REVIEW ARTICLE

Carbon Sequestration Potential and Co-benefits of Agroforestry Systems: A Comprehensive Review

Jothieswaran V[1] and Vidhyavathi A[1*]

[1]Department of Agricultural Economics, Tamil Nadu Agricultural University, Coimbatore-641003, India

Received: 11 Mar 2025

Revised: 20 Mar 2025

Accepted: 03 Apr 2025

ABSTRACT

Agroforestry, characterized by the integration of trees and crops on the same land, has emerged as a viable strategy to address environmental and socio-economic challenges in India. This comprehensive review evaluates the carbon sequestration potential of diverse agroforestry systems and their associated co-benefits. These systems efficiently sequester atmospheric CO2 in both above-ground biomass and soil, thus playing a role in climate change. Carbon sequestration potential varies with agroforestry practices because of differences in tree species, management practices, and site conditions. Some of these systems include alley cropping, silvopasture, home gardens, windbreaks, and riparian buffers, can sequester carbon. Besides carbon sequestration, agroforestry systems provide numerous ecosystem services, including soil protection, species conservation, water control, food production, income diversification and vulnerability reduction to climatic fluctuations. Economic analyses suggest that it can produce income through carbon offset markets, wood, and other non-wood products. Examples include the Subabul Agroforestry System in Haryana, Agri-Horti-Silviculture Systems in the North Eastern Hill areas, and the Wadi Model in Gujarat to capture carbon and store, which helps to earn additional income and empower the society. However, constraints like low technical know-how, poor policies and legislations on land tenure systems are barriers to adopting agroforestry. Future research efforts should focus on the following; estimation of sequestration capacity per region, examination of co-benefits, duplication of successful strategies by other regions, and incorporation of agroforestry into existing agriculture frameworks. This means that interdisciplinary cooperation and knowledge sharing must be encouraged and strengthened.

Key words: *Agroforestry; Carbon sequestration; Co-benefits; Economic valuation; Climate change mitigation; Sustainable land use.*

INTRODUCTION

Agroforestry is a technique of integrating trees with crops on the same plot, which has gained importance as an approach to environmental and socio-economic issues in India. Due to the different agro-climatic zones in India, there is high potential for adopting agroforestry practices. At its core, one crucial attribute of agroforestry is that it helps sequester both carbon

*Corresponding author mail: jothieswaranv3@gmail.com

dioxide (CO2) from atmosphere into biomass and soils thus contributing to climate change mitigation efforts (Montagnini & Nair, 2004a; Nair *et al.,* 2021). At present estimates are that approximately 25.32 million hectares of Indian land are covered by agroforestry which accounts for about 8.2% of the total geographical area (National Agroforestry Policy, 2014). Agroforestry incorporates approaches such as alley cropping, silvopasture, windbreaks, and forest farming specific ecological and socio-economic contexts (Nair *et al.,* 2021). The National Mission for Sustainable Agriculture (NMSA) has set a target of extending the practice over an additional five million ha by 2030 because it offers multiple benefits like carbon sequestration, soil conservation, an increase in biodiversity, and provides an extra income stream for farmers.

Several studies have highlighted agroforestry systems' carbon sequestration potential through aboveground biomass and soil (Feliciano *et al.,* 2018; Zomer *et al.,* 2016). This, accompanied by the multiple functions that agroforestry systems offer, shows that it is a viable climate change mitigation strategy (Dagar & Tewari, 2016b; Jose & Bardhan, 2012; Rosenstock *et al.*, 2019). There are diverse co-benefits of agroforestry systems over and above carbon sequestration, which contribute to sustainable development and climate change adaptation, such as biodiversity conservation, soil amelioration, water regulation and livelihood diversification (Coulibaly *et al.*, 2017; Dagar & Tewari, 2016a; Jose, 2009; Jose & Bardhan, 2012). To successfully realize of agroforestry systems' full potential regarding climate change adaptation and mitigation measures all these co-benefits need to be correctly understood and evaluated. For the complete economic value of agroforestry systems to be captured as well as decision-making processes informed, it is essential to quantify and appraise these co-benefits (Branca *et al.,* 2013; Tschakert *et al.,* 2007).

This review aims to comprehensively overview of agroforestry systems and their role in climate change mitigation. It will explore the significance of carbon sequestration and associated co-benefits within the climate change framework, drawing on recent research and empirical evidence to underscore the importance of agroforestry as a sustainable land-use strategy in combating climate change.

Conceptual framework

The conceptual framework depicts an overall view of the article as shown in Figure1. It delineates the intricate interaction between agroforestry systems, their potential for carbon sequestration, economic feasibility, and the many co-benefits they offer. The core premise claims that agroforestry systems essentially hold the capacity to trap atmospheric carbon, therefore contributing to climate change mitigation. However, these systems' broad acceptance and scalability depend on their economic feasibility,

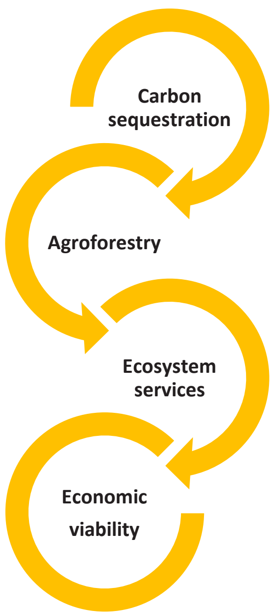


Figure 1 depicts the conceptual framework.

which is influenced by the balance between incurred expenses and possible revenue sources. Additionally, agroforestry systems provide various co-benefits that support environmental sustainability, food security, and socioeconomic development, boosting their total value proposition and attractiveness.

An overview of the literature study is mentioned as a PRISMA flow chart as illustrated in Figure 2 as shown below.

Carbon sequestration is a critical measure that involves trapping and holding onto atmospheric CO2 to mitigate climate change. With Indian scholars' insights and global sources' perspectives, this review is meant to examine these differences. The efficiency of carbon sequestration in agroforestry systems varies significantly depending on factors such as different agroforestry techniques used, types of tree species involved, management practices adopted, and environmental factors (Albrecht & Kandji, 2003).

