**Review Article**

**Carbon Dynamics in Agroforestry Systems: Implications for Climate Change Mitigation and Adaptation**

**Abstract**

Agroforestry—the deliberate integration of trees and shrubs into agricultural landscapes—has re-emerged as a pivotal strategy for climate-smart agriculture. This review synthesizes current knowledge on carbon dynamics within agroforestry systems, exploring their potential to mitigate climate change and enhance ecosystem resilience. Agroforestry practices sequester significant quantities of carbon in aboveground and belowground biomass, soil organic carbon (SOC), and litter, with sequestration rates ranging from 0.29 to 15.21 Mg C ha⁻¹ yr⁻¹ depending on species, management, and site conditions. Multistrata systems such as home gardens and silvopastures show the highest carbon storage potential. Beyond mitigation, agroforestry improves microclimate regulation, hydrological buffering, and biodiversity, making it a robust adaptation strategy. The paper discusses spatial variability in carbon stocks across regions, from high SOC gains in tropical Asia to effective silvopastoral systems in Latin America. Methodologies for carbon assessment—ranging from allometric equations to remote sensing and life cycle assessment—are reviewed. Challenges related to knowledge gaps, tenure insecurity, and limited access to carbon finance hinder large-scale adoption. The review highlights emerging innovations in MRV (Measurement, Reporting, and Verification), modeling, and biochar integration as research frontiers. By bridging biophysical evidence with socioeconomic insights, the paper positions agroforestry as an indispensable nature-based solution in global climate policy. Scaling agroforestry systems requires interdisciplinary research, supportive policies, and equitable financing mechanisms to unlock their full mitigation and adaptation potential.

**Keywords:** Agroforestry, Carbon sequestration, Greenhouse gases, Climate resilience, Soil organic carbon, Climate-smart agriculture

**1. Introduction**

Agroforestry—the strategic integration of woody perennials such as trees and shrubs with crops and/or livestock within the same land-use management system—has emerged as a cornerstone of climate-smart agriculture (CSA). It offers multifunctional landscapes that simultaneously address food security, ecosystem service enhancement, and climate resilience. As climate change intensifies, threatening the sustainability of global agriculture and natural ecosystems, agroforestry presents itself not merely as an alternative but as a necessity for sustainable land management (FAO, 2020; Mbow et al., 2014). The global agricultural sector is under increasing pressure due to growing food demand, land degradation, loss of biodiversity, and the escalating impacts of climate change. Current estimates suggest that agricultural production will need to increase by at least 60% by 2050 to meet the nutritional requirements of a projected global population exceeding 9.7 billion (Alexandratos & Bruinsma, 2012). However, this expansion must occur within the constraints of limited arable land, diminishing freshwater resources, and increasing environmental degradation. Agroforestry, by its design and function, offers a sustainable intensification strategy that contributes to productivity, ecological health, and climate mitigation and adaptation (Nair & Garrity, 2012).

The Agriculture, Forestry, and Other Land Use (AFOLU) sector is both a major source and a potential sink for greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC), the AFOLU sector accounts for approximately 22% of global anthropogenic GHG emissions, primarily through deforestation, soil degradation, biomass burning, and enteric fermentation (IPCC, 2022). Yet, this vary sector holds the most promise for nature-based climate solutions. Agroforestry, by integrating trees in farming landscapes, plays a pivotal role in reducing net emissions through increased carbon sequestration and enhanced land productivity (Nair & Nair, 2023). Agroforestry systems—ranging from alley cropping, silvopastoral systems, and agrisilvicultural systems to complex home gardens and multistrata systems—vary in structure, composition, and function. Despite this diversity, they share a common potential: the ability to store significant amounts of carbon in both biomass and soils. A growing body of evidence suggests that agroforestry systems sequester more carbon than conventional agriculture and pastures, especially in tropical and subtropical regions (Jose, 2009; Montagnini & Nair, 2004). Estimates indicate that agroforestry systems can sequester between 0.29 to 15.21 Mg C ha⁻¹ yr⁻¹ depending on tree species, age, density, soil type, climate, and management practices (Albrecht & Kandji, 2003; Kumar & Nair, 2011). Moreover, the permanence of carbon storage in agroforestry systems is enhanced by their longevity and resilience to climate extremes. Unlike annual cropping systems, agroforestry maintains perennial vegetation that sustains long-term carbon accumulation, particularly in woody biomass and stabilized soil organic carbon pools. The inclusion of deep-rooted trees also facilitates carbon translocation to deeper soil layers, thus enhancing carbon residence time (Mutuo et al., 2005).

Beyond carbon sequestration, agroforestry contributes to climate change adaptation by offering a suite of ecosystem services: improving microclimates, conserving soil moisture, increasing biodiversity, providing windbreaks, and reducing the vulnerability of farming communities to climate shocks. Trees moderate local temperatures through shade and evapotranspiration, reducing heat stress on crops and livestock. Their roots reduce erosion, improve soil structure, and promote nutrient cycling, thereby enhancing soil fertility and water retention (Garrity, 2004). These benefits are particularly critical for smallholder farmers in the Global South, who often face disproportionate climate risks. At the landscape level, agroforestry contributes to biodiversity conservation by creating ecological corridors, enhancing habitat heterogeneity, and supporting pollinators and beneficial insects (Schroth et al., 2004). This biodiversity fosters ecological resilience, a key component in adapting to environmental uncertainties brought on by climate change. In addition, many agroforestry systems provide non-timber forest products (NTFPs), fuelwood, fodder, fruits, and medicinal plants, diversifying incomes and improving livelihoods—important socio-economic dimensions of climate resilience (Mbow et al., 2014).

From a policy perspective, agroforestry aligns with multiple international frameworks and goals, including the Paris Agreement, United Nations Framework Convention on Climate Change (UNFCCC), Sustainable Development Goals (SDGs), and Land Degradation Neutrality (LDN) targets. Several countries have already incorporated agroforestry into their Nationally Determined Contributions (NDCs), acknowledging its role in both mitigation and adaptation. However, the scaling of agroforestry faces challenges—such as tenure insecurity, lack of incentives, knowledge gaps, and inadequate policy support—that require integrated solutions (Verchot et al., 2007). Globally, agroforestry is practiced across nearly one billion hectares, including traditional systems in Asia, Africa, and Latin America, as well as more formalized designs in North America and Europe (FAO, 2020). The scalability and versatility of agroforestry systems, along with their compatibility with both subsistence and commercial farming, make them uniquely positioned to contribute to climate-resilient development pathways. Despite the well-documented benefits, a comprehensive understanding of carbon dynamics in agroforestry systems remains fragmented due to variability in methodologies, time scales, and ecological contexts. There is a need for more robust, standardized assessments that account for spatial and temporal heterogeneity in carbon stocks and fluxes. Emerging technologies such as remote sensing, eddy covariance flux towers, isotopic tracing, and modeling approaches are increasingly being employed to close these knowledge gaps and provide accurate, scalable estimates of carbon sequestration potential (Cardinael et al., 2017; Rosenstock et al., 2019).

This review aims to synthesize the current knowledge and evidence on carbon dynamics in agroforestry systems, including above- and below-ground carbon sequestration processes, influencing factors, system-specific differences, and their implications for climate change mitigation and adaptation. It also explores the socio-political and economic drivers, challenges, and opportunities that shape the adoption and effectiveness of agroforestry systems in diverse contexts. By bridging biophysical science with policy and practice, the review seeks to inform research priorities, support climate policy formulation, and guide the implementation of agroforestry-based interventions at the field level. Ultimately, understanding carbon dynamics in agroforestry is not just a scientific pursuit but a strategic imperative for climate-resilient development. As the world confronts escalating climate risks and strives for low-emission, sustainable food systems, agroforestry holds the promise of delivering integrated solutions that benefit people, the planet, and the climate.

**1.2. Scope and Methodology**

This review systematically synthesizes peer-reviewed literature, technical reports, and global assessments published between 1985 and 2025 that examine carbon dynamics within agroforestry systems. The scope includes empirical and modeling studies that address carbon stocks, greenhouse gas (GHG) fluxes, and the mitigation potential of agroforestry across different ecological zones and system types. Specific emphasis is placed on studies that utilize field-based carbon measurements, such as eddy covariance (EC) techniques, remote sensing, life cycle assessments (LCA), and biogeochemical models to estimate carbon fluxes and storage capacities.

