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Carbon Sequestration Potential of Agroforestry Systems: A Tool for Climate Change Mitigation

*Savitha Shivannanavar, Venkatesh L and Krishna K S
Department of Silviculture and Agroforestry, College of Forestry, Sirsi-581401
*Corresponding Author's email: venkatesh@usad.in

Climate change is one of the major environmental challenges facing agriculture, forestry and rural livelihoods. Agroforestry, which involves the deliberate integration of trees with crops and/or livestock, provides an important nature-based approach for both climate-change mitigation and adaptation. Trees in agroforestry systems capture atmospheric carbon dioxide through photosynthesis and store carbon in above-ground biomass, roots, soil and long-lasting wood products. Compared with conventional agricultural systems, agroforestry can increase carbon storage while simultaneously providing food, fuelwood, fodder, timber and other ecosystem services. A 2023 meta-analysis of Indian agroforestry systems found that conversion to agroforestry was associated with about 25.34% higher carbon sequestration than non-agroforestry systems, while agrihorticultural systems had a mean soil carbon stock of 38.11 Mg C ha^{-1}. Agroforestry therefore has considerable potential to contribute to climate mitigation while improving farm productivity and resilience.

Keywords: Agroforestry, carbon sequestration, climate change, carbon stock, soil organic carbon, biomass, sustainable agriculture

Introduction

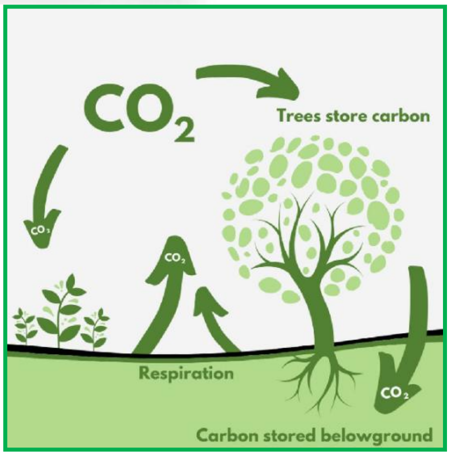
The increasing concentration of greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere is a major driver of global climate change. Agriculture contributes to greenhouse-gas emissions, but agricultural landscapes can also become important carbon sinks when trees are incorporated into farming systems. Agroforestry provides a way of combining agricultural production with tree-based carbon storage. Trees capture atmospheric CO_2 and convert it into organic carbon through photosynthesis. Part of this carbon is stored in trunks, branches, leaves and roots, while some enters the soil through litter, root turnover and decomposition. The Food and Agriculture Organization (FAO) recognizes agroforestry as a strategy for both climate-change mitigation and adaptation. Trees on agricultural land can sequester carbon, improve soil conditions and provide additional products and income to farmers.

Concept of Carbon Sequestration

Carbon sequestration is the process of capturing atmospheric carbon dioxide and storing the carbon in vegetation, soils, oceans or geological formations.

In agroforestry, the major carbon pools are:

- Above-ground tree biomass
- Below-ground root biomass
- Soil organic carbon
- Crop biomass
- Deadwood and litter
- Harvested wood products



The simplified process can be represented as:
Atmospheric CO_2 → Photosynthesis → Plant biomass → Litter/root inputs → Soil organic carbon
Thus, agroforestry transfers carbon from the atmosphere into biological and soil carbon pools.

How Agroforestry Sequesters Carbon

Above-ground biomass

Trees store substantial quantities of carbon in their:

- Trunks
- Branches
- Leaves
- Bark

As trees increase in diameter and height, their biomass and carbon stock generally increase.

Below-ground biomass

Tree roots store carbon below the soil surface. Fine-root turnover also adds organic matter to the soil.

Soil carbon sequestration

Leaves, roots and other organic materials decompose and contribute carbon to the soil. Agroforestry can therefore increase soil organic carbon compared with some conventional agricultural systems.

Carbon in harvested products

Timber, poles and other durable wood products can continue storing carbon after harvesting, provided the carbon remains in long-lived products.

Major Agroforestry Systems and Carbon Storage

Different agroforestry systems have different carbon-sequestration capacities. Agroforestry system Components Major carbon pools.

- Agrisilviculture -Trees + crops
- Silvopasture -Trees + pasture + livestock
- Agrihorticulture -Fruit trees + crops
- Agrosilvopasture -Trees + crops + livestock
- Home gardens -Trees + vegetables/crops
- Boundary plantations-Trees around agricultural fields
- Alley cropping -Trees/shrubs + crops
- Coffee/cocoa agroforestry
- Perennial crops + shade trees
- Tree biomass + soil

Carbon-Sequestration Potential

Carbon sequestration varies considerably with tree species, age, climate, soil, rainfall, management and previous land use. An Indian meta-analysis reported that conversion to agroforestry resulted in 25.34% greater carbon sequestration compared with non-agroforestry systems. The study reported the highest mean soil carbon stock in agrihorticulture, at 38.11 Mg C ha^{-1}. An earlier ICAR review reported carbon sequestration potentials in Indian agroforestry systems ranging from 0.25–76.55 Mg C ha^{-1} yr^{-1} for tree components, 0.01–0.60 Mg C ha^{-1} yr^{-1} for crop components, and 0.003–3.98 Mg C ha^{-1} yr^{-1} for soil carbon sequestration, demonstrating the large variation among systems and locations. Globally, the IPCC has estimated the technical mitigation potential of agroforestry to be substantial, although estimates vary depending on assumptions about the area converted, system type and carbon accumulation rates.