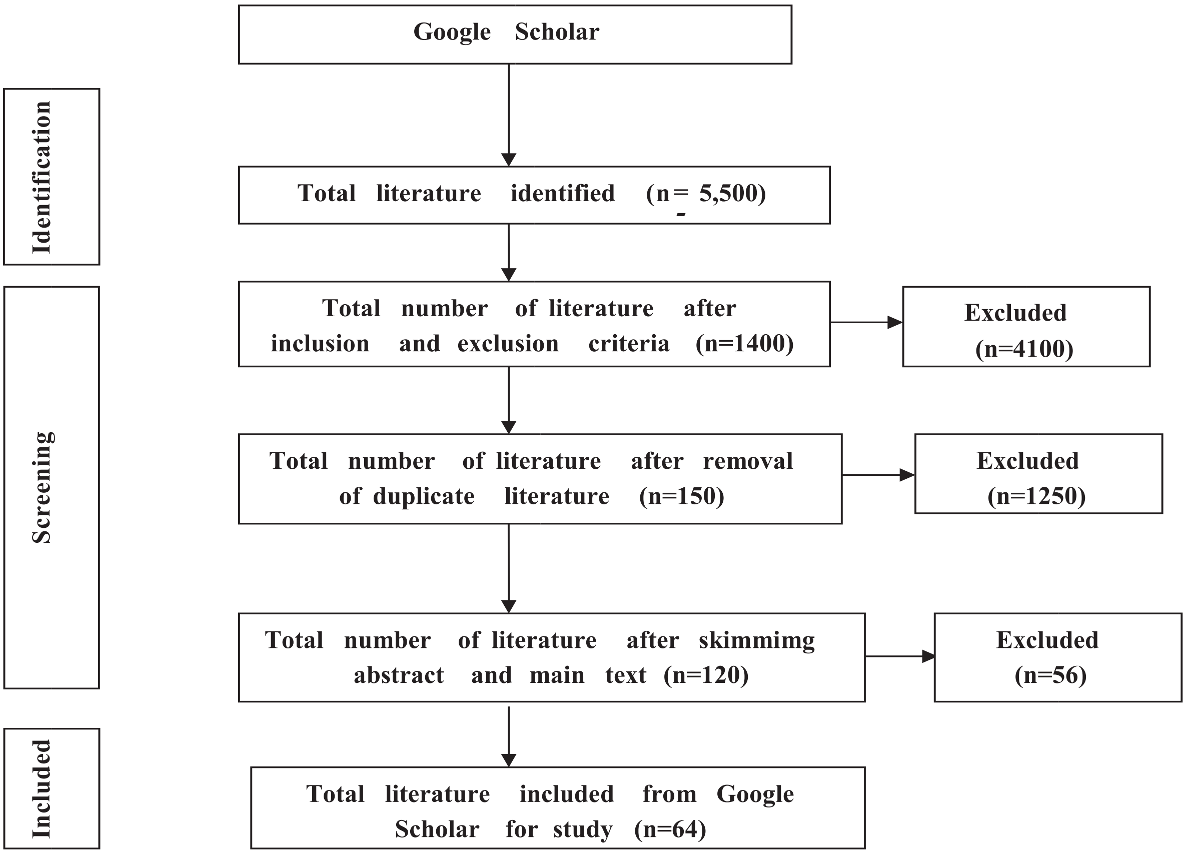


Figure 2: PRISMA diagram demonstrating systematic screening progress of the article Carbon Sequestration Potential of Agroforestry Systems.

Carbon Pools in Agroforestry Systems

Agroforestry systems can sequester carbon in various ways, including aboveground biomass, belowground biomass, and soil organic carbon (SOC)(Montagnini & Nair, 2004a; Nair *et al.,* 2009). Aboveground biomass consists of the trees' main stem, branches and leaves, including those from other perennials. It is an essential carbon store for agroforestry systems (Nair et al., 2009). The latter depends on tree species, age, density and management practices that determine its potential capability to sequestrate. This reservoir's capacity for sequestration is determined by variables such as the type of tree species, the density of trees per unit area, the age of trees in the system and management operations (Albrecht & Kandji, 2003).

In addition, belowground biomass contributes to carbon sequestration in agroforestry systems through roots and associated organic matter, including leaf litter deposition root exudation etc. Extensive root systems produced by these types of vegetation are essential in enhancing soil carbon storage, through which carbon gets transferred from above-ground biomasses into the soil, hence helping the entire process of managing agroforestry systems (Montagnini & Nair, 2004a). They may also lead to higher SOC levels due to increased input through processes like adding leaf litter or pruning residues while building more solid soil structures while mitigating erosion, thus favoring an environment conducive for SOC buildup. Soil structure is improved by having trees and perennials integrated into these systems so that instead of being eroded, less amounts are stored as Carbon.

Factors Influencing Carbon Sequestration in Agroforestry Systems

Tree Species and Density

The choice of tree species and their densities in agroforestry determines the capacity for carbon capture. Plant materials with high biomass production rates, deep root systems, and long-life spans generally have substantial carbon capture potential (Chavan *et al.,* 2023; Nair *et al*., 2010a). Notably, Chavan (2023) provides empirical evidence showing that certain tree species, including poplar and eucalyptus, found in the Indo-Gangetic plains of India possess substantial capacities for accumulating carbon.

Management Practices

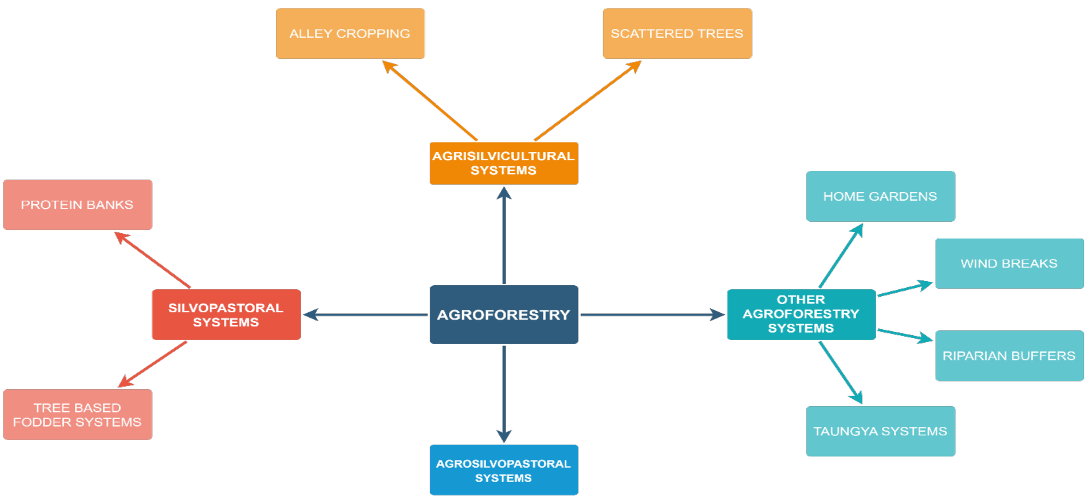
Among agroforestry practices, such as pruning, thinning, and coppicing, that are effective in managing carbon sequestration within these systems (Mandal *et al*., 2022; Montagnini & Nair, 2004b; Murthy *et al*., 2013). These management activities enhance system resilience, promote synergies between adaptation and mitigation strategies, and contribute to soil health improvement, thereby augmenting carbon sequestration. However, further investigation and research are required to quantify the extent of this potential and its actualization.

Environmental Conditions

Carbon sequestration capacity of agroforestry systems is significantly influenced by environmental variables such as climate conditions, soil characteristics, and topographical features (Montagnini & Nair, 2004b; Nair *et al*., 2009). For example, in warmer climates, trees grow faster and store more carbon while nutrient-rich soils produce high biomass (Minj, 2008). They are known to be more efficient at capturing and holding atmospheric carbon dioxide than conventional land tillage practices do (Wang & Feng, 1995). In tropical areas, especially, these methods can add above-ground and soil carbon sinks, leading to lessened soil deterioration and reduced greenhouse gas emissions(Mutuo *et al.,* 2005).

