Carbon Sequestration Potential of Agroforestry-Based Cropping Systems under Semi-Arid Environments

Wei Chen Zhang [1*], Li Ming Zhao [2]

[1] Institute of Agroforestry and Sustainable Agriculture, Chinese Academy of Agricultural Sciences, China
[2] College of Environmental and Resource Sciences, Zhejiang University, China

*Corresponding author: **Wei Chen Zhang**

Received: 07 May 2025
Revised: 22 May 2025
Accepted: 12 Jun 2025
Published: 02 Jul 2025

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2025.5.2.01-07

ABSTRACT
Climate change, accelerated land degradation, and desertification pose severe threats to agricultural sustainability, ecological balance, and rural livelihoods in semi-arid environments. The escalation of atmospheric carbon dioxide concentrations highlights an urgent need for sustainable land-management interventions that enhance terrestrial carbon sinks. Agroforestry-based cropping systems offer a scientifically validated approach to combine climate change mitigation with resilient agricultural production. This comprehensive paper analyzes the carbon sequestration potential of various agroforestry configurations—including Agri silvicultural, clavipectoral, and hortisilvicultural systems—operating within fragile, moisture-stressed semi-arid regions. By evaluating aboveground woody biomass accumulation and belowground soil organic carbon (SOC) dynamics down to deep profiles, this study details how perennial-annual combinations optimize carbon stabilization.
Empirical synthesis indicates that commercial and indigenous agroforestry interventions in semi-arid regions can sequester substantial volumes of carbon, with vegetation stocks ranging from 15 to over 200 Mg C per hectare depending on system maturity and species density, alongside vertical soil carbon enrichment. Beyond ecological restoration, these systems improve moisture retention, enhance water-use efficiency, and optimize the carbon sustainability index of marginal lands. This paper outlines structural classifications, biomass allocation patterns, experimental carbon pools, technological barriers, and market-driven policy frameworks required to scale agroforestry as a core pillar of global carbon farming initiatives.

Keywords: Agroforestry Systems, Carbon Sequestration, Semi-Arid Environments, Soil Organic Carbon, Climate Change Mitigation, Land Degradation, Carbon Farming, Biomass Accumulation, Ecosystem Restoration, Sustainable Land Management

1. Introduction
Global climate change represents one of the most pressing ecological and macroeconomic crises of the modern era. Anthropogenic greenhouse gas emissions, primarily driven by fossil fuel combustion, industrialization, and disruptive land-use practices, have elevated atmospheric carbon dioxide concentrations to unprecedented thresholds. This rapid atmospheric enrichment drives extreme weather events, shifts precipitation baselines, and accelerates land degradation globally. Among the most vulnerable landscapes are semi-arid environments, which are characterized by chronic moisture deficits, high potential evapotranspiration, low inherent soil fertility, and recurrent droughts. In these fragile ecosystems, conventional monoculture agriculture often exacerbates topsoil erosion, depletes soil organic matter, and triggers a progressive loss of terrestrial carbon pools into the atmosphere (Lal, 2004) [18].
To counteract this ecological decline, stabilizing global thermal baselines requires a dual approach: minimizing active emissions and aggressively expanding terrestrial carbon sinks. While traditional afforestation and reforestation are valuable, they frequently compete with food security initiatives for arable land. Consequently, the integration of perennial woody vegetation with annual food crops or livestock on the same management unit—collectively termed agroforestry—has emerged as an ecologically sound strategy. Agroforestry systems capture atmospheric carbon within their multi-tier vegetative structures and facilitate long-term organic carbon stabilization within the soil matrix (Nair *et al*., 2010) [5].
In semi-arid zones, where the biophysical environment severely restricts dense forest formation, agroforestry-based cropping systems function as managed carbon oases. These setups exploit the complementary ecological niches of deep-rooted perennial trees and shallow-rooted seasonal crops to maximize solar radiation capture, regulate microclimates, and optimize nutrient cycling (Dhyani, 2014) [2] (Rathore *et al*., 2022) [3]. This research paper evaluates the carbon sequestration dynamics of agroforestry systems in semi-arid environments.

It examines the mechanisms of aboveground and belowground carbon accumulation, details structural variations across distinct agroforestry typologies, synthesizes empirical datasets via comprehensive cross-comparisons, and reviews the policy frameworks necessary to integrate smallholder farming communities into the global carbon economy (Nair *et al*., 2010) [5] (Kuyah *et al*., 2019) [21].

