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SOIL CARBON SEQUESTRATION AND CLIMATE CHANGE MITIGATION

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ABSTRACT:
Soils constitute the largest terrestrial pool of organic carbon, holding nearly three times as much carbon as the atmosphere, and are therefore central to strategies for mitigating anthropogenic climate change. This review synthesises current understanding of soil carbon sequestration (SCS) as a nature-based climate mitigation option, covering the size and dynamics of the soil organic carbon (SOC) and soil inorganic carbon (SIC) pools, the biophysical and microbial mechanisms that stabilise carbon in soil, and the management practices — conservation agriculture, residue retention, cover cropping, agroforestry, integrated nutrient management, and improved grazing — shown to enhance SOC stocks. It also examines emerging tools for quantifying and verifying sequestration, including remote sensing, proximal sensing, and process-based biogeochemical models, and discusses the policy architecture (carbon markets, national inventories, and international commitments) that translates soil-based sequestration into climate accounting. Sequestration potential is shown to be strongly conditioned by soil texture, climate, land-use history, and management duration, with saturation limits and reversibility risk constraining long-term storage. The review concludes that SCS is a credible, cost-effective complement to direct emission reductions — not a substitute for them — and identifies priority research needs in long-term monitoring networks, standardised measurement–reporting–verification (MRV) protocols, and region-specific management guidance, with particular relevance to intensively cultivated, semi-arid agroecosystems such as those of north-west India.

KEYWORDS:soil organic carbon; soil inorganic carbon; carbon sequestration; climate change mitigation; conservation agriculture; carbon markets; remote sensing

INTRODUCTION

Atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) have risen sharply since the pre-industrial era, driving global warming and associated shifts in precipitation, extreme-weather frequency, and ecosystem function. Global mean surface temperature has already increased by more than 1.1 °C above the 1850–1900 baseline, and the Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasised that limiting warming to well below 2 °C, and preferably 1.5 °C, requires both deep cuts in emissions and substantial deployment of carbon dioxide removal (CDR) approaches [2]. Alongside decarbonisation of energy and industry, nature-based solutions that draw down atmospheric CO_2 and store it in biological reservoirs have gained prominence in climate policy, in part because several of them can be implemented using existing agricultural infrastructure and knowledge systems [4,5].

Among nature-based CDR options, soil carbon sequestration (SCS) — the net removal of atmospheric CO_2 and its storage as soil organic carbon (SOC) or soil inorganic carbon (SIC) — is widely regarded as one of the most immediately deployable, because it can be achieved largely through changes in existing land-management practice rather than new infrastructure [4]. The international '4 per 1000' initiative, launched at COP21, popularised the idea that an annual increase of just 0.4% in global soil carbon stocks could offset a substantial share of anthropogenic CO_2 emissions; while the feasibility of this specific target at a global scale remains debated, it usefully framed SCS as a quantifiable, policy-relevant lever [3].

Global soils hold an estimated 1,500–1,600 Pg of organic carbon in the top metre and several hundred additional petagrams as inorganic carbon, together substantially exceeding the atmospheric carbon pool (Figure 1) [1,6]. Even modest proportional increases in this stock, sustained across large cultivated and grazing areas, translate into globally significant CO_2 removal. Recent global assessments estimate technical SOC sequestration potential on croplands and grazing lands at tens of gigatonnes of CO_2-equivalent cumulatively, with a meaningful share achievable at costs below US$100 per tonne of CO_2, positioning SCS as economically competitive with several engineered carbon-removal pathways [5,16].

This review synthesises the current evidence base on SCS as a climate mitigation strategy. It addresses: (i) the size, distribution, and dynamics of soil carbon pools; (ii) the mechanistic basis of carbon stabilisation in soil; (iii) management practices demonstrated to enhance sequestration; (iv) methods for measuring, monitoring, reporting, and verifying (MMRV) soil carbon change; (v) modelling approaches and the concept of SOC saturation; (vi) the policy and carbon-market context; (vii) a regional perspective on semi-arid, intensively cropped systems typical of the Indo-Gangetic Plains; and (viii) key limitations, uncertainties, and priority research directions.