Types of Agroforestry Systems and Their Carbon Sequestration Potential

Agroforestry encompasses diverse land-use strategies integrating trees, crops, and livestock, offering numerous benefits, notably including carbon sequestration. The subsequent sections delineate various agroforestry modalities and their respective carbon storage capacities.



Source: Author’s work

Figure 3 depicts the types of agroforestry.

Agri silvicultural Systems

Agro-silvicultural systems that incorporate trees and crops within the same agricultural setting come with numerous advantages, like improved soil fertility, better water quality, and increased biodiversity (basawa *et al.,* 2017). These are economically and ecologically viable options that also contribute to climate change mitigation by enhancing other resources and services(Toppo & Toppo, 2019). They are essential for broadening agricultural outputs diversified income sources, and enhanced delivery mechanisms for environmental goods. (Cardinael *et al.,* 2020). However, further research is needed to optimize the integration of vegetable crops with fruit trees within these systems (Maqrot *et al.,* 2023).

Alley Cropping

Alley cropping, a type of agroforestry, has diverse advantages such as carbon storage, conserving soil, and increased nutrient cycling(Marin, 2016; Quinkenstein *et al.,* 2009). In this method, food crops are grown in alleyways formed by hedgerows of trees or shrubs that are regularly pruned to reduce shade and competition for nutrients (Ya & Qi, 2001)Carbon sequestration rates have been observed to range from 1.5 to 3.5 t C ha-1 yr-1 in different studies depending on tree species diversity, pruning frequency, soil fertility, and climate (Albrecht & Kandji, 2003; Nair *et al*., 2009). These results demonstrate the potential of alley cropping as a sustainable land management practice that enhances both food production and biomass while providing ecological benefits.

Silvopastoral Systems

In India, there are systems for silvopastoral that have been shown to sequester a significant amount of carbon by integrating trees and grasses that result in the increase of organic carbon reserve in the soils compared to single tree or pasture configurations (Mangalassery, 2014). These arrangements also promote biodiversity, facilitate nutrient recycling, and optimize resource utilization efficiency (Mosquera-Losada *et al.,* 2013). Silvopastoral systems have revealed significant improvements in carbon sequestration as well as nitrogen cycling particularly in sodic soils through the proper selection of tree and grass species(Kaur *et al.,* 2004).

Protein Banks

Protein banks are one type of silvopastoral system where high-protein tree species like Leucaena leucocephala are planted in dense hedges or blocks regularly pruned for cattle feed. The practice promotes carbon sequestration by the trees themselves and also by soils, with figures ranging between 2.0 and 4.0 t C ha-1 yr-1 based on varying factors such as tree density, grazing intensity, and soil properties (Haile *et al.,* 2008; Nair *et al.,* 2010a).

Tree-Based Fodder Systems

To achieve this end, these systems involve planting and maintaining trees or bushes for purposeful fodder production, thus becoming a source of animal feed that satisfies both ecological and economic needs. The extent to which these systems can sequester varies depending on the tree species involved, the management practices employed, as well as the environmental conditions prevailing in the area (Murgueitio *et al.,* 2011)

Agro-silvopastoral Systems

Agro-silvopastoral combines trees with crops and livestock within one landscape unit. These systems can potentially sequester carbon across tree biomass, soil besides nutrient and organic matter cycling. The effectiveness of carbon sequestration in agrosilvopastoral systems depends on factors such as tree species composition, density, crop rotation patterns, and animal management practices (Mosquera-Losada *et al.,* 2013).

Other Agroforestry Systems

Furthermore, various agroforestry systems, including home gardens, windbreaks, riparian buffers, enhanced fallows, and the Taungya system, also contribute to carbon sequestration. These systems exhibit diversity in their design, management strategies, and carbon sequestration potential, influenced by factors such as tree species diversity, soil properties, hydrological dynamics, and climatic conditions (Dagar & Tewari, 2016b; Saha *et al.,* 2009).

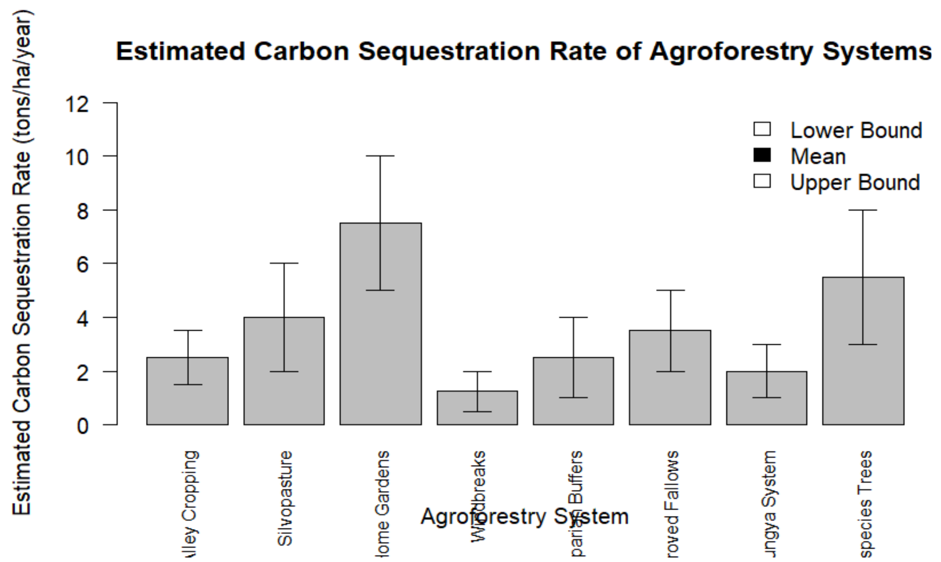
For instance, indigenous home gardens have been registered to fix between 5.0 and 10.0 tons of carbon per hectare annually through the integration of a combination of trees, crops, and meticulous management practices within these systems (Saha *et al.,* 2009). An alternative example would be multi-species trees, having their sequestration rate ranging from 3.0 to 8.0 tons per hectare per year, which depend on the combinations of different tree species, correct

Table 1 illustrates the carbon sequestration potential of several agroforestry systems.

