Carbon and Nitrogen in Mitigating and Adapting Agriculture to Climate Change

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ABSTRACT

Carbon and nitrogen management plays a crucial role in mitigating and adapting agriculture to climate change. Agriculture contributes to greenhouse gas emissions through nitrous oxide emissions from nitrogen fertilizers, methane from livestock and rice cultivation and carbon dioxide from soil carbon losses and land-use changes. This paper highlights the importance of integrated carbon and nitrogen management in promoting climate-smart agriculture. Soil organic carbon improves soil structure, water-holding capacity, nutrient availability and biological activity, thereby enhancing soil health and resilience to climatic extremes. Practices such as conservation tillage, crop residue retention, cover cropping, diversified crop rotations, agroforestry, compost application and restoration of degraded soils contribute to carbon sequestration. Efficient nitrogen management through the 4R nutrient-stewardship approach, biological nitrogen fixation, legumes and enhanced-efficiency fertilizers reduces nutrient losses and nitrous oxide emissions. Integrating these practices with efficient water management, farmer awareness and supportive policies can enhance agricultural productivity, strengthen climate resilience and promote sustainable food security.

INTRODUCTION:

Agriculture serve as a foundation of human civilization is intricately linked to earth climate system. The shift in temperature patterns, rainfall distribution, the frequency of drought floods and other climatic extremes threatens crop productivity, soil health, resource-use efficiency and food security. In addition to being a statistic of climate change, agriculture also contributes a substantial amount of greenhouse gas (GHG) emissions as nitrous oxide (N_2O) is closely associated with agricultural nitrogen (N) cycling, particularly through inefficient fertilizer use, manure management and decomposition of crop residues. Methane (CH_4) is linked to cattle production and flooded rice systems, whereas carbon dioxide (CO_2) is emitted through land-use change, soil organic carbon losses, biomass decomposition and energy consumption. Thus, carbon (C) and N cycling lie at the heart of the relationship between agriculture and climate change. Carbon is the foundation of soil organic matter and is essential for soil structure, biological activity, water retention and long-term fertility. Nitrogen is an indispensable nutrient for plant proteins, chlorophyll, enzymes and grain production. However, excessive, poorly timed, or inefficient nitrogen use can cause nitrous oxide emissions, ammonia volatilization, nitrate leaching, water pollution and economic losses.

The challenge is therefore not simply to add more carbon or apply more nitrogen. It is to manage the two cycles together. Healthy soils need carbon-rich organic matter to sustain nutrient cycling, while adequate nitrogen helps crops produce the biomass that can return carbon to soil. In climate-smart agriculture, the goal is to increase productivity and resilience while lowering emissions per unit of food produced.

The Intergovernmental Panel on Climate Change identifies improved crop and livestock management, soil-carbon management, agroforestry and biochar as important agricultural mitigation options. Together, these measures could contribute an estimated 1.8-4.1 gigatonnes of carbon-dioxide equivalent emission reductions annually when implemented sustainably. Therefore, transforming agricultural systems toward climate-resilience is essential for sustaining food production while mitigating further climate change.

Carbon and climate-smart agriculture

Soil carbon and its functions

Soil organic carbon (SOC) is the carbon component of soil organic matter. It originates mainly from crop residues, roots, manure, compost, cover crops, trees and other biological materials. Soil organic matter is not merely stored carbon; it is a living and dynamic system that supports nutrient availability, soil organisms, aggregation, infiltration and root development.

Globally, soils represent the largest terrestrial store of carbon. When agricultural soils are degraded through erosion, intensive tillage, residue burning, overgrazing, drainage of organic soils, or conversion of forests and grasslands, much of this carbon is released to the atmosphere as carbon dioxide. Conversely, restoring degraded soils and adopting sustainable soil-management practices helps to rebuild soil carbon stocks while improving agricultural resilience.

Soil-carbon restoration is therefore both a mitigation and adaptation strategy. It removes some carbon dioxide from the atmosphere through plant photosynthesis and transfers part of that carbon into soil organic matter. At the

same time, it helps to cope with drought, irregular rainfall and soil degradation.