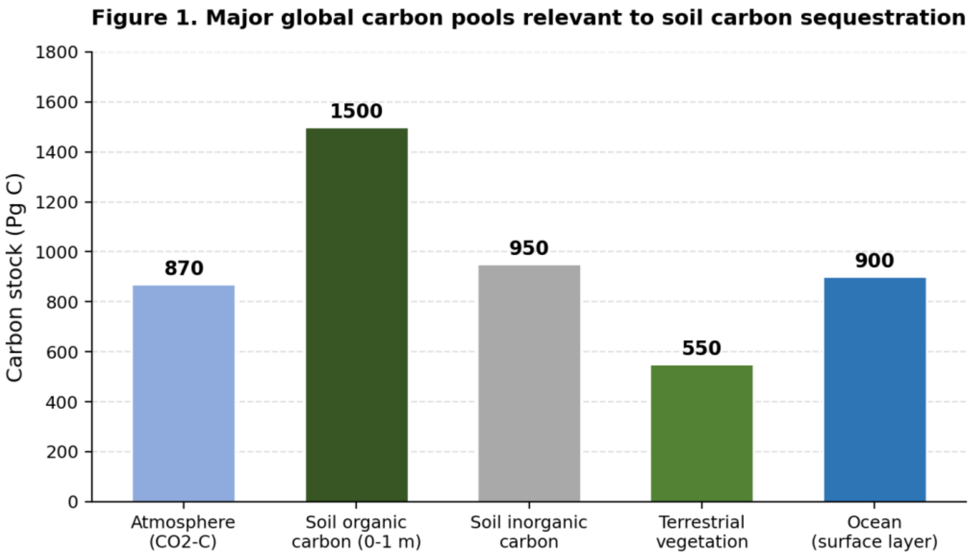

Figure 1. Major global carbon pools relevant to soil carbon sequestration. Soil organic and inorganic carbon together substantially exceed the atmospheric CO2-carbon pool, underscoring the climate relevance of even small proportional changes in soil carbon stocks. (Illustrative values compiled from published global estimates.)

2. Soil Carbon Pools and Global Distribution

2.1 Soil organic carbon (SOC)

Soil organic carbon derives from plant, root, and microbial residues and is distributed across a continuum of turnover times. Labile fractions, associated with particulate organic matter and fresh residues, turn over within weeks to a few years and are highly sensitive to management change — both gains and losses are detectable relatively quickly in this pool. Intermediate fractions, physically protected within soil aggregates, persist over years to decades. Mineral-associated organic matter, formed through sorption onto clay minerals and metal oxides, can persist for centuries to millennia and represents the most climate-relevant fraction for long-term carbon storage, since it is least vulnerable to short-term disturbance [8,10].

2.2 Soil inorganic carbon (SIC)

Soil inorganic carbon, comprising primary (lithogenic) and pedogenic carbonates, is particularly significant in arid and semi-arid soils, where calcium and magnesium carbonates accumulate through weathering and re-precipitation reactions. Pedogenic carbonate formation can itself sequester atmospheric CO_2 over long timescales, although the net climate benefit depends on the source of dissolved inorganic carbon and can be partially offset by CO_2 release during carbonate dissolution under certain irrigation and fertilisation regimes. SIC turnover is slower than that of labile SOC but can still respond to management and hydrology over decadal timescales, making it a relevant, if often overlooked, component of the soil carbon balance in calcareous and semi-arid landscapes such as much of north-west India [15].

2.3 Controls on SOC stock and distribution

SOC stocks vary widely with climate, parent material, texture, and land use. Fine-textured (clay- and loam-rich) soils generally sequester and retain more carbon than coarse, sandy soils because of greater mineral surface area available for organo-mineral association and better aggregate stability. Cooler and wetter climates generally support higher SOC stocks than hot, dry climates because decomposition rates decline with lower temperature and, up to a point, with waterlogging-induced anaerobiosis. Cultivated soils worldwide have typically lost 25–75% of their original SOC stock relative to native vegetation, chiefly through tillage-induced aggregate disruption, reduced carbon inputs relative to natural vegetation, and erosion — meaning that a substantial share of the historical soil carbon deficit is, in principle, recoverable through improved management, and that this recoverable deficit is itself an approximate upper bound on near-term sequestration potential for a given soil type and climate [6].

3. Mechanisms of Carbon Stabilisation

Carbon stabilisation in soil operates through three broadly recognised, interacting mechanisms, summarised in Figure 2.

3.1 Physical protection

Physical protection occurs when organic matter is occluded within soil aggregates, limiting microbial and enzymatic access. Macro-aggregates form around fresh particulate organic matter and fungal hyphae; as these are broken down by tillage or wetting–drying cycles, the enclosed carbon becomes newly accessible to decomposers and is rapidly mineralised. Conventional intensive tillage is therefore one of the most consistent drivers of SOC loss identified across long-term experiments, because it repeatedly exposes previously protected carbon [7].

3.2 Chemical (organo-mineral) stabilisation

Chemical stabilisation arises from sorption of organic molecules onto clay minerals and iron/aluminium oxides, forming mineral-associated organic matter (MAOM). Because this bonding is a surface phenomenon, soils with higher clay content and greater proportions of reactive iron/aluminium oxides have a correspondingly higher physicochemical capacity to stabilise carbon — a key reason why texture is one of the strongest predictors of long-term SOC storage capacity across soil types [8,10].