Agroforestry System	Estimated Carbon Sequestration Rate (tons/ha/year)	Influencing Factors	References
Alley Cropping	1.5 - 3.5	Tree species, pruning management, soil fertility, and climate	(Albrecht & Kandji, 2003; Nair et al., 2009)
Silvopasture	2.0 - 6.0	Tree density, grazing intensity, soil type, and rainfall	(Haile et al., 2008; Nair et al., 2010b)
Home Gardens	5.0 - 10.0	Tree species diversity, management intensity, soil quality, and altitude	(Nair et al., 2009; Saha et al., 2009)
Windbreaks	0.5 - 2.0	Tree species, spacing, climate, and soil conditions	(Dagar & Tewari, 2016a; Nair et al., 2009)
Riparian Buffers	1.0 - 4.0	Tree species, buffer width, hydrological regime, and soil texture	(Dagar & Tewari, 2016a; Nair et al., 2009)
Improved Fallows	2.0 - 5.0	Tree species, fallow duration, soil fertility, and rainfall	(Albrecht & Kandji, 2003; Nair et al., 2010b)
Taungya System	1.0 - 3.0	Tree species, crop rotation, soil management, and climate	(Dagar & Tewari, 2016b; Nair et al., 2009)
Multispecies Trees	3.0 - 8.0	Tree species composition, density, soil conditions, and climate	(Swamy & Puri, 2005)

density and favorable soil and climatic conditions acting synergistically. Similarly, silvopasture systems range from improved fallows to riparian buffers with moderate sequestration rates between 1.0-6.0 tC/ha/year. Tree density, intensity of grazing, fallow duration, hydrological dynamics, among others, influence their sequestration potential.

In contrast, alley cropping is rated at <1 ton C/ha for annual carbon sequestration, while other examples, such as windbreaks and the Taungya system, comes with the second-lowest rating among all land uses, with total amount annexed estimated at not less than 2 tonnes C/ha/year (Garrity *et al.,* 2010). While contributing to carbon



SOFTWARE: R-4.4

Figure 4 displays the carbon sequestration rate.

sequestration, their effectiveness depends on variables such as tree species selection, pruning practices, spatial arrangement, crop rotation patterns, and soil management techniques.

Regional and Practice-Specific Variations in Carbon Sequestration Potential

Various factors influence agroforestry systems' carbon sequestration capacity, resulting in significant variability across different geographical regions and practices. Understanding these variations is crucial for identifying effective agroforestry systems and expanding their use for climate change mitigation (Rosenstock *et al*., 2019).

Regional Variations in Carbon Sequestration

Disparities in the potential of carbon sequestration on a regional basis are mainly because of climatic conditions, soil characteristics, and socioeconomic aspects (Feliciano et al., 2018). Carbon sequestration capacity differs widely between regions due to variation in temperature, soil attributes and land use management practices. For example, tropical regions usually have a high carbon sequestration capacity due to their rich vegetation cover and favourable climatic conditions. Tropical forests contribute significantly to global carbon sequestration capacity than temperate zones as highlighted by (Pan *et al.,* 2011)and(Swamy & Puri, 2005), which emphasizes the need for preservation of these ecosystems.

In India, there is considerable heterogeneity in carbon sequestration potential as indicated by regional studies. As an illustration, the Western Ghats, which is a biodiversity hotspot, has significant potential for carbon storage through large forested areas and high biomass density (Ravindranath *et al.,* 1997). Similarly, research conducted in the Himalayan region reveals that there is a significant amount of carbon being stored within the sub-alpine and alpine forests that are important for the regional carbon balance (Singh *et al.,* 2010)..

Studies in Kerala, India, indicate that home gardens, a form of agroforestry, harbor substantial carbon stocks due to the presence of long-lived, multi-purpose tree species (Saha *et al.,* 2009). Conversely, agroforestry systems in arid and semi-arid regions may exhibit reduced carbon sequestration capacity due to water limitations and harsh environmental conditions (Nair *et al.,* 2009). However, the inclusion of drought-tolerant tree species and appropriate management practices can enhance the carbon sequestration potential of agroforestry systems in these regions (Swamy & Puri, 2005).

Practice-Specific Variations in Carbon Sequestration

Soil carbon sequestration potential is greatly affected by farming methods. Soil organic carbon (SOC) storage in agricultural soils is enhanced by conservation tillage practices such as reduced tillage, cover crops, and the use of organic amendments (Lal, 2004). Agronomic improvements can increase soil organic carbon stocks considerably; zero tillage and organic farming have a positive impact on these stores in Punjab and Haryana (India) (Siddiqui *et al*., 2012).

The choice of agroforestry technology also determines its capacity for storing carbon. Silvopastoral systems, which integrate trees with grasslands or livestock, are known to have a greater capacity for sequestering carbon especially in the soil component (Haile *et al.,* 2008). Conversely, alley cropping systems where trees are grown in rows together with field crops may have lesser capacities for carbon sequestration as a result of regular pruning or coppicing of the trees(Albrecht & Kandji, 2003).

Another critical factor affecting the carbon sequestration capacity is the selection of tree species and their management practices. Longer-lived tree species with deep root systems and high biomass production per unit area tend to store more C than short-lived, low-density species. An account by (Saha *et al.,* 2009) gives that long-lived high-density trees that develop extensive root systems and produce large amounts of biomass are expected to take up more CO2 during photosynthesis than short-lived low-density species. Proper management techniques, such as pruning, thinning, and fertilization, can also enhance the carbon sequestration potential of agroforestry systems(Dagar & Tewari, 2016a).

Impact of Land Use Change

Changes in land use, mainly deforestation and urbanization, significantly affect carbon sequestration capacity. Deforestation in tropical areas such as parts of India results in massive emissions of carbon dioxide as well as a decline in storage capacities. On the other hand, restoration projects and afforestation can replenish carbon stocks. (Kaul *et al.,* 2010) observed that afforestation programmes undertaken in Central India significantly improved carbon sequestration, hence making reforestation a prospective mitigation strategy.

Co-Benefits of Agroforestry Systems

While some agroforestry systems may excel in carbon sequestration, others may provide additional co-benefits such as improved soil fertility, biodiversity conservation or enhanced livelihoods. Consequently, for the sustainable promotion of agroforestry practices there is need for a comprehensive approach that looks at both carbon sequestration and other co-benefits (Coulibaly *et al.,* 2017).

Ecosystem Services

Agroforestry systems supply several ecosystem services that contribute to environmental sustainability.

Soil Conservation

The agroforestry practices help improve soil health by reducing erosion, enhancing soil structure and increasing organic matter content. Windbreaks whose primary role is to mitigate wind erosion, while root systems prevent soil from being washed away, are formed by trees and shrubs. (Nair, 2011) emphasizes the better physical attributes for soil quality and erosion control through agroforestry than those found under conventional agriculture.

Biodiversity

To foster biodiversity, agroforestry systems create varied habitats for plants and animals. The use of different plant species and the development of multi-layered vegetation structures enable a broad range of species to be supported in one system. In the Western Ghats in India, Agroforestry landscapes are shown by (Bhagwat *et al*., 2008) to have significant biodiversity, like natural forests which is essential for ecosystem stability and resilience. In southern India, (Nair *et al*., 2009) research reveals that agroforestry practices contribute to carbon sequestration and other co-benefits such as preservation of biodiversity and improved livelihoods.

Water Regulation

The trees in agroforestry ecosystems control water by promoting groundwater recharge, reduction of surface runoff, and improving quality. According to (Verchot *et al*., 2007), mitigation of floods and drought risks is achieved by water infiltration into the soil through agroforestry systems.

