OPEN ACCESS

Haya: The Saudi Journal of Life Sciences
Abbreviated Key Title: Haya Saudi J Life Sci
ISSN 2415-623X (Print) | ISSN 2415-6221 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Review Article

Navigating Synergies: A Comprehensive Review of Agroforestry System and Agronomy Crops

Muhammad Awais Arshad[1], Sana Rouf[2*], Rana Nadeem Abbas[1], Zainab Shahbaz[2], Kainat Aleem[2], Hafsah Shahbaz[4], Rida Pervaiz[3], Amna Sarwar[2], Haseeb ur Rehman[2]

[1]Department of Agronomy, Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan
[2]Department of Forestry & Range Management, Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan
[3]Department of Botany, Faculty of Sciences, University of Agriculture Faisalabad, Pakistan
[4]Institute of Environmental Health and Ecological Security, School of Environment and Safety Engineering, Jiangsu Province Engineering Research Center of Green Technology and Contingency Management for Emerging Pollutants, Jiangsu University, Zhenjiang 212013, People's Republic of China

DOI: 10.36348/sjls.2024.v09i04.003 | **Received:** 07.03.2024 | **Accepted:** 16.04.2024 | **Published:** 23.04.2024

***Corresponding author:** Sana Rouf
Department of Forestry & Range Management, Faculty of Agriculture, University of Agriculture Faisalabad, Pakistan

Abstract

Agroforestry, the integration of trees with agricultural or livestock systems, holds significant promise for sustainable land management and addressing various environmental challenges. This comprehensive review explores the multifaceted benefits and challenges associated with agroforestry systems, focusing on their interactions with agronomy crops. We delve into the ecological, socio-economic, and climate-related dimensions of agroforestry, highlighting its potential to enhance productivity, conserve resources, and mitigate climate change impacts. The review begins by examining the historical context and conceptual foundations of agroforestry, elucidating its diverse array of products and services. Through case studies and empirical research, we explore the ecological benefits of integrating trees with crop production, emphasizing improvements in soil fertility, water quality, and biodiversity conservation. Furthermore, we discuss the role of agroforestry in climate change adaptation and mitigation, including its capacity for carbon sequestration, soil restoration, and resilience-building in the face of extreme weather events. A critical analysis of agroforestry's implications for agronomy crops reveals both opportunities and challenges. While agroforestry systems have shown potential to enhance crop yields, improve soil health, and diversify income sources, they also present complexities related to competition for resources and management practices. Insights from studies conducted in various agro-ecological contexts provide valuable guidance for optimizing the design and implementation of agroforestry systems to maximize their benefits for agronomy crops. This review underscores the importance of interdisciplinary collaboration and knowledge exchange in advancing agroforestry research and practice. By integrating principles from agronomy, ecology, economics, and forestry, we can develop innovative strategies to harness the full potential of agroforestry for sustainable agriculture and environmental conservation.

Keywords: Agroforestry, Agronomy crops, Ecological benefits, Climate change adaptation, Soil fertility, Carbon sequestration, Resource conservation, Interdisciplinary collaboration, Sustainable agriculture.

INTRODUCTION

The practice of cultivating trees in conjunction with crops or animals, commonly referred to as agroforestry, has not yet achieved widespread acceptance. While some scientists advocate for agroforestry as an innovative and valuable land-use option with unwavering enthusiasm, others, including farmers, scientists, developers, and policymakers, view it as a passing environmental trend and give it little recognition. Agroforestry provides multiple products (such as food, wood, fodder, mulch, fibers, and medicines) or services (such as soil fertility maintenance, erosion control, improvement of microclimate, enhancement of biodiversity, and protection of watersheds) through the presence of trees. The main challenges of agroforestry primarily revolve around potential competition between trees and crops for vital resources like water, light, nutrients, as well as for farm resources such as land and labor (Torquebiau *et al.*, 2000).

The quest for a clear definition of agroforestry began in the middle of the 1970s and advanced quickly as studies examined the variety and scope of agroforestry activities. Agroforestry's future was hampered in the late 1970s and early 1980s by too many definitions and a general lack of comprehension because of an information deficit. These earlier battles to define an expansive new field of study have produced a conceptual understanding that can be used to examine complex systems and procedures. Agroforestry's core ideas are captured in at least one other old definition. Thus, agroforestry is defined as a viable farming system that increases total production by using management practices that are in line with local cultural norms and bringing together agricultural crops with forest plants and/or animals at the same time or related manner (Bene *et al.*, 1977). Agroforestry represents a sustainable land management approach entailing the deliberate incorporation or integration of trees or other perennial woody plants within agricultural or animal production systems, aimed at harnessing the ecological and economic benefits that result. This definition, however, is perhaps the most appropriate among the many attempts to clarify the science and art of agroforestry (Nair, 1984).