3.3 Biochemical recalcitrance and the microbial carbon pump

Biochemical stabilisation reflects the intrinsic resistance of certain organic compounds — lignin-derived residues, microbially processed necromass, and other complex biomolecules — to enzymatic decomposition. Contemporary soil biogeochemistry increasingly emphasises the 'microbial carbon pump': rather than simply resisting decay, much of the most persistent SOC is actually microbial in origin, formed as microbial biomass and metabolic by-products are repeatedly processed, die, and become incorporated into mineral-associated pools [9]. This reframes management priorities away from simply adding recalcitrant plant material and toward sustaining active, diverse microbial communities that efficiently convert carbon inputs into stable microbial residues [8,9].

3.4 Root inputs and rhizodeposition

Root architecture and rhizodeposition are increasingly recognised as disproportionately important carbon inputs relative to aboveground residues on a per-unit-carbon basis, because root-derived carbon is deposited directly at depth, is often chemically labile and thus rapidly assimilated by microbes, and is preferentially incorporated into mineral-associated pools via microbial processing [9]. Deep-rooted cover crops and perennial vegetation therefore contribute to SOC building more efficiently, per unit of carbon added, than equivalent aboveground residue inputs alone.

3.5 Environmental controls

Soil moisture, temperature, and aeration regulate the balance between these stabilising processes and decomposition, such that management effects on SCS are strongly climate- and site-contingent. Waterlogged or anaerobic conditions slow decomposition and favour carbon accumulation (as in wetland and some paddy soils), while warm, well-aerated, and periodically disturbed conditions favour rapid mineralisation — a distinction of direct relevance to rice–wheat cropping systems, where flooded and non-flooded phases alternate within a single year [12,30].

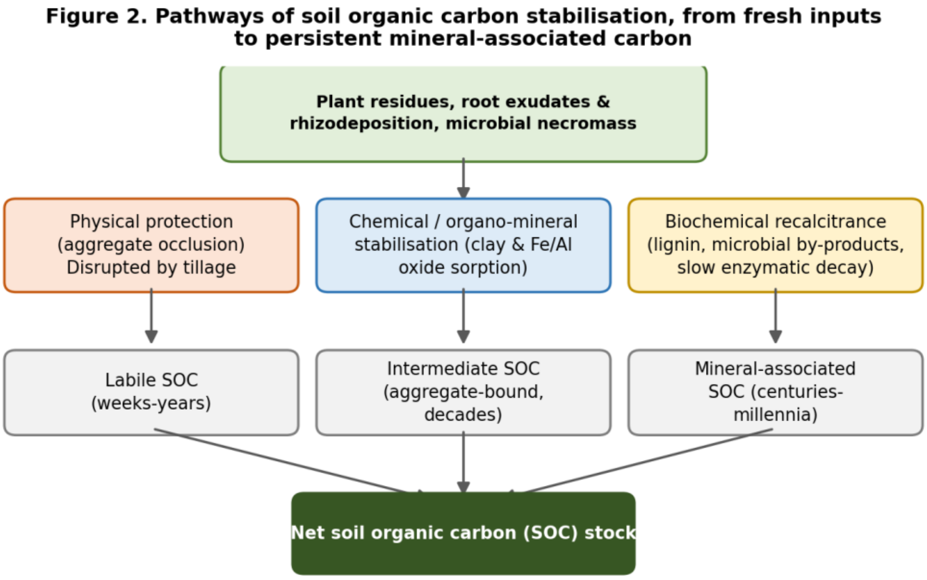

Figure 2. Pathways of soil organic carbon stabilisation, from fresh plant and microbial inputs through physical, chemical, and biochemical stabilisation mechanisms to the net soil organic carbon stock.

4. Management Practices Enhancing Soil Carbon Sequestration

A wide range of agronomic and land-use practices have been shown, across long-term experiments and meta-analyses, to increase SOC relative to conventional management (Figure 3, Table 1).