2. Characterization of Semi-Arid Environments and Ecosystem Degradation

Semi-arid regions occupy more than one-third of the earth's total land surface and house a significant portion of the global agrarian population. These environments are primarily defined by highly variable annual rainfall (typically ranging between 300 mm and 800 mm), uneven seasonal distribution, and high temperatures that drive elevated evaporative demands. The prevailing soils, such as Aridisols, Alfisols, and Inceptisols, are inherently restricted by low clay content, poor structural stability, and minimal baseline organic matter content, often falling below a fraction of a percent in the surface layers (Rathore *et al*., 2022) [3].

Conventional intensive agriculture in these areas relies heavily on excessive tillage and monocropping, which disrupts fragile soil aggregates. Exposed to high solar radiation, the rate of soil organic matter decomposition accelerates, leading to structural collapse, reduced infiltration, and severe wind and water erosion. This feedback loop reduces crop yields and depletes the terrestrial carbon pool (Lorenz and Lal, 2014) [4].

When a natural ecosystem or long-term fallow is converted into conventional cropland, the soil organic carbon (SOC) pool can drop significantly within the first few decades. Restoring these depleted stocks is essential for mitigating atmospheric carbon loads and revitalizing the physical, chemical, and biological functionalities of the soil. Agroforestry addresses this degradation by reintroducing structural complexity. Tree root systems anchor vulnerable topsoil, while the perennial canopy reduces the kinetic energy of rainfall, minimizing splash erosion and improving moisture retention (Nair *et al*., 2010) [5].

3. Agroforestry System Configurations in Semi-Arid Zones

The architecture of agroforestry systems in semi-arid environments must be selected to minimize biophysical competition for scarce water and nutrient resources while maximizing economic and ecological output. These configurations are broadly categorized into three major functional frameworks:

3.1. Agrisilvicultural Systems

Agrisilvicultural configurations combine agricultural field crops with deliberately spaced woody perennials. In semi-arid zones, this layout typically utilizes alley cropping or dispersed block plantations. Fast-growing, high-biomass species like Populus deltoides (poplar) and Eucalyptus species are often deployed alongside indigenous, drought-hardy species such as Prosopis cineraria, Ailanthus excelsa, and Melia dubia (Chavan *et al*., 2023) [1]. Annual field crops, including pearl millet, sorghum, mustard, and various short-duration legumes, are cultivated within the interspaces. As the tree canopy expands, shade-tolerant or early-maturing under-tree intercrops are introduced to maintain steady food production while the woody component accumulates biomass.

3.2. Silvopastoral Systems

Silvopastoral configurations integrate trees with forage crops and livestock grazing. This approach is highly effective for marginal and highly degraded semi-arid lands where crop cultivation is unviable. Perennial nitrogen-fixing trees such as Leucaena leucocephala (subabul), Acacia nilotica, and Faidherbia albida are paired with resilient pasture grasses like Cenchrus ciliaris or Stylosanthes species (Tonucci *et al*., 2023) [7]. This structural arrangement generates fodder during dry lean seasons, prevents overgrazing through rotational paddock management, and incorporates livestock manure into the nutrient cycle, accelerating belowground carbon accumulation.

3.3. Hortisilvicultural and Horti-Agrisilvicultural Systems

Hortisilvicultural structures incorporate fruit-bearing perennial trees (Mangifera indica, Ziziphus mauritiana, Citrus spp.) with timber or fuel-wood species and annual crops. This multi-tier system provides early financial returns through fruit harvesting while building a stable, long-term woody biomass sink (Ram Newaj *et al*., 2021) [8]. Integrating short-duration leguminous or oilseed crops within the alley zones creates a complex, multi-strata production model that stabilizes seasonal farm income and enhances total ecosystem carbon storage.

The following table details the typical structural attributes and tree densities maintained across these primary agroforestry typologies in semi-arid landscapes.

Table 1: Structural Characteristics and Tree Density of Common Agroforestry Systems in Semi-Arid Zones

Agroforestry System Typology	Representative Perennial Species Included	Target Annual Intercrops / Forage	Typical Tree Density (Trees per Hectare)	Primary Spatial Spatial Orientation
Agrisilvicultural (Commercial)	*Eucalyptus tereticornis, Populus deltoides*	Wheat, Mustard, Sugarcane	400 – 600	Boundary rows or tight linear alleys
Agrisilvicultural (Indigenous)	*Prosopis cineraria, Ailanthus excelsa*	Pearl Millet, Cluster Bean, Chickpea	100 – 250	Dispersed parkland or wide alleys
Silvopastoral	*Acacia tortilis, Leucaena leucocephala*	*Cenchrus ciliaris, Stylosanthes hamata*	300 – 500	Block plantations or rotational paddocks
Hortisilvicultural	*Mangifera indica, Citrus sinensis*	Green Gram, Cowpea, Groundnut	150 – 300	Structured matrix with regular spacing
Horti-Agrisilvicultural	*Ziziphus mauritiana, Melia dubia*	Black Gram, Barley, Sesame	200 – 400	Alternating fruit and timber rows
Boundary/Block Forestry	*Casuarina equisetifolia, Azadirachta indica*	Diverse seasonal field crops	800 – 1200	Dense perimeter shelterbelts or blocks