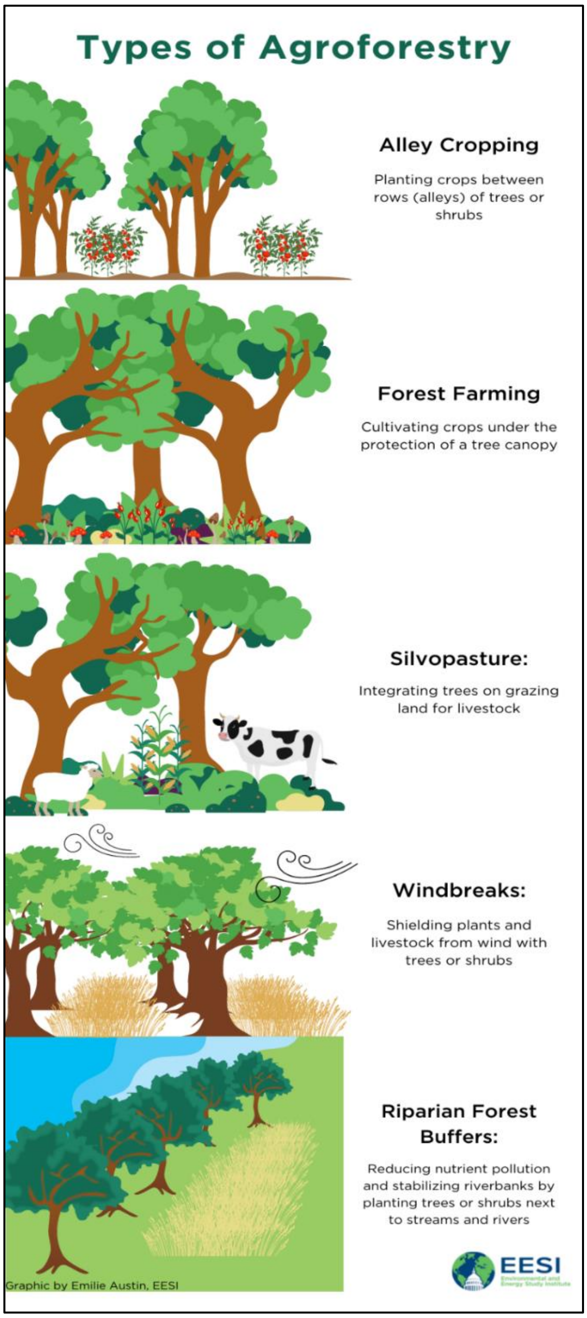

Figure 1: Common agroforestry practices include: alley cropping (planting crops between rows of trees), forest farming (growing crops beneath forest canopy), silvopasture (integrating trees, crops, and grazing livestock), riparian forest buffers (planting trees and shrubs along river banks), and windbreaks (using trees to shelter crops from wind or other extreme weather)
(Source: USDA National Agroforestry Center)

The inherent significance of agroforestry is evidenced by its expansive reach and potential. Tree species are strategically incorporated into diverse landscapes including boundaries, bunds, wastelands, and fields where annual crops flourish. As highlighted by Fanish and Priya (2013), agroforestry offers a myriad of potential advantages, encompassing enhanced overall productivity, augmented soil fertility, soil conservation, improved nutrient cycling, microclimate modulation, carbon sequestration, bio drainage, bio-energy, and biofuel production. Moreover, key components inherent to agroforestry systems that facilitate adaptation to climate change include modifications in microclimate, provision of permanent cover for protection, opportunities for diversification of agricultural systems, enhanced efficiency in soil, water, and climatic resource utilization, contribution to soil fertility enhancement, reduction of carbon emissions, increased sequestration, and promotion of gender equity (Rao *et al*., 2007).

Agroforestry, the intentional integration of trees and shrubs alongside crops or livestock, is recognized as a versatile strategy within our food system. It predates the actual cultivation of land by about fifty years as an ecologically sound agricultural technique (Nair *et al*., 2012). Benefits of agroforestry include decreased runoff of fertilizer and pesticides, storing carbon, improved soil health, reduced use of fossil fuels, erosion control, modified wildlife habitat, and increased resilience to an uncertain future in agriculture (Davis *et al*., 2012). In essence, the incorporation of trees and other perennial vegetation into landscapes serves to mitigate the adverse impacts of agriculture. The substantial potential of agroforestry as a land use strategy in both developing and affluent nations is underscored by its ability to simultaneously provide economic, ecological, and aesthetic benefits (Jose *et al*., 2012).

Agroforestry yields favorable impacts on soil and water quality. The enrichment of organic matter and the diversification of microbial communities contribute to enhancing soil quality, nutrient cycling, crop productivity, and resilience to drought (Baah-Acheamfoue *et al.,* 2014). Water quality is improved through the integration of agroforestry vegetative buffer strips, which mitigate non-point source pollution originating from row crops (Jose *et al.,* 2009). A watershed study conducted in Missouri, employing a "paired" approach, illustrated that agroforestry and grass buffer strips effectively reduced phosphorus and nitrogen runoff from a corn-soybean rotation (Udawatta *et al*., 2002). The presence of perennial vegetation increases above-ground biomass, diminishing runoff velocity and capturing up to 95% of sediment at risk of erosion (Schultz *et al.,* 2009). Furthermore, the subterranean roots of agroforestry systems absorb 80% or more of surplus nutrients and harbor microbial communities capable of metabolizing pesticides (Udawatta *et al*., 2010).

Role of Agroforestry in Soybean cultivation

Agroforestry systems can mitigate climate change impacts on crop performance by buffering against soil water decreases. Despite farmer reluctance due to yield loss concerns, a study in southern Ontario, Canada, found stable soybean yields in the tree-crop zone of a mature agroforestry system under full-season water deficit, with higher N2-fixation compensating for lower yields compared to monoculture. Adaptation of nodulation patterns to soil moisture suggests potential resilience to future drier conditions, increasing agroforestry system viability in climate-affected areas (Nasielski *et al.*, 2015).

