patterns may affect terrestrial C storage. The net primary production C inputs to the soils and soil C decomposition rates are significantly affected by the change in temperature, precipitation, and CO₂ concentration. Changing climatic patterns may also accelerate land-use change and, thus, alters the terrestrial C fluxes (Zeng *et al.*, 2019)^[32]

Causes of soil organic carbon depletion

Generally, soil organic carbon (SOC) is mainly influenced by climatic conditions, soil structure, hydrology, soil topography and vegetation.

1. Climatic condition

Soil carbon cycling is affected by a variety of factors, including biotic controls (*i.e.*, the amount and rate of C added by plants to soils and their resistance to decay), physical controls (*e.g.*, the area and chemical composition of surfaces for stabilizing organic matter), and the availability (*e.g.*, oxidants) of decomposers (*i.e.*, decomposers of organic matter). These mechanisms work on very different

timescales. For example, plant productivity and microbial communities in soil respond to changing climate conditions in as little as an hour (Linn & Doran, 1984)^[19], while annual changes in production or respiration are associated with inter-annual variations in climate (Harte *et al.*, 1992)^[8].

2. Deforestation and over grazing

Clearing forests or converting natural ecosystems into agricultural land can result in the loss of organic matter in the soil. The removal of vegetation reduces the input of organic material through leaf litter and root exudates. Moreover, excessive grazing by livestock can lead to the removal of vegetation cover, soil compaction, and erosion, all of which can accelerate SOC loss. Overall, overgrazing can contribute to a decline in soil organic carbon levels, which can have long-term negative consequences for soil health, fertility, and ecosystem sustainability. Sustainable grazing management practices, such as rotational grazing and maintaining appropriate stocking rates, can help mitigate the impacts of overgrazing and promote soil carbon preservation (Change, 2014).

3. Improper agricultural Practices

Intensive agricultural practices such as excessive tilling, mono-cropping, and the use of synthetic fertilizers and pesticides can reduce organic matter input into the soil and increase the decomposition of existing organic matter. Removing crop residues from fields for industrial purposes or as animal feed can deprive the soil of organic matter that would otherwise contribute to soil carbon. Inadequate irrigation practices can lead to water logging or soil salinity, which can negatively impact soil microbial activity and organic matter decomposition (Lal, 2004^[15]; Shubham *et al.*, 2021)^[26].

4. Rapid industrialization and urbanization

Urban development can lead to the sealing of soils with impermeable surfaces like concrete and asphalt, preventing organic matter from accumulating in the soil. It's important to note that the extent of soil carbon depletion due to urbanization can vary depending on factors such as the density of development, urban planning practices, and efforts to mitigate the environmental impacts of urban growth. Sustainable urban planning and design can help reduce the negative effects of urbanization on soil carbon by incorporating green infrastructure, urban forests, and measures to protect and enhance soil quality (Lal, 2007)^[16].

5. Soil Erosion

Erosion can wash away the topsoil, which is typically rich in organic matter, leading to the depletion of SOC. Soil erosion is the process by which topsoil is detached, transported, and eventually deposited in another location, often as sediment in rivers or streams. During this process, valuable organic matter, which is rich in carbon, can be lost from the soil. Inadequate land management practices, such as improper crop residue management, can result in the loss of valuable organic material that could otherwise enrich the soil.

6. Environmental pollution:

Pollution from industrial and agricultural sources can have detrimental effects on soil microorganisms, reducing their ability to decompose organic matter and contribute to SOC. Industrial pollution, such as the release of heavy metals,

pesticides, herbicides, and other toxic chemicals, can harm soil microorganisms responsible for organic matter decomposition. When these microorganisms are disrupted or killed, the breakdown of organic matter, including carbon-rich material, can slow down, leading to carbon accumulation or loss, depending on the specific circumstances. Acid rain, which results from the release of sulphur dioxide (SO₂) and nitrogen oxides (NO_x) into the atmosphere, can lower soil pH levels. Highly acidic soils can inhibit microbial activity, which may reduce the decomposition of organic matter, including soil carbon (Lal, 2004)^[15].