•Conservation and reduced/no tillage — minimises aggregate disruption and slows oxidation of protected carbon, though gains are often concentrated near the soil surface and can be climate-dependent; some studies report limited or no net gain when measured to greater soil depths [26,29].
•Crop residue retention and mulching — sustains organic carbon inputs, moderates soil temperature and moisture, suppresses weeds, and reduces erosion losses, though residue burning (common in some rice–wheat systems) forfeits much of this potential and additionally emits black carbon and other pollutants [25].
•Cover cropping and diversified rotations — extend the period of living root presence, increasing rhizodeposition-driven carbon inputs and microbial activity between main-season crops [28].
•Integrated nutrient management, including balanced and nano-formulated fertilisers and organic amendments (farmyard manure, compost, biochar) — improves biomass productivity and carbon-use efficiency while, in the case of biochar, adding a highly recalcitrant carbon form with centennial-to-millennial residence times [23].
•Agroforestry and perennial systems — combine woody and herbaceous biomass carbon inputs with reduced soil disturbance and can sequester carbon in both above- and below-ground biomass alongside SOC [31,32].
•Improved grazing and rotational livestock management — sustains grassland productivity and root turnover while avoiding overgrazing-induced degradation and compaction [27].
•Water and salinity management in irrigated systems — maintaining favourable electrical conductivity (EC) and sodium adsorption ratio (SAR) conditions supports biomass productivity and, indirectly, carbon inputs in salt-affected soils, which otherwise show constrained microbial activity, poor aggregation, and limited carbon stabilisation until reclaimed (e.g., through gypsum application, leaching, and salt-tolerant cropping) [33].
Meta-analyses generally report the largest relative SOC gains where degraded or carbon-depleted soils are brought under combined practices (e.g., no-till plus residue retention plus cover cropping) rather than any single intervention, and where practices are sustained over multiple decades — reflecting the slow, asymptotic approach of SOC toward a new, higher equilibrium under improved management (see Section 6) [21,22,24,27].

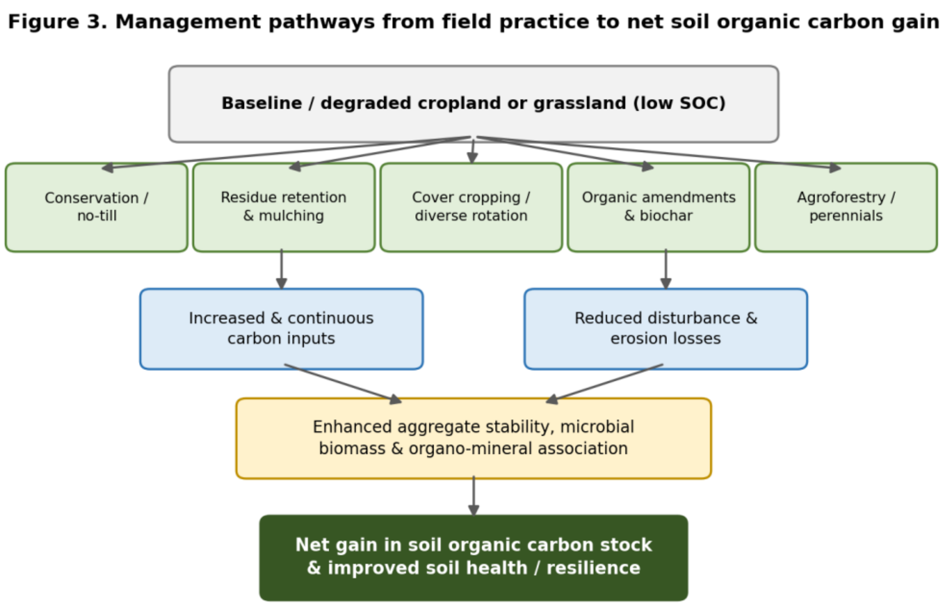

Figure 3. Management pathways linking specific field practices, through increased carbon inputs and reduced disturbance, to net gains in soil organic carbon stock and soil health.

Practice	Primary mechanism	Typical reported SOC response*
No-till / reduced tillage	Reduced aggregate disruption	Moderate gain, often surface-concentrated
Residue retention	Sustained carbon input	Small-to-moderate gain; large loss if residues burned
Cover cropping	Extended living-root period	Moderate gain, builds over 5-10+ years
Organic amendments / biochar	Added recalcitrant carbon	Moderate-to-large gain, amendment-dependent
Agroforestry	Woody biomass + reduced disturbance	Large gain over decadal timescales
Improved grazing management	Sustained root turnover	Small-to-moderate gain, site-dependent

*Indicative direction and relative magnitude only, synthesised from published meta-analyses and reviews [21–29]; absolute rates vary widely with baseline SOC, climate, soil texture, and monitoring depth, and should be sourced from site- or region-specific studies for quantitative use.

5. Measurement, Monitoring, Reporting, and Verification (MMRV)

5.1 Conventional ground-based measurement

Robust MMRV is essential both for scientific attribution of sequestration to specific practices and for participation in carbon markets. Conventional approaches rely on repeated soil sampling and laboratory analysis (dry combustion or wet oxidation) across fixed depth increments, with bulk density correction needed to convert concentration data into equivalent-mass carbon stocks. These methods are accurate at the point scale but are labour-intensive, spatially sparse, and subject to high field variability, particularly for detecting the modest annual SOC changes (often well under 0.1% absolute) that are typical even under effective management — a statistical detection challenge that has historically limited confidence in short-term monitoring results [20].

