



AGRI MAGAZINE

(International E-Magazine for Agricultural Articles)

Volume: 03, Issue: 10 (October, 2026)

Available online at <http://www.agrimagazine.in>

©Agri Magazine, ISSN: 3048-8656

Carbon and Nitrogen Sequestration in Soils

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Rising atmospheric concentrations of carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) intensify climate change, highlighting the need for sustainable agricultural practices. Intensive tillage, residue burning, imbalanced fertilization and inefficient irrigation deplete soil organic carbon and increase nitrogen losses through leaching, volatilization, runoff and denitrification, degrading soil fertility, reducing nitrogen use efficiency and increasing greenhouse gas emissions. Carbon sequestration stabilizes organic carbon in soil, while nitrogen retention maintains nitrogen in soil, plant and microbial pools for crop uptake. These processes are interconnected through microbial activity, organic matter decomposition and the carbon-to-nitrogen (C) ratio. Practices such as residue retention, cover cropping, crop rotation, reduced tillage, organic amendments, balanced fertilization, erosion control and efficient water management can improve both processes. Their effectiveness depends on soil type, climate, cropping system and management history. This review examines the mechanisms, integrated management practices and field evidence for enhancing soil carbon storage, nitrogen use efficiency, soil health and climate change mitigation while minimizing environmental losses. Integrated carbon and nitrogen management enhances soil organic carbon, minimizes nutrient losses, improves nitrogen use efficiency and reduces greenhouse gas emissions, promoting productive, climate-resilient and sustainable agriculture.

Keywords: soil organic carbon, nitrogen retention, nutrient cycling, carbon sequestration, integrated soil fertility management

Introduction

Soils are living systems that regulate nutrient cycling, water storage, plant productivity and exchanges of greenhouse gases with the atmosphere. Soil organic matter contributes to aggregation, infiltration, cation exchange capacity and biological activity, while nitrogen is an essential component of proteins, enzymes, chlorophyll and nucleic acids. Depletion of soil organic matter and inefficient nitrogen use can reduce yields and increase pollution. Conversely, practices that build soil organic carbon (SOC) and retain nitrogen can improve resilience and contribute to climate-change mitigation (Paustian et al., 2016). Carbon and nitrogen management should not be treated as separate tasks. Carbon-rich residues provide energy for soil organisms, while nitrogen is needed to build microbial biomass and decompose organic materials. Nitrogen availability can influence how much plant carbon is converted into persistent soil organic matter. At the same time, carbon-rich amendments can temporarily immobilize mineral nitrogen, and excessive nitrogen inputs may increase nitrate leaching or nitrous oxide emissions. Integrated management balances these interactions rather than maximizing either element in isolation.

Key Concepts and Processes

Soil carbon sequestration

Soil carbon sequestration is the net increase in soil carbon stocks over time, usually measured to a defined soil depth and accounting for changes in bulk density. Plants capture atmospheric

carbon dioxide through photosynthesis and transfer a portion below ground through roots, root turnover, exudates and crop residues. Microorganisms transform these materials into microbial products and soil organic matter. Some carbon is rapidly decomposed and returned to the atmosphere as CO₂, while another fraction becomes associated with minerals or is physically protected within soil aggregates. These forms can persist longer, although no soil carbon pool is permanently immune to disturbance (Kavya et al., 2023). The amount of carbon stored depends on carbon inputs, decomposition rates, soil texture and mineralogy, moisture, temperature, vegetation and management. Sequestration is therefore a change in stock not simply the presence of organic matter or the application of compost. Practices can raise carbon stocks where inputs increase or losses decline, but gains may slow as soils approach a new equilibrium. Repeated measurement and consistent sampling depth are important when assessing results.