Factors Affecting Carbon Sequestration

- Tree species: Fast-growing and long-lived trees can accumulate considerable biomass.

- Tree age: Older trees generally contain more carbon, although sequestration rates can vary with age.
- Tree density: Higher density may increase total tree carbon but can create competition with crops.
- Climate: Rainfall and temperature influence tree growth and soil carbon accumulation.
- Soil characteristics: Soil texture, organic matter and fertility influence carbon storage.
- Management practices: Pruning, harvesting, irrigation and fertilization affect carbon stocks.
- Previous land use: Carbon gains after conversion to agroforestry depend strongly on what was present before.
- System design: Agrisilviculture, silvopasture and agrihorticulture may have different carbon-storage patterns.
- The Indian meta-analysis identified previous land use, agroforestry system type, tree age and rainfall as important factors controlling soil carbon sequestration.

Role in Climate Change Mitigation

Agroforestry contributes to climate mitigation through several pathways:
Direct benefits:

- Removes CO_2 from the atmosphere.
- Stores carbon in tree biomass.
- Increases soil organic carbon.
- Reduces soil erosion and associated carbon losses.
- Indirect benefits
- Provides fuelwood and timber from farms, potentially reducing pressure on natural forests.
- Produces fodder and other biomass.
- Can reduce dependence on external agricultural inputs in some systems.
- Improves soil fertility and resource-use efficiency.

FAO notes that on-farm wood production can reduce the need to harvest trees elsewhere, while improved nutrient management can also reduce some agricultural greenhouse-gas emissions.

Role in Climate Change Adaptation

Agroforestry is not limited to carbon sequestration. It can also make agricultural systems more resilient to climate variability.
Trees can:

- Provide shade to crops and livestock.
- Reduce wind speed.
- Moderate field temperature.
- Improve soil moisture conditions.
- Reduce soil erosion.
- Provide additional products during crop failure.
- Improve biodiversity and habitat.
- Support farmer income diversification.
- FAO describes agroforestry systems as relatively diverse systems that can help farmers cope with droughts, floods, storms and other environmental stresses.

Measurement of Carbon Stocks

Carbon estimation is important for evaluating the effectiveness of agroforestry as a climate-mitigation strategy.
Common measurements

- Tree biomass
- Diameter at breast height (DBH)

- Tree height
- Number of trees
- Wood density
- Allometric equations can then be used to estimate tree biomass and carbon stocks. DBH is particularly useful because it is relatively easy to measure in field inventories.
- Soil carbon
- Soil samples are collected at different depths.
- Soil organic carbon concentration is determined in the laboratory.
- Carbon stock is calculated using soil bulk density, carbon concentration and soil depth.

Benefits of Agroforestry

Apart from carbon sequestration, agroforestry provides multiple benefits:

- Food production
- Fuelwood production
- Fodder production
- Timber and poles
- Fruit production
- Soil conservation
- Water conservation
- Biodiversity conservation
- Income diversification
- Microclimate regulation
- Improved soil organic matter
- Climate-change adaptation

Thus, agroforestry can provide both environmental and economic benefits.

Limitations and Challenges

- Despite its potential, several challenges need attention:
- Competition between trees and crops for water, nutrients and light
- Long time required for trees to accumulate substantial biomass
- Difficulty in accurately measuring total carbon stocks
- Variation in carbon sequestration between sites and species
- Risk of reduced crop yield if the system is poorly designed
- Lack of technical knowledge among farmers
- Limited access to quality planting material
- Land-tenure constraints
- Uncertainty regarding carbon-market benefits

Importantly, agroforestry should complement rather than replace natural forests. The Indian meta-analysis found that conversion from forest to agroforestry could reduce soil carbon sequestration, emphasizing that agroforestry is particularly valuable on appropriate agricultural and degraded lands rather than as a substitute for conserving natural forests.

Future Prospects

The future of agroforestry-based carbon sequestration depends on:

- Selection of suitable tree–crop combinations
- Development of climate-resilient agroforestry models
- Improved carbon measurement techniques
- Remote sensing and GIS-based carbon monitoring
- Development of reliable carbon-credit systems
- Farmer incentives and financial support
- Better extension services
- Long-term field experiments

- Integration of agroforestry into climate policies

Conclusion

Agroforestry is a promising land-management strategy for addressing climate change because it combines carbon sequestration, agricultural production and ecosystem conservation. Trees incorporated into agricultural landscapes store carbon in above-ground and below-ground biomass, while litter and root inputs can increase soil organic carbon. Evidence from India shows that well-designed agroforestry systems can have substantially greater carbon sequestration than comparable non-agroforestry systems. However, carbon sequestration varies with tree species, system design, climate, soil, tree age and management. Therefore, site-specific agroforestry models, appropriate incentives and accurate carbon monitoring are essential. When implemented on suitable agricultural and degraded lands while protecting natural forests, agroforestry can become an important component of climate-change mitigation, adaptation and sustainable rural development.

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