5.2 Remote sensing and digital soil mapping

Remote sensing and geospatial approaches are increasingly used to complement ground sampling. Multispectral and hyperspectral satellite and airborne imagery support empirical and physically based SOC prediction models, typically calibrated against field-sampled reference data [34,35]. Synthetic aperture radar (SAR) contributes soil moisture information relevant to decomposition dynamics and can penetrate cloud cover, which is valuable in monsoon-affected regions [37]. Digital soil mapping frameworks integrate satellite covariates, terrain attributes (elevation, slope, wetness indices), and legacy soil survey data via machine-learning algorithms — such as random forest and gradient boosting — to produce spatially continuous SOC stock and change estimates across large administrative areas [34–36,38]. Unmanned aerial vehicle (UAV)-based proximal sensing offers finer-resolution calibration and validation data where satellite resolution is limiting, and is particularly useful for field-scale trials and pilot monitoring programmes [37,39].

5.3 Process-based modelling

Process-based biogeochemical models — including DSSAT, DNDC, RothC, and CENTURY/DayCent — are used to simulate SOC trajectories under alternative management and climate scenarios. These models provide a mechanistic complement to empirically driven remote-sensing products, allow scenario analysis (e.g., projecting SOC change under a proposed shift to conservation agriculture before it is implemented), and support extrapolation of results from well-instrumented long-term experimental sites to broader landscapes with similar soil–climate conditions [20].

5.4 Integrated frameworks

Combining repeated, geolocated ground sampling with remote-sensing-calibrated spatial models and process-based simulation is increasingly regarded as the most credible basis for regional-to-national soil carbon MMRV (Figure 4) [36,38], and is broadly consistent with the tiered approaches recommended under IPCC national GHG inventory guidance, which allow countries to progress from default emission factors (Tier 1) toward country-specific, spatially explicit estimates (Tier 3) as data and capacity permit [2].

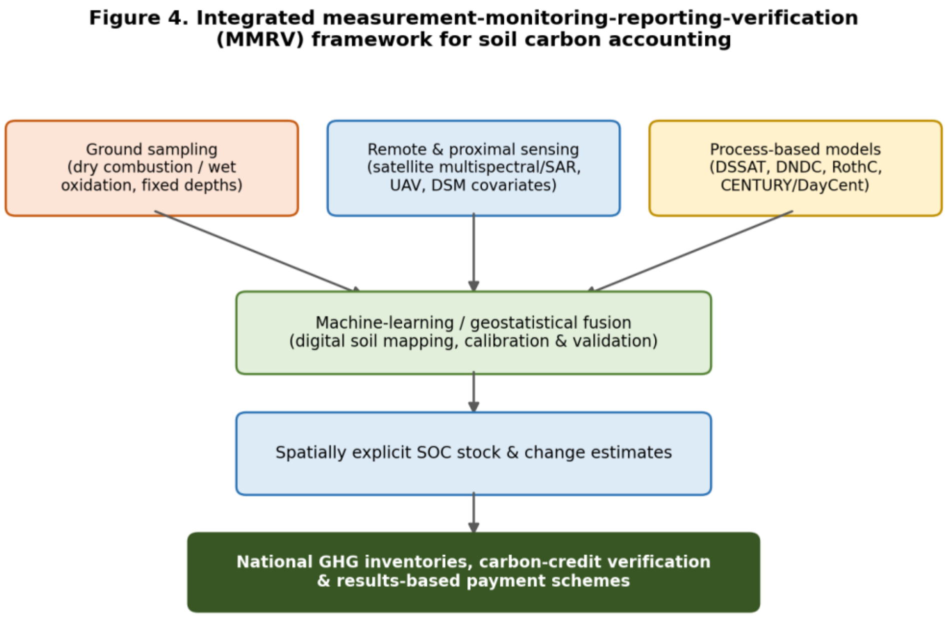

Figure 4. Integrated measurement-monitoring-reporting-verification (MMRV) framework combining ground sampling, remote/proximal sensing, and process-based modelling to support national GHG inventories and carbon-credit verification.

6. Modelling Soil Carbon Trajectories and the Saturation Concept

A central, policy-relevant feature of SOC dynamics is that stocks do not increase indefinitely under improved management; rather, they follow an asymptotic trajectory toward a new, practice- and climate-specific equilibrium, often termed the SOC saturation level (Figure 5) [1,11]. Early years after adoption of an improved practice typically show the fastest relative rate of SOC gain, with the rate of increase declining as the soil approaches its new equilibrium — a pattern consistent with first-order kinetics of carbon input and decomposition. This has two practical implications for climate policy and carbon crediting. First, the climate benefit of a given practice is front-loaded in early years but is not permanent unless the practice is sustained indefinitely; reversion to degrading practices can release a substantial share of the accumulated carbon within a much shorter period than it took to accumulate [11]. Second, crediting periods and additionality rules for soil-carbon offset programmes need to account for this diminishing-returns trajectory rather than assuming a constant annual sequestration rate over the life of a project [41].