Nitrogen retention and cycling

Nitrogen enters agricultural soils through biological nitrogen fixation, fertilizers, manure, compost, crop residues, irrigation water and atmospheric deposition. Plants take up nitrogen mainly as nitrate (NO₃⁻) and ammonium (NH₄⁺). Microorganisms convert organic nitrogen into ammonium through mineralization; ammonium may be taken up, retained on exchange sites or converted to nitrate by nitrification. Plants and microbes can also immobilize mineral nitrogen into organic forms. Nitrogen retention means keeping nitrogen in the root zone or in useful biological pools for later crop uptake. Nitrogen can be lost when nitrate moves below the root zone through leaching, when dissolved or particulate nitrogen leaves in runoff and erosion, when ammonia volatilizes from the soil or manure surface, or when denitrification produces N₂O and N₂ under oxygen-limited conditions. The size of each pathway depends on soil drainage, pH, temperature, rainfall, fertilizer placement and timing, crop demand and residue quality. Nitrogen-use efficiency improves when supply is synchronized with crop uptake and avoidable losses are reduced (Robertson & Vitousek, 2009).

Why carbon and nitrogen are linked:

The C:N ratio of plant residues affects decomposition and nitrogen availability. High-C:N residues may temporarily immobilize nitrogen, while nitrogen-rich materials generally release it faster. Soil organic matter stores carbon and nitrogen, while stable aggregates and mineral associations protect them from decomposition (Meng et al., 2022). Therefore, effective management must balance carbon inputs and nitrogen availability, as carbon addition alone does not ensure long-term sequestration or prevent nitrogen losses.

Practices for Carbon Sequestration

Retaining crop residues and adding organic matter

Leaving suitable crop residues on the soil surface, incorporating residues where appropriate, and applying well-managed farmyard manure or compost can increase carbon inputs. Residues also reduce raindrop impact, protect against erosion and help conserve moisture. Organic amendments should be applied according to nutrient content, crop needs and local regulations; poor-quality or contaminated materials can introduce weeds, pathogens or pollutants. Carbon benefits depend on the amount and stability of the material and on whether its use replaces or supplements other carbon inputs.

Cover crops, rotations and perennial phases

Cover crops maintain living roots during periods when the main crop is absent. Their roots and residues add carbon, reduce bare-soil periods, improve aggregation and limit erosion. Legumes can also add biologically fixed nitrogen, while grasses and other non-legumes are effective at scavenging residual nitrate. Diverse rotations and perennial forage phases can increase the duration and depth of root activity and spread risk across seasons. Species selection should reflect rainfall, growing-season length, water availability and the following crop's nutrient needs.

Reduced tillage, erosion control and agroforestry

Reduced or strategic tillage can limit disruption of soil aggregates and reduce erosion, especially when combined with residue cover and diverse rotations. Its effect on whole-

profile carbon stocks varies by soil and climate, so surface carbon concentration alone may give an incomplete picture. Contour farming, grass strips, terraces where suitable, windbreaks and maintaining ground cover reduce the movement of carbon-rich topsoil. Agroforestry and trees integrated with crops or livestock can add deep roots, litter and woody biomass, although competition for light and water must be managed.

Soil-test-based fertility and water management

Adequate nutrient supply, including nitrogen where needed, supports crop growth and the return of biomass to soil. Soil testing and balanced fertilization help avoid nutrient deficiencies and excessive applications. Irrigation and drainage should maintain conditions that support crop growth without causing prolonged waterlogging, unnecessary decomposition or enhanced nutrient movement. Carbon practices work best as a system rather than as isolated interventions (Paustian et al., 2016).

Practices for Nitrogen Retention

Match nitrogen supply to crop demand

Applying the right nitrogen source, rate, timing and placement is a core principle of efficient nitrogen management. Split applications can better match periods of rapid crop uptake and reduce the time mineral nitrogen remains vulnerable to loss. Band placement or incorporation may reduce ammonia volatilization in suitable systems. Fertilizer rates should account for soil tests, expected yield, previous legumes, manure inputs and residual nitrogen, rather than relying on a fixed rate for every field.