A total of over 150 scientific sources were screened using inclusion criteria focused on relevance, methodological rigor, and representativeness of diverse agroecological zones. From these, 88 high-quality studies were selected for an in-depth analysis. These include meta-analyses, IPCC assessment reports, regional case studies, and national carbon accounting studies, providing a robust evidentiary basis for the synthesis. Key parameters extracted from the literature include above- and below-ground biomass carbon, soil organic carbon (SOC), net ecosystem carbon balance (NECB), and GHG fluxes (CO₂, CH₄, N₂O).

The review also integrates direct observational datasets and experimental results from eddy covariance flux tower measurements, which allow for high-resolution, continuous monitoring of CO₂ exchange in agroforestry systems under real-world conditions (Chatterjee et al., 2021). In addition, life cycle assessment frameworks are referenced where available to understand the cradle-to-grave carbon balance and trade-offs of agroforestry-based interventions.

The methodology of this review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework for transparency and reproducibility in literature selection and synthesis. Studies were classified by system type (e.g., silvopastoral, agrosilvicultural, multistrata), geographic region (e.g., tropics, temperate, arid), and methodological approach (e.g., empirical field measurements vs. model-based estimates). The findings are organized thematically to explore carbon sequestration patterns, influencing factors, and their broader implications for climate change mitigation and adaptation.

**2. Concept of Agroforestry Systems**

Agroforestry refers to the intentional, systematic integration of trees and shrubs with crops and/or livestock within the same land management unit, aiming to optimize the ecological and economic benefits of combined land use. As a multifunctional land-use system, agroforestry enhances productivity, promotes ecosystem sustainability, and contributes significantly to climate change mitigation and adaptation strategies (Nair, 1993; Garrity, 2004). The distinguishing feature of agroforestry systems lies in the deliberate arrangement of multiple components—woody perennials, herbaceous crops, and animals—based on ecological principles that enhance resource-use efficiency, biodiversity, and resilience.

Agroforestry systems promote positive ecological interactions between components, which facilitate nutrient cycling, water retention, soil fertility enhancement, and carbon sequestration. These interactions reduce the need for external inputs and create resilient agroecosystems capable of withstanding climatic shocks such as droughts, floods, and temperature extremes (Jose, 2009). Unlike monocultures, agroforestry maximizes vertical and horizontal space utilization, mimicking natural forest structures and leading to increased carbon capture both above and below ground (Montagnini & Nair, 2004). Agroforestry also supports livelihood diversification by providing multiple outputs—timber, fuelwood, fruits, fodder, and non-timber forest products (NTFPs). This diversity contributes to food security, income stability, and reduced dependence on external markets. The adoption of agroforestry is particularly significant for smallholder farmers in tropical and subtropical regions where land degradation, erratic rainfall, and declining soil fertility are prevalent (Mbow et al., 2014). To optimize carbon benefits, systems must be carefully designed to balance ecological services with productivity and socioeconomic needs (Nair et al., 2010).

**2.1 Typologies of Agroforestry**

Agroforestry systems exhibit great diversity based on ecological conditions, cultural practices, and land-use objectives. These systems can be broadly categorized into several major types, each with distinct structural characteristics and carbon sequestration potentials. The following typologies represent the core classifications of agroforestry systems globally:

**Agrosilvicultural Systems:** These systems integrate trees with agricultural crops on the same plot of land. One common form is alley cropping, where rows of nitrogen-fixing trees or shrubs (e.g., *Gliricidia sepium*, *Leucaena leucocephala*) are interplanted with food or cash crops such as maize, millet, or vegetables. The tree rows improve soil structure, reduce erosion, and provide green manure or mulch. The trees also sequester significant amounts of carbon in both biomass and soils, depending on species and rotation length (Albrecht & Kandji, 2003).

**Silvopastoral Systems:** Silvopastoral systems combine trees or shrubs with forage grasses and livestock. Trees in pastures provide shade, fodder, fuelwood, and shelter for animals. Common species include *Faidherbia albida*, *Acacia spp.*, and *Prosopis juliflora*. These systems enhance carbon sequestration by increasing above-ground biomass and improving soil organic carbon through root activity and organic matter deposition from dung and leaf litter (Nair et al., 2009). They are particularly effective in semi-arid and degraded regions.

**Agrosilvopastoral Systems:** This is a more complex system that integrates trees, crops, and livestock in a unified land-use framework. Examples include traditional home gardens in South and Southeast Asia, where diverse species are spatially arranged in vertical strata. Such systems optimize space use and ecological efficiency, supporting high biodiversity and long-term carbon storage (Kumar & Nair, 2006). Home gardens also offer nutritional security and resilience against market or climatic shocks.

**Improved Fallow Systems:** In this system, fast-growing, often leguminous trees are planted during fallow periods to restore soil fertility. Species such as *Sesbania sesban*, *Tephrosia vogelii*, and *Cajanus cajan* are commonly used to fix atmospheric nitrogen and enhance soil organic matter. Improved fallows accelerate the natural regeneration of land and increase carbon sequestration rates in both biomass and soils compared to traditional bush fallows (Mafongoya et al., 2006).

**Windbreaks and Shelterbelts:** These systems involve planting rows of trees or shrubs along field boundaries or across landscapes to reduce wind speed, prevent erosion, and improve microclimatic conditions. Windbreaks protect crops from desiccation and can enhance yields while simultaneously storing carbon in tree biomass. Species selection for windbreaks often includes hardy, fast-growing species such as *Casuarina equisetifolia* or *Eucalyptus spp.* (Brandle et al., 2004).

**Forest Farming:** Forest farming refers to the cultivation of high-value shade-tolerant crops such as mushrooms, spices, medicinal herbs, and ornamental plants under a managed forest canopy. This system is common in temperate and tropical forests and is suitable for smallholders seeking alternative income without forest clearance. Forest farming contributes to carbon sequestration by maintaining tree cover while utilizing understory space for economic benefit (Gold & Garrett, 2009).

**2.2 Carbon Pools and Dynamics in Agroforestry**

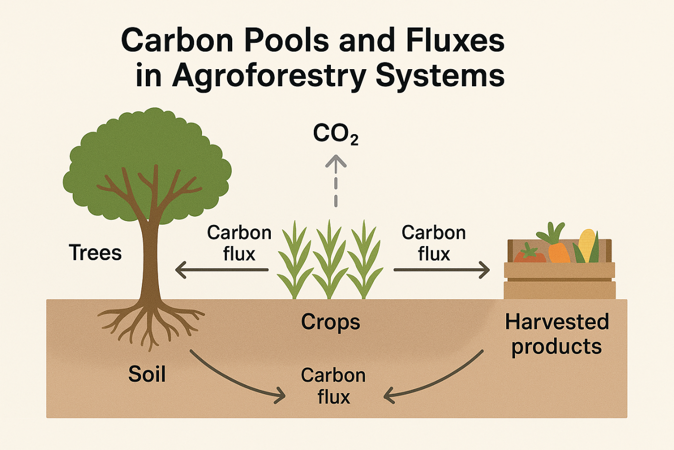
Agroforestry systems encompass several carbon pools:

* **Aboveground biomass carbon** – Stored in stems, branches, and foliage.
* **Belowground biomass carbon** – Root systems contribute significantly to soil carbon inputs.
* **Soil organic carbon (SOC)** – Derived from decaying biomass, root exudates, and microbial residues.
* **Dead organic matter** – Includes leaf litter, mulch, and woody debris that decompose and enrich SOC.

Carbon fluxes within agroforestry are influenced by biological (e.g., photosynthesis, respiration), physical (e.g., temperature, moisture), and management-driven (e.g., pruning, mulching) processes.

Soil organic carbon (SOC) and biomass carbon (BMC) constitute the two primary pools influenced by agroforestry. Carbon enters the system through photosynthesis, root exudation, and organic amendments, is transferred among pools via litter fall and root turnover, and exits mainly through respiration, leaching, or harvest removals (Jose, 2009). The presence of multi-strata canopies modifies microclimates, slows mineralization, and enhances physical protection of SOC (Schroeder, 1994).

The pathways and feedback~~s~~ among pools are illustrated below.



**Fig. 1: Carbon pools and fluxes in agroforestry systems (Adapted from Jose, 2009)**

**3. Carbon Pools and Mechanisms of Carbon Storage**

Agroforestry systems sequester carbon through multiple interconnected carbon pools, including aboveground biomass, belowground biomass, soil organic carbon, litter, and deadwood. These pools act as sinks for atmospheric CO₂ through photosynthesis and long-term carbon stabilization mechanisms. Understanding the nature and dynamics of these pools is essential to accurately quantify the climate mitigation potential of agroforestry and to design interventions that optimize carbon storage across spatial and temporal scales (Nair et al., 2009).