Combined practices (e.g., no-till plus residue retention plus cover cropping) tend to raise both the rate of approach to equilibrium and the equilibrium level itself relative to any single practice in isolation, consistent with their complementary mechanisms of action (increased inputs together with reduced losses) [22,26].

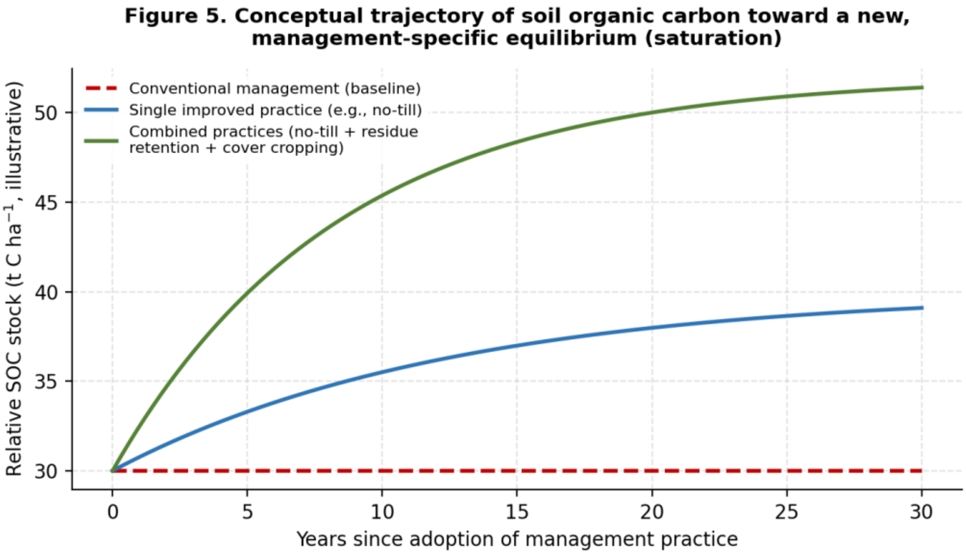

Figure 5. Conceptual trajectory of soil organic carbon stock following adoption of improved management, illustrating the asymptotic approach toward a new, practice-specific equilibrium (saturation) relative to a conventional-management baseline.

7. Policy Context and Carbon Markets

Soil carbon sequestration is recognised within the Paris Agreement framework as a component of nationally determined contributions (NDCs) and within voluntary and compliance carbon markets as an eligible offset category under approved methodologies (e.g., under Verra's VM0042 soil carbon methodology and comparable protocols) [40,41]. Uptake nonetheless remains constrained by measurement uncertainty, the cost of verification relative to credit value — which can be prohibitive for smallholder farms — additionality and permanence concerns (sequestered carbon can be re-released by a reversion to intensive tillage, drought, or land-use change), and the long timeframes needed to demonstrate statistically robust SOC gains against high background spatial variability [11,17].

Policy instruments that have shown promise include results-based payment schemes tied to verified SOC change, bundling of SCS with co-benefits (soil health, water retention, yield stability) to improve farmer participation and reduce reliance on carbon price alone, and public soil-carbon monitoring networks that lower the marginal MMRV cost for individual land managers by amortising sampling and remote-sensing infrastructure across many participants [17]. For India specifically, integration of SCS objectives with existing Soil Health Card and precision-agriculture programmes offers a practical pathway to embed carbon monitoring within infrastructure that is already being scaled nationally, potentially reducing the marginal cost of establishing a dedicated soil-carbon MMRV system [33].

8. Regional Perspective: Semi-Arid and Salt-Affected Agroecosystems

Much of the discussion above applies with particular force to intensively cultivated, semi-arid systems such as the rice–wheat cropping belt of the Indo-Gangetic Plains [30]. These systems combine high baseline productivity and fertiliser use with substantial residue-burning pressure, seasonal flooding–drying cycles that alternate anaerobic and aerobic decomposition regimes, and, in many districts, secondary soil salinisation and sodicity that constrain both biomass productivity and microbial activity. In such settings, SCS strategies need to be integrated with salinity/sodicity management (gypsum application, leaching, salt-tolerant cultivars, and appropriate irrigation scheduling) rather than treated as an independent intervention, since carbon-input potential itself is capped by crop productivity under saline or sodic conditions [33]. Similarly, greenhouse-gas trade-offs are especially relevant here: alternate wetting-and-drying irrigation in rice can reduce methane emissions and may support SOC accrual, but its net GHG balance depends on concurrent effects on nitrous oxide emissions, underscoring the need for full-GHG rather than SOC-only assessment in these systems [30]. Geospatial tools — satellite- and UAV-based monitoring of salinity, soil moisture, and vegetation vigour, integrated with soil health card data — offer a practical, scalable basis for targeting and verifying SCS interventions across the many thousands of hectares typical of state- and district-level programmes in this region [34,36].