7. Soil Compaction

Compaction from heavy machinery and intensive agricultural practices can reduce soil aeration, limiting the activity of soil organisms responsible for organic matter decomposition. Soil compaction reduces pore space and limits air circulation in the soil. This restricted aeration can affect soil microbial activity, slowing down the decomposition of organic matter and carbon cycling in the soil. It may also promote anaerobic conditions that alter carbon decomposition pathways (Lal, 1999)^[13]. Compacted soils can inhibit root growth and penetration, making it challenging for plants to establish deep root systems. As a result, the input of organic carbon through root exudates and the decomposition of root biomass may be reduced in compacted soils (Eitel *et al.*, 2006)^[5].

Management of Soil Organic Carbon

Managing soil organic carbon (SOC) is critical for improving soil health, increasing agricultural productivity, and mitigating climate change. SOC refers to the organic matter in soil, including plant and animal residues which are crucial for soil structure, fertility, and carbon sequestration. Conservation tillage practices, such as no-till or reduced tillage, help to minimize soil disturbance, which can prevent the oxidation and loss of SOC (Lal, 1997)^[12]. Low carbon agriculture is a sustainable way to help protect the environment, increase crop yields, and reduce the impact of global warming. By increasing the organic matter in the soil, the main nutrients are more available for crops to grow and be more productive. Low C agricultural practices reduce emissions of greenhouse gases, like CO₂, and store SOC and vegetation. It's all about using the best management practices to protect the environment, natural resources, and crops. It's one of the best ways to reduce greenhouse gas emissions (Gouvello, 2010)^[6]. It is essential to consider local conditions and adapt these strategies to specific soil types and climates. Additionally, ongoing research and experimentation are keys to refining SOC management practices and their impacts on soil health and carbon sequestration. Raising awareness and providing education to farmers and landowners about the importance of SOC management is crucial for its widespread adoption (Wander & Bollero, 1999^[31]; Shubham *et al.*, 2022)^[27].

By implementing practices such as conservation tillage, cover cropping, organic matter amendments, and crop rotation farmers can enhance soil organic carbon (SOC) levels. These strategies improve soil structure, fertility, and resilience while simultaneously sequestering carbon in the soil, reducing carbon emissions, and contributing to climate change mitigation. Agro-forestry and forest preservation further play a significant role in SOC management. In

addition to increasing SOC levels, soil testing and monitoring are essential for evaluating the effectiveness of these practices. Carbon farming, which encompasses a range of carbon-enhancing agricultural techniques, holds promise for achieving both agricultural and environmental goals. Government policies, incentives, and educational outreach are key drivers for widespread adoption of SOC management practices. As sustainable agriculture gains momentum, the potential for SOC management to mitigate climate change and promote soil health remains substantial (Paustian *et al.*, 2016^[22]; Shubham *et al.*, 2023)^[24, 25].

Conventional Tillage and Soil Carbon Stocks

Conventional tillage practices, which involve intensive ploughing, can have a significant impact on soil carbon stocks (CS). These practices can accelerate the decomposition of organic matter, leading to a decrease in CS and increased carbon dioxide emissions. The disruption of soil structure through conventional tillage can expose SOC to microbial decomposition, resulting in carbon loss (Sweet *et al.*, 2021)^[29]. Conventional tillage practices can have a substantial impact on soil carbon stocks (CS). These practices typically involve frequent and intensive soil disturbance through ploughing and other mechanical operations, which can lead to increased decomposition of soil organic carbon (SOC). This results in reduced CS and contributes to elevated carbon dioxide emissions into the atmosphere (Blanco-Canqui & Lal, 2008)^[3].