Agroforestry systems offer a sustainable alternative to address agricultural concerns, but their full potential for soybean cultivation remains uncertain. A study in Southern Brazil evaluated soybean growth and yield in different agroforestry setups and full sun conditions during the 2014/2015 crop year. Findings indicate that specific configurations of agroforestry, particularly those characterized by wider spacing and the inclusion of *Peltophorum dubium* forest species, demonstrate potential. However, additional research is necessary to refine soybean cultivation within agroforestry systems, including investigations into early crop insertion and strategies for minimizing intraspecific competition (Cristo *et al*., 2020).

This study evaluates the influence of agroforestry systems, specifically those incorporating Eucalyptus *urophylla* x *Eucalyptus grandis* and *Peltophorum dubium*, on soybean yield and solar radiation dynamics in Southern Brazil. Findings reveal that soybean growth beneath *Peltophorum dubium* trees resulted in the highest yield. Moreover, the implementation of tree pruning techniques improves solar radiation penetration in the understory, thereby increasing soybean productivity, particularly when combined with *Peltophorum dubium* (Caron *et al.*, 2018).

Overview of Agroforestry System

One traditional land use strategy that could help with agricultural environmental problems is agroforestry. Agroforestry is the deliberate blending of shrubs or forests with animal systems and crops in order to gain advantage from the consequent economic and ecological relationships. Recent research suggests that the global agro-food sector has the potential to achieve greater sustainability in food and fiber production. This transition could benefit farmers economically and contribute positively to environmental sustainability. The widespread adoption of agroforestry concepts and practices is proposed as a key strategy to achieve these goals. Agroforestry encourages eco-intensification by using resources more effectively while providing a range of ecosystem services and environmental advantages. On the other hand, not much current research has been done regarding the whole environmental benefit of agroforestry, particularly with regard to forest fires, carbon absorption, and climate change. Agroforestry offers a variety of environmental benefits (Pantera *et al.*, 2021).

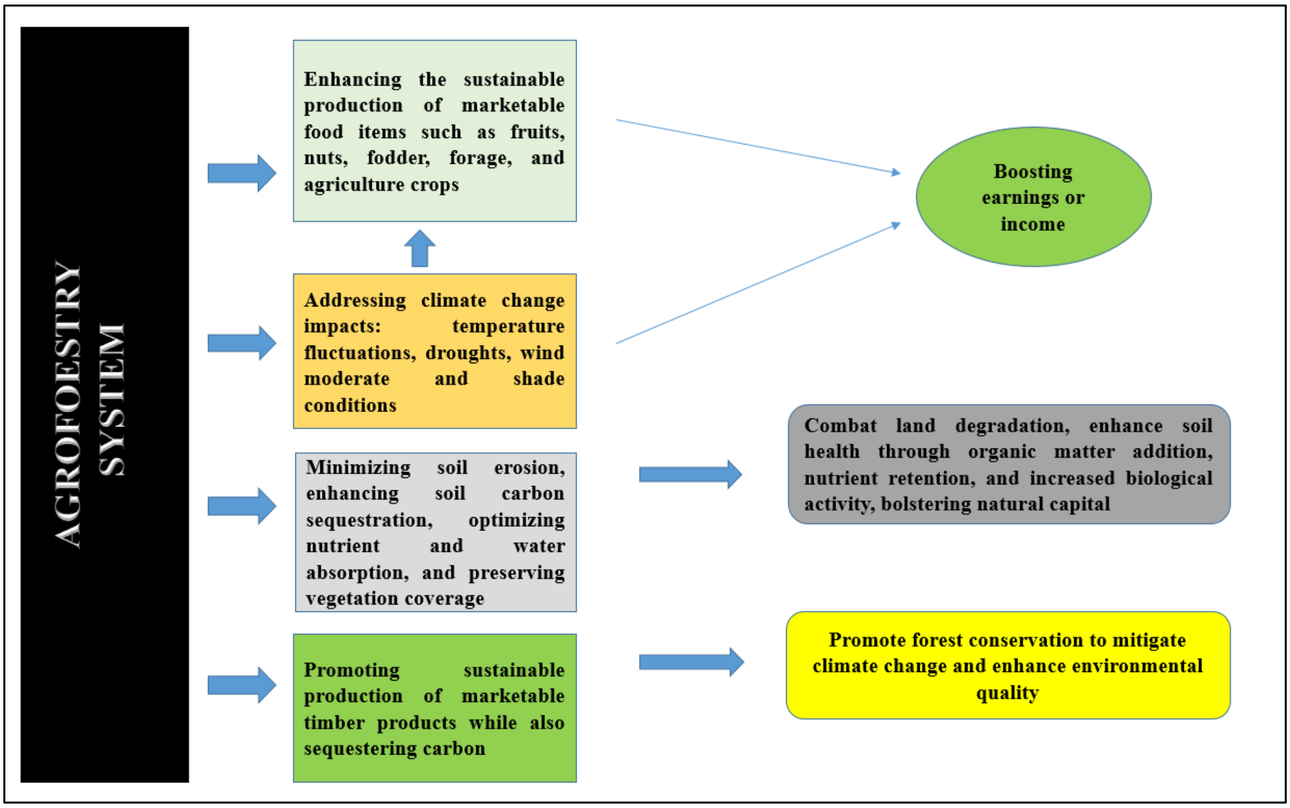

Figure 2: Agroforestry System: Enhancing Sustainability and Resilience in Agriculture through Integrated Tree-Crop Systems

