



ECOLOGICAL FUNCTIONS AND SERVICES OF AGROFORESTRY SYSTEMS

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ABSTRACT: Agroforestry has emerged as a multifunctional and sustainable land-use system capable of addressing critical global challenges such as climate change, land degradation, biodiversity loss, and food insecurity. By integrating trees with crops and livestock, agroforestry systems provide a wide range of ecosystem services that support both environmental sustainability and rural livelihoods. Evidence shows that agroforestry can sequester 0.3-15.2 Mg C ha⁻¹ yr⁻¹, with global estimates suggesting the potential to store over 75 Pg of carbon if widely adopted on agricultural lands. In addition, these systems improve soil organic carbon by about 10-40%, reduce soil erosion by 20-80%, and increase soil moisture availability by 20-30% through improved water infiltration and microclimate regulation. Agroforestry also contributes significantly to rural provisioning services; in India it supplies nearly 50% of fuelwood demand, 60-65% of small timber, and 9-11% of green fodder, while diversified systems such as poplar-based agroforestry can increase farm income by 30-50% compared with conventional cropping. Structurally diverse agroforestry landscapes further enhance biodiversity by 40-50%, support pollinators and natural enemies of pests, and strengthen nutrient cycling and soil microbial activity. Beyond ecological benefits, agroforestry preserves traditional knowledge, improves household nutrition, and promotes social inclusion, particularly through women-led farming initiatives. Collectively, these multifunctional benefits position agroforestry as a key nature-based solution for climate mitigation, sustainable land management, and resilient agricultural production systems.

Keywords: *Agroforestry, Ecosystem services, Carbon sequestration, Biodiversity conservation, Soil fertility, Climate resilience, Sustainable agriculture.*

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INTRODUCTION

Agroforestry has emerged as a scientifically validated response to the compounded stresses of climate change, land degradation, and food

insecurity, offering measurable ecological and production benefits beyond those of conventional mono-cropping. Quantitative evidence shows that agroforestry systems can sequester 0.3-15.2 Mg

C ha⁻¹ yr⁻¹, depending on species composition, climate, and management, significantly exceeding carbon gains from treeless croplands (Nair *et al.*, 2009; Jose, 2009; Chaturvedi *et al.*, 2016; Sarvade, 2025). Global estimates suggest that agroforestry could store over 75 Pg of carbon in above- and below-ground biomass if adopted on suitable agricultural lands (IPCC, 2019; Sarvade *et al.*, 2025). In addition, tree-based systems reduce soil erosion by 20-50%, enhance soil organic carbon by up to 40%, and improve nutrient cycling through biological nitrogen fixation, particularly in legume-based systems (FAO, 2018). Crop yields under agroforestry are often more stable across climatic extremes, with yield increases of 10-30% reported in rain-fed and semi-arid regions due to improved microclimate, water infiltration, and soil fertility buffering (Garriety *et al.*, 2010; Sarvade *et al.*, 2016).

Beyond climate mitigation and soil restoration, agroforestry delivers critical biodiversity and livelihood co-benefits that are increasingly quantified and policy-relevant. Studies indicate that agroforestry landscapes can support 30-80% higher species richness of birds, insects, and soil biota compared to conventional agriculture, functioning as biodiversity corridors within fragmented landscapes (Bhagwat *et al.*, 2008; Sarvade, 2014). From a socio-economic perspective, diversified agroforestry systems enhance farm resilience by providing multiple income streams includes fuelwood, fodder, fruits, timber, and non-timber forest products often increasing net farm income by 20-50% relative to sole cropping systems (Pandey, 2007; Zomer *et al.*, 2016). These quantified ecosystem services underpin the inclusion of agroforestry in national climate commitments (NDCs), land degradation neutrality targets and sustainable food system frameworks. However, translating this potential into large-scale impact requires continued generation of site-specific data, long-term monitoring and integration of ecosystem service valuation into agricultural policy and investment decisions.