Conventional tillage practices, characterized by frequent and deep soil disturbance, often result in a reduction of soil carbon stocks (CS). These practices accelerate the decomposition of soil organic matter and expose it to microbial activity, leading to increased carbon dioxide emissions. Research has shown that conventional tillage can deplete CS, which may have negative consequences for soil health and long-term agricultural sustainability (Sommer *et al.*, 2016; Shubham *et al.*, 2023)^[24, 25]. Tillage practices can cause a lot of damage to the roots of plants and the soil. The heavy mechanical cultivation can cause the roots to break down quickly, which can cause the soil's organic matter to be lost. Plus, it can lead to a decrease in the amount of oxygen in the air and an increase in the amount of organic matter in the soil. Agricultural practices that rely on intensive tillage have been linked to an increase in greenhouse gas emissions, which adds to the problem of global warming (Gupta *et al.*, 2015)^[7].

Relation of conservation agriculture and no tillage with soil organic carbon

Conservation agriculture (CA) and no-tillage (NT) are sustainable farming practices that play a significant role in preserving and increasing soil organic carbon (SOC). These practices aim to reduce soil disturbance, minimize erosion, and enhance carbon sequestration in agricultural soils. Here's how CA and NT can impact SOC:

1. Reduced Soil Disturbance: Conservation agriculture involves minimal soil disturbance, which includes practices like reduced or no-tillage, maintaining crop residues on the field, and crop rotation. By reducing soil disruption, CA helps protect existing SOC from accelerated decomposition, as is often the case with conventional tillage.

2. Crop Residue Management: CA practices encourage the retention of crop residues on the field surface. These residues add organic matter to the soil, gradually contributing to SOC. The organic matter serves as a carbon source for soil microorganisms, promoting the sequestration of carbon in the soil.

3. Erosion Prevention: Both CA and NT practices help reduce soil erosion. Soil erosion not only leads to the loss of fertile topsoil but also the carbon contained within it. By minimizing erosion, CA and NT preserve SOC in the topsoil.

4. Improved Soil Structure: Reduced soil disturbance and enhanced organic matter content resulting from CA practices improve soil structure. This benefits SOC preservation as well, as well-structured soils are less prone to carbon loss through erosion and microbial decomposition.

5. Carbon Sequestration: CA and NT practices, especially when combined with cover cropping, can lead to an overall increase in SOC. As organic matter accumulates in the soil over time, it contributes to carbon sequestration. The increased SOC can help mitigate climate change by locking up carbon in the soil.

6. Microbial Activity: CA and NT practices can create conditions in the soil that favor mycorrhizal fungi and other soil organisms that promote the stabilization of organic carbon. This, in turn, can enhance SOC levels [Lal, 2009]^[17].

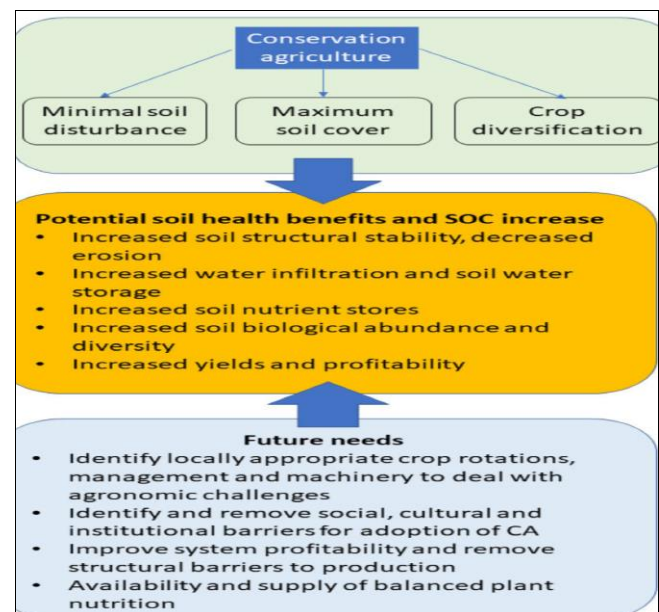


Fig 1: Principles of conservation agriculture, benefits of increasing SOC (Page *et al.*, 2020)^[21]