9. Limitations, Uncertainties, and Research Gaps

•equilibrium; once near saturation, further gains are minimal, and stocks can be lost rapidly upon reversion to degrading practices [1,11].

•Spatial and temporal heterogeneity: high inherent variability in SOC complicates detection of management-driven change against background noise, particularly over short (fewer than 5-10 year) monitoring windows [20].

•Interaction with other GHGs: some practices that raise SOC (e.g., certain irrigation or organic-amendment regimes) can simultaneously increase soil nitrous oxide or methane emissions, requiring full GHG-balance rather than SOC-only assessment [30].

•Deep-soil and subsoil carbon dynamics remain comparatively understudied relative to surface layers, despite evidence that subsoil carbon can be substantial and differently responsive to management [26].

•Standardisation gap: the absence of harmonised, low-cost MMRV protocols remains a primary barrier to scaling soil-carbon crediting, particularly for smallholder-dominated systems [17,41].

•Climate-change feedback: warming and altered precipitation may themselves accelerate decomposition in some regions, potentially eroding a portion of the sequestration achieved through management, a dynamic that is not yet well constrained empirically [11].

Addressing these gaps will require sustained long-term experimental networks, wider adoption of harmonised sampling and modelling protocols, and closer integration of remote-sensing-based monitoring with field verification — an area where geospatial and GIS-based soil information systems can make a direct contribution.

10. Future Research Directions

- Development and validation of low-cost, high-frequency SOC sensing (e.g., in-field spectroscopy) to reduce reliance on laboratory analysis and shorten detection timeframes for management-induced change.
- Deeper integration of satellite, UAV, and ground-sensor data streams within operational digital soil mapping pipelines at state and national scale, building on existing soil health card and precision-agriculture infrastructure.
- Longer-duration, deeper-sampling (sub-1 m) long-term experiments, particularly in under-represented semi-arid and salt-affected agroecosystems, to better constrain saturation levels and subsoil carbon response.
- Coupled SOC-greenhouse-gas accounting frameworks that jointly track CO2, N2O, and CH4 to avoid crediting practices that raise SOC while increasing net radiative forcing overall.
- Socioeconomic and behavioural research on smallholder participation in carbon markets, including transaction-cost-reducing aggregation models and co-benefit-based (rather than carbon-price-only) incentive design.

11. CONCLUSION

Soil carbon sequestration offers a scientifically credible and cost-effective nature-based contribution to climate change mitigation, with the added benefit of improving soil health, water-holding capacity, and agricultural resilience. Its climate value is nonetheless bounded by saturation limits, reversibility risk, and persistent measurement uncertainty, and it should be pursued as a complement to, not a substitute for, direct reductions in fossil-fuel and industrial GHG emissions. Realising SCS potential at scale will depend on combining proven agronomic practices with robust, geospatially enabled MMRV systems and supportive policy instruments — an integration that is particularly relevant to intensively cultivated, resource-constrained agroecosystems seeking to reconcile food security with climate commitments.

REFERENCES

1. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), 1623–1627.
2. IPCC. (2021). 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 University Press.
3. Minasny, B., Malone, B. P., McBratney, A. B., et al. (2017). Soil carbon 4 per mille. Geoderma, 292, 59–86.
4. Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. Nature, 532, 49–57.
5. Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., et al. (2020). The role of soil carbon in natural climate solutions. Nature Sustainability, 3, 391–398.
6. Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences, 114(36), 9575–9580.
7. Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil, 241, 155–176.
8. Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework. Global Change Biology, 19(4), 988–995.