Food Security and Livelihood Enhancement

Diverse sources of income are created in these agroforestry systems leading to extensive food

Figure 5 depicts the agroforestry services.

security improvements and better livelihoods because crop yields are increased dramatically. Such systems produce different goods, including food crops, fuelwood and feed; they also provide critical ecosystem services like pollination, necessary for food production. They also provide small-scale farmers with an additional source of earnings by selling tree products and surplus foodstuffs.

Diversified Income Sources

The integrating fruit, nut, and timber-yielding trees and shrubs can substantially increase farm income and mitigate economic risks associated with market fluctuations. Farmers can generate additional income and enhance their economic resilience by incorporating these alternative products into their farming systems

Improved Crop Yields

Trees in agroforestry systems can ameliorate microclimatic conditions, enhancing crop growth and yields.

Climate Change Adaptation and Resilience

Agroforestry systems enhance resilience to climate change by improving ecosystem stability and providing climate-regulating services.

Resilience to Climatic Extremes

Extreme weather events like droughts and floods can be mitigated through agroforestry practices. The study by(Quandt *et al*., 2017) also showed that it directly and indirectly impacts livelihood resilience against this kind of climate variation, thereby adding to its robustness as a concept. Studies by (Nguyen *et al.,* 2013) and (Simelton *et al*., 2015) further support these findings, highlighting the role of agroforestry in mitigating vulnerability to climatic variability.

Carbon Sequestration

Agroforestry systems effectively sequester carbon, thus aiding in climate change mitigation. Nair *et al.* (2009) estimated significant global carbon sequestration in agroforestry systems, underscoring their role in reducing atmospheric CO2 levels.

Economic Valuation of Co-Benefits

Quantifying the economic value of co-benefits provided by agroforestry systems is crucial for policy and decision-making.

Valuation Methods

Economic valuation approaches such as cost-benefit analysis, contingent valuation, and ecosystem service pricing are employed to assess the monetary value of agroforestry benefits. Incorporating ecosystem service values into economic models can profoundly influence land-use planning and policy decisions, as noted by(Costanza *et al*., 1997).

Indian Context

Research carried out in India consistently shows the tremendous economic value of agroforestry systems, particularly when assessed using economic valuation methods.(Yadav *et al.,* 2018) case study in partial equilibrium analysis demonstrates profitable returns to farmers in Indian central Himalayas with a higher benefit cost ratio at greater heights. Similarly, Sangeetha & Shanmugam, 2015 have evidenced significant net returns from tree yield under commercial agroforestry systems operating in North Tamil Nadu. Dhyan *et al*., 2016 ideas emphasize the economic advantages of agroforestry systems found within varied Agroclimatic zones across India whereby basic needs are met and income is enhanced among rural folks. The work highlights the potential for Agri-forestry to meet subsistence requirements for farming families living across various Agro-climatic zones in India while emphasizing economic benefits associated with such land use systems.

Cost-Benefit Analysis and Economic Feasibility of Agroforestry Systems

Agroforestry has considerable environmental and economic benefits. However, the effective implementation of agroforestry systems depends significantly on their economic feasibility, which can be examined through cost-benefit analysis (CBA).

Cost Components

Establishment Costs

Initial costs in agroforestry are related to site preparation, planting materials, labour, and initial infrastructure (B. M. Swaminathan *et al,* 1982). These expenses can be substantial depending on the scale and type of agroforestry system(Rao *et al.,* 1997). Effective agroforestry systems creation in India requires initial investment in tree seedlings, fencing, and human resources for planting (C.Dey & Mishra,2014). However, such systems are not easily implemented due to variables like high labour charges and low seed prices (Puri & Nair, 2004). Nevertheless, India’s experience agroforestry research highlights these systems’ promise, primarily when their scientific basis is acknowledged and their advantages to society are compelling (Puri & Nair, 2004).

Maintenance Costs

The maintenance budget involves recurrent expenditures incurred in running the agro forestry system, such as pruning, pest management, fertilization, irrigation, among others. It also includes training fees and extension services that ensure farmers adhere to optimum practices. Maintenance costs can be high; nonetheless, they are necessary for maintaining production capacities as well as the health status of the AF system (Rao *et al.,* 1997).

Opportunity Costs

Opportunity costs refer to the potential earnings that are forgone when one chooses agro forestry over other land uses such as grazing or monocropping. The expenses can be very different depending on the kind of agroforestry system used and alternative uses for land. According to (Swamy & Puri, 2005), in Indian contexts, opportunity costs might be a crucial factor affecting farmer's decisions to embrace agroforestry practices.

Potential Revenue Streams

Carbon Credits

Carbon credits are among the significant sources of revenue from agroforestry. In carbon markets, carbon can be sequestrated by agroforestry systems and monetized.(Lal, 2004) explores the potential of agroforestry in carbon sequestration and how trading in carbon credits can also yield economic benefits. In India, initiatives registered under the Clean Development Mechanism (CDM) have proven that farmers can benefit from applicable incomes through selling carbon credits (Kaul *et al*., 2010).

Timber and Non-Timber Products

The income derived from nontimber products like fruits, nuts, medicinal plants form the most significant proportion of the economic benefits of agroforesty. (Nair *et al*., 2009) note that a diversity of products from agroforesty systems enable multiple revenue streams of stable nature, thereby giving farmers a lot of economic stability. (Dhanya *et al.,* 2016) established the economic worthiness of traditional agroforesty systems, where those with high value trees within irrigated systems were found to be most profitable. (Romabai *et al*.,2023) identified important commercially valuable tree-based NTFPs in the Indo-Burma region indicating possibilities for value addition towards improved market prices. The researcher's study points out that dry deciduous forests have higher net present values arising from NTFPs such as honey which is three times more profitable than other alternative land use.

Successful Examples and Best Practices from Different Regions

Subabul Agroforestry System in Haryana

The Subabul Agroforestry System in Haryana is a strong force in the socio-economic realm, contributing around 30% of the family's income and sequestering approximately 2.5-3.0 tonnes of carbon per hectare annually. It also enhances soil fertility and is profitable in other parts of India (Rizvi *et al.,* 2016). Such systems present in semi-arid regions of North-West India have positive effects on crop and fodder yields, soil organic carbon content and soil pH (Kaushik *et al.,* 2017), with implications for agriculture and ecosystem services within Haryana.

Agri-Horti-Silviculture Systems in North-Eastern Hill Regions

In these northeastern hill areas, traditional agri-horti-silviculture systems have been successful in terms of carbon sequestration and generating various economic benefits. For instance, they have flourished into food, fodder, fruit-bearing trees, timber trees that play vital roles in the local economy for states like Nagaland, Mizoram and Meghalaya (Yadav *et al*., 2019). Rainfed Vertisols – horti-silvi-agricultural systems are adaptable to these conditions (TN, 2002).