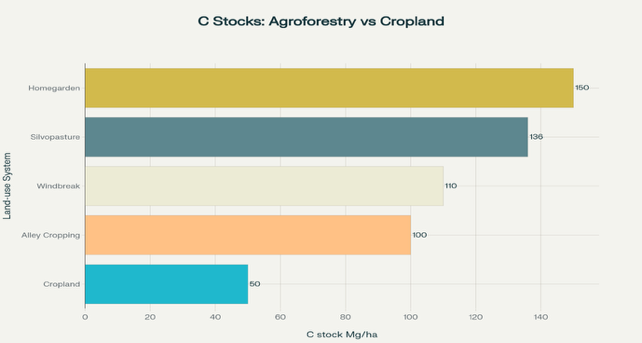
Trees in agroforestry systems act as long-term reservoirs for carbon. Unlike annual crops, which return most of their biomass to the atmosphere within a season, woody perennials accumulate and retain carbon over decades. The effectiveness of carbon sequestration varies with factors such as species composition, system design, tree age, and ecological conditions. Furthermore, deep root systems and complex canopy structures in agroforestry facilitate both vertical and horizontal distribution of carbon within ecosystems, contributing to enhanced stability of carbon storage (Montagnini & Nair, 2004).

**3.1 Aboveground Biomass**

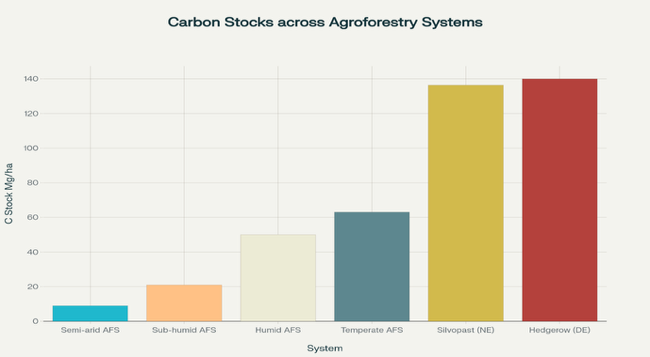
Aboveground biomass includes carbon stored in tree trunks, branches, leaves, and woody stems. The rate of carbon accumulation in this pool is influenced by tree species, wood density, climatic zone, stand age, and management intensity. Fast-growing species with high wood density typically exhibit higher carbon storage potential. In temperate silvopastoral systems, mature trees such as oaks (*Quercus spp.*) have been found to contribute an additional 30–70 Mg C ha⁻¹ compared to treeless pastures (Jose, 2009; Drexler & Don, 2020). In tropical regions, particularly in diverse home garden agroforestry systems, aboveground carbon stocks vary significantly based on altitude and species mix. For example, studies in Ethiopian home gardens report carbon stocks ranging from 9 to 36 Mg C ha⁻¹, with higher values linked to increased species richness and tree density (Negash & Starr, 2015).

**3.2 Belowground Biomass**

Belowground biomass comprises carbon stored in roots, which accounts for 20–40% of total tree biomass carbon. Root biomass contributes to carbon sequestration not only by storing carbon directly but also by influencing soil structure, microbial communities, and nutrient cycling. Deep-rooted trees like *Faidherbia albida* can transfer carbon to depths below 1.0 meter, promoting subsoil carbon stabilization where decomposition rates are lower and carbon compounds form stable mineral associations (Lorenz & Lal, 2014). These deeper carbon deposits are less susceptible to disturbance, making them vital for long-term carbon storage. Agroforestry systems with perennial deep-rooted species enhance the resilience and permanence of sequestered carbon compared to shallow-rooted crops or grasses (Nair et al., 2010).



**Fig. 2: Comparative carbon stocks across agroforestry systems (Source: CIFOR-ICRAF, 2023)**



**Fig. 3: Comparison of carbon stocks in different agroforestry settings (Source: CIFOR-ICRAF, 2023)**

**3.3 Soil Organic Carbon (SOC)**

Soil organic carbon (SOC) is a critical carbon pool influenced by agroforestry practices. SOC results from the integration of organic matter inputs (leaf litter, root residues, animal manure) with microbial activity, leading to stable humus formation. SOC is particularly important in regulating soil fertility, water retention, and microbial diversity.

Mechanisms through which agroforestry enhances SOC include:

* Litterfall and mulching from pruned biomass and fallen leaves.
* Root exudation and rhizodeposition, which provide carbon substrates to microbes.
* Reduced erosion and soil disturbance due to permanent tree cover and minimal tillage.

According to a meta-analysis of 427 global comparisons, agroforestry soils stored on average 19% more SOC (0–1 m) than adjacent cropland or pasture (Nair et al., 2017). In tropical home gardens, SOC stocks can reach 60–90 Mg C ha⁻¹, largely due to consistent biomass input and minimal disturbance (Kumar & Kunhamu, 2021). Agroforestry also increases the stability of SOC through the formation of mineral-associated organic matter (MAOM), which resists microbial decomposition and remains in the soil for decades or centuries (Schmidt et al., 2011).

**Table 1: Summarizes representative mean carbon stocks across common agroforestry systems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **System Type** | **Climate Zone** | **Mean Above-Ground C (Mg ha⁻¹)** | **Mean SOC (Mg ha⁻¹, 0–30 cm)** | **Key Sources** |
| Hedgerows | Temperate | 48–105 | +29 over cropland | Drexler & Don, 2020 |
| Silvopasture | Humid Cont. (U.S.) | 41–62 | No SOC change detected | Orefice et al., 2025 |
| Homegardens | Tropical | 14–52 | 60–90 | Kumar & Kunhamu, 2021 |
| Alley Cropping | Mediterranean | 9–28 | Gains after > 10 yrs | Sánchez-Navarro et al., 2022 |
| Windbreaks | Semi-arid | 9–21 | Moderate increases | TM et al., 2023 |

**3.4 Dead Organic Matter and Litterfall**

Litterfall and decomposing organic residues form a transient but ecologically vital carbon pool. This includes leaves, twigs, pruning residues, and applied mulches that serve as a carbon-rich substrate for microbial activity and nutrient cycling. For instance, *Gliricidia sepium* hedgerows in alley cropping systems contribute over 4 t ha⁻¹ yr⁻¹ of litter, significantly enhancing surface SOC in the upper 20 cm of soil (Makumba et al., 2007). Continuous input of organic residues supports particulate organic carbon (POC) formation, which serves as an intermediate carbon pool between labile and stabilized organic matter. High-quality litter with low lignin content decomposes faster, releasing nutrients and carbon into the soil system. Conversely, woody residues decompose slowly, offering long-term carbon benefits.

**3.5 Microbial Processes and Stabilization**

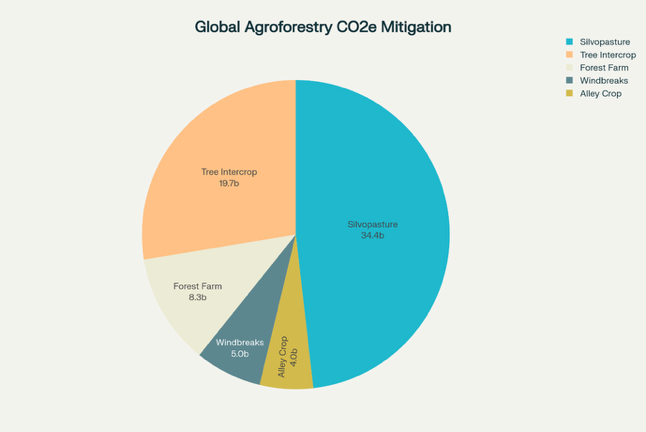
Soil microbes play a central role in SOC transformation and stabilization. Microorganisms, particularly fungi and bacteria, decompose plant residues and convert them into humic substances and stable microbial necromass, which form the foundation of long-term SOC (Cotrufo et al., 2013). Tree-root zones in agroforestry systems support robust microbial communities and arbuscular mycorrhizal fungi (AMF) networks, which facilitate the aggregation of soil particles and protection of organic matter from enzymatic breakdown (Laishram et al., 2024). Enhanced microbial activity in agroforestry systems accelerates the formation of mineral-associated organic matter (MAOM), which represents one of the most stable forms of SOC. The interaction between microbial products and soil minerals creates a protective matrix that limits microbial access, slowing decomposition and enhancing carbon permanence (Lehmann & Kleber, 2015).