4. Biomass Accumulation and Aboveground Carbon Pools

The aboveground carbon pool of an agroforestry system is primarily determined by the capacity of its woody perennials to fix atmospheric carbon into permanent structural components, including the bole, branches, and foliage. In semi-arid regions, biomass accumulation rates vary based on genetic constraints, moisture availability, soil depth, and management interventions like pruning or thinning (Jose and Bardhan, 2012) [9].

Commercial fast-growing species exhibit high biomass accumulation rates when supplied with targeted irrigation or localized water harvesting. Data from the Indo-Gangetic plains and adjacent semi-arid fringes indicate that Eucalyptus and Populus systems can achieve substantial standing biomass within short rotation cycles (typically 6 to 8 years) (Gupta *et al*., 2013) [10] (Chavan *et al*., 2023) [1]. Conversely, indigenous species like Prosopis cineraria accumulate biomass more slowly but demonstrate superior survival rates, higher wood density, and sustained carbon retention under severe drought stress (Marone *et al*., 2017) [11].

To quantify these pools, researchers use non-destructive allometric equations derived from tree height and diameter at breast height (DBH) measurements, converting total calculated dry biomass to carbon equivalence using a standard mass fraction (typically around 45% to 50%) (Nair *et al*., 2010) [5]. The table below presents synthesized empirical data regarding biomass partition dynamics and associated aboveground carbon pools for key semi-arid perennial systems.

Table 2: Aboveground and Belowground Biomass Allocation in Perennial Components

Perennial Tree Species	Mean DBH at Maturity (cm)	Aboveground Biomass (Mg Dry Matter per Hectare)	Belowground Biomass (Mg Dry Matter per Hectare)	Total Carbon Stock Equivalents (Mg C per Hectare)	Net Carbon Sequestration Rate (Mg C per Hectare per Year)
Eucalyptus tereticornis	24.5	165.2	41.3	92.9	11.6
Populus deltoides	28.2	148.0	34.0	81.9	10.2
Melia dubia	22.1	110.5	26.5	61.6	8.8
Prosopis cineraria	18.7	55.4	22.2	34.9	2.9
Ailanthus excelsa	20.4	78.1	18.7	43.6	4.8
Leucaena leucocephala	15.3	64.2	19.3	37.6	5.4

5. Belowground Carbon Sequestration and Soil Organic Carbon (SOC) Dynamics

While aboveground biomass provides a visible, high-capacity carbon sink, it remains vulnerable to short-term disturbances such as logging, fires, or pest outbreaks. Consequently, the belowground carbon pool—comprising root biomass and the soil organic carbon (SOC) matrix—is critical for long-term ecological stabilization (Feliciano *et al*., 2018) [13].