Mechanism of Soil Carbon Sequestration

Soil carbon sequestration is the process of transferring atmospheric CO₂ to the soil of a soil unit via its plants. Soil C sequestration has the following co-benefits: improving food and nutrition security improving renewability and water quality improving biodiversity strengthening elemental recycling Soil organic CO₂ in the soil root zone has a threshold level of 1.5-2.0 per cent SOC is affected by land use soil management soil systems soil is degraded soil

is depleted of its SOC stock soil quality needs to be restored soil SOC concentration needs to be increased by adopting good management practices (e.g. conservation agriculture) soil C budget needs to be increased globally by 4 per 1000 per year to mitigate climate change to advance food security soil C pool contains over 50% of the total C pool (0.3-m depth) (Lal *et al.*, 2015)^[18].

Earth land ecosystems contain the third largest C pool in the world at 2.344 Pg C up to 3 m. SOC (soil organic carbon) in soils is about 1015 g (1 *Peta gram*). SOC in tropical soils accounts for about 30 per cent of the total global pool. Abiotic factors that moderate soil C sequestration include soil clay content, soil mineralogy, soil structural stability, soil landscape position, soil moisture and temperature regime, etc. On the other hand, soil biotic factors are responsible for soil C sequestration. However, models do not account for the formation, stabilization, and lifespan of soil aggregates, including roots. This is not only because there are few studies on this topic, but also because soil organisms play an important role in soil aggregation. There is also a lack of in-depth knowledge on the processes that regulate dissolved organic carbon fluxes (DOC) in soils and its part in the global budget for C sequestration (Jimenez & Lal, 2006)^[10].

Conclusions and Future Perspectives

Carbon capture and storage is becoming more and more popular as a way to help mitigate climate change. But it also has other benefits like improving soil health, water retention and fertility. It's a great idea in theory, but it's hard to make it work in practice because of a few things. Some of the biggest challenges are measuring soil carbon stocks, how long they last, how many carbon pools have different timescales, how they're separated, and how the soil can reach saturation when the maximum amount of carbon it can capture is reached. We've made progress on some of these issues, but there's still a lot of work to be done to get more people and policy makers on board. Overall objective is to develop an insight on how the soils can capture and store atmospheric CO₂ and ultimately helps in reducing the environmental pollution. Researchers should be working hard to find solutions to the problems that make it hard to make this happen.