Wadi Model in Gujarat

Tribal Settlements in Gujarat have been transformed by the Wadi model, which the BAIF Development Research Foundation developed. This method plants fruit trees with cereal crops to promote carbon sequestration through agroforestry, food security, and income stability. Children cultivate their English language skills and knowledge of Spanish culture through total immersion, live-in programs (Tripathy, 2018). The Wadi model has been successful in southern Gujarat, western Maharashtra, southern Rajasthan, and parts of Karnataka, and it involves creating market opportunities for tribal farmers' produce while generating livelihoods. It fosters community engagement and collective action that strengthens social cohesiveness and resilience. The technique captures about 4.5-5.0 tons of CO2 per acre every year while giving monetary returns from selling fruits like mangoes and cashews in addition to traditional crops. Capacity building activities make farmers improve in terms of their skills, hence increasing their abilities.

Challenges and Barriers to Adoption

Despite excellent examples, various constraints and barriers limit the broad adoption of agroforestry systems for carbon sequestration and economic benefits:

1. *Limited Information and Technical Expertise:* Inadequate knowledge and technical skills among farmers and extension workers regarding the carbon sequestration potential and economic benefits of agroforestry systems restrict adoption(Nair *et al.,* 2009).

2. *Lack of Policy Support and Financial Incentives:* Insufficient government support, lack of financial incentives, and limited access to carbon markets prevent farmers from implementing agroforestry practices for carbon sequestration (Pandey, 2007).

3. Land Tenure Issues: Insecure land tenure is a key hurdle, as farmers are reluctant to invest in long-term agroforestry activities without certain land rights(Bhattacharya *et al.,* 2010). This issue is frequent in places with fragmented landholdings and ambiguous land titles.

4. Information and understanding: Limited understanding about the benefits and procedures of agroforestry, coupled with limited extension services, causes a gap in information transfer from research to practice.

Lessons Learned and Potential Scalability for Carbon Sequestration in Agroforestry and Their Economic Benefits in India

1. Enhancing information Transmission: Effective extension services are vital for information dissemination. Training programs, farmer field schools, and ICT tools can bridge the knowledge gap (Mittal & Mehar, 2016).

2. Integrating Agroforestry with Existing Agricultural Systems: Promoting the integration of agroforestry systems with existing agricultural practices will assist in managing competing land and resource demands while boosting carbon sequestration and economic benefits (Nair *et al*., 2009).

3. Developing Policy Support and Financial Incentives: Implementing policies that support agroforestry for carbon sequestration, giving financial incentives, and allowing access to carbon markets can inspire farmers to embrace these practices (Pandey, 2007).

4. Resolving Cultural Considerations: Understanding and resolving cultural variables can facilitate adoption. Involving local populations in planning and decision-making ensures that agroforestry practices are customized to local conditions and embraced by farmers.

5. Improving Access to Financial Resources: Economic incentives and financial support are crucial for scalability. Government subsidies, low-interest loans, and carbon credits can make agroforestry financially viable for smallholder farmers.

6. Securing Land Tenure: Promoting community-based land tenure systems can give collective security and stimulate investment in agroforestry. Transparent and secure land rights are vital for long-term planning and investment.

CONCLUSION

This research highlights the significant potential of agroforestry systems in terms of carbon sequestration and economic benefits, as well as other sustainable development co-benefits. Alley cropping, silvopasture, home gardens, and other types of agroforestry practices have different rates of carbon sequestration due to various tree species, management practices and environmental conditions. Economic appraisals show that agroforestry can bring money through carbon credits, timber and nontimber products. This is illustrated by examples from India, such as Subabul system, Agri-Horti-Silviculture or the Wadi model.

Nevertheless, some constraints, which include lack of technical skills, policy gaps and land tenure issues, hinder their wider application. Future research should consider this by focusing on quantifying regional-specific carbon capture in monetary terms, pricing co-benefits more comprehensively, replicating successful models via supportive policies and financing, and integrating climate resilient agriculture with current agricultural practices using agroforestry. Interdisciplinary cooperation bridges knowledge gaps and assist the transition to agroforestry-based sustainable land use.

In tropical regions, various forms of agroforestry provide a wide range of benefits concerning carbon stock influenced by such factors as tree type, density, management approaches, and weather circumstances. Tropical forests offer the highest carbon sequestration rates, with home gardens achieving between 5.0 and 10.0 tons per hectare yearly. Understanding tree selection determinants is vital to combining local food and fuel needs with global climate regulation aims.

ACKNOWLEDGEMENTS

We want to extend our heartfelt appreciation to all the individuals and organizations who have contributed to the publications of this research.

Compliance with ethical standards

Conflict of interest: There is no conflict of interest between the authors.

Ethical issues: None

Consent for Publication: All authors have agreed to the content of the article and its publication in the journal.

Author Contributions: For this study, Jothieswaran V initially conceptualized and designed the manuscript, and the remaining authors supervised and revised the manuscript critically for intellectual content.

REFERENCES

Albrecht, A., & Kandji, S. T. (2003). Carbon sequestration in tropical agroforestry systems. Agriculture, Ecosystems & Environment, 99(1-3), 15-27. https://doi.org/10.1016/S0167-8809(03)00138-5

Basawa, D., Murthy, M. M., & Chittapur, B. M. (2017). Assessment of Tree Diversity in Agroforestry Systems in Irrigated Ecosystem. International Journal of Current Microbiology and Applied Sciences, 6, 3111-3127. https://api.semanticscholar.org/CorpusID:133710797https://doi.org/10.20546/ijcmas.2017.610.366

Bhagwat, S. A., Willis, K. J., Birks, H. J. B., & Whittaker, R. J. (2008). Agroforestry: a shelter for tropical biodiversity? Trends in Ecology & Evolution, 23(5), 261-267. https://doi.org/10.1016/j.tree.2008.01.005

Bhattacharya, P., Pradhan, L., & Yadav, G. (2010). Joint forest management in India: experiences of two decades. Resources, Conservation and Recycling, 54(8), 469-480. https://doi.org/10.1016/j.resconrec.2009.10.003

Branca, G., Lipper, L., McCarthy, N., & Jolejole, M. C. (2013). Food security, climate change, and sustainable land management. A review. Agronomy for Sustainable Development, 33, 635-650. https://doi.org/10.1007/s13593-013-0133-1

Cardinael, R., Mao, Z., Chenu, C., & Hinsinger, P. (2020). Belowground functioning of agroforestry systems: current advancements and perspectives. Plant and Soil, 1-13. https://api.semanticscholar.org/CorpusID:220431141 https://doi.org/10.1007/s11104-020-04633-x

Chavan, S. B., Dhillon, R. S., Sirohi, C., Uthappa, A. R., Jinger, D., Jatav, H. S., Chichaghare, A. R., Kakade, V., Paramesh, V., & Kumari, S. (2023). Carbon sequestration potential of commercial agroforestry systems in Indo-Gangetic Plains of India: Poplar and eucalyptus-based agroforestry systems. Forests, 14(3), 559. https://doi.org/10.3390/f14030559

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R. v, & Paruelo, J. (1997). The value of the world's ecosystem services and natural capital. Nature, 387(6630), 253-260. https://doi.org/10.1038/387253a0

Coulibaly, J. Y., Chiputwa, B., Nakelse, T., & Kundhlande, G. (2017). Adoption of agroforestry and the impact on household food security among farmers in Malawi. Agricultural Systems, 155, 52-69. https://doi.org/10.1016/j.agsy.2017.03.017

Dagar, J. C., & Tewari, J. C. (2016a). Agroforestry research advancements. Nova Science Publishers New York, NY, USA.