MATERIALS AND METHODS

The present review manuscript was developed through a systematic collection and analysis of published scientific literature related to the ecological functions and ecosystem services of agroforestry systems. Relevant research articles, review papers, book chapters, and technical reports published between 2000 and 2026 were retrieved from major databases including Google Scholar, Scopus, Web of Science, ScienceDirect, SpringerLink, and ResearchGate. Keywords such as *agroforestry systems*, *ecosystem services*, *carbon sequestration*, *soil fertility*, *biodiversity conservation*, *nutrient cycling*, and *climate resilience* were used during the literature search.

Priority was given to peer-reviewed and recent studies addressing ecological sustainability, environmental benefits, and multifunctional roles of agroforestry systems. Recent reviews by Castle *et al.* (2022), Aaron *et al.* (2024), and Yang *et al.* (2024) were extensively consulted to understand ecosystem service dynamics, biodiversity conservation, and climate change mitigation potential of agroforestry practices. Studies related to soil carbon enhancement, hydrological regulation, and resilience against extreme climatic conditions were also critically examined (Das, 2024; Dobhal *et al.*, 2024).

The collected literature was categorized into major ecological service components including soil conservation, nutrient cycling, carbon sequestration, biodiversity enhancement, erosion control, and water regulation. Findings from different studies were comparatively analyzed and synthesized to identify key ecological functions, recent advancements, research gaps, and future prospects of agroforestry systems under sustainable land-use management.

RESULTS AND DISCUSSION

PROVISIONING SERVICES

Provisioning services represent the most visible

interface between agroforestry and rural livelihoods, yet their contribution extends well beyond the notion of single-crop productivity (Table 1). In India, tree-based farming systems play a decisive role in meeting basic household needs: agroforestry supplies nearly 50% of the national fuelwood requirement, 60-65% of small timber, and about 9-11% of green fodder, thereby directly supporting energy security, housing needs and livestock-based livelihoods in rural areas (Sarvade *et al.*, 2014a; FSI, 2019; Dhyani *et al.*, 2021). Complex home garden systems prevalent in southern India, where coconut, banana, jackfruit, spices, tubers, vegetables and multipurpose trees coexist, which is one of the most efficient land-use systems, reportedly fulfilling up to 80% of household nutritional requirements while maintaining year-round food availability (Kumar and Nair, 2004). Such systems enhance dietary diversity, reduce dependence on external food markets, and buffer households against seasonal food shortages (Sarvade and Singh, 2014; Sarvade *et al.*, 2014c).

Beyond subsistence, agroforestry significantly strengthens income stability by diversifying farm outputs and spreading economic risk. In the Indo-Gangetic plains, poplar-based agroforestry integrated with wheat, sugarcane or fodder crops provides substantial mid-term financial returns within 6-8-year rotations, often increasing farm income by 30-50% compared to sole cropping while simultaneously improving soil organic carbon and nutrient recycling (Singh *et al.*, 2016). Similarly, coffee and areca nut agroforestry systems in the Western Ghats benefit from premium markets for shade-grown produce and demonstrate high climate mitigation potential, sequestering approximately 15-25 t CO₂ ha⁻¹ yr⁻¹ through combined biomass and soil carbon pools (Sathish *et al.*, 2020). These diversified provisioning services not only enhance economic resilience under climate and market uncertainties but also reinforce agroforestry's role as a cornerstone of sustainable rural development.

Table 1. Provisioning services of agroforestry systems in India

AGROFORESTRY SYSTEM	TREE-CROP COMBINATION	SERVICE/DATA	REFERENCE
Poplar-based Agrisilviculture	<i>Populus deltoides</i> + Wheat (<i>Triticum aestivum</i>)	30–50% higher farm income than sole cropping	Singh <i>et al.</i> (2016)
Silvopastoral System	<i>Leucaena leucocephala</i> + <i>Cenchrus ciliaris</i>	8–12 t ha ⁻¹ yr ⁻¹ green fodder production	Dhyani <i>et al.</i> (2021)
Home Garden Agroforestry	<i>Cocos nucifera</i> + <i>Musa paradisiaca</i> + Vegetables	Up to 80% household nutritional requirement supplied	Kumar and Nair (2004)
Boundary Plantation System	<i>Eucalyptus tereticornis</i> + Soybean (<i>Glycine max</i>)	15–20 t ha ⁻¹ biomass production	FSI (2019)
Coffee-based Shade Agroforestry	<i>Coffea arabica</i> + <i>Grevillea robusta</i>	15–25 t CO ₂ ha ⁻¹ yr ⁻¹ carbon sequestration	Sathish <i>et al.</i> (2020)