Agroforestry techniques, characterized by the close integration of trees with agricultural elements on a field scale, are often conflated with entire farm and forest systems within current classification schemes. In actuality, farming systems frequently incorporate a variety of unique agroforestry techniques on various terrain types. A generic classification is intended to distinguish between various forms of agroforestry and combine those that are comparable in order to facilitate communication and well-organized information storage. A new categorization scheme is suggested, which centers on the "practice" as the unit of classification instead of the "system". By using this method, activities with comparable underlying ecologies and management prospects can be efficiently grouped. It is suggested to define agroforestry in two stages, differentiating between an integrated set of land use activities and an interdisciplinary approach to land use. The analysis of the role of trees in agricultural landscapes identifies four layers of organization: the overarching land use system, specific land use categories within these systems, distinct groups comprising managed components such as trees, crops, and animals, and functionally related groupings of these practices over time and location. This analytical strategy adheres to recognized systems analysis methodologies and is consistent with the body of existing research. The components involved and the prevalent land usage are the main factors taken into consideration when classifying the major categories of agroforestry practices. Established on the configuration, density, and variety of tree constituents, a secondary system further categories these activities (Sinclair *et al.*, 1999).

Agroforestry represents a dual-purpose land management system that fosters both productivity and environmental protection, ensuring the preservation of biodiversity and the sustainable management of water and soil resources. Hairiah *et al.* (2002) assert that agroforestry stands out as a sustainable land management approach. At the meso scale, agroforestry has been scientifically validated to effectively fulfill its role, particularly in conserving natural resources and safeguarding the environment, particularly regarding land suitability. The positive impacts of agroforestry systems at this scale encompass maintaining soil physical properties and fertility, preserving hydrological functions, conserving carbon stocks, mitigating greenhouse gas emissions, and safeguarding biodiversity. The specific composition and arrangement of plant and tree species within agroforestry systems significantly contribute to their beneficial function, as emphasized by Widianto *et al.* (2003). Agroforestry systems possess distinct characteristics compared to monoculture farming systems. In an agroforestry system, various components such as trees, plants, and livestock interact with one another. Additionally, agroforestry systems possess unique characteristics in terms of the types of products produced, the time it takes to obtain these products, and the orientation of product usage. Agroforestry systems yield a wide array of products, ranging from commercial commodities like food, fruits, fodder, timber, firewood, leaves, skins, and latex to ecosystem services (Yamani *et al.*, 2010). The advancement of agroforestry is primarily driven by objectives related to land use optimization and rural development, with a focus on harnessing the potential and opportunities for enhancing human well-being through sustainable resource management and environmental preservation.

Agroforestry practices are increasingly gaining traction in temperate regions spanning continents such as North America, Europe, the highlands of Asia, Oceania, and the regions of Chile and Argentina in South America. The distinctive seasonal patterns observed in temperate climates have led to the adoption of various agroforestry systems tailored to these conditions. These systems include woodlots, windbreaks, protected areas, silvopastoral systems, woodland grazing, intercropped orchards, and agri-horti-silviculture systems. Predominant tree species in these temperate agroforestry systems include Pinus radiata, various Populus and Salix species, Eucalyptus species, Paulownia spp., Robinia pseudoacacia, as well as several fruit tree species such as apple, plum, apricot, peach, and pear. While less diverse compared to tropical agroforestry systems, temperate agroforestry systems significantly contribute to income generation, climate modification, and biodiversity conservation (Bhardwai *et al.*, 2017).

Interaction between Agroforestry and Agronomy

Agroforestry is increasingly recognized for its capacity to address tree product shortages and provide socio-economic and environmental benefits. With its potential to enhance livelihood security and resilience to climate change, agroforestry is crucial in achieving targets like the 33% forest cover outlined in India's "Greening India" report. This multidisciplinary field integrates principles from agronomy and requires collaboration among agronomists, soil scientists, foresters, economists, and others to explore its complexities and potentials, particularly in relation to sustainable agriculture and climate change mitigation (Dhvani *et al.*, 2009).