Dagar, J. C., & Tewari, J. C. (2016b). Agroforestry research developments: anecdotal to modern science. Agroforestry Research Developments. Nova Publishers, New York, 1-45.

Dhanya, B., Purushothaman, S., & Viswanath, S. (2016). Economic justification of traditional agroforestry systems: a case-study of Ficus trees in semiarid agro-ecosystems in Karnataka, southern India. Forests, Trees and Livelihoods, 25(4), 267-281. https://doi.org/10.1080/14728028.2016.1218800

Dhyan, S. K., Ram, A., & Dev, I. (2016). Potential of agroforestry systems in carbon sequestration in India. Dhyani, SK, Ram, A., Dev, I, 1103-1112. https://doi.org/10.56093/ijas.v86i9.61348

Feliciano, D., Ledo, A., Hillier, J., & Nayak, D. R. (2018). Which agroforestry options deliver the most soil and above ground carbon benefits in different world regions? Agriculture, Ecosystems & Environment, 254, 117-129. https://doi.org/10.1016/j.agee.2017.11.032

Haile, S. G., Nair, P. K. R., & Nair, V. D. (2008). Carbon storage of distinct soilsize fractions in Florida silvopastoral systems. Journal of Environmental Quality, 37(5), 1789-1797. https://doi.org/10.2134/jeq2007.0509

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Systems, 76, 1-10. https://doi.org/10.1007/978-90-481-3323-9_1 https://doi.org/10.1007/s10457-009-9229-7

Jose, S., & Bardhan, S. (2012). Agroforestry for biomass production and carbon sequestration: an overview. Agroforestry Systems, 86, 105-111. https://doi.org/10.1007/s10457-012-9573-x

Kaul, M., Mohren, G. M. J., & Dadhwal, V. K. (2010). Carbon storage and sequestration capacity of selected tree species in India. Mitigation and Adaptation Strategies for Global Change, 15, 489-510. https://doi.org/10.1007/s11027-010-9230-5

Kaur, B., Gupta, S., & Singh, G. S. B. (2004). Carbon storage and nitrogen cycling in silvopastoral systems on a sodic in northwestern India. Agroforestry Systems, 54, 21-29. https://api.semanticscholar.org/CorpusID:2118948 https://doi.org/10.1023/A:1014269221934

Kaushik, N., Tikkoo, A., Yadav, P. K., Deswal, R. P. S., & Singh, S. (2017). Agri-silvi-horti systems for semiarid regions of north-west India. Agricultural Research, 6, 150-158. https://doi.org/10.1007/s40003-017-0247-9

Lal, R. (2004a). Soil carbon sequestration implications on global climate change and food security. Science, 304(5677), 1623-1627. https://doi.org/10.1126/science.1097396

Lal, R. (2004b). Soil carbon sequestration to alleviate climate change. Geoderma, 123(1-2), 1-22. https://doi.org/10.1016/j.geoderma.2004.01.032

Mandal, A., Majumder, A., Dhaliwal, S. S., Toor, A. S., Mani, P. K., Naresh, R. K., Gupta, R. K., & Mitran, T. (2022). Impact of agricultural management approaches on soil carbon sequestration and its monitoring by simulation models and remote sensing techniques: A review. Critical Reviews in Environmental Science and Technology, 52(1), 1-49. https://doi.org/10.1080/10643389.2020.1811590

Mangalassery, S. (2014). Carbon sequestration in agroforestry and pasture systems in arid northwestern India. Current Science, 107. https://api.semanticscholar.org/CorpusID:87708593

Maqrot, S., de Givry, S., Quesnel, G., & Tchamitchian, M. (2023). Mixed Fruit-Vegetable Crop Allocation Problem utilizing MIP. https://api.semanticscholar.org/CorpusID:261959642

Marin, R.A. (2016). Jatropha-based alley cropping system's contribution to carbon sequestration. https://api.semanticscholar.org/CorpusID:212473388

Minj, A. v. (2008). Carbon Sequestration Potential of Agroforestry Systems-an Evaluation in Low and Mid Hills of Western Himalayas. https://api.semanticscholar.org/CorpusID:146706062

Mittal, S., & Mehar, M. (2016). Socio-economic factors affecting adoption of contemporary information and communication technologies by farmers in India: Analysis utilizing multivariate probit model. The Journal of Agricultural Education and Extension, 22(2), 199-212. https://doi.org/10.1080/1389224X.2014.997255

Montagnini, F., & Nair, P. K. R. (2004a). Carbon sequestration: an underexploited environmental benefit of agroforestry systems. New Vistas in Agroforestry: A Compendium for 1st World Congress of Agroforestry, 2004, 281-295. https://doi.org/10.1007/978-94-017-2424-1_20

Montagnini, F., & Nair, P. K. R. (2004b). Carbon sequestration: an underexploited environmental benefit of agroforestry systems. New Vistas in Agroforestry: A Compendium for 1st World Congress of Agroforestry, 2004, 281-295. https://doi.org/10.1007/978-94-017-2424-1_20

Mosquera-Losada, M. R., Rigueiro-Rodríguez, A., Helgadóttir, Á., & Hopkins, A. (2013). Silvopasture: a combination of grasslands and trees to green livestock productivity. https://api.semanticscholar.org/CorpusID:126636444

Murgueitio, E., Calle, Z., Uribe, F., Calle, A., & Solorio, B. (2011). Native plants and shrubs for the profitable rehabilitation of tropical cow ranching grounds. Forest Ecology and Management, 261(10), 1654-1663. https://doi.org/10.1016/j.foreco.2010.09.027

Murthy, I. K., Gupta, M., Tomar, S., Munsi, M., Tiwari, R., Hegde, G. T., & Ravindranath, N. H. (2013). Carbon sequestration potential of agroforestry systems in India. J Earth Sci Climate Change, 4(1), 1-7. https://doi.org/10.4172/2157-7617.1000131

Mutuo, P. K., Cadisch, G., Albrecht, A., Palm, C. A., & Verchot, L. (2005). Potential of agroforestry for carbon storage and moderation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling in Agroecosystems, 71, 43-54. https://doi.org/10.1007/s10705-004-5285-6

Nair, P. K. R. (2011). Agroforestry systems and environmental quality: introduction. Journal of Environmental Quality, 40(3), 784-790. https://doi.org/10.2134/jeq2011.0076

Nair, P. K. R., Kumar, B. M., & Nair, V. D. (2021). An introduction to agroforestry: four decades of scientific breakthroughs. Springer. https://doi.org/10.1007/978-3-030-75358-0