**4. Agroforestry System Types and Sequestration Potential**

Agroforestry encompasses a wide range of land-use practices in which trees and shrubs are purposefully integrated with crops and/or livestock. The structure, composition, and management of these systems vary across ecological regions, directly influencing their capacity to sequester carbon. The differences in species diversity, tree density, spatial arrangement, rotation period, and biomass turnover contribute to variability in carbon dynamics across agroforestry types (Nair et al., 2009; Jose, 2009). Carbon sequestration in agroforestry occurs through multiple pathways, including biomass accumulation (above- and below-ground), soil organic carbon (SOC) enhancement, root activity, and microbial stabilization. Different agroforestry system types demonstrate unique strengths in these areas, influenced by both biophysical and socio-economic factors. This section details the most widely studied agroforestry types and their respective carbon sequestration potentials.

**4.1 Silvopastoral Systems**

Silvopastoral systems integrate trees with livestock pastures, promoting synergies between tree biomass accumulation, forage production, and manure deposition. These systems are particularly prominent in Latin America, Africa, and Europe, where they enhance productivity and environmental services on grazing lands. Trees in silvopastoral systems provide fodder, shade, timber, and shelter, while simultaneously sequestering carbon in above- and below-ground biomass. The presence of livestock contributes to soil organic matter via manure deposition and stimulates root growth and microbial activity, enhancing SOC over time (Nair et al., 2009; Taylor et al., 2022). In Central America, silvopastoral systems with species like *Leucaena leucocephala*, *Erythrina poeppigiana*, and *Ficus spp.* have demonstrated carbon sequestration rates up to 5 Mg C ha⁻¹ yr⁻¹, offsetting up to 60% of livestock-related greenhouse gas (GHG) emissions (da Fonseca et al., 2023). Furthermore, these systems improve resilience to climate stress by reducing heat stress on animals and improving forage quality.



**Fig. 4: Projected mitigation potential of leading agroforestry practices (Adapted from Zomer et al., 2022)**

**4.2 Home Gardens**

Home gardens are multistrata agroforestry systems found primarily in tropical Asia, Africa, and parts of Latin America. These highly diverse systems typically include trees, shrubs, herbs, vines, and livestock, arranged in vertical layers to mimic forest structures. Their high tree density (often 500–2,000 trees per hectare) and year-round vegetative cover contribute significantly to carbon sequestration and household food security. In Kerala, India, tropical home gardens have shown exceptional carbon sequestration potential, with SOC stocks reaching up to 90 Mg C ha⁻¹ in the topsoil layer (Sharma et al., 2023). The stratified structure enables efficient use of light, water, and nutrients, maximizing both photosynthetic productivity and organic matter input through litterfall and pruning residues (Kumar & Nair, 2006). Besides ecological benefits, home gardens offer continuous economic output through the sale of fruits, spices, timber, and medicinal plants, making them attractive for climate-smart, low-input farming systems.

**4.3 Alley Cropping**

Alley cropping, also known as hedgerow intercropping, involves planting rows of trees or shrubs (usually legumes such as *Gliricidia sepium* or *Leucaena leucocephala*) interspersed with annual or perennial crops. The tree rows are regularly pruned to prevent excessive shading of crops and to provide mulch or green manure.

This system enhances carbon storage through multiple mechanisms:

* Litterfall from pruned biomass contributes organic matter to soil.
* Biological nitrogen fixation improves soil fertility and promotes biomass growth.
* Root turnover deposits organic residues deep into the soil profile.

SOC gains of up to 26% have been recorded in alley cropping systems over a period of 10–15 years, particularly when integrated with minimal tillage and organic amendments (Sánchez-Navarro et al., 2022). While aboveground biomass accumulation may be limited due to regular pruning, the soil-based carbon sequestration makes alley cropping a valuable option for sustainable intensification.

**4.4 Hedgerows and Shelterbelts**

Hedgerows and shelterbelts are linear plantings of trees or shrubs along field boundaries or contour lines, primarily established for erosion control, wind reduction, and biodiversity enhancement. Though narrow in width, these systems provide disproportionately large ecological benefits, including carbon sequestration. In European agricultural landscapes, hedgerows were shown to increase SOC by up to 32% compared to adjacent cropland soils, with detectable subsoil carbon enrichment beyond 1.0 meter depth (Drexler & Don, 2020). The increased litterfall, root inputs, and physical soil protection from erosion contribute to long-term SOC build-up. Hedgerows also provide wildlife corridors, pollinator habitat, and landscape connectivity, making them a multifunctional agroecological tool. Their narrow spatial footprint often leads to underestimation in regional carbon inventories, yet their cumulative impact can be substantial when integrated systematically across agricultural landscapes.

**4.5 Windbreaks and Forest Farming**

Windbreaks consist of single or multiple rows of trees or shrubs planted perpendicular to prevailing winds to reduce wind speed, evapotranspiration, and soil erosion. They indirectly promote carbon retention by protecting crop fields and improving microclimates. Over time, they also sequester carbon in biomass and soil, especially when combined with rotational biomass harvesting. In semi-arid regions, windbreaks composed of *Casuarina*, *Eucalyptus*, or *Prosopis* species have shown moderate but consistent carbon sequestration benefits (Zomer et al., 2024). SOC gains are particularly noted in leeward zones where organic matter accumulation is higher due to wind barrier effects.

Forest farming, by contrast, involves cultivating shade-tolerant understory crops (e.g., mushrooms, ginseng, turmeric) under a managed forest canopy. This system conserves existing forest biomass while utilizing understory productivity, maintaining high SOC levels and minimal disturbance. Forest farming leverages existing tree covers to stabilize soil structure, enhance microbial activity, and reduce GHG emissions (Gold & Garrett, 2009). Agroforestry systems are not monolithic; their structure, function, and carbon sequestration potential vary greatly by type. While silvopastoral systems excel in integrating livestock and trees for soil carbon enrichment and emission offsets, multistrata homegardens and alley cropping systems demonstrate high SOC buildup and biomass productivity. Shelterbelts, windbreaks, and forest farming offer targeted solutions for landscape protection and sustainable production. When implemented at scale, these agroforestry types contribute significantly to nature-based climate solutions, supporting both climate mitigation and rural resilience across varied agroecological zones.

**Table 2. Global Distribution and Typology of Agroforestry Systems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **System** | **Typical Climate Zone** | **Dominant Tree Function** | **Representative Species** | **Spatial Configuration** |
| Alley Cropping | Humid & sub-humid tropics; temperate zones | Soil fertility & mulch | *Gliricidia sepium*, *Leucaena leucocephala* | Hedgerows 4–15 m apart |
| Silvopasture | Temperate & tropical grasslands | Shade & fodder | *Quercus spp.*, *Prosopis spp.*, *Faidherbia albida* | Scattered trees 30–100 trees ha⁻¹ |
| Homegarden | Tropics & subtropics | Food & income diversification | Banana, mango, cacao | Multistrata 500–2 000 trees ha⁻¹ |
| Windbreak | Semi-arid & temperate croplands | Wind reduction | *Casuarina equisetifolia*, *Populus* spp. | Single/multiple rows along field edges |
| Forest Farming | Temperate woodlands | Non-timber products | Ginseng, mushrooms | Understory cultivation beneath canopy |

**(Sources: Nair & Nair, 2012)**

**5. Regional Variability in Carbon Storage**

Agroforestry’s potential as a climate mitigation strategy is widely acknowledged, yet its effectiveness is highly context-specific. Regional variation in climate, soil type, topography, land-use history, and socio-economic factors leads to significant differences in both the magnitude and dynamics of carbon sequestration across agroforestry systems. Understanding these variations is crucial for tailoring agroforestry practices to local conditions and for informing national and regional climate policies (Nair, 2012). Carbon storage in agroforestry systems occurs through above- and below-ground biomass, litter accumulation, and improvements in soil organic carbon (SOC). However, the species composition, tree density, management intensity, and land tenure systems differ significantly by region, influencing carbon sequestration rates. This section examines the carbon sequestration potential of agroforestry across four key global regions: Asia, Africa, Latin America, and temperate zones.

**5.1 Asia**

In Asia, particularly South and Southeast Asia, agroforestry is deeply rooted in traditional farming practices and includes homegardens, intercropping, boundary planting, and agrosilvicultural systems. These systems are typically characterized by high species diversity, multilayered canopies, and year-round productivity, which contribute to robust carbon sequestration. Homegarden systems, such as those found in Kerala, India, are among the most studied in the region. These systems integrate fruit trees, timber species, herbs, and shrubs, resulting in high biomass density and continuous litter input. Studies have shown that homegardens in Kerala store over 100 Mg C ha⁻¹ in total biomass and up to 90 Mg C ha⁻¹ in SOC, depending on species composition and management practices (Kumar & Kunhamu, 2021; Sharma et al., 2023). Similar systems in Indonesia, Sri Lanka, and Bangladesh exhibit comparable levels of carbon storage. The high productivity and multifunctionality of these systems make them suitable for both mitigation and adaptation goals. Moreover, their integration into smallholder farms supports food security, income diversification, and climate resilience.