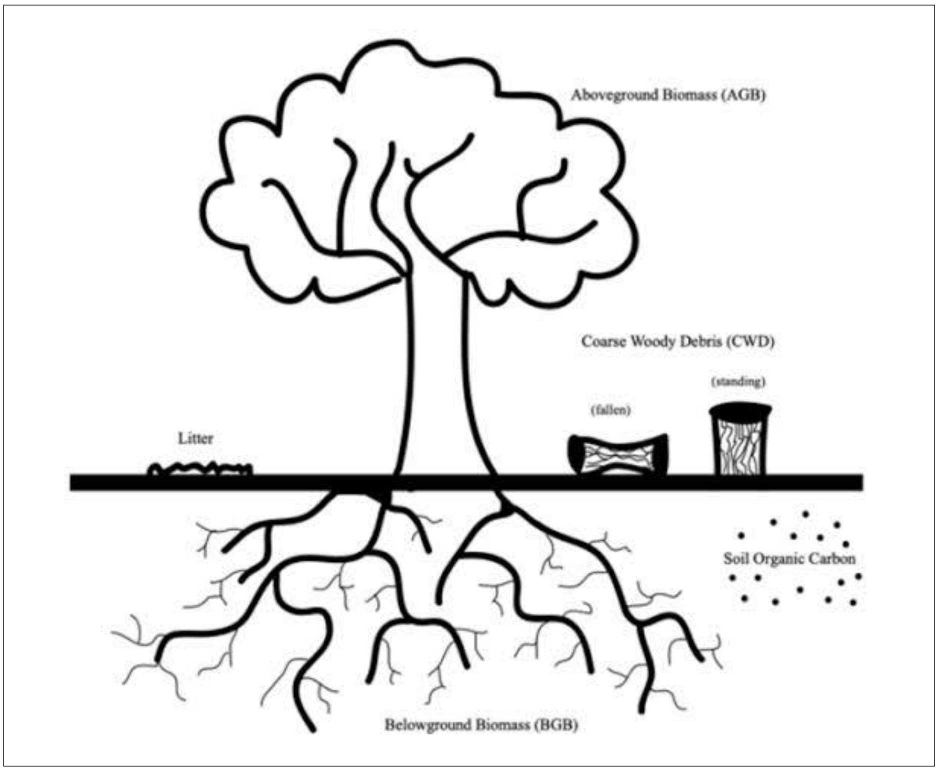

Fig 1: Structural Allocation of Terrestrial Carbon Pools.

As illustrated in the structural diagram above, terrestrial carbon sequestration operates across several coupled pools. In semi-arid agroforestry setups, these distinct segments interact continuously. Atmospheric carbon fixed in the Aboveground Biomass (AGB) eventually enters the soil via litterfall and coarse woody debris, while the deep architecture of the Belowground Biomass (BGB) directly injects organic carbon into deeper soil profiles through root turnover and rhizodeposition. This multi-pool distribution enhances total ecosystem carbon retention compared to shallow-rooted annual monocultures (Sharrow and Ismail, 2004) [14].

5.1. Mechanisms of Soil Carbon Enrichment

Agroforestry systems transfer carbon into the soil through several primary path mechanisms:

- **Litterfall Decomposition:** The seasonal shed of leaves, twigs, and reproductive structures forms a protective organic mulch layer on the soil surface. Soil macro- and micro-fauna progressively decompose this material, humifying organic complexes and incorporating them into the upper mineral horizons (Nair *et al*., 2010) [5].
- **Root Turnover and Exudation:** Roots continuously shed fine roots and release low-molecular-weight organic compounds (carbohydrates, amino acids, phenolics) into the rhizosphere. This root exudation provides an active energy source for microbial communities, driving the formation of stable microbial-derived organic matter (Lorenz and Lal, 2014) [4].
- **Microclimate Modification:** Tree canopies shield the soil surface from extreme solar radiation, lowering soil temperatures. In semi-arid regions, this thermal regulation reduces the baseline rate of microbial heterotrophic respiration, slowing the oxidation of stored organic carbon back into gaseous (Lorenz and Lal, 2014) [4].

5.2. Deep-Profile Carbon Saturation and Stabilization

A key advantage of agroforestry over conventional annual cropping is its capacity to store carbon in deeper soil horizons. Annual crop roots rarely penetrate beyond 30 cm, leaving subsoil layers carbon-undersaturated. In contrast, deep-rooted agroforestry trees modify the physical and chemical conditions of the subsoil down to depths exceeding 100 cm (Babu *et al*., 2022) [30].

At these lower depths, lower oxygen availability and reduced microbial activity slow down decomposition rates. Consequently, carbon transferred to deeper profiles via deep root turnover remains sequestered for longer periods. This deep-profile carbon allocation is detailed in the empirical soil profile dataset below.

Table 3: Soil Organic Carbon (SOC) Stocks across Different Soil Layers (0-100 cm)

Agroforestry Design Profile	SOC Stock at 0-20 cm (Mg C per Hectare)	SOC Stock at 22-40 cm (Mg C per Hectare)	SOC Stock at 41-60 cm (Mg C per Hectare)	SOC Stock at 61-100 cm (Mg C per Hectare)	Cumulative SOC Stock (0-100 cm) (Mg C per Hectare)
Pure Crop Monoculture	12.4	8.1	5.2	4.1	29.8
Poplar + Wheat System	28.5	19.4	14.8	11.2	73.9
Eucalyptus Alleys	31.2	22.1	16.3	12.9	82.5
Prosopis Parkland	22.4	17.8	13.5	10.8	64.5
Silvopastoral Matrix	26.8	18.9	12.1	9.4	67.2
Hortisilvicultural Orchard	24.1	16.3	11.4	8.7	60.5

6. Comparative Assessment of Cropping Systems

The carbon sequestration efficiency of an agroforestry system depends on the structural synergy between its perennial and annual components. Selecting incompatible components can create intense competition for moisture and nutrients, reducing overall system biomass accumulation and carbon capture (Murthy *et al*., 2013) [19].

