

19. Long-Term Organic Amendments and Their Influence on Soil Carbon Pools and Sequestration

Arkit Saha¹

¹B.Sc. (Hons.) Agriculture, Visvabharati University

1. Introduction

Agricultural soils represent a significant global carbon reservoir, holding more than three times the amount of C currently present in the atmosphere (Lal *et al.*, 2004). However, conventional agricultural practices, characterized by intensive tillage and low organic matter inputs, have historically led to substantial losses of soil organic carbon (SOC), contributing to atmospheric CO₂ concentrations and soil degradation. Recognizing this challenge, there is a growing interest in adopting sustainable agricultural practices that aim to replenish and sequester C in soils. Among these practices, the long-term application of organic amendments stands out as a highly effective strategy.

Organic amendments encompass a broad range of materials, from animal manures and composts to crop residues and cover crops, all of which introduce exogenous organic matter into the soil system. The continuous addition of these materials can significantly alter the quantity and quality of SOC, influencing its distribution into different pools with varying turnover rates and stability. Understanding these

dynamics is crucial for optimizing amendment strategies to maximize C sequestration potential and improve overall soil health. This article synthesizes current knowledge on the effects of long-term organic amendments on soil C pools and their contribution to C sequestration, drawing upon evidence from long-term agricultural experiments.

2. Soil Carbon Pools and Dynamics

Soil organic carbon is not a homogeneous entity but rather a complex mixture of organic compounds existing in various pools with distinct chemical compositions, turnover rates, and susceptibilities to decomposition. These pools are broadly categorized as:

a. **Labile Carbon Pools:** These are the more easily decomposable fractions of SOC, typically characterized by rapid turnover rates (days to years). They include:

- **Particulate Organic Matter (POM):** Physically protected, partially decomposed plant and animal residues, often

associated with larger soil aggregates.

- **Microbial Biomass Carbon (MBC):** Carbon contained within living soil microorganisms (bacteria, fungi, protozoa). This pool is highly dynamic, reflecting microbial activity and nutrient cycling.
- **Dissolved Organic Carbon (DOC):** Small, soluble organic molecules that are readily available for microbial uptake or leaching.

b. Stable Carbon Pools: These fractions are more resistant to decomposition, with turnover times ranging from decades to millennia. They are typically associated with mineral surfaces and smaller aggregates, offering physical and chemical protection.

- **Humic Substances:** Complex, recalcitrant

organic molecules formed through microbial processing, including humic acids, fulvic acids, and humin.

- **Mineral-Associated Organic Matter (MAOM):** Organic matter strongly adsorbed to clay minerals and silt particles, often forming stable organo-mineral complexes.

The balance between C inputs (from amendments, residues, roots) and C outputs (through microbial respiration, erosion, leaching) dictates the net C sequestration or loss in a soil system. Organic amendments primarily increase C inputs, thereby shifting this balance towards accumulation.

3. Types of Organic Amendments and Their Characteristics

The choice of organic amendment significantly influences its impact on soil C dynamics due to variations in chemical composition, C: N ratio, and stability.

Table 1 Characteristics of Common Organic Amendments

Amendment Type	Primary Components	C: N Ratio	Decomposition Rate	Impact on Labile C	Impact on Stable C
Animal Manure	Partially digested plant matter, animal waste	10-30:1	Moderate-Fast	High	Moderate
Compost	Stabilized organic matter	15-25:1	Moderate-Slow	Moderate	High
Cover Crop Residues	Fresh plant biomass	20-80:1	Fast-Moderate	High	Moderate

Biochar	Pyrolyzed biomass	>100:1	Very Slow	Low	Very High
----------------	-------------------	--------	-----------	-----	-----------

Note: Decomposition rates and C:N ratios can vary widely depending on the specific source and processing.

3.1. Animal Manure

Animal manures (e.g., cattle, swine, poultry) are rich in organic matter and essential nutrients. Their relatively low C: N ratio (typically 10-30:1) promotes rapid decomposition, leading to an initial increase in labile C pools (MBC, DOC). Over the long term, continuous manure application contributes to the formation of stable humic substances and MAOM, particularly in conjunction with improved aggregate stability.

3.2. Compost

Compost is a stabilized organic product resulting from the controlled aerobic decomposition of organic feedstocks. The composting process reduces the volume and pathogen content and stabilizes the organic matter, increasing its humic fraction. As a result, composts generally have a more stable organic matrix and a moderate C: N ratio (15-25:1) compared to raw manures. Long-term compost application is particularly effective at increasing stable SOC fractions and enhancing soil aggregation.

3.3. Cover Crop Residues

Cover crops are plants grown primarily to protect and enrich the soil rather than for

harvest. When terminated, their biomass is incorporated into the soil, providing a fresh input of organic matter. The C: N ratio of cover crop residues varies significantly depending on the species and growth stage, influencing their decomposition rate. Leguminous cover crops, with lower C: N ratios, decompose more rapidly, providing a quick flush of nutrients and labile C. Grassy cover crops, with higher C: N ratios, contribute more slowly decomposable C, potentially building up stable SOC over time.