**5.2 Africa**

In Sub-Saharan Africa, agroforestry systems are primarily implemented as parklands, improved fallows, boundary planting, and mixed cropping systems. These are often low-input, extensive systems adapted to semi-arid and savanna ecosystems. The inclusion of trees in farming landscapes significantly enhances soil fertility, water retention, and SOC sequestration. One of the most well-documented examples is the *Faidherbia albida* parkland system found across the Sahel. This nitrogen-fixing, deep-rooted tree species enhances SOC accumulation, improves nutrient cycling, and boosts crop yields. Parkland systems can increase SOC by 20–40% compared to treeless cropland (Bayala et al., 2008). In Malawi and Zambia, improved fallows using fast-growing legumes such as *Sesbania* and *Tephrosia* have also shown SOC increases of 10–25 Mg C ha⁻¹ within a decade (Akinnifesi et al., 2010).

**5.3 Latin America**

In Latin America, particularly Central and South America, agroforestry is widely practiced in the form of silvopastoral systems, shade-grown coffee, cocoa agroforestry, and forest gardens. These systems provide multiple ecosystem services, including carbon sequestration, biodiversity conservation, and livelihood support for smallholder farmers. Silvopastoral systems, which integrate trees into pastures, are common in Colombia, Costa Rica, and Brazil. Studies have shown that dairy farms in Central America using tree-based systems can sequester up to 1.43 Mg C ha⁻¹ yr⁻¹, while reducing the product-level carbon footprint by 21% compared to conventional systems (Taylor et al., 2022). These systems improve carbon storage not only through tree biomass but also by increasing SOC through manure deposition, litterfall, and improved root activity. Cocoa agroforestry systems, particularly in countries like Peru, Ecuador, and Brazil, maintain high above-ground carbon stocks (up to 70 Mg C ha⁻¹) while supporting understory biodiversity. The presence of shade trees regulates microclimate, increases moisture retention, and contributes to long-term soil carbon build-up (Somarriba et al., 2013). Additionally, these systems provide economic resilience through diversified income from cocoa, timber, and non-timber forest products.

**5.4 Temperate Regions**

Agroforestry in temperate regions—including Europe, North America, and parts of China and Central Asia—often takes the form of alley cropping, hedgerows, shelterbelts, and silvopasture. Although these systems typically store less carbon per unit area compared to tropical systems, their vast potential area of implementation offers substantial mitigation capacity. In Europe, converting 10% of arable land to alley cropping systems has been projected to remove 6–10 Mt CO₂ per year, based on model simulations accounting for both biomass and soil carbon gains (Drexler & Don, 2020). Similarly, hedgerow networks are being recognized as vital carbon sinks in agricultural landscapes.

For instance, a recent U.K. study found that planting 7,000 km of new hedgerows annually could offset up to 4.5% of national agricultural CO₂ emissions by 2050 (Biffi et al., 2023). These systems also enhance biodiversity corridors, reduce wind erosion, and provide habitat for beneficial insects and pollinators. In the United States, agroforestry systems are increasingly promoted through climate-smart agriculture policies. Silvopasture and windbreaks are being adopted across the Midwest and Southeast, offering co-benefits in carbon storage, livestock welfare, and soil conservation (Jose & Dollinger, 2019).

**Table 3. Representative agroforestry typologies and geographic prevalence**

| **Typology** | **Core Components** | **Dominant Regions** |
| --- | --- | --- |
| Silvopasture | Fodder trees + livestock | Latin America, Europe, N. America |
| Alley cropping | Tree rows + annual crops | Europe, N. America, Mediterranean |
| Homegardens | Multistrata trees + crops | S. Asia, SE Asia, E. Africa |
| Windbreaks/hedgerows | Linear tree belts | Temperate regions worldwide |
| Parklands | Scattered trees + crops | Sahel, W. Africa |

**6. Carbon Fluxes and Greenhouse Gas (GHG) Dynamics**

While much attention in agroforestry research has focused on carbon stock accumulation in biomass and soil, agroforestry systems also play a crucial role in mediating carbon and greenhouse gas (GHG) fluxes, thereby influencing their net climate impact. These systems act as biogeochemical moderators, influencing the fluxes of carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄)—the three primary anthropogenic greenhouse gases contributing to global warming. The degree to which agroforestry systems mitigate or amplify GHG emissions depends on multiple factors, including land-use history, tree species composition, soil conditions, microclimate, and management practices. Understanding these dynamics is essential for accurate climate accounting and for enhancing the efficacy of agroforestry as a climate-smart land-use strategy (Jose, 2009; IPCC, 2022).

**6.1 Net Ecosystem Exchange (NEE)**

Net Ecosystem Exchange (NEE) represents the balance between CO₂ absorbed via photosynthesis and that released via respiration. Agroforestry systems generally act as net carbon sinks, especially when perennial trees are integrated into annual cropping or grazing systems. Eddy covariance measurements, which allow high-frequency tracking of CO₂ exchange, provide robust evidence of agroforestry’s positive role in atmospheric carbon uptake.

In temperate Europe, German alley cropping systems (e.g., poplar intercropped with wheat or barley) show 15–30% higher daytime CO₂ uptake than adjacent monoculture cereal systems. These systems recorded annual net sequestration rates between 0.5–1.2 t C ha⁻¹, suggesting significant mitigation potential over decadal timescales (Luo et al., 2022). Importantly, this carbon gain is distributed across aboveground biomass, root systems, and soil organic matter, supporting both mitigation and soil health goals. The long-term persistence of carbon in these systems depends on tree longevity, harvest cycles, and post-harvest residue management, all of which influence the net GHG balance.

**6.2 Nitrous Oxide (N₂O) Emissions**

Nitrous oxide (N₂O) is a potent greenhouse gas with a global warming potential nearly 298 times that of CO₂ over a 100-year timescale. N₂O emissions from agroecosystems mainly arise from nitrification and denitrification processes in the soil, especially under high nitrogen inputs and wet conditions. Agroforestry systems have shown significant potential in suppressing N₂O emissions, particularly when compared to intensive monoculture systems reliant on synthetic fertilizers. Several mechanisms contribute to this suppression:

* Tree roots enhance soil aeration and reduce anaerobic microsites.
* Nitrogen-fixing trees (e.g., *Faidherbia albida*, *Leucaena leucocephala*) promote more efficient N cycling.
* Organic inputs from litter and pruning decompose more slowly, reducing the nitrate pool available for denitrification.

For example, Sánchez-Navarro et al. (2022) reported that tree rows in Mediterranean alley cropping systems suppressed N₂O emissions by 6–36% compared to crop-only rows. Similarly, Bayala et al. (2008) found that parklands in West Africa, particularly those with *Faidherbia albida*, reduced N₂O fluxes significantly during the rainy season. However, certain micro-sites, such as low-lying tree basins or overly wet soils, may experience temporary N₂O spikes, especially where organic matter accumulates and drainage is poor. Hence, site-specific hydrology and management must be considered in mitigation assessments.

**6.3 Methane (CH₄) Fluxes**

Methane (CH₄) emissions primarily originate from anaerobic decomposition in waterlogged soils, such as rice paddies or wetlands. Agroforestry systems generally reduce CH₄ emissions by improving soil aeration, modifying microclimate, and increasing organic matter quality, thus shifting microbial communities away from methanogenic pathways. In silvopastoral systems established in wetlands or high-rainfall zones, tree islands improve drainage and lower water saturation, thus reducing CH₄ efflux compared to treeless paddies or overgrazed pastures. A study in East African silvopastoral systems showed a reduction in CH₄ emissions of up to 45%, attributed to improved redox conditions and shading-induced cooler soil temperatures (Gebrekirstos, 2022). In shade-grown coffee systems, CH₄ emissions were found to be up to 64% lower than those in adjacent open-field systems. This reduction is partly due to less soil compaction, higher organic matter turnover, and cooler microclimates, all of which influence microbial respiration and CH₄ dynamics (Jose, 2009).