In semi-arid regions, combining short-duration leguminous crops (such as mung bean, cluster bean, or chickpea) with deep-rooted perennials often creates positive ecological interactions. Legumes fix atmospheric nitrogen, satisfying a portion of the tree component's nutrient demands, while the shade provided by the tree canopy reduces moisture stress for the understory crops during peak thermal periods (Nair *et al*., 2010) [5] (Dhyani, 2014) [2].

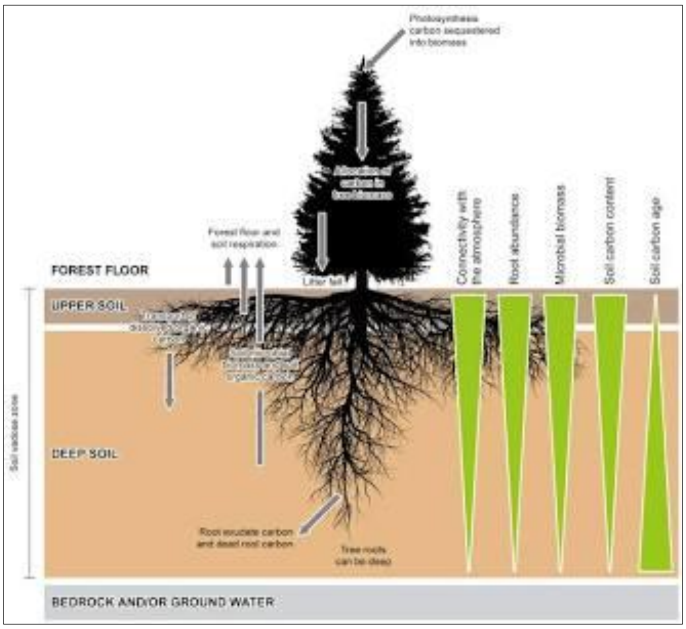

Fig 2: Mechanisms of Vertical Carbon Distribution and Subsoil Stabilization

As shown in the scientific schematic above, the input of root exudates, dead roots, and dissolved organic carbon flows downward through the soil profile. This process creates a vertical gradient where upper soil zones exhibit higher microbial biomass and active carbon cycling, while deeper subsoil layers facilitate long-term carbon age retention due to stable mineral interactions.

To evaluate these system dynamics, the following tables detail net sequestration performance, annual litterfall contributions, and overall carbon sustainability metrics across various land-use designs.

Table 4: Carbon Sequestration Rates of Selected Agroforestry-Based Cropping Systems

Evaluated System Framework	Total Vegetation Carbon (Mg C per Hectare)	Base Soil Carbon Pool (Mg C per Hectare)	Net System Carbon Stock (Mg C per Hectare)	Mean Sequestration Rate (Mg C per Hectare per Year)
Poplar + Rice-Wheat	84.5	72.1	156.6	3.45
Eucalyptus + Mustard	96.2	78.4	174.6	3.92
Melia Dubia + Groundnut	63.1	58.9	122.0	2.85
Prosopis + Pearl Millet	36.4	62.3	98.7	1.15
Ailanthus + Cluster Bean	44.8	54.2	99.0	1.62
Citrus + Mung Bean Orchard	28.9	51.6	80.5	1.40

Table 5: System Dynamics: Litterfall Contribution and Carbon Input to Soil

Agroforestry System Design	Annual Total Litterfall (Mg per Hectare per Year)	Carbon Content in Litter (%)	Annual Direct Organic C Input (Mg C per Hectare per Year)	Fine Root Turnover Mass (Mg per Hectare per Year)	Total Annual Belowground Carbon Flux
Poplar Alleys	4.85	44.2	2.14	1.85	3.05
Eucalyptus Boundary	3.90	46.1	1.80	1.42	2.51
Melia Dubia Rows	4.20	43.5	1.83	1.60	2.65
Prosopis Parkland	2.65	45.0	1.19	1.10	1.74
Ailanthus Intercrop	3.10	42.8	1.33	1.25	1.96
Silvopastoral Grassland	5.12	41.5	2.12	2.90	3.85

Table 6: Carbon Sustainability Indices and Water-Use Efficiency for Selected Systems

System Code Designation	Carbon Pool Index Value	Carbon Management Index	Carbon Sustainability Index	System Water-Use Efficiency (kg/ha-mm)	Runoff Mitigation Potential (%)
AF-Poplar-01	1.65	145.2	24.6	28.5	42.5
AF-Euc-02	1.82	158.4	26.1	31.2	48.0
AF-Melia-03	1.48	122.6	21.3	26.4	38.5
AF-Prosop-04	1.35	115.1	25.8	34.6	55.0
AF-Ailanth-05	1.42	119.8	22.4	29.1	44.2
HF-Phalsa-06	1.28	108.5	27.6	33.0	52.1

7. Methodological Approaches for Carbon Quantification

Accurately quantifying carbon pools in semi-arid agroforestry requires robust field sampling and laboratory analysis techniques. Because direct destructive sampling of large trees is often restricted or impractical, researchers utilize standard volumetric models and allometric scaling relationships (Nair *et al*., 2010) [5].