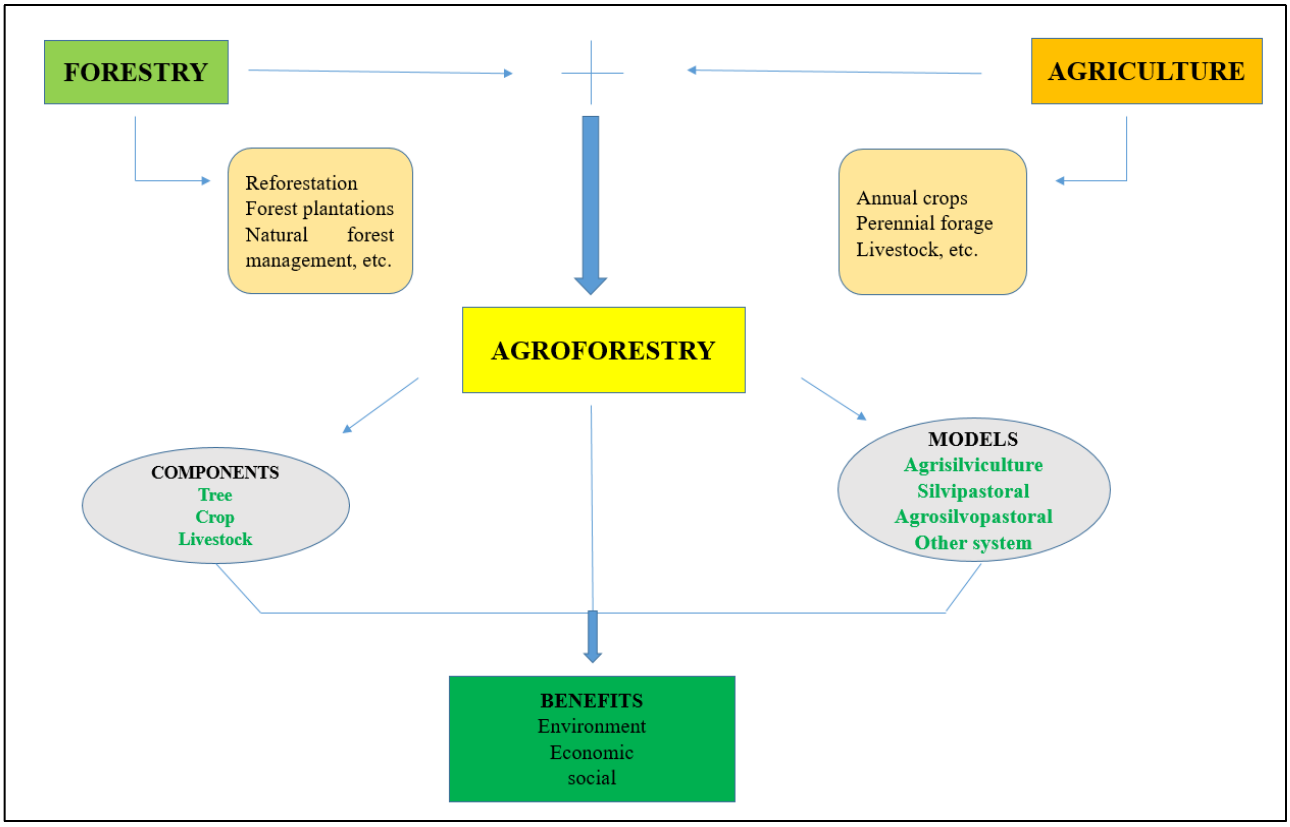

Figure 3: Synergistic Interactions and Benefits of Agroforestry: A Comprehensive Model Integrating Agriculture, Trees, and Forest Components for Sustainable Land Use

Because of the lengthy lifespan of trees and the abundance of possible species, it frequently takes a while to determine, through empirical methods, the relative benefits and viability of alternative agroforestry strategies in new locations. This makes it challenging to define recommendation domains for certain technology. For a quicker ex-ante evaluation of performance potentials, tools are required. Such instruments must take into account the effects of climate change because planted trees can stay in their current location for decades (Luedeling *et al.*, 2014). Process-based modelling has been found to be a feasible method for producing these projections (Bayala *et al.*, 2015); nonetheless, in order for agroforestry models to effectively meet this issue, a number of challenges need to be addressed.

This study in semi-arid Kenya examined the impact of *Grevillea robusta* and *Gliricidia sepium* trees on soil water, crop yield, and root dynamics when grown alongside maize. Despite deeper tree root penetration, both tree and maize roots were concentrated in the top 200 mm of soil, leading to temporal separation of root activity but no spatial separation. While *G. sepium* exhibited greater competitiveness with maize compared to *G. robusta*, both trees significantly reduced crop yield, with *G. sepium* causing a 50% reduction and *G. robusta* a 40% reduction relative to control plots without trees. Soil moisture was lower in plots with trees, especially near tree rows, with *G. sepium* plots exhibiting the lowest soil moisture levels (Odhiambo *et al*., 2001).

Ecological benefits of integrating tree with crop production

The use of physical resources above and below ground is investigated in the context of ecological relationships between trees and crops. The analysis focuses on interactions that occur above ground, like variations in temperature, light, and humidity, and how they might affect crops growing in the understory. According to our research, atmospheric interactions in semi-arid tropical alley cropping are favorable but not as important as below-ground interactions.

In semi-arid tropical regions, negative interactions between plants were attributed to competition for soil moisture. To investigate this, below-ground interactions were studied by employing a short polythene barrier (0.5 m) to separate root systems. Measurements of root distribution revealed that the roots of *Leucaena leucocephala* L trees are primarily concentrated in the top thirty centimeters of the soil. The presence of a root barrier effectively restricts their lateral movement. The idea that trees' deep root systems prevent them from competing with crops is called into question by these findings.nFurthermore, the goal of this research is to draw attention to the different difficulties that agroforestry and intercropping systems provide. Potential methods for attaining beneficial relationships are examined, and the importance of root investigations is underlined (Ong *et al.*, 1991).