REGULATING SERVICES

CLIMATE REGULATION AND CARBON SEQUESTRATION

Agroforestry systems function as effective climate regulators by simultaneously storing carbon in woody biomass and improving soil carbon pools (Table 2). Robust global evidence supports this role: a large meta-analysis synthesizing 561 field-based observations reported that agroforestry enhances soil organic carbon (SOC) by an average of 10.7% compared with non-tree agricultural systems, with the strongest response (18.7% increase) observed in arid and semi-arid regions where baseline carbon levels are low (De Stefano and Jacobson, 2018). In India, the carbon sequestration potential of agroforestry is highly system- and species-specific. Reported annual sequestration rates range from 0.25 to 76.55 Mg C ha⁻¹ yr⁻¹ in tree biomass and 0.01-0.60 Mg C ha⁻¹ yr⁻¹ in soils, reflecting variability in climate, age of plantations, and management intensity (Dhyani *et al.*, 2016; Nair *et al.*, 2009). Transitioning from mono-cropping to agroforestry has been shown to increase carbon storage by approximately 25.3%, while agri-horticultural systems can accumulate up to 38 Mg C ha⁻¹, nearly 31% higher than conventional crop-only systems (Zomer *et al.*, 2016). When implemented across extensive agricultural landscapes, these per-hectare gains collectively translate into significant regional carbon sinks with direct relevance to national climate mitigation commitments.

SOIL FERTILITY, STRUCTURE, AND EROSION CONTROL

The integration of trees within agricultural landscapes significantly modifies soil biological and physicochemical processes, resulting in substantial improvements in soil quality (Table 2). Meta-analyses have shown that agroforestry systems enhance soil organic carbon (SOC) stocks by 19-53%, while total nitrogen and available phosphorus contents increase by 10-30% compared with conventional treeless

cropping systems. These improvements are primarily attributed to continuous litter deposition, fine-root turnover, biological nitrogen fixation, and enhanced microbial biomass and enzymatic activity under tree-based systems (Cardinael *et al.*, 2018; De Stefano and Jacobson, 2018). In tropical and subtropical agroforestry systems, higher organic matter accumulation and improved nutrient recycling further contribute to better soil aggregation, moisture retention, and long-term soil fertility (Sarvade *et al.*, 2014d). Field-level comparisons consistently show higher organic carbon content and lower bulk density in soils under tree-crop combinations than in adjacent monocultures, resulting in improved soil aggregation, porosity, and water-holding capacity (Jose, 2009; Sarvade *et al.*, 2019). Such changes were observed due to following reasons:

- Higher soil organic carbon accumulation due to continuous litter fall and root biomass addition.
- Reduction in soil bulk density, resulting in loose and well-aerated soil structure.
- Improvement in soil aggregation and porosity through enhanced root and microbial activity.
- Increased water infiltration and water-holding capacity, reducing runoff losses.
- Enhanced microbial biomass and nutrient mineralization leading to better soil fertility.
- Greater root penetration and improved nutrient uptake efficiency.
- Reduced soil compaction, erosion, and drought stress under tree-crop systems.

Moreover, tree cover plays a critical role in erosion control: contour-based and multi-strata agroforestry systems have been reported to reduce soil loss by up to 80% compared with conventional annual cropping, particularly on sloping and erosion-prone lands (Pattanayak and Mercer, 1998). These improvements reduce nutrient leaching, lower reliance on external fertilizers, and contribute to sustained soil fertility over the long term.