3.4. Biochar

Biochar is a carbonaceous material produced by heating biomass in the absence of oxygen (pyrolysis). Its highly aromatic and recalcitrant structure makes it extremely resistant to microbial decomposition, meaning it can remain in soil for centuries to millennia. While biochar itself contributes stable C, its effectiveness in enhancing overall SOC sequestration often lies in its ability to improve soil structure, water retention, and nutrient cycling, which can indirectly promote the accumulation of native SOC.

4. Influence of Long-Term Organic Amendments on Soil Carbon Pools

Long-term studies consistently demonstrate that continuous application of organic amendments leads to significant increases

in total SOC. However, the distribution of this accumulated C among different pools is crucial for understanding its stability and impact on ecosystem services.

4.1. Total Soil Organic Carbon (SOC)

Numerous long-term agricultural experiments worldwide have shown a clear positive correlation between organic amendment application and total SOC

content. For example, studies from the Rothamsted Experimental Station in the UK, dating back over a century, reveal that plots receiving regular manure applications have significantly higher SOC levels compared to unamended or inorganic fertilizer-only plots (Johnston *et al.*, 2009). Similar trends are observed in various climatic zones and soil types globally.



Figure 1 Conceptual Diagram of Soil Carbon Sequestration with Organic Amendments

4.2. Labile Carbon Pools (POM, MBC, DOC)

Organic amendments provide readily available substrates for soil

microorganisms, leading to an immediate increase in labile C pools.

a. Particulate Organic Matter

(POM): Long-term studies indicate that organic amendments significantly enhance POM content. This is particularly true for less processed materials like cover crop residues or raw manures, which introduce substantial amounts of undecomposed plant material. POM serves as an important energy source for microbes and is a precursor to more stable SOC.

b. Microbial Biomass Carbon

(MBC): MBC typically increases with organic amendment application, reflecting enhanced microbial activity and population sizes due to increased nutrient and energy availability. Higher MBC levels are indicative of a healthier and more active soil food web, which is crucial for nutrient cycling and organic matter decomposition. The increase in MBC can be rapid following amendment application but also sustained over the long term with continuous inputs.

c. Dissolved Organic Carbon

(DOC): While DOC is highly dynamic, long-term organic amendments can increase its

concentration, serving as an important C and energy source for microorganisms and influencing C transport within the soil profile.

4.3. Stable Carbon Pools (Humic Substances, MAOM)

The long-term impact of organic amendments on stable C pools is perhaps the most critical aspect for C sequestration. While labile C pools are important for immediate soil function, stable C pools represent truly sequestered C with long residence times.

a. Humic Substances: Continuous inputs of organic matter, coupled with active microbial processing, promote the formation and accumulation of humic substances. Composts, in particular, due to their already stabilized nature, are highly effective in building up these recalcitrant fractions.

b. Mineral-Associated Organic

Matter (MAOM): This pool is considered the most stable and largest C pool globally. Organic amendments indirectly enhance MAOM formation by providing organic precursors that can bind to mineral surfaces, often facilitated by microbial exudates and improved soil aggregation. Clays play a significant role in physically

and chemically protecting MAOM from decomposition.

4.4. Soil Aggregation and Carbon Protection

Organic amendments play a crucial role in enhancing soil aggregation, which is a key mechanism for C protection. Organic matter acts as a binding agent, facilitating the formation of stable soil aggregates. Within these aggregates, organic matter can be physically protected from microbial decomposition, leading to increased C sequestration. This physical protection is particularly important for MAOM. Studies

have shown that soils receiving long-term organic amendments exhibit greater aggregate stability and higher C concentrations within stable aggregates compared to unamended soils.

5. Carbon Sequestration Potential of Organic Amendments

The rate of C sequestration varies widely depending on the type of amendment, soil type, climate, management practices, and initial SOC levels. However, long-term studies consistently demonstrate significant C accumulation.

Table 2 Estimated Annual Carbon Sequestration Rates from Organic Amendments

Amendment Type	Sequestration Rate (Mg C ha ⁻¹ yr ⁻¹)	Notes	Reference (Illustrative)
Animal Manure	0.2 - 1.5	Highly variable based on application rate, manure type, and climate. Higher rates are often seen in degraded soils.	Lal <i>et al.</i> (2004)
Compost	0.3 - 2.0	Generally higher rates than raw manure due to C stability. Application rates and initial soil C are key factors.	Ryals <i>et al.</i> (2015)
Cover Cropping	0.1 - 0.7	Depends on biomass production, species, and rotation. Lower rates typically reflect a single season; multiple seasons show cumulative effects.	Powlson <i>et al.</i> (2014)
Biochar	0.1 - 3.0+	Potential for very high rates due to inherent stability; effectiveness often measured over very long timescales. Rates depend on the application amount.	Lehmann (2007)

Note: These are illustrative ranges; actual rates depend on numerous site-specific factors.