**6.4 Biochar Integration**

Biochar, a stable form of carbon-rich material produced through the pyrolysis of organic matter, offers a powerful tool to enhance GHG mitigation when integrated into agroforestry systems. It acts as a long-lasting soil amendment, improving soil structure, nutrient retention, microbial habitat, and carbon stabilization. In East African agroforestry systems, the application of biochar derived from agroforestry residues led to additional sequestration of up to 2 t C ha⁻¹ yr⁻¹, while also increasing crop yields by 30–70% due to enhanced nutrient and water holding capacity (World Agroforestry Centre, 2021). Furthermore, biochar has been shown to reduce N₂O emissions by 20–50% and suppress CH₄ formation, making it an effective strategy for low-emission, high-resilience agroforestry. When combined with tree litter, manure, and mulching practices, biochar improves the sorption of labile organic compounds, thereby promoting long-term SOC stabilization and reducing leaching of reactive nitrogen species.

Agroforestry systems are dynamic landscapes that not only store carbon in biomass and soils but also regulate GHG fluxes through complex ecological interactions. The evidence from Net Ecosystem Exchange (NEE) studies confirms that well-managed systems function as net carbon sinks. Simultaneously, agroforestry has proven effective in reducing N₂O and CH₄ emissions, especially under low-input, organically managed, and species-diverse configurations. The integration of biochar further amplifies these benefits, enhancing soil health while locking away stable forms of carbon for decades or longer. As agroforestry scales up globally, a deeper understanding of these GHG dynamics is essential for refining carbon accounting methodologies and designing effective climate-smart interventions.

**7. Methodologies for Assessing Carbon Sequestration**

As agroforestry emerges as a central strategy for climate change mitigation and sustainable land use, accurate and reliable assessment methodologies are essential. Quantifying carbon sequestration in agroforestry systems informs carbon credit schemes, policy frameworks, climate-smart agricultural planning, and scientific understanding of biogeochemical cycles. However, the complexity of these systems—due to diverse tree-crop-livestock interactions, spatial heterogeneity, and temporal dynamics—demands a multi-method approach that combines field data, laboratory analysis, modeling, and remote sensing.

**7.1 Allometric Equations**

Allometric equations are the most commonly used tools for estimating aboveground biomass (AGB) and associated carbon stocks. These equations relate tree biomass to easily measurable parameters such as diameter at breast height (DBH), tree height, and wood density. The choice of equation greatly affects accuracy, as allometry is species-, region-, and age-specific (Chave et al., 2014). For instance, in tropical agroforestry systems, generalized allometric models developed for moist and dry forests can be applied, but site-specific calibration improves precision. The biomass carbon content is typically assumed to be 45–50% of dry biomass, although this can vary depending on species and wood type. Tools such as GlobAllomeTree and IPCC Tier 2 guidelines provide regionally adapted allometric models, helping standardize biomass estimations across different agroforestry types.

**7.2 Soil Sampling and Laboratory Analysis**

Estimating soil organic carbon (SOC)—one of the largest and most persistent carbon pools in agroforestry systems—requires rigorous soil sampling protocols. Samples are typically collected at different soil depths (e.g., 0–30 cm, 30–60 cm, 60–100 cm) to capture vertical distribution patterns.

Common analytical methods include:

* **Dry combustion (Elemental analyzer/CHN analyzers)** – Highly accurate and widely accepted for scientific studies.
* **Walkley-Black method** – A more accessible wet-oxidation technique used in many developing regions, though it may underestimate total SOC by up to 30% (Nelson & Sommers, 1996).

The paired plot design, where agroforestry plots are compared with adjacent monoculture or baseline systems, provides the most reliable estimate of net SOC change attributable to tree integration (Nair et al., 2010).

**7.3 Remote Sensing and GIS**

With advancements in satellite technology, remote sensing (RS) and geographic information systems (GIS) have become indispensable tools for assessing carbon dynamics over large spatial and temporal scales. Remote sensing enables monitoring of:

* Canopy cover
* Vegetation indices (e.g., NDVI, EVI)
* Land-use change
* Biomass density

Satellites like Landsat, Sentinel-2, and MODIS, as well as LiDAR and UAV (drone) systems, provide data at varying resolutions. LiDAR, in particular, excels at capturing three-dimensional vegetation structure, allowing detailed estimation of both above- and below-canopy biomass. GIS-based integration of RS data with field-based carbon estimates allows regional carbon accounting, spatial modeling of sequestration potential, and hotspot identification for conservation or restoration interventions (Zomer et al., 2016).

**7.4 Simulation and Carbon Models**

To complement empirical measurements, carbon simulation models project carbon fluxes, stocks, and sequestration trajectories under varying scenarios. These models are invaluable for ex-ante analysis, long-term forecasting, and policy design.

Commonly used models include:

* **CO2FIX:** Simulates biomass and SOC dynamics in forest and agroforestry systems over long time frames. Useful for carbon accounting in Clean Development Mechanism (CDM) projects.
* **CENTURY:** A process-based ecosystem model that simulates SOC changes based on climate, crop management, and residue input.
* **COMAP (Carbon Monitoring and Action Project):** Focuses on project-level carbon accounting, allowing evaluation of sequestration benefits in land use projects.

These models require detailed input on climate, soil, land use, species, and management and often incorporate IPCC Tier 2 and Tier 3 methodologies for improved accuracy (Paustian et al., 2002).

**7.5 Permanent Sample Plots**

Permanent sample plots (PSPs) are fixed locations established for long-term monitoring of biomass accumulation, carbon fluxes, and SOC dynamics. These plots provide:

* Baseline data for temporal comparisons
* High-resolution tracking of tree growth rates
* Repeated measurements under consistent methodologies

Establishing PSPs in diverse agroforestry systems across climatic gradients supports meta-analyses, enhances model validation, and informs regional sequestration estimates. PSP data are particularly useful for understanding successional changes, rotation cycles, and carbon residence times (Kumar & Nair, 2011).

**7.6 Life Cycle Assessment (LCA)**

Life Cycle Assessment (LCA) offers a comprehensive framework for assessing the net GHG balance of agroforestry-derived products, from cradle-to-grave. LCA considers:

* Upstream emissions from inputs (fertilizers, energy, transport)
* On-farm sequestration and emissions (biomass, SOC, CH₄, N₂O)
* Downstream impacts including processing, packaging, and distribution

Although LCA provides valuable insight into product-level carbon footprints, many current LCAs underestimate agroforestry benefits because they:

* Ignore soil carbon dynamics
* Overlook multifunctionality (e.g., co-benefits of shade, erosion control)
* Lack integration with GHG flux models

Emerging hybrid approaches combining LCA with NEE, remote sensing, and simulation models are helping address these gaps (Brandão et al., 2011). Robust methodologies for assessing carbon sequestration in agroforestry systems are fundamental to their inclusion in carbon markets, climate mitigation strategies, and sustainable land management policies. While field-based approaches like allometry and soil sampling remain foundational, technological innovations in remote sensing, GIS, and carbon modeling are expanding the scope and scalability of carbon accounting. Moreover, long-term monitoring through permanent plots and life cycle assessments enriches our understanding of system-level performance and carbon efficiency. Integrating these tools into national greenhouse gas inventories, climate-smart agriculture programs, and voluntary carbon markets will help unlock the full potential of agroforestry in addressing climate change.

**8. Agroforestry in Climate Change Mitigation**

Agroforestry stands at the forefront of nature-based solutions to climate change. By integrating trees with crops and/or livestock, agroforestry systems directly sequester atmospheric carbon dioxide (CO₂), enhance land productivity, and reduce greenhouse gas (GHG) emissions associated with conventional agricultural practices. The approach is now increasingly embedded in international climate agreements, national mitigation strategies, and carbon market mechanisms. Beyond its biophysical impacts, agroforestry delivers multiple co-benefits, such as improved biodiversity, water regulation, food security, and rural livelihoods—making it one of the most cost-effective and socially inclusive solutions to address both climate change mitigation and adaptation (Jose, 2009; Nair & Nair, 2023).

**8.1 Carbon Sequestration Potential**

Agroforestry systems act as carbon sinks by storing carbon in tree biomass, soils, litter, and root systems. A growing body of global meta-analyses underscores agroforestry’s massive carbon sequestration potential if scaled appropriately. According to Zomer et al. (2024), global expansion of agroforestry across suitable landscapes could sequester 4–19 petagrams (Pg) of carbon (equivalent to 14.7–69.7 Pg CO₂) by 2050, depending on land-use policy, adoption rates, and socioeconomic constraints. The sequestration potential of different system types is significant:

* **Silvopasture:** 26–42 Gt CO₂-e from 2020 to 2050
* **Tree intercropping:** ~20 Gt CO₂-e
* **Windbreaks and hedgerows:** 5–10 Gt CO₂-e combined
* This mitigation capacity rivals that of large-scale afforestation, with the added benefit of maintaining or increasing agricultural productivity on the same land. Moreover, unlike monoculture forestry, agroforestry systems often begin delivering measurable benefits within 5–10 years of establishment, making them suitable for medium-term climate targets under the Paris Agreement.