References

- Bai ZG, Dent DL, Olsson L, Schaepman ME. Proxy global assessment of land degradation. *Soil use and management*,2008:24(3):223-234.
- Baker HS, Millar RJ, Karoly DJ, Beyerle U, Guillod BP, Mitchell D, *et al.* Higher CO₂ concentrations increase extreme event risk in a 1.5 C world. *Nature Climate Change*,2018:8(7):604-608.
- Blanco-Canqui H, Lal R. No-tillage and soil-profile carbon sequestration: An on-farm assessment. *Soil Science Society of America Journal*,2008:72(3):693-701.
- Change IC. Impacts, adaptation and vulnerability. *Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental Panel on Climate Change*, 2014, 1132.
- Eitel JU, Gessler PE, Smith AM, Robberecht R. Suitability of existing and novel spectral indices to remotely detect water stress in *Populus* spp. *Forest Ecology and Management*,2006:229(1-3):170-182.
- Gouvello CD. Brazil low carbon country case study, 2010.
- Gupta DK, Bhatia A, Kumar A, Chakrabarti B, Jain N, Pathak H. Global warming potential of rice-wheat cropping system of the indo-gangetic plains. ICAR, 2015.
- Harte J, Torn M, Jensen D. The nature and consequences of indirect linkages between climate change and biological diversity. *Global warming and biological diversity*, 1992, 325-343.
- Hussain S, Hussain S, Guo R, Sarwar M, Ren X, Krstic D, El-Esawi MA. Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants*,2021:10(10):2001.
- Jimenez JJ, Lal R. Mechanisms of C sequestration in soils of Latin America. *Critical Reviews in Plant Sciences*,2006:25(4):337-365.
- Kendall HW, Pimentel D. Constraints on the expansion of the global food supply. *Ambio*, 1994, 198-205.
- Lal R. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO₂-enrichment. *Soil and tillage research*,1997:43(1-2):81-107.
- Lal R. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Progress in environmental Science*,1999:1(4):307-326.
- Lal R. Erosional Effects on Agronomic Productivity. *Soil Erosion and Dryland Farming*. CRC Press LLC, 2000, 229-246.
- Lal R. Soil carbon sequestration to mitigate climate change. *Geoderma*,2004:123(1-2):1-22.
- Lal R. Soil science and the carbon civilization. *Soil Science Society of America Journal*,2007:71(5):1425-1437.
- Lal R. Sequestering carbon in soils of arid ecosystems. *Land Degradation & Development*,2009:20(4):441-454.
- Lal RN egassa W, Lorenz K. Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*,2015:15:79-86.
- Linn DM, Doran JW. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal*,1984:48(6):1267-1272.
- Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, van Ypserle JP. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*, 2014, 151. Ippc.
- Page KL, Dang YP, Dalal RC. The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. *Frontiers in sustainable food systems*,2020:4:31.
- Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. *Nature*,2016:532(7597):49-57.
- Pimentel D, Burgess M. Soil erosion threatens food production. *Agriculture*,2013:3(3):443-463.

24. Shubham, Sharma U, Kaushal R. Effect of nitrification inhibitors on quality, yield and economics of cauliflower cv. PSB K1 in Typic Eutrochrept under mid hills of North Western Himalayas, *Journal of Plant Nutrition*,2023;46(17):4096-4109, DOI: 10.1080/01904167.2023.2220741
25. Shubham, Sharma U, Kaushal R. Potential of Different Nitrification Inhibitors on Growth of Late Sown Cauliflower Var. Pusa Snowball K-1 and Behavior of Soil NH_4^+ and NO_3^- in Typic Eutrochrept Under Mid Hills of NW Himalayas, *Communications in Soil Science and Plant Analysis*,2023;54(10):1368-1378, DOI: 10.1080/00103624.2022.2146130
26. Shubham, Sharma U, Chahal A. Effect of forest fire on ammonification and nitrification: A study under chir pine (*Pinus roxburghii*) forest areas of Himachal Pradesh. *Indian Journal of Ecology*,2021;48(2):376-380.
27. Shubham Sharma U, Kaushal R, Sharma YP. Effect of Forest Fires on Soil Carbon Dynamics in Different Land Uses under NW Himalayas. *Indian Journal of Ecology*,2022;49(6):2322-2329. DOI: <https://doi.org/10.55362/IJE/2022/3828>.
28. Sommer R, Braslow J, Savini I, Cordingley JE, Winowiecki LA, Silva MAD. State of the Art of Soil Research at International Agricultural Research Centres, 2015.
29. Sweet SK, Schuldt JP, Lehmann J, Bossio DA, Woolf D. Perceptions of naturalness predict US public support for Soil Carbon Storage as a climate solution. *Climatic Change*,2021;166(1-2):22.
30. Vermeulen SJ, Aggarwal PK, Ainslie A, Angelone C, Campbell BM, Challinor AJ, Wollenberg E. Options for support to agriculture and food security under climate change. *Environmental Science & Policy*,2012;15(1):136-144.
31. Wander MM, Bollero GA. Soil quality assessment of tillage impacts in Illinois. *Soil Science Society of America Journal*,1999;63(4):961-971.
32. Zeng S, Liu Z, Kaufmann G. Sensitivity of the global carbonate weathering carbon-sink flux to climate and land-use changes. *Nature communications*,2019;10(1):5749.