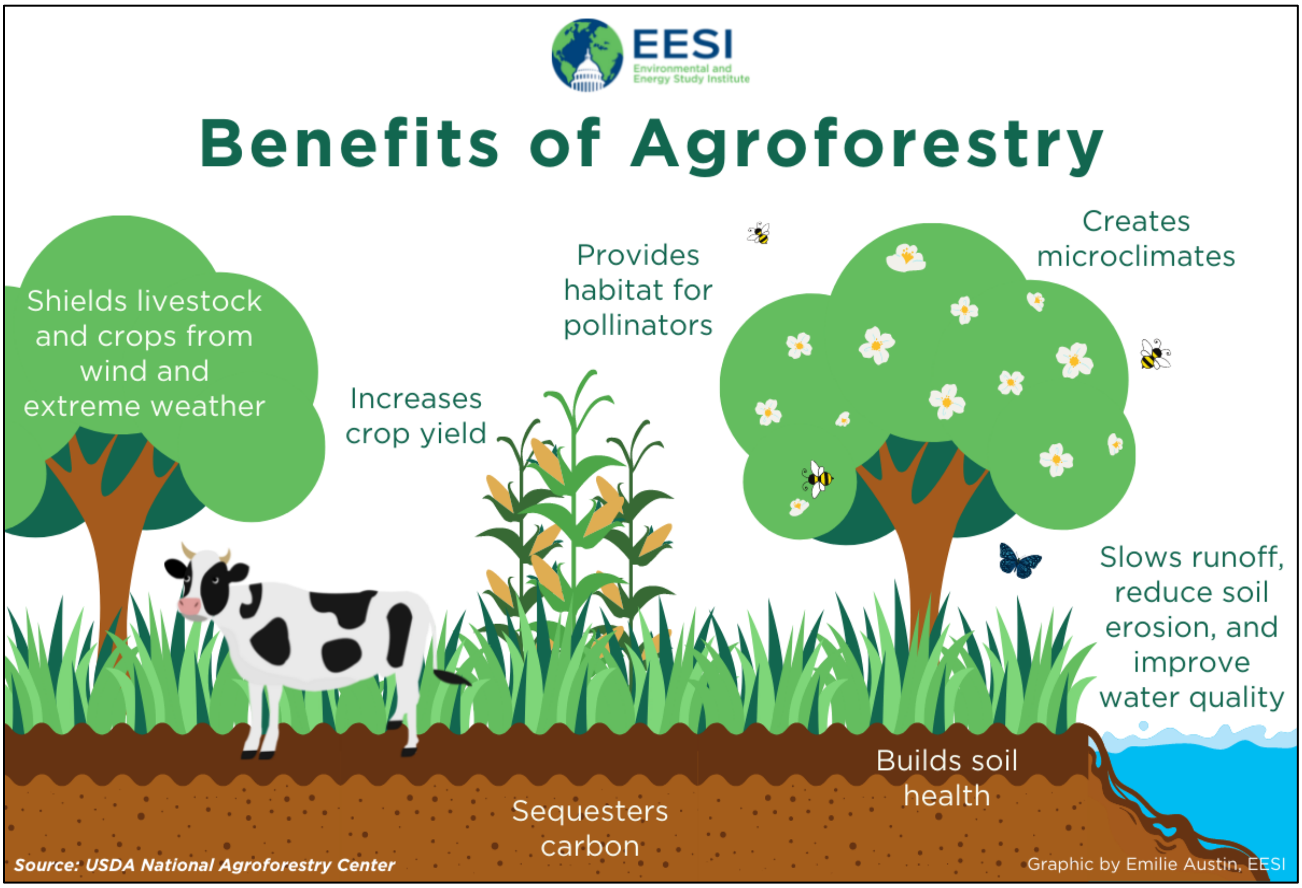

Figure 4: Benefits of Agroforestry: Sustainable agriculture practices that can help farmers mitigate and adapt to the climate crisis

(Source: USDA National Agroforestry Center)

Agroforestry emerges as a compelling solution in the fight against climate change. Recognized by the IPCC as a potent method for carbon sequestration, agroforestry holds promise in mitigating the impacts of climate change (Watson *et al.*, 2000). Additionally, it offers benefits such as bolstering agricultural yields and curbing soil erosion (Prinsley, 1990). The multifaceted biomass produced through agroforestry serves various purposes including fuelwood, food, construction materials, and medicinal resources, thereby alleviating pressure on natural forests. Furthermore, agroforestry presents an opportunity for continuous land utilization, countering the need for fallow periods in shifting cultivation systems. For example, sustainably managing one hectare of land with agroforestry could potentially replace 5-10 hectares subjected to shifting rotation slash and burn practices (Trexler, 1993). In urban settings, agroforestry not only provides local biomass but also highlights the advantages of tree planting to the public. The potential for urban tree planting in the United States and Europe alone to absorb 50 million tons of carbon annually underscores its significance (Kulp, 1990). Moreover, agroforestry's indirect benefits, such as substituting for fossil fuels, have the potential to prevent the release of 17 million tons of carbon globally each year (Evans, 1992). Agroforestry emerges as an optimal strategy for enhancing productivity in wastelands, expanding tree cover beyond forests, and alleviating pressure on forests across various agro-ecological regions of India. According to an IPCC special report (IPCC, 2000), converting unproductive croplands and grasslands to agroforestry holds the highest potential for atmospheric carbon sequestration. In the realm of agroforestry, soil restoration involves replenishing organic-based nutrients through the enhancement of soil organic matter, which comprises approximately half of soil carbon.