**8.2 GHG Offsetting and Emission Reduction**

Agroforestry contributes to climate change mitigation not only by removing CO₂ from the atmosphere but also by reducing emissions from land-based activities. The inclusion of trees in farming systems alters GHG dynamics through multiple pathways:

* Nitrous oxide (N₂O) emissions from fertilized fields can be reduced by up to 36%, particularly when nitrogen-fixing trees (e.g., *Leucaena leucocephala*, *Faidherbia albida*) are present and synthetic inputs are minimized (Sánchez-Navarro et al., 2022).
* On-farm biomass production reduces dependence on wood from natural forests, thereby curbing deforestation and associated carbon losses.
* Tree shade improves microclimate, which lowers irrigation needs, reduces evapotranspiration, and conserves soil moisture, contributing to energy savings in water pumping and irrigation infrastructure.
* Certain agroforestry systems enhance surface albedo and create localized cooling effects, especially in arid and semi-arid landscapes (Lasco et al., 2014).

Agroforestry also allows farmers to substitute energy-intensive inputs, such as synthetic fertilizers, with natural nutrient cycling, further reducing indirect GHG emissions.

**8.3 Integration with Climate Strategies**

Recognizing its mitigation potential, agroforestry has been increasingly integrated into climate policies and frameworks at both national and international levels.

* Under REDD+ (Reducing Emissions from Deforestation and Forest Degradation), agroforestry qualifies as an eligible land-use strategy, particularly in buffer zones and degraded lands.
* Many countries have included agroforestry in their Nationally Determined Contributions (NDCs) under the Paris Agreement, citing it as a priority sector for emissions reduction and carbon enhancement (FAO, 2022).
* Low Emission Development Strategies (LEDS) increasingly incorporate agroforestry as a scalable, low-cost mitigation option that aligns with broader development goals.

For instance, India’s National Agroforestry Policy (2014) aims to increase tree cover on farmland by incentivizing tree planting, simplifying regulations, and mainstreaming agroforestry in rural development. Similarly, Kenya and Brazil have actively promoted agroforestry through national action plans that emphasize both carbon benefits and rural resilience (Nair & Nair, 2023). Such policy integrations not only facilitate access to climate finance (e.g., from the Green Climate Fund) but also support carbon credit generation under voluntary and compliance markets.

**8.4 Co-Benefits and Cost-Effectiveness**

Compared to other mitigation options—such as renewable energy transitions or large-scale reforestation—agroforestry offers unique advantages in terms of cost-effectiveness, feasibility, and livelihood co-benefits.

* Agroforestry practices typically have lower opportunity costs, as they do not require land-use conversion and can be implemented on existing farms.
* Carbon returns begin accruing earlier (often within 5 years), compared to forests that may take decades to reach sequestration maturity.
* Systems such as homegardens and silvopastures enhance food security, nutrition, and diversified income, thereby reinforcing climate resilience.

Taylor et al. (2022) found that incorporating trees into dairy systems in Central America led to a 21% reduction in product-level carbon footprints, while improving forage quality and milk yields. Similarly, Orefice et al. (2025) reported carbon footprint reductions up to 45% in silvopastoral beef systems in the southeastern United States. These integrated benefits make agroforestry a compelling option for inclusion in climate-smart agriculture portfolios, especially in smallholder-dominated landscapes of Asia, Africa, and Latin America.

**9. Agroforestry in Climate Adaptation**

While agroforestry is widely acknowledged for its role in climate change mitigation, its value in enhancing climate resilience and adaptation is equally significant. Agroforestry systems strengthen the ability of agroecosystems and rural communities to withstand and recover from climate shocks such as heatwaves, droughts, floods, and erratic rainfall. These systems work by improving microclimatic conditions, enhancing water retention, providing diversified income sources, and fostering biodiversity—each of which plays a critical role in supporting sustainable and climate-resilient agriculture (Lasco et al., 2014; Nair & Nair, 2023).

**9.1 Microclimate Regulation**

Agroforestry improves local microclimate conditions, providing thermal comfort for crops, livestock, and even farmers. Trees and shrubs in agroforestry systems create shaded environments, reduce wind speeds, and increase humidity—all of which buffer crops from temperature extremes and evaporative stress. Studies in Brazilian integrated crop-livestock-forestry systems show that tree cover can reduce air and soil temperatures by 2–4°C, significantly reducing heat stress in livestock and enhancing photosynthetic efficiency in heat-sensitive crops (Gebrekirstos, 2022). In particular, black-globe temperatures—used as a proxy for heat stress in animals—were observed to drop by up to 26% under tree cover compared to open pastures (Sharma et al., 2023). This thermal buffering not only stabilizes yields but also reduces water demand, helping smallholder systems adapt to increasing temperature variability due to climate change.

**9.2 Hydrological Buffering**

Agroforestry systems enhance hydrological functions by improving rainwater infiltration, reducing runoff, and increasing soil water-holding capacity. These characteristics are critical in both drought-prone and flood-prone regions, where climate extremes are intensifying. The deep and extensive root systems of trees break up compacted soil layers, facilitating water percolation into subsoil layers. In addition, leaf litter and organic matter accumulation enhance soil structure and porosity, which further boosts water retention capacity (Terasaki Hart et al., 2023). Such improvements can reduce surface runoff by 20–50%, thereby minimizing erosion and downstream sedimentation. Moreover, agroforestry systems increase groundwater recharge, creating a buffer during dry spells and reducing reliance on irrigation. In East African highlands, farms practicing contour hedgerows and boundary agroforestry observed 40% higher soil moisture during dry periods compared to monoculture plots (FAO, 2022).

**9.3 Livelihood Diversification and Risk Reduction**

Agroforestry significantly enhances farm income stability and household resilience by diversifying sources of food, fuel, fodder, and marketable products. This income and subsistence diversification reduces the economic vulnerability of smallholders, particularly in the face of climate-induced crop failure, market price volatility, or pest outbreaks. Tree products such as fruits, nuts, timber, medicinal plants, and non-timber forest products (NTFPs) offer off-season and multi-year revenue streams, reducing dependence on single-season crops. Furthermore, many tree species are more drought-tolerant and less sensitive to short-term weather fluctuations, providing a natural safety net during adverse seasons. Empirical data from Kenya during the 2010–2011 drought shows that households practicing agroforestry achieved 150% higher crop yields than non-adopters, owing to better microclimate and soil moisture conditions (Lasco et al., 2014). Similarly, in South Asia, farmers reported improved household food availability and nutrition security from agroforestry-based homegardens during lean agricultural periods (Kumar & Kunhamu, 2021).

**9.4 Ecosystem Services and Biodiversity**

Agroforestry enhances the ecological resilience of landscapes by promoting ecosystem services such as pollination, pest control, nutrient cycling, and seed dispersal. It supports both functional and structural biodiversity, thereby making agroecosystems more resistant to climate-related stressors.

* Pollinators and pest predators benefit from the diverse habitats provided by agroforestry vegetation, including tree canopies, understorey shrubs, and flower-rich margins.
* Agroforestry also aids in situ conservation of native and endangered species by creating micro-refugia and habitat continuity in fragmented agricultural landscapes (Nair & Nair, 2023).
* Practices such as alley cropping, homegardens, and silvopasture facilitate species richness and structural complexity, improving landscape connectivity and fostering ecological redundancy, a key principle in resilient ecosystems.

For instance, studies in West Africa show that traditional agroforestry parklands contribute to genetic conservation of wild fruit trees such as *Vitellaria paradoxa* (shea) and *Parkia biglobosa*, which are essential for both local diets and ecosystem functioning (Bayala et al., 2008). Furthermore, increased biodiversity under agroforestry reduces the prevalence of invasive pests and pathogens, thus acting as a biological insurance against crop failures—a growing concern under changing climate conditions.

**10. Challenges and Limitations**

 Agroforestry offers well‑documented climate‑smart benefits, but scaling it from isolated successes to landscape or national levels remains difficult. The constraints fall into five broad categories: knowledge gaps, insecure tenure, finance, biophysical limits, and weak measurement, reporting, and verification (MRV) systems.

**10.1 Knowledge and Capacity Gaps**

Many smallholders are unaware that trees can raise soil organic carbon, buffer temperature shocks, or qualify for carbon payments. Even where interest exists, farmers often lack practical skills for species selection, spacing, coppicing, grafting, and pruning suited to local markets and climates. Extension services are thinly staffed—often fewer than one officer per 3,000 farmers in sub‑Saharan Africa—hampering peer learning and rapid troubleshooting (Kiptot & Franzel, 2012). Limited local research on tree–crop interactions under future climate scenarios compounds the problem, leading to sub‑optimal designs and disappointing early results.