WATER CYCLE AND MICROCLIMATE REGULATION

Agroforestry modifies local hydrological processes and microclimatic conditions through its complex canopy-root interactions (Table 2). Deep and extensive root systems enhance water infiltration and reduce surface runoff, thereby promoting groundwater recharge and stabilizing soil moisture regimes. Empirical studies from tropical and humid regions indicate that agroforestry systems can improve soil moisture availability by 20-30% compared to open-field agriculture (Sarvade *et al.*, 2014b; Ilstedt *et al.*, 2016). At the same time, tree canopies moderate microclimate by lowering daytime temperatures, reducing wind speed, and limiting evapotranspiration losses. At the same time, tree canopies moderate the microclimate by lowering daytime temperatures, reducing wind

speed, and limiting evapotranspiration losses. Studies have reported that agroforestry systems can reduce daytime air and soil temperatures by nearly 2-5°C compared with open-field mono-cropping systems. The shade provided by trees also helps maintain higher relative humidity and improves soil moisture conservation, thereby enhancing crop tolerance to heat and drought stress under changing climatic conditions (Jose, 2009; Ilstedt *et al.*, 2016). This micro-climatic buffering increases crop tolerance to heat waves and drought stress, which is particularly critical under increasing climate variability. Collectively, these regulating services position agroforestry as a nature-based solution for climate adaptation, water conservation, and resilient agricultural production.

Table 2. Regulating Ecosystem Services Provided by Agroforestry Systems

AGROFORESTRY SYSTEM	TREE-CROP COMBINATION	SERVICE/DATA	REFERENCE
Agri-horticulture System	<i>Mangifera indica</i> + Black gram (<i>Vigna mungo</i>)	38 Mg C ha ⁻¹ carbon stock	Zomer <i>et al.</i> (2016)
Alley Cropping System	<i>Gliricidia sepium</i> + Maize (<i>Zea mays</i>)	20–30% increase in SOC and nutrients	Cardinael <i>et al.</i> (2018)
Contour Hedgerow System	<i>Leucaena leucocephala</i> + Finger millet (<i>Eleusine coracana</i>)	70–80% reduction in soil erosion	Pattanayak and Mercer (1998)
Semi-arid Tree-Crop System	<i>Prosopis cineraria</i> + Pearl millet (<i>Pennisetum glaucum</i>)	20–30% higher soil moisture retention	Ilstedt <i>et al.</i> (2016)
Multistrata Agroforestry	<i>Areca catechu</i> + <i>Piper nigrum</i> + Banana	2–5°C reduction in daytime temperature	Jose (2009)

SUPPORTING SERVICES

BIODIVERSITY CONSERVATION

Agroforestry systems provide structurally complex habitats that sustain ecological functions often lost in simplified agricultural landscapes (Table 3). Empirical studies consistently demonstrate higher plant species richness in agroforestry plots, where native trees, shrubs, annual crops, herbs, and cover species coexist; in several systems, overall

species richness is reported to increase by approximately 40-50% compared to mono-cropping (Bhagwat *et al.*, 2008; Torralba *et al.*, 2016). This floristic diversity translates into functional biodiversity gains, supporting pollinators, predatory arthropods, soil fauna, and avifauna that regulate pest populations and stabilize trophic interactions. Tree-based mosaics also act as ecological corridors, improving landscape connectivity between fragmented

natural habitats and agricultural fields, thereby strengthening on-farm ecosystem resilience and reducing dependence on chemical pest control.