Carbon Sequestration for Mitigation

Carbon sequestration in agricultural soils occurs when carbon inputs exceed carbon losses over time. Plant roots, crop residues, compost, manure, cover crops and trees increase carbon inputs, while reduced tillage and erosion help conserve existing soil carbon.

Major carbon sequestration practices include:

- Conservation or reduced tillage
- Retention of crop residues instead of burning
- Cover cropping and diversified crop rotations
- Integration of legumes and perennial crops
- Application of compost, FYM and green manures
- Agroforestry and shelterbelts
- Improved pasture and grazing management
- Restoration of degraded lands and appropriate biochar application

Conservation agriculture, based on minimum soil disturbance, permanent soil cover and crop diversification, helps reduce erosion and protect soil organic matter. However, carbon sequestration varies with soil type, climate and management practices. Therefore, changes in soil carbon should be assessed across the farming system and at appropriate soil depths.

Agroforestry contributes to carbon storage in both aboveground biomass and soil. It also provides fodder, fuelwood, fruits and timber while reducing wind erosion and improving soil protection. Biochar, produced by heating biomass under limited oxygen, can store carbon in a relatively stable form and may improve nutrient retention and water availability, depending on soil conditions and production methods.

Carbon for Adaptation

Soil organic carbon improves soil structure, porosity and water infiltration. This helps reduce runoff and erosion during heavy rainfall and increases water retention during dry periods.

Higher soil organic carbon generally supports crop productivity and yield stability, although it cannot fully compensate for severe drought or inadequate water supply. Carbon-rich soils can also improve the effectiveness of other adaptation practices, including drought-tolerant varieties, rainwater harvesting, supplemental irrigation and efficient nutrient management.

Thus, soil carbon contributes to climate change mitigation by storing carbon and supports adaptation by improving soil health, water availability and the resilience of agricultural systems.

Nitrogen: Productivity and Emissions

Why Nitrogen Matters

Nitrogen is an essential nutrient required for the synthesis of amino acids, proteins, chlorophyll, nucleic acids and enzymes. Adequate nitrogen promotes plant growth, biomass production and crop yield. However, excessive or poorly managed nitrogen application can cause environmental pollution and greenhouse gas emissions.

Crops absorb only a portion of the nitrogen applied as fertilizer. The remaining nitrogen may be stored in soil organic matter, immobilized by microorganisms, leached as nitrate, lost as ammonia, or converted into gaseous forms such as nitrous oxide (N_2O) and

nitrogen gas. Nitrous oxide is a potent greenhouse gas and also contributes to ozone depletion. Agricultural soils are a major source of N_2O emissions, primarily due to synthetic fertilizers and manure application. Improved nitrogen management can substantially reduce these emissions while maintaining agricultural productivity.

Nitrogen Pathways in Soil

Nitrogen cycling is regulated by soil microorganisms, temperature, moisture, oxygen availability and agricultural management. The major processes include:

- Mineralization: Conversion of organic nitrogen into plant-available ammonium by soil microorganisms.
- Immobilization: Temporary incorporation of available nitrogen into microbial biomass during decomposition.
- Nitrification: Conversion of ammonium into nitrate under aerobic conditions, with possible N_2O production.
- Denitrification: Conversion of nitrate into gaseous forms, including N_2O and nitrogen gas, under oxygen-limited conditions.
- Volatilization: Loss of nitrogen as ammonia, particularly from surface-applied urea and manure.
- Leaching: Movement of nitrate below the root zone, potentially contaminating groundwater.

Climate change can intensify nitrogen losses. Heavy rainfall may increase nitrate leaching and denitrification, while waterlogging can promote N_2O emissions. Higher temperatures may accelerate nitrogen mineralization, whereas drought can reduce crop uptake and increase the risk of nitrogen loss when rainfall returns.

Nitrogen-Use Efficiency (NUE)

Nitrogen-use efficiency refers to the crop yield or nitrogen uptake achieved per unit of nitrogen supplied. Improving NUE helps maintain productivity while reducing fertilizer losses, production costs and greenhouse gas emissions.