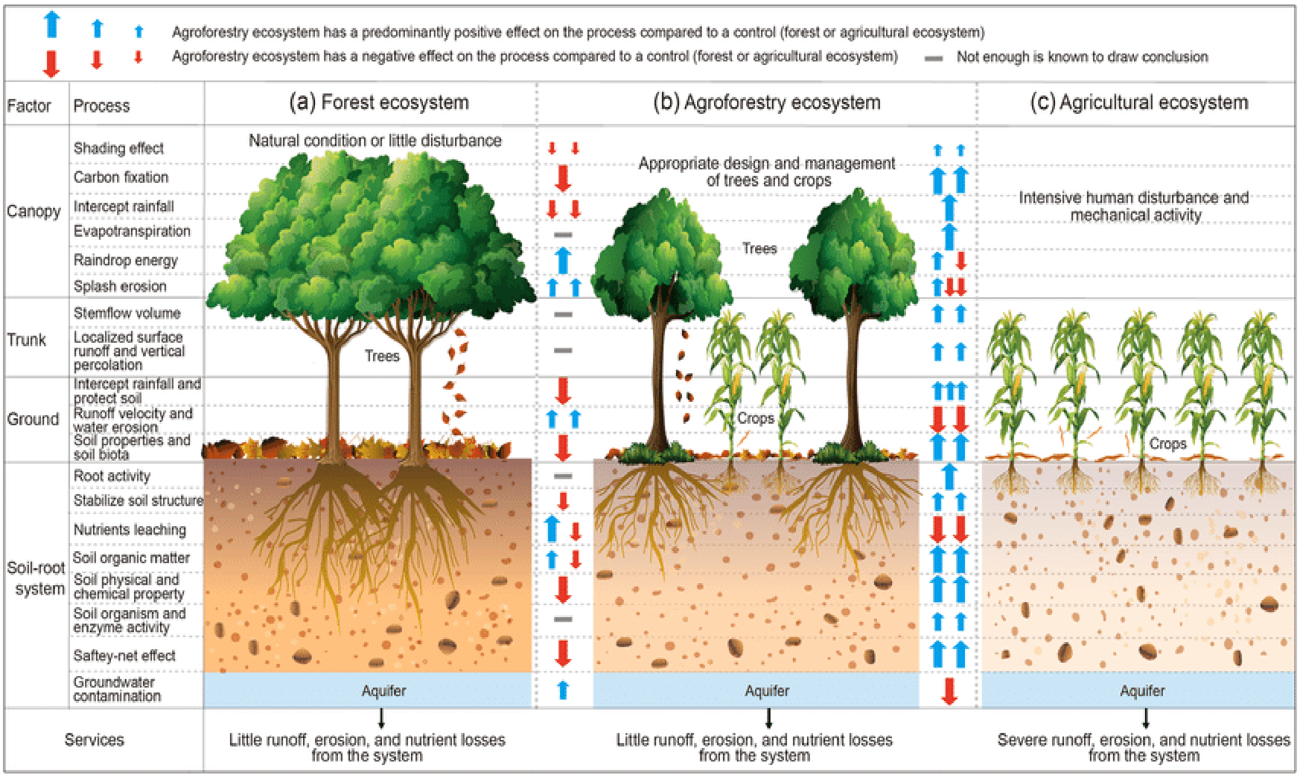

Figure 5: Agroforestry traits and their potential impact on processes of reductions in water, soil and nutrient losses, and associated water contamination compared to the natural forest and conventional agricultural systems, based on the literature reported in the main text. Size and number of pointing arrows indicate the amount of evidence available, this figure was uploaded by Rémi Cardinael (Zhu *et al.*, 2020)

Alley cropping systems (ACS) integrating short rotation coppices in temperate Europe offer dual benefits of crop and woody biomass production, diversifying market goods provision. Despite lacking substantial evidence on tree-crop interactions, ACS are recognized for enhancing ecosystem services like carbon sequestration, soil fertility, and resource optimization compared to conventional agriculture. This review highlights ACS's potential to regulate water quality, boost biodiversity, and enhance productivity, particularly on marginal sites, advocating for their widespread adoption in temperate regions (Tsonkova *et al.*, 2012).

There are significant advantages to simultaneously addressing climate change adaptation and mitigation in agricultural contexts, both from a technological and financial perspective. Here's why: Firstly, planning for adaptation often serves as a prerequisite for effective mitigation planning, especially when evaluating future climate risks for investment in mitigation efforts. Secondly, certain land-use strategies can yield benefits for both adaptation and mitigation objectives. Lastly, leveraging carbon finance can provide crucial support for adaptation initiatives that are currently underfunded. The integration of climate change adaptation and mitigation goals, particularly through agroforestry and ecosystem conservation, represents essential strategies. These approaches frequently yield substantial co-benefits for local ecosystems and biodiversity. The alignment of adaptation and mitigation efforts is particularly feasible in projects focused on income diversification through tree and forest product utilization, enhancing resilience to extreme weather events, improving soil fertility, implementing fire management strategies, establishing windbreaks, and conserving and restoring forested and riparian areas, wetlands, and mangroves. However, conflicts may arise between adaptation and mitigation objectives in certain scenarios. For example, conflicts may occur when the cultivation of fast-growing tree monocultures for mitigation purposes clashes with local tree and forest utilization practices, leading to heightened livelihood vulnerability. Similarly, conflicts may arise when regional water usage conflicts with tree planting in water-limited areas. Additionally, tensions may arise when the promotion of "climate-smart" agroforestry techniques clashes with the imperative for agricultural intensification to meet growing food demands. Effective mitigation project planning should integrate considerations for adaptation, and there should be a concerted effort to prioritize integrated adaptation and mitigation activities in carbon markets and policy formulation processes (Matocha *et al*., 2012).