Biological nitrogen fixation and diversified rotations

Legumes form symbiotic relationships with nitrogen-fixing bacteria and can contribute new reactive nitrogen to farming systems. Including legumes in rotations, cover crops or forage phases can reduce dependence on synthetic fertilizer when their nitrogen contribution is properly credited. Legume residues release nitrogen as they decompose, but the timing may not match the next crop's demand (Drinkwater et al., 1998). Rotation planning and residue management are therefore needed to capture the benefit and avoid nitrate accumulation during fallow periods.

Azolla as a biological nitrogen source and organic input

Azolla is a small floating aquatic fern that forms a symbiotic association with the nitrogen-fixing cyanobacterium *Anabaena azollae*. It fixes atmospheric nitrogen and is widely used as green manure, particularly in flooded rice fields. After incorporation into the soil, Azolla decomposes and releases nitrogen for crop uptake, potentially reducing mineral fertilizer requirements. Azolla also adds organic carbon to the soil; however, its main benefit is nitrogen input rather than long-term carbon sequestration. Its effectiveness depends on biomass production, decomposition, and crop nitrogen demand. Therefore, Azolla should be integrated with fertilizer management and other carbon-building practices for sustainable soil carbon and nitrogen management.

Catch crops, buffers and erosion control

Non-legume catch crops can absorb nitrate remaining after harvest and temporarily store it in plant biomass. When that biomass decomposes, part of the captured nitrogen becomes available to later crops. Vegetated buffer strips, riparian zones and grassed waterways can slow runoff and trap sediment-bound nutrients. Maintaining soil cover and improving infiltration reduce erosion and the loss of organic nitrogen with topsoil. These measures are especially useful where intense rainfall or sloping land increases the risk of nutrient transport.

Manage manure, irrigation and soil conditions

Manure and compost should be analyzed or estimated for nutrient content and applied at rates that meet crop needs without exceeding soil and crop capacity. Prompt incorporation or appropriate application methods can reduce ammonia loss, while avoiding application before heavy rain reduces runoff and leaching risk. Irrigation scheduling should avoid overwatering and deep drainage. Soil pH correction, where indicated by testing, can improve crop and microbial functioning. In wet soils, improved drainage and careful nitrogen timing can reduce conditions that promote denitrification and N₂O production.

Integrated Management of Carbon and Nitrogen:

Integrated carbon and nitrogen management combines crop rotation, cover crops, residue retention, legumes, organic amendments and soil-test-based fertilization. These practices improve soil carbon storage and nitrogen retention while reducing erosion and nutrient losses. High-carbon residues may temporarily immobilize nitrogen, whereas excessive nitrogen application can increase nitrate leaching and greenhouse-gas emissions. Management should be adapted to soil texture, drainage, pH and climate, with balanced nutrient inputs to improve soil health and crop productivity (Khan, 2025).

Monitoring, Constraints and Future Directions:

Monitoring should include soil organic carbon stocks, pH, mineral nitrogen, crop yield, residue inputs and nutrient losses. Carbon measurements should use consistent sampling depths and account for bulk density. Nitrogen management can be assessed through nutrient budgets, crop nitrogen uptake, yield response and records of fertilizer and manure applications. Major constraints include the cost and availability of organic materials, competing uses of crop residues, limited soil-testing facilities, short-term yield concerns and uncertainty about long-term carbon gains. Climate change may further affect decomposition and nitrogen losses. Improved soil testing, farmer training, long-term field experiments and locally adapted recommendations are essential to evaluate integrated practices and improve carbon storage, nitrogen retention and crop productivity.

Conclusion

Soil carbon sequestration and nitrogen retention are connected processes that underpin soil fertility, climate regulation and sustainable crop production. Carbon sequestration depends on increasing plant-derived inputs and protecting a portion of that carbon from rapid decomposition, while nitrogen retention depends on keeping nitrogen in soil and biological pools and matching its availability to crop demand. Residue retention, cover crops, diversified rotations, legumes, reduced disturbance, organic amendments, balanced fertilizer use, erosion control and careful water management can contribute to both goals. The most effective approach is integrated, site-specific management that increases carbon and nitrogen inputs, improves retention and stabilization, and minimizes losses to water and the atmosphere.

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