Field protocols begin with establishing representative sample plots. Non-destructive measurements record tree height, crown diameter, and diameter at breast height (DBH) at a standardized height of 1.3 meters. These measurements are processed using species-specific allometric datasets that model wood density and structural forms to estimate total dry aboveground biomass (Jose and Bardhan, 2012) [9].

Belowground root biomass is estimated using standard root-to-shoot ratios or core soil extraction methods across specific depth profiles. The total dry vegetative biomass is converted to carbon mass using elemental fraction multipliers (Feliciano *et al*., 2018) [13].

For soil carbon pools, researchers collect core samples across distinct vertical layers down to a depth of one meter. Laboratory processing removes stones and root fragments before analyzing the samples for bulk density and carbon content.

The walkley-Black wet oxidation method uses chemical reagents to measure organic carbon levels via colorimetric or titrimetric analysis. For high-precision research, automated dry combustion analyzers incinerate soil samples at elevated temperatures, measuring the released carbon dioxide gas to determine absolute carbon fractions. These values are combined with bulk density metrics to calculate total soil organic carbon stocks per unit area (Lorenz and Lal, 2014) [4].

8. Socio-Economic Co-benefits and Technological Barriers

Integrating trees into semi-arid agricultural landscapes modifies biophysical processes and transforms local socioeconomic structures. The primary barrier to adopting agroforestry is often the delay between initial planting and market maturity. While traditional annual crops generate income within months, perennial trees require several years to yield harvestable timber, pulpwood, or fruit (Miller *et al*., 2019) [23].

To bridge this income gap, designers rely on diversified intercropping systems. Cultivating short-duration food crops within tree alleys provides a steady stream of seasonal revenue and food security while the primary woody biomass sink develops (Kuyah *et al.*, 2019) [21]. Furthermore, the microclimatic shielding provided by tree canopies buffers companion crops against extreme temperature spikes and reduces field-level wind speeds, lowering crop transpirational water stress.