**10.2 Land Tenure Insecurity**

Tree planting is a long‑term investment; farmers hesitate when land rights are unclear, seasonal, or contested. In communal rangelands or rental agreements, tenants rarely receive compensation for trees left behind, suppressing adoption (Deininger & Feder, 2009). Innovative arrangements—e.g., joint‐benefit contracts, community by‑laws that recognise tree ownership, and streamlined permitting for on‑farm timber harvest—have improved uptake in Kenya and Viet Nam, but remain exceptions (Minang et al., 2015).

**10.3 Financial Barriers**

Up‑front costs for seedlings, fencing, and extra labour can reach US $350–500 ha⁻¹ prohibitive outlay for resource‑constrained households (Pattanayak et al., 2014). Trees may not yield cash for 3–7 years, creating a “valley of death” between investment and return. Most smallholders lack collateral for bank loans, and carbon‑credit programmes often impose high transaction fees and verification costs that favour large projects. Blended finance—combining grants for establishment with low‑interest loans or results‑based carbon payments—has shown promise but is not yet widely accessible (FAO, 2022).

**10.4 Biophysical Constraints**

Agroforestry is not a panacea for every landscape. Poor, saline, or highly acidic soils; annual rainfall below 400 mm; or frequent cyclones can cause high seedling mortality. In fertile zones, aggressive root competition or excessive shade from poorly placed trees can cut maize yields by 15–30 % (Duguma et al., 2014). Species provenance matters: drought‑tolerant, nitrogen‑fixing trees such as *Faidherbia albida* or *Prosopis juliflora* thrive where exotics like *Grevillea robusta* fail, yet planting material for these climatically “right” species is often scarce.

**10.5 Monitoring and Verification Limitations**

Crediting agroforestry in carbon markets or national GHG inventories requires robust measurement, reporting, and verification (MRV). Smallholder projects struggle with heterogeneous plots, dispersed geography, and limited internet connectivity. Current protocols under‑report below‑ground biomass, deep‑soil carbon (>1 m), and non‑CO₂ fluxes (N₂O, CH₄), undervaluing true mitigation benefits (Nair et al., 2023). Harmonised, low‑cost approaches—e.g., smartphone apps that couple GPS data with simplified allometry and satellite imagery—are emerging but need wider testing and institutional acceptance.

*In sum*, bridging these technical, institutional, and socioeconomic gaps is critical for mainstreaming agroforestry into climate and development agendas. Targeted investments in extension, secure tenure, blended finance, climate‑smart species selection, and farmer‑friendly MRV could unlock the full mitigation‑adaptation potential of agroforestry.

**11. Research Priorities**

Agroforestry holds immense promise as a climate-smart land-use strategy, but realizing its full potential for carbon sequestration, climate adaptation, and livelihood resilience depends on filling key knowledge gaps. While empirical studies have established general trends and benefits, more granular, site-specific, and long-term research is required—particularly under changing climatic and socioeconomic conditions. Priority research areas must include deep soil carbon monitoring, biochar integration, decision-support modeling, social equity, and MRV innovations (FAO, 2022; Nair & Nair, 2023).

**11.1 Deep Soil Carbon Monitoring**

Soil organic carbon (SOC) storage below 30 cm—and especially beyond 1 meter—remains poorly characterized in most agroforestry studies, despite emerging evidence suggesting that 20–50% of total SOC may reside below this depth (Minasny et al., 2017). Deep-rooted trees such as *Faidherbia albida*, *Prosopis juliflora*, and *Acacia spp.* may enhance carbon inputs to deep soil layers through root turnover and rhizodeposition. New research must use deep-core sampling (to 2 meters or more) and carbon isotope tracing (e.g., δ¹³C) to quantify long-term stabilization of carbon in subsoil mineral fractions (Kätterer et al., 2019). Establishing multi-decadal experimental plots across diverse agroecological zones—including degraded lands, semi-arid regions, and tropical wetlands—will be essential for tracking slow but critical changes in deep soil carbon stocks.

**11.2 Integration of Biochar and Agroforestry**

Biochar—a stable, carbon-rich material produced from biomass pyrolysis—offers a powerful tool for enhancing soil fertility and long-term carbon sequestration. When co-applied with agroforestry residues (e.g., pruned branches, husks, shells), biochar can improve nutrient retention, microbial activity, and water holding capacity, especially in degraded or sandy soils (Lehmann et al., 2021).

Research must focus on:

* Optimal biochar feedstocks and application rates across soil types
* Synergistic interactions between biochar, tree roots, and microbial communities
* Co-benefits in drought resilience, yield stability, and GHG mitigation

Field-scale trials in East Africa, India, and Latin America suggest additional sequestration of 1–2 t C ha⁻¹ yr⁻¹ from biochar–agroforestry systems, but more region-specific evaluations are needed (World Agroforestry Centre, 2021).

**11.3 Modeling and Decision Tools**

Agroforestry systems are biologically and economically complex, making decision-making difficult without robust tools. Most simulation models currently used—such as CENTURY, CO2FIX, and AGB-BGC—lack the capacity to simulate tree–crop–livestock interactions in a dynamic climate and market context (Kumar et al., 2023).

Future modelling tools must:

* Be region- and species-specific
* Integrate climate projections, soil variability, and management options
* Link carbon flows to economic returns, resilience indicators, and policy incentives

User-friendly interfaces and mobile applications for these models would also improve uptake among practitioners and extension agents.

**11.4 Socioeconomic and Equity Analyses**

Agroforestry’s impacts vary by gender, landholding size, wealth status, and cultural background. Women and marginalized communities often face limited access to tree tenure, training, or market opportunities (Kiptot & Franzel, 2012). Additionally, the economic viability of agroforestry under various carbon pricing schemes, payment for ecosystem services (PES), or green certification programs remains understudied.

Key priorities include:

* Disaggregated impact assessments by gender and social group
* Cost–benefit analyses of different agroforestry models under realistic conditions
* Risk assessments considering labor availability, land tenure, and market access

Such research will support more inclusive policy design, reducing the risk of inadvertently widening equity gaps in climate finance distribution.

**11.5 MRV Innovation**

The expansion of agroforestry into climate markets and national GHG inventories depends on cost-effective, scalable, and transparent MRV systems. Current protocols often underreport below-ground biomass, non-CO₂ GHGs, and sub-field heterogeneity, reducing credibility and financial returns (Nair et al., 2023).

Next-generation MRV research should:

* Develop open-source toolkits for low-cost field measurements
* Integrate remote sensing (e.g., Sentinel-2, LiDAR) with ground-truthing
* Use blockchain and sensor-based technologies for transparent data sharing
* Automate data pipelines from farmer reporting to carbon registries

Pilot projects using these technologies are emerging in Kenya, Brazil, and India, but need policy support and international harmonization.

**Conclusion**

Agroforestry represents a holistic and transformative approach to land management that addresses the intertwined crises of climate change, land degradation, and rural vulnerability. By integrating trees into farming systems, agroforestry sequesters carbon efficiently while simultaneously improving soil health, conserving water, enhancing biodiversity, and diversifying livelihoods. This review confirms that agroforestry systems—particularly silvopastoral, alley cropping, windbreaks, and homegardens—consistently outperform monocultures in both carbon storage and resilience outcomes. Regional variability in carbon dynamics underscores the need for context-specific interventions and adaptive management. While technological advancements in carbon measurement, remote sensing, and simulation modeling have improved our understanding of agroforestry's climate impact, challenges persist. These include gaps in long-term data, limited access to MRV tools for smallholders, financial constraints, and insecure land tenure. Policy integration, such as inclusion in Nationally Determined Contributions (NDCs) and Low Emission Development Strategies (LEDS), has expanded, yet practical implementation remains limited. Moving forward, future research must prioritize deep soil carbon analysis, socio-economic equity assessments, and synergistic innovations like biochar. Equally important is the development of inclusive finance and knowledge-sharing platforms that empower smallholders to adopt and sustain agroforestry practices. In a world increasingly defined by climate volatility and food insecurity, agroforestry offers a scalable, equitable, and ecologically sound solution. Its multifunctional benefits make it not only a climate mitigation tool but also a pillar of sustainable development. To unlock its full potential, global and local authorities must collaborate across science, policy, and practice to embed agroforestry in mainstream climate and land-use agendas.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing interests

Authors have declared that no competing interests exist.

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