Nair, P. K. R., Nair, V. D., Kumar, B. M., & Haile, S. G. (2009). Soil carbon sequestration in tropical agroforestry systems: a feasibility analysis. Environmental Science & Policy, 12(8), 1099-1111. https://doi.org/10.1016/j.envsci.2009.01.010

Nair, P. K. R., Nair, V. D., Kumar, B. M., & Showalter, J. M. (2010a). Carbon sequestration in agroforestry systems. Advances in Agronomy, 108, 237-307. https://doi.org/10.1016/S0065-2113(10)08005-3

Nguyen, Q., Hoang, M. H., Öborn, I., & van Noordwijk, M. (2013). Multipurpose agroforestry as a climate change resistance option for farmers: an example of local adaptation in Vietnam. Climatic Change, 117(1), 241-257. https://doi.org/10.1007/s10584-012-0550-1

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 114(7), 1518-1523. https://doi.org/10.1073/pnas.1609244114

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., & Canadell, J. G. (2011). A massive and persistent carbon sink in the world's forests. Science, 333(6045), 988-993. https://doi.org/10.1126/science.1201609

Pandey, D. N. (2007). Multifunctional agroforestry systems in India. Current Science, 455-463.

Puri, S., & Nair, P. K. R. (2004). Agroforestry research for development in India: 25 years of experiences of a national program. Agroforestry Systems, 61, 437-452. https://doi.org/10.1023/B:AGFO.0000029014.66729.e0 https://doi.org/10.1007/978-94-017-2424-1_30

Quandt, A., Neufeldt, H., & McCabe, J. T. (2017). The importance of agroforestry in improving livelihood resilience to floods and drought in semiarid Kenya. Ecology and Society, 22(3). https://doi.org/10.5751/ES-09461-220310

Quinkenstein, A., Wöllecke, J., Böhm, C. O., Grünewald, H., Freese, D., Schneider, B. U., & Hüttl, R. F. (2009). Ecological benefits of the alley cropping agroforestry system in vulnerable parts of Europe. Environmental Science & Policy, 12, 1112-1121. https://api.semanticscholar.org/CorpusID:153815471https://doi.org/10.1016/j.envsci.2009.08.008

Rao, M. R., Nair, P. K. R., & Ong, C. K. (1997). Biophysical interactions in tropical agroforestry systems. Agroforestry Systems, 38, 3-50. https://doi.org/10.1023/A:1005971525590

Ravindranath, N. H., Somashekhar, B. S., & Gadgil, M. (1997). Carbon flux in Indian forests. Climatic Change, 35, 297-320. https://doi.org/10.1023/A:1005303405404

Rizvi, R. H., Newaj, R., Karmakar, P. S., Saxena, A., & Dhyani, S. K. (2016). Remote sensing analysis of agroforestry in Bathinda and Patiala districts of Punjab utilizing sub-pixel approach and medium resolution data. Journal of the Indian Society of Remote Sensing, 44(4), 657-664. https://doi.org/10.1007/s12524-015-0463-3

Romabai, W., Pamei, T., Pf, M., Nevidita, L., & Panmei, R. (2023). Assessment of economically important tree-based NTFPs in Indo-Burma region, Manipur, India. Forests, Trees and Livelihoods, 32(1), 1-11. https://doi.org/10.1080/14728028.2022.2146606

Rosenstock, T. S., Wilke, A., Jallo, C., Namoi, N., Bulusu, M., Suber, M., Mboi, D., Mulia, R., Simelton, E., & Richards, M. (2019). Making trees count: Measurement and reporting of agroforestry in UNFCCC national communications of non-

Annex I countries. Agriculture, Ecosystems & Environment, 284, 106569. https://doi.org/10.1016/j.agee.2019.106569

Saha, S. K., Nair, P. K., Nair, V. D., & Kumar, B. M. (2009). Soil carbon stock in connection to plant diversity in homegardens in Kerala, India. In Advances in Agroforestry (pp. 53-65). Springer. https://doi.org/10.1007/s10457-009-9228-8

Sangeetha, R., & Shanmugam, T. R. (2015). External gain and external cost in the economics agroforestry systems in north western areas of Tamil Nadu. International Journal of Commerce and Business Management, 8(1), 28-35. https://doi.org/10.15740/HAS/IJCBM/8.1/28-35

Simelton, E., Dam, B. V., & Catacutan, D. (2015). Trees and agroforestry for coping with extreme weather events: experiences from northern and central Viet Nam. Agroforestry Systems, 89(6), 1065-1082. https://doi.org/10.1007/s10457-015-9835-5

Singh, S. P., Singh, V., & Skutsch, M. (2010). Rapid warming in the Himalayas: Ecosystem reactions and development alternatives. Climate and Development, 2(3), 221-232. https://doi.org/10.3763/cdev.2010.004

Swamy, S. L., & Puri, S. (2005). Biomass production and C-sequestration of Gmelina arborea in plantation and agroforestry system in India. Agroforestry Systems, 64, 181-195. https://doi.org/10.1007/s10457-004-1999-3

Toppo, P., & Toppo, S. (2019). Tree crop interaction in agroforestry system: A review. International Journal of Chemical Studies, 7, 2359-2361. https://api.semanticscholar.org/CorpusID:230432862

Tripathy, S. (2018). Tribal development through horticulture plantations under WADI. Horticulture International Journal, 92(3), 90-93. https://doi.org/10.15406/hij.2018.02.00033

Tschakert, P., Coomes, O. T., & Potvin, C. (2007). Indigenous lives, slash-and-burn agriculture, and carbon stocks in Eastern Panama. Ecological Economics, 60(4), 807-820. https://doi.org/10.1016/j.ecolecon.2006.02.001

Verchot, L. v, van Noordwijk, M., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K. v, & Palm, C. (2007). Climate change: connecting adaptation and mitigation through agroforestry. Mitigation and Adaptation Strategies for Global Change, 12, 901-918. https://doi.org/10.1007/s11027-007-9105-6

Wang, X., & Feng, Z. (1995). Atmospheric carbon sequestration using agroforestry in China. Energy, 20(2), 117-121. https://doi.org/10.1016/0360-5442(94)00057-A

Ya, T., & Qi, Z. (2001). Review of research on nitrogen contribution and recovery in alley cropping systems. Chinese Journal of Eco-Agriculture. https://api.semanticscholar.org/CorpusID:88716515

Yadav, R. P., Gupta, B., Bhutia, P. L., & Bisht, J. K. (2018). Sustainable agroforestry systems for livelihood security and their economic appraisal in Indian Himalayas. Economic Affairs, 63(3), 633-639. https://doi.org/10.30954/0424-2513.3.2018.7

Yadav, R. P., Gupta, B., Bhutia, P. L., Bisht, J. K., & Pattanayak, A. (2019). Sustainable agroforestry systems and their structural components as livelihood possibilities along elevation gradient in central Himalaya. Biological Agriculture & Horticulture, 35(2), 73-95. https://doi.org/10.1080/01448765.2018.1457982

Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., van Noordwijk, M., & Wang, M. (2016). Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. Scientific Reports, 6(1), 29987. https://doi.org/10.1038/srep29987