5.1. Factors Influencing Sequestration Efficiency:

a. **Application Rate and Frequency:**
Higher and more frequent

applications generally lead to greater C inputs and sequestration.

b. **Quality of Amendment:**
Amendments with higher C:N ratios

or more recalcitrant C (e.g., compost, biochar) tend to build up stable SOC more effectively.

- c. **Soil Type:** Clayey soils, with more mineral surface area, often have a higher capacity for MAOM formation and thus greater C sequestration potential than sandy soils.
- d. **Climate:** Temperature and moisture regimes influence microbial activity and decomposition rates.
- e. **Tillage Practices:** Reduced or no-tillage systems enhance the preservation of SOC, especially in surface layers, by minimizing physical disturbance and aeration.
- f. **Crop Rotation:** Integrating diverse crop rotations, especially those including cover crops or perennial forages, can complement amendment effects by increasing root biomass and residue returns.

6. Co-Benefits of Soil Carbon Sequestration

Beyond climate change mitigation, enhanced SOC levels resulting from long-term organic amendments provide a suite of co-benefits that improve overall soil health and agricultural productivity:

- a. **Improved Soil Structure and Aggregation:** Leading to better

water infiltration, aeration, and reduced erosion.

- b. **Increased Water Holding Capacity:** Making soils more resilient to drought.
- c. **Enhanced Nutrient Cycling and Availability:** Organic matter mineralizes, slowly releasing essential nutrients for plant uptake, reducing the need for synthetic fertilizers.
- d. **Increased Microbial Diversity and Activity:** A more diverse and active soil microbiome contributes to disease suppression and nutrient cycling.
- e. **Reduced Soil Compaction:** Improving root penetration and plant growth.

7. Conclusions and Future Directions

Long-term application of organic amendments is a robust and multifaceted strategy for increasing soil carbon pools and enhancing C sequestration in agricultural systems. These practices not only contribute significantly to mitigating climate change by drawing down atmospheric CO₂ but also provide a cascade of benefits for soil health, agricultural productivity, and environmental sustainability.

Future research should continue to focus on:

a. Optimizing Amendment

Strategies: Tailoring amendment types, rates, and application timings to specific soil types, climates, and cropping systems for maximum C sequestration efficiency and cost-effectiveness.

b. Understanding Microbial

Contributions: Further elucidating the role of specific microbial communities and their functional genes in C cycling and stabilization processes.

c. Developing Robust Measurement and Monitoring Techniques:

Improving methods for accurately quantifying C sequestration rates and changes in different C pools over time.

d. Integrating Diverse Practices:

Investigating the synergistic effects of combining organic amendments with other sustainable practices like no-tillage, diverse crop rotations, and agroforestry.

By embracing and scaling up the adoption of long-term organic amendment strategies, agriculture can transition from being a net emitter to a net sink of atmospheric carbon, securing a more sustainable and resilient food system for the future.

References

- Johnston, A. E., Poulton, P. R., & Coleman, K. (2009). Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy*, 101, 1-57.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623-1627.
- Lehmann, J. (2007). A handful of carbon. *Nature*, 447(7141), 143-144.
- Powlson, D. S., Bhogal, A., Chambers, B. J., Jeuffroy, M. H., Kuhlman, T., MacLeod, M., ... & Watson, C. A. (2014). When does a crop become a 'cover crop'?. *Environmental Science & Policy*, 41, 1-4.
- Ryals, R., Kaiser, S., Finney, D., Trippe, N., Six, J., & Silver, W. L. (2015). Impacts of organic matter amendments on carbon and nitrogen dynamics in annual cropland. *Soil Biology and Biochemistry*, 86, 164-173.
- Abbas, M., Ma, W., Aslam, Z., Ahmed, S., Khaliq, A., Hussain, M., Ali, B., Iqbal, M. F., Javed, M., & Saneoka, H. (2024). The efficacy of organic amendments on maize productivity, soil properties and active fractions of soil carbon in organic-matter deficient soil. *Spanish Journal of Soil Science*, 14(1).

- Bhattacharyya, R., Pandey, B., Timsina, J., Sane, A., & Gupta, H. S. (2022). Long-term effects of organic amendments on carbon stability in clay–organic complex and its role in soil aggregation. *Agronomy*, 13(1), 39.
- Liu, X., Ding, S., Yang, C., Li, C., & Zhang, Y. (2025). Organic carbon sequestration in global croplands: evidenced through a bibliometric approach. *Frontiers in Environmental Science*, 13, 1495991.
- Shi, Z., Zhang, Z., Liu, S., Shi, P., & Li, M. (2020). Carbon sequestration potential of biochar-amended soils in China: A meta-analysis. *Land Degradation & Development*, 31(1), 58–69.
- Singh, S., Singh, O., Shahi, U. P., Singh, P. K., Singh, A., Rajput, V., Minkina, T., El-Ramady, H., & Ghazaryan, K. (2024). Carbon sequestration through organic amendments, clay mineralogy and agronomic practices: A review. *Egyptian Journal of Soil Science*, 64(2), 581–598.