The 4R nutrient-stewardship approach provides a practical framework for efficient nitrogen management:

Principle	Practical application	Main benefit
Right source	Select a suitable fertilizer or organic nutrient source	Matches nutrient supply to soil and crop requirements
Right rate	Apply nitrogen according to crop demand and yield targets	Prevents overapplication
Right time	Apply nitrogen when crop demand is high, using split applications where appropriate	Reduces exposure to leaching and gaseous losses
Right place	Place fertilizer near active roots or use suitable banding or incorporation methods	Improves uptake and reduces nutrient losses

Precision agriculture tools, including soil testing, crop sensors, remote sensing and weather forecasts, can further improve nitrogen management when adapted to local conditions.

Managing Carbon and Nitrogen Together

Carbon and nitrogen cycles are closely interconnected. Soil organic matter improves soil structure, microbial activity, nutrient retention and water-holding capacity. However, increasing soil carbon without

adequate nitrogen may restrict plant growth and organic matter formation. Similarly, excessive nitrogen application in degraded soils can increase nutrient losses.

Integrated soil fertility management combines organic inputs, mineral fertilizers, suitable crop varieties, crop rotations and soil and water conservation practices. Its objective is to use available nutrient sources efficiently rather than completely replacing mineral fertilizers. This approach supports crop productivity, improves soil health and reduces environmental losses.

Crop Residues, Compost and Manure

Returning crop residues to the soil recycles nutrients and increases organic carbon inputs. Compost and well-managed manure supply nutrients and organic matter while improving soil aggregation and microbial activity.

Organic inputs may not necessarily be ecologically sound, nevertheless poor manure management can release methane and nitrous oxide, while inappropriate application can cause runoff and nitrogen losses. Effective management includes appropriate manure storage, suitable application rates and avoiding application before heavy rainfall. Crop residues must also be allocated according to competing needs such as livestock feed, fuel and soil cover.

Legumes and Biological Nitrogen Fixation

Leguminous crops, including pulses, soybean, groundnut, clover and peas, form symbiotic associations with nitrogen-fixing bacteria. These bacteria convert atmospheric nitrogen into forms usable by plants, potentially reducing the need for synthetic nitrogen fertilizers.

Legumes also contribute nitrogen-rich residues, diversify cropping systems and may improve soil fertility and farm income. However, nitrogen fixation depends on factors such as soil pH, phosphorus availability, moisture, bacterial effectiveness and crop management. Proper timing of residue decomposition is important to synchronize nitrogen release with the requirements of the following crop.

Cover Crops and Diversified Crop Rotations

Cover crops protect the soil during fallow periods by reducing erosion, suppressing weed growth and capturing residual soil nitrate, thereby minimizing nitrogen leaching. Leguminous cover crops contribute biologically fixed nitrogen, whereas grass cover crops are particularly effective in scavenging residual soil nitrogen. Cover crop mixtures can combine these complementary functions, improving nutrient cycling and soil protection.

Diversified crop rotations involving cereals, legumes and oilseeds help balance nutrient demand, disrupt pest and disease cycles and maintain soil cover. They can also improve soil fertility, reduce dependence on individual crops and enhance the resilience of agricultural systems to climatic variability and market fluctuations.

Enhanced-Efficiency Fertilizers

Enhanced-efficiency fertilizers, such as controlled-release fertilizers, urease inhibitors and nitrification inhibitors reduce nitrogen losses under suitable conditions. Urease inhibitors reduce ammonia volatilization, while nitrification inhibitors slow ammonium conversion to nitrate, potentially reducing nitrate leaching and N_2O emissions.

Their effectiveness depends on soil properties, temperature, moisture, crop type and application method. Therefore, they should supplement rather than replace the adequate

water management, timing, location and fertilizer rates.

Pathways for Action

A climate-smart strategy for carbon and nitrogen management must be adapted to local soil, climatic and farming conditions. Practices suitable for high-rainfall rice systems may not be equally effective in semi-arid maize fields, irrigated vegetable production, or grazing-based livestock systems. Therefore, management decisions should consider local resource availability, crop requirements and the major sources of carbon and nitrogen losses.