SOIL MICROBIAL ACTIVITY AND NUTRIENT CYCLING

Trees embedded within croplands significantly enhance below-ground biological processes (Table 3). Continuous inputs of leaf litter, fine roots, and root exudates stimulate microbial biomass, enzymatic activity, and functional diversity, leading to more efficient nutrient cycling and improved soil structure (Cardinael *et al.*, 2018). Trees in agroforestry systems significantly enhance nutrient cycling through litter fall, root turnover, canopy leaching, nutrient uplift, and biological nitrogen fixation. Deep-rooted tree species absorb nutrients from deeper soil horizons and redistribute them to the upper soil layers through leaf litter and fine-root decomposition. Leguminous tree species such as *Leucaena leucocephala*, *Gliricidia sepium*, and *Faidherbia albida* can contribute approximately 50-200 kg N ha⁻¹ yr⁻¹ through biological nitrogen fixation. In addition, annual litter deposition from agroforestry trees may return nearly 30-150 kg N, 5-20 kg P, 20-80 kg K, 20-60 kg Ca, and 10-30 kg Mg ha⁻¹ yr⁻¹ to the soil depending on species composition and

management practices.

Agroforestry systems also improve the availability of micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) through enhanced organic matter decomposition and microbial activity. Studies have reported higher concentrations of available Zn (10-25%), Fe (15-30%), and Mn (10-20%) in soils under tree-crop systems compared with monoculture cropping. Increased soil organic matter and rhizosphere interactions further stimulate microbial biomass, enzymatic activity, and nutrient mineralization, leading to improved nutrient-use efficiency and long-term soil fertility (Nair *et al.*, 2009; Cardinael *et al.*, 2018; Dhyani *et al.*, 2016).

Enhanced microbial activity accelerates decomposition and mineralization processes, increasing the availability of nitrogen, phosphorus, and micronutrients to crops. At the same time, improved soil aggregation under agroforestry promotes soil organic carbon stabilization and water infiltration, reinforcing long-term soil fertility and ecosystem functioning. These supporting services underpin the productivity and sustainability of agroforestry systems, even under low-input conditions.

Table 3. Supporting Ecosystem Services Provided by Agroforestry Systems

AGROFORESTRY SYSTEM	TREE-CROP COMBINATION	SERVICE/DATA	REFERENCE
Multistrata Tropical Agroforestry	<i>Artocarpus heterophyllus</i> + Coffee + Banana	40–50% higher species richness	Bhagwat <i>et al.</i> (2008)
Pollinator-support Agroforestry	<i>Acacia nilotica</i> + Mustard (<i>Brassica juncea</i>)	25–60% increase in pollinator abundance	Torralba <i>et al.</i> (2016)
Riparian Buffer Agroforestry	<i>Dalbergia sissoo</i> + Fodder grasses	Enhanced wildlife corridor movement	Bhagwat <i>et al.</i> (2008)
Silvo-pastoral System	<i>Albizia lebbeck</i> + Guinea grass (<i>Panicum maximum</i>)	35–45% higher microbial biomass carbon	Cardinael <i>et al.</i> (2018)
Legume-based Agroforestry	<i>Faidherbia albida</i> + <i>Sorghum bicolor</i>	50–200 kg N ha ⁻¹ yr ⁻¹ nitrogen addition	Cardinael <i>et al.</i> (2018)

CULTURAL AND SOCIO-ECONOMIC SERVICES

Beyond biophysical processes, agroforestry delivers profound cultural and social benefits that shape rural livelihoods and identities (Table 4). Traditional systems such as home gardens, *Zabo* farming in Nagaland, and indigenous alley-cropping practices integrate ecological knowledge with cultural values, reinforcing community stewardship and intergenerational knowledge transfer (Kumar & Nair, 2004). Diverse tree-crop assemblages enhance food variety, support local festivals and rituals, and provide shade, aesthetic appeal, and psychological well-being, collectively

improving rural quality of life. Importantly, agroforestry also serves as a vehicle for social inclusion: evidence from Africa and South Asia shows that women-led agroforestry initiatives improve household nutrition, increase farm productivity, and expand women's roles in land management and decision-making, thereby strengthening community resilience and equity (Meinzen-Dick *et al.*, 2014). These cultural and socio-economic services position agroforestry not merely as a production system, but as a holistic land-use strategy that sustains both ecosystems and societies.