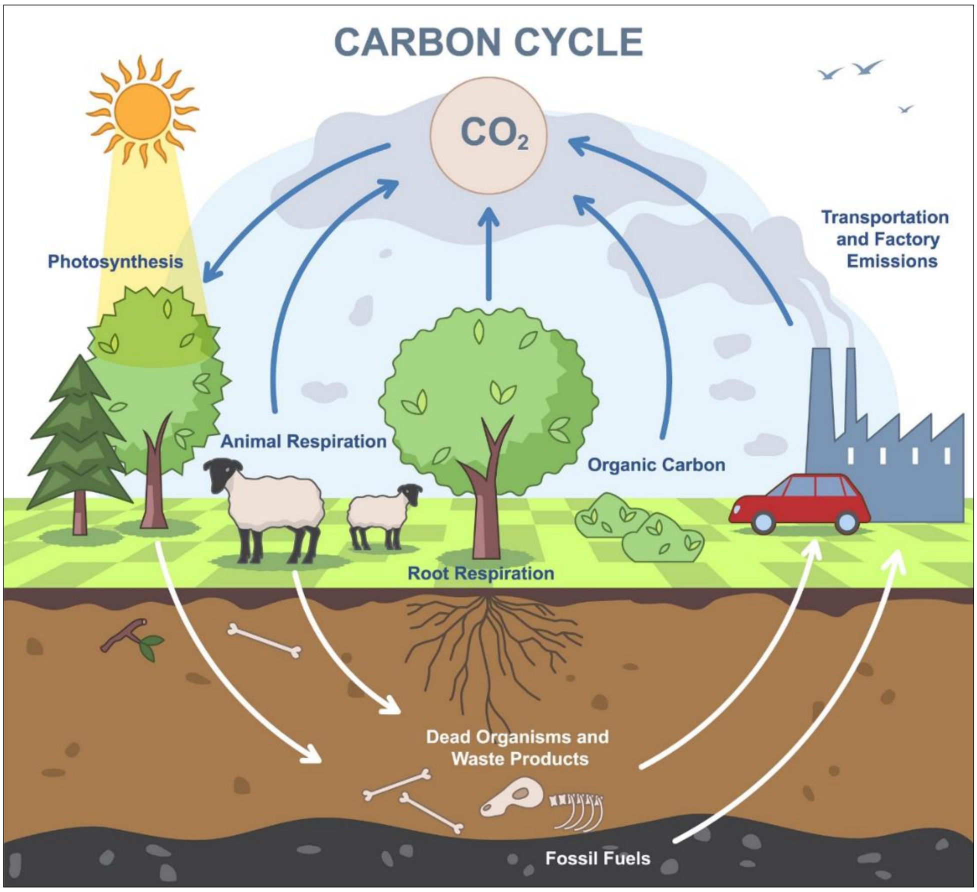

Fig 3: Ecosystem Context of the Carbon Cycle

As illustrated in the global carbon cycle diagram above, vegetative systems operate within a wider atmospheric-terrestrial exchange network. In semi-arid regions, managing this cycle through agroforestry helps lock carbon into stable biological reservoirs, offsetting localized emissions from land use and machinery.

Despite these clear ecological advantages, several institutional and biophysical constraints hinder large-scale adoption:

- **Water Scarcity and Competition:** In years with severe rainfall deficits, shallow tree roots can compete directly with seasonal crops for limited soil moisture, potentially reducing food yields if the species lack spatial root stratification27.
- **Land Tenure Insecurity:** Smallholder tenant farmers are often hesitant to plant long-term tree assets on land they do not legally own or lease securely over multiple decades28.
- **Lack of Quality Planting Material:** Access to elite, high-biomass, drought-resilient clones remains limited in remote semi-arid regions, forcing reliance on low-yielding wild seed stocks.
- **Underdeveloped Carbon Market Infrastructure:** Monetizing carbon sequestration via formal carbon credits remains complex and costly for individual smallholders, highlighting the need for institutional aggregators and streamlined credit certification29.

9. Future Research Paradigms and Policy Implications

To realize the full potential of agroforestry as a climate mitigation strategy, future research must focus on optimizing belowground carbon stabilization and scaling institutional support frameworks. Key research and policy priorities include:

- **Rhizosphere-Targeted Allometrics:** Developing high-resolution root architecture datasets to select species that minimize shallow water competition while maximizing deep subsoil carbon deposition.
- **Carbon Credit Integration:** Creating digital verification platforms that use remote sensing and machine learning to estimate biomass accumulation, allowing smallholders to verify and trade carbon credits efficiently.
- **Subsidized Institutional Credit:** Providing low-interest loans and carbon farming subsidies to support farmers during the early, non-income-generating years of tree growth.
- **Climate-Resilient Germplasm Pipelines:** Establishing decentralized nurseries to distribute certified, drought-tolerant clones optimized for specific semi-arid microclimates30.

10. Conclusion

Agroforestry-based cropping systems provide a scalable, ecologically viable pathway for atmospheric carbon sequestration within fragile semi-arid environments. By integrating perennial trees with annual crops or livestock, these configurations optimize aboveground woody carbon storage and promote deep-profile soil organic carbon stabilization. Beyond climate mitigation, agroforestry delivers essential co-benefits, including erosion control, enhanced water-use efficiency, microclimatic buffering, and diversified income streams for vulnerable farming communities. Overcoming barriers related to early-stage income gaps, land tenure security, and carbon market access requires targeted policy interventions, credit aggregation frameworks, and localized biophysical design. Transitioning from conventional monocultures to multi-tier agroforestry configurations is critical for building resilient agricultural landscapes and achieving long-term global carbon management goals.