Farm-Level Actions

Farmers can improve carbon storage and nitrogen-use efficiency through a series of practical and scientifically informed measures.

1. **Assess the field:** Soil testing helps determine pH, soil organic carbon, nutrient deficiencies, salinity risks and nitrogen requirements. This information provides a basis for selecting appropriate soil and nutrient management practices.

2. **Protect existing soil carbon:** Reducing unnecessary tillage, controlling erosion, avoiding crop-residue burning and maintaining adequate soil cover help conserve soil organic matter. Preventing the degradation of grasslands and organic soils is also important for reducing carbon losses.

3. **Increase organic matter inputs:** Crop rotations, cover crops, compost, farmyard manure, green manures, mulches, perennial vegetation and agroforestry can increase carbon inputs and improve soil biological activity. The selection of practices should depend on local conditions and the availability of organic resources.

4. **Improve nitrogen management:** Nitrogen application should be based on crop requirements, soil fertility and realistic yield targets. Split applications can improve crop uptake and reduce losses. Fertilizer application should be planned carefully to avoid periods of heavy rainfall, flooding, or conditions that increase the risk of nutrient loss.

5. **Integrate water and nutrient management:** Efficient irrigation scheduling, appropriate drainage, rainwater harvesting, mulching and maintaining soil cover influence nitrogen availability, crop uptake and greenhouse gas emissions. Coordinating water and fertilizer applications can improve resource-use efficiency.

6. **Diversify farming systems:** Incorporating legumes, fodder crops, trees and climate-resilient crop varieties can improve nutrient cycling, diversify farm production and reduce climatic and economic risks.

7. **Monitor outcomes:** Changes in crop yield, input costs, fertilizer-use efficiency, soil organic carbon and water use should be monitored over time. Field indicators such as infiltration rate, earthworm activity, soil structure surface run off and erosion help to assess improvements in soil health.

Policy and Institutional Support

The adoption of climate-smart soil management practices depends not only on farmers' decisions but also on access to financial resources, technical knowledge, machinery, quality seeds and reliable advisory services. Many practices require initial investment and additional labour, while uncertain land tenure and limited market access may discourage long-term investment in soil improvement.

- Governments, research institutions, agricultural extension services, financial organizations and private-sector agencies can support adoption through the following measures:
- Providing affordable soil testing and site-specific nutrient advisory services.
- Strengthening extension training in integrated soil fertility and nutrient management.
- Improving access to legume seeds, microbial inoculants, composting facilities and cover-crop seeds.
- Providing timely weather forecasts and climate information tailored to farmers' needs.
- Offering incentives for erosion control, agroforestry and the restoration of degraded soils.
- Supporting research on enhanced-efficiency fertilizers suitable for local soil and climatic conditions.
- Developing reliable, affordable and transparent soil-carbon monitoring systems.
- Promoting policies that discourage crop-residue burning and inefficient fertilizer use.
- Improving access to credit, crop insurance and markets for farmers adopting diversified and sustainable production systems.

Soil-carbon markets may provide additional financial incentives for farmers who increase carbon storage through improved land management. However, these schemes require careful implementation because changes in soil carbon are difficult to measure accurately, sequestration rates vary among soils and stored carbon may be lost if management practices change. Monitoring and verification costs should not place a disproportionate burden on farmers. Carbon-finance programmes should therefore reward genuine improvements in soil health and rural livelihoods while safeguarding food security, biodiversity and water quality.

CONCLUSION

Carbon and nitrogen management is essential for climate-resilient agriculture. Soil organic carbon improves soil structure, water retention, nutrient availability and biological activity, while efficient nitrogen management supports crop productivity and reduces nitrous oxide emissions and nutrient losses.

An integrated approach combining organic matter management, crop diversification, legumes, balanced fertilizer application and efficient water management can reduce emissions while maintaining agricultural productivity. Although soil management cannot replace reductions in fossil-fuel emissions, it plays an important role in climate change mitigation and adaptation by improving soil health, food security and the long-term sustainability of farming systems.

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