9. Liang, C., Schimel, J. P., & Jastrow, J. D. (2017). The importance of anabolism in microbial control over soil carbon storage. Nature Microbiology, 2, 17105.
10. Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528, 60–68.
11. Durrer, M., et al. (2023). Carbon sequestration in soils and climate change mitigation — definitions and pitfalls. Global Change Biology, 29(24), 6914–6931.
12. Understanding soil carbon sequestration: mechanistic insights, management approaches, and future challenges. (2025). Discover Soil, Springer Nature.
13. Soil carbon sequestration: A mechanistic perspective on limitations and future possibilities. (2025). Sustainability, 17(13), 6015.
14. Bibliometric analysis of research trends in agricultural soil organic carbon components from 2000 to 2023. (2024). PMC11652143.
15. Soil inorganic carbon stocks increase non-synergistically with soil organic carbon after ecological restoration practices in drylands. (2023–2025). Global Change Biology / Geoderma (Loess Plateau study).
16. Kamasela, D. F., Fujimori, S., Hasegawa, T., & Vishwanathan, S. S. (2025). Global soil organic carbon sequestration potential under sustainable food systems and climate mitigation. Environmental Research Letters, 20(12), 124062. (Erratum: Environmental Research Letters, 21(5), 059601, 2026.)
17. Soil carbon sequestration and its role in reducing global carbon footprints: strategies, challenges and policy implications. (2026). Carbon Footprints, published online 5 March 2026.
18. Soil carbon sequestration and climate change mitigation. (2025). Extension Journal (review article).
19. Murali, M., Gayathri, M., Singh, V., Raj, S., Singh, V., Chaubey, C., & Inamdar, F. (2023). Soil carbon sequestration in the age of climate change: A review. International Journal of Environment and Climate Change, 13, 1668–1677.
20. Petropoulos, T., Benos, L., Busato, P., Kyriakarakos, G., Kateris, D., Aidonis, D., & Bochtis, D. (2025). Soil organic carbon assessment for carbon farming: A review. Agriculture, 15(5), 567.
21. Padbhushan, R., Kumar, U., Sinha, A. K., et al. (2024). Impacts of conservation agriculture on crop yield and soil carbon sequestration: A meta-analysis in the Indian subcontinent. Environmental Geochemistry and Health, 46, 251.
22. Differential impacts of regenerative agriculture practices on soil organic carbon: A meta-analysis of studies from India. (2025). Scientific Reports.
23. Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. (2025). [conservation tillage, cover crops, biochar; 3,049 paired measurements from 417 articles].
24. Das, S., Chatterjee, S., & Rajbanshi, J. (2022). Responses of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: A meta-analysis. Science of the Total Environment, 805, 150428.
25. Bohoussou, Y. N. D., Kou, Y. H., Yu, W. B., Lin, B. J., Virk, A. L., Zhao, X., Dang, Y. P., & Zhang, H. L. (2022). Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: A global meta-analysis. Science of the Total Environment, 842, 156822.
26. Enhancing soil organic carbon sequestration through conservation tillage: A comprehensive mega-analysis. (2026). Frontiers of Earth Science.
27. Unlocking the potential of conservation agriculture for soil carbon sequestration influenced by soil texture and climate: A worldwide systematic review. (2023). Journal of Aridland Agriculture.
28. Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops — A meta-analysis. Agriculture, Ecosystems & Environment, 200, 33–41.
29. Powlson, D. S., Stirling, C. M., Thierfelder, C., White, R. P., & Jat, M. L. (2014). Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agriculture, Ecosystems & Environment, 187, 116–132.
30. Dheri, G. S., & Nazir, G. (2021). A review on carbon pools and sequestration as influenced by long-term management practices in a rice–wheat cropping system. Carbon Management, 12, 559–580.
31. George, A., Joseph, S., Mohan, M., & Kunhamu, T. K. (2025). Carbon pools in the agroforestry landscapes of the Western Ghats biodiversity hotspot of Kerala, India. Catena, 250, 108807.
32. Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2021). Soil organic matter (SOM) and nutrient cycling. In An Introduction to Agroforestry (pp. 383–411). Springer, Cham.
33. Swarup, A., Manna, M. C., & Singh, G. B. (2019). Impact of land use and management practices on organic carbon dynamics in soils of India. In R. Lal, D. K. Majumdar, & B. A. Stewart (Eds.), Global Climate Change and Tropical Ecosystems (pp. 261–281).
34. Open remote sensing data in digital soil organic carbon mapping: A review. (2024). Agriculture, 14(7), 1005.
35. Digital mapping of soil organic carbon using remote sensing data: A systematic review. (2023). Catena / Geoderma [217 papers, 2010–2023].
36. Geospatial digital mapping of soil organic carbon using machine learning and geostatistical methods in different land uses. (2025). Scientific Reports.
37. Remote sensing-based soil organic carbon monitoring using advanced machine learning techniques under conservation agriculture systems. (2025). Science of the Total Environment / Environmental Technology & Innovation.
38. A comprehensive review of soil organic carbon estimates: Integrating remote sensing and machine learning technologies. (2024). Journal of Soils and Sediments.

39. Soil organic carbon retrieval using a machine learning approach from satellite and environmental covariates in the Lower Brazos River Watershed, Texas, USA. (2025). Science of the Total Environment / Remote Sensing Applications.
40. UNFCCC. (2015). Paris Agreement. United Nations Framework Convention on Climate Change.
41. Verra. (2022). VM0042: Methodology for Improved Agricultural Land Management, v2.0. Verra.