References

1. Chavan SB, Dhillon RS, Sirohi C, Uthappa AR, Jinger D, Jatav HS, *et al*. Carbon Sequestration Potential of Commercial Agroforestry Systems in Indo-Gangetic Plains of India: Poplar and Eucalyptus-Based Agroforestry Systems. Forests. 2023;14(3):559.
2. Dhyani SK. Potential of agroforestry systems in carbon sequestration in India. Indian Journal of Agricultural Sciences. 2014;84(3):291-303.
3. Rathore SS, Babu S, El-Sappah AH, Shekhawat K, Singh VK, Singh RK, *et al*. Integrated agroforestry systems improve soil carbon storage, water productivity, and economic returns in the marginal land of the semi-arid region. Saudi Journal of Biological Sciences. 2022;29(10):103427.
4. Lorenz K, Lal R. Soil organic carbon sequestration in agroforestry systems: A review. Agronomy for Sustainable Development. 2014;34(2):443-454.
5. Nair PKR, Nair VD, Kumar BM, Showalter JM. Carbon sequestration in agroforestry systems. Advances in Agronomy. 2010;108:237-307.
6. Benbi DK, Brar K, Singh P. Soil carbon pools under poplar-based agroforestry, rice-wheat, and maize-wheat cropping systems in semi-arid India. Nutrient Cycling in Agroecosystems. 2011;90(3):417-427.
7. Tonucci RG, Vogado RF, Silva RD, Pompeu RCFF, Oda-Souza M, Souza HA. Agroforestry system improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid region. Revista Brasileira de Ciência do Solo. 2023;47:e0220124.
8. Ram Newaj, Chavan SB, Prasad R. Agroforestry Systems for Carbon Sequestration: Present Status and Prospects in India. CABI Digital Library. 2021;12(4):185-198.
9. Jose S, Bardhan S. Agroforestry for biomass production and carbon sequestration: an overview. Agroforestry Systems. 2012;86(2):105-111.
10. Gupta A, Dhyani SK, Ram Newaj, Handa AK, Prasad R, Alam B, *et al*. Modeling analysis of potential carbon sequestration under existing agroforestry systems in three districts of Indo-Gangetic plains in India. Agroforestry Systems. 2013;87(3):1129-1146.
11. Marone D, Poirier V, Coyea M, Olivier A, Munson AD. Carbon storage in agroforestry systems in the semi-arid zone of Niayes, Senegal. Agroforestry Systems. 2017;91(5):941-954.
12. Elibariki Nnko L. Carbon Sequestration in Agroforestry Technologies as a Strategy for Climate Change Mitigation. In: The Nature, Causes, Effects and Mitigation of Climate Change on the Environment. IntechOpen; 2022. p. 115-132.
13. Feliciano D, Ledo A, Hillier J, Nayak DR. Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agriculture, Ecosystems & Environment. 2018;254:117-129.
14. Sharrow SH, Ismail S. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agroforestry Systems. 2004;60(2):123-130.
15. Baah-Acheamfour M, Chang SX, Bork EW, Carlyle CN. The potential of agroforestry to reduce atmospheric greenhouse gases in Canada: Insights from pairwise comparisons with traditional agriculture. The Forestry Chronicle. 2017;93(2):180-189.
16. Yadav D, Lal R, Babu S. Carbon farming: Innovations, potential, and challenges for sustainable future. Indian Journal of Agronomy. 2025;70(1):12-25.
17. Magar LK, Kafle G, Aryal P. Assessment of Soil Organic Carbon in tropical agroforests in the Churiya Range of Makawanpur, Nepal. International Journal of Forestry Research. 2020;2020:8816433.
18. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304(5677):1623-1627.
19. Murthy IK, Gupta M, Tomar S, Munsi M, Tiwari R, Hegde GT, *et al*. Carbon sequestration potential of agroforestry systems in India. Journal of Earth Science & Climatic Change. 2013;4(1):1-7.
20. Paustian K, Larson E, Kent J, Marx E, Swan A. Soil C sequestration as a biological negative emission strategy. Frontiers in Climate. 2019;1:8.
21. Kuyah S, Whitney CW, Jonsson M, Sonneveld B, Oborn I, Neufeldt H, *et al*. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. Agronomy for Sustainable Development. 2019;39(5):47.
22. Dollinger J, Jose S. Agroforestry for ecosystem services. Agroforestry Systems. 2018;92(6):1375-1382.
23. Miller RE, Sills EO, Pattanayak SK. How do farmers adapt to climate change? Agroforestry adoption in marginal environments. World Development. 2019;119:142-153.
24. Thiollet-Scholtus M, Brewer L, Lazcano C. Barriers and opportunities to increase soil organic carbon in vineyards: A case study of extension personnel. OENO One. 2024;58(2):45-59.
25. Sykes AJ, Macleod M, Eory V, Rees RM, Payen FT. Characterising the potential for soil organic carbon sequestration across diverse agricultural systems. Global Change Biology. 2020;26(3):1085-1101.
26. Visconti A, Prairie N, Olson BL. Meta-analysis of multi-level soil carbon sequestration dynamics under semi-arid management regimes. Environmental Research Letters. 2024;19(4):044021.
27. Awasthi KD, Singh B, Khanal BK. Agroforestry interventions for restoring degraded agricultural soils in semi-arid ecologies. Journal of Soil and Water Conservation. 2010;65(2):104-112.
28. Coulibaly JY, Chiputwa B, Kundu L, Agama S. Mandating climate smart agriculture: The role of land tenure security in agroforestry adoption. Land Use Policy. 2020;99:104867.
29. Khanal S, Fulton J, Klopfenstein RD. Financing carbon farming: Barriers and contract designs for smallholder agricultural carbon markets. Climate Policy. 2021;21(7):912-927.
30. Babu S, Singh R, Yadav SK, Rathore SS. Deep rooting perennial selections optimize subsoil carbon persistence under moisture-stressed environments. Nature Climate Change. 2022;12(8):745-752.