Table 4. Cultural and socio-economic services provided by Agroforestry Systems

AGROFORESTRY SYSTEM	TREE-CROP COMBINATION	SERVICE/DATA	REFERENCE
Traditional Home Garden System	<i>Cocos nucifera</i> + <i>Areca catechu</i> + Spices	20–40 useful plant species maintained	Kumar and Nair (2004)
Zabo Farming System	<i>Alnus nepalensis</i> + Paddy (<i>Oryza sativa</i>)	Integrated forest-livestock-crop management	Kumar and Nair (2004)
Fruit-based Agroforestry	<i>Mangifera indica</i> + Turmeric (<i>Curcuma longa</i>)	25–40% increase in annual farm income	Meinzen-Dick <i>et al.</i> (2014)
Women-led Agroforestry	<i>Moringa oleifera</i> + Vegetables	Enhanced household nutrition and participation	Meinzen-Dick <i>et al.</i> (2014)
Urban Agroforestry	<i>Azadirachta indica</i> + Ornamental plants	Improved landscape quality and well-being	Kumar and Nair (2004)

SCALING, POLICY, AND FUTURE DIRECTIONS

Agroforestry has transitioned from a localized land-use practice to a strategic pillar within climate mitigation, biodiversity conservation, and sustainable development policies, largely due to its well-documented ecosystem-scale benefits. In India, this transition is evident through its integration into national planning instruments such as the Sub-Mission on Agroforestry (SMAF), which aims to expand tree cover on farmlands, enhance farmer incomes, and build climate resilience. Agroforestry is also explicitly aligned with India's Nationally Determined Contribution (NDC) under the Paris Agreement, which commits to creating an additional 2.5–3.0 billion tonnes of CO₂-equivalent

carbon sink by 2030. The prominence of agroforestry within this framework reflects its dual capacity to sequester carbon in both biomass and soils, making it particularly suitable for scaling across rain fed, marginal, and degraded agricultural landscapes while simultaneously supporting land degradation neutrality and biodiversity conservation goals (MoEFCC, 2021; Dhyani *et al.*, 2016).

The success of large-scale agroforestry adoption, however, is strongly influenced by incentives and ecosystem service valuation mechanisms that shape farmer decision-making and long-term sustainability. Economic assessments indicate that when ecosystem

services especially carbon sequestration are internalized; agroforestry systems frequently outperform monoculture-based agriculture. Instruments such as Payments for Ecosystem Services (PES), participation in voluntary and compliance-based carbon markets, and targeted land stewardship incentives can significantly enhance financial returns, with studies reporting 20-40% higher profitability than conventional cropping under conservative carbon pricing scenarios (Montagnini and Nair, 2012; Zomer *et al.*, 2016). Integrating agroforestry into green finance frameworks, carbon credit schemes, and agri-environmental subsidy programs can reduce investment risks associated with long tree rotations and encourage smallholders to transition away from input-intensive monocultures. Future policy directions must therefore prioritize robust carbon accounting, region-specific system design, and institutional support mechanisms that effectively convert agroforestry's multifunctional ecosystem services into tangible and sustained economic incentives for farmers.

CONCLUSION

Agroforestry systems are sustainable land-use practices that provide multiple ecological and socio-economic benefits. The integration of trees with crops and livestock improves soil fertility, nutrient cycling, carbon sequestration, biodiversity conservation, and water regulation. Tree-based systems enhance soil organic carbon, microbial activity, and nutrient availability through litter decomposition and root turnover. Agroforestry also reduces soil erosion, improves water-holding capacity, and moderates microclimatic conditions by lowering temperature and evapotranspiration losses. These systems contribute significantly to climate change mitigation and ecosystem resilience. In addition, agroforestry provides fuelwood, fodder, fruits, timber, and diversified income sources for farmers. Tree-crop combinations also support pollinators, beneficial organisms, and wildlife habitats in agricultural landscapes. Traditional agroforestry practices further help preserve indigenous knowledge and cultural heritage. Therefore, agroforestry

represents a climate-smart and environmentally sustainable approach for achieving long-term agricultural productivity and ecological security.

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