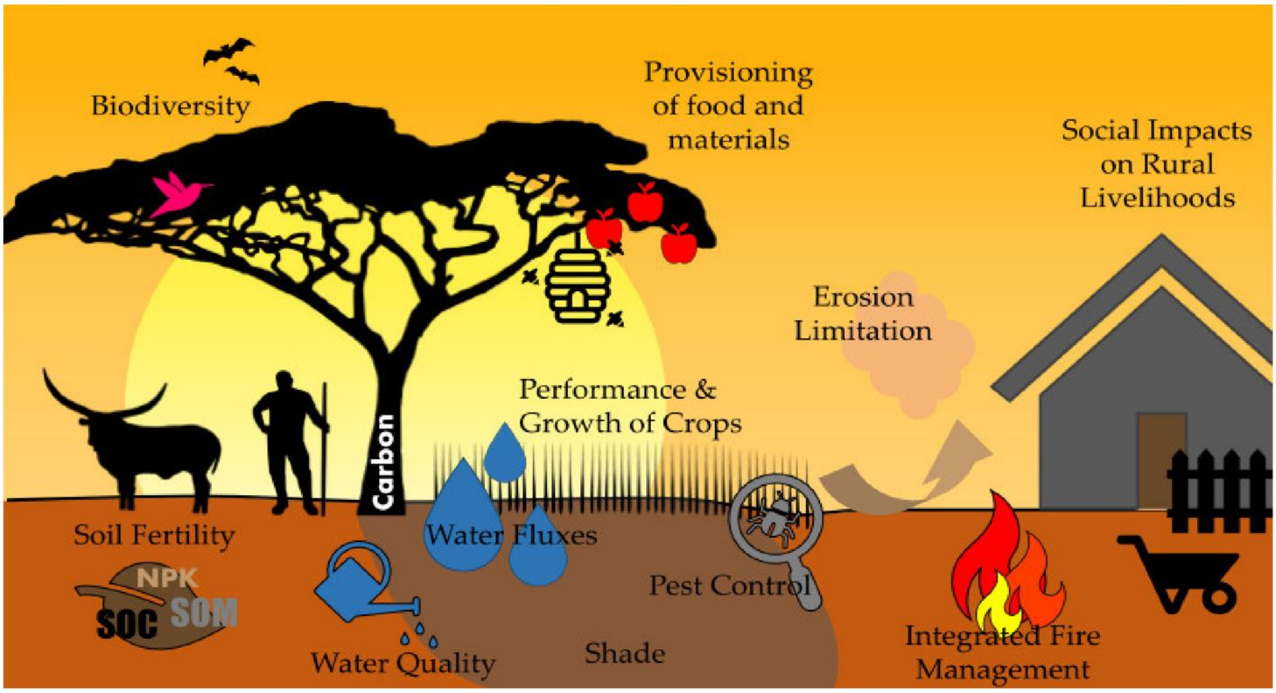

Figure 6: On- and off-site benefits of agroforestry systems (AFS) in the southern African region for direct and indirect mitigation of predicted climate change impacts (Sheppard *et al*., 2020)

Over the past three decades, investments in agroforestry research have significantly advanced understanding of trees' role in integrated farming systems and their ecological and economic benefits. This special collection of nine papers focuses on three key environmental advantages of agroforestry systems: water-quality enhancement, carbon sequestration, and soil improvement. The papers underscore the importance of generating diverse research datasets and integrating them with robust statistical tools to ensure broad applicability of results, while also emphasizing the need for tailored management practices to exploit these benefits effectively. Challenges remain, such as the lack of standardized norms and limitations in statistical modeling, but overall, this collection underscores the promise of agroforestry systems in addressing environmental quality issues (Nair, 2011).

Enhancing soil health and Fertility through agroforestry

Soil degradation entails a reduction in soil quality or its capacity to support economic activities and ecosystem functions (Lal *et al.*, 2010). This degradation can manifest in various forms, including soil compaction, salinization, nutrient depletion, loss of biodiversity, and contamination, all of which can diminish soil productivity. The severity of these effects is influenced by factors such as the types of crops cultivated, soil characteristics, and agricultural practices within the ecosystem. Agro-ecosystems offer a multitude of services, encompassing provisioning, regulating, supporting, and cultural ecosystem services. Among these, provisioning services such as food, fodder, fiber, and fuelwood are particularly noteworthy due to their economic value (Ghaley *et al.*, 2014). Trees play a vital role in maintaining soil structure and stability. Their presence on farmlands can enhance soil physical properties such as permeability, aggregate stability, water retention, and soil temperature, thereby creating more conducive conditions for plant growth (Nair, 1987). Moreover, trees serve as a natural shield against erosion induced by rainfall and wind. Tree canopies intercept and redirect rainfall and wind in ways that minimize soil disturbance (del Castillo *et al.*, 1994). Additionally, the physical barriers formed by tree stems, roots, and litterfall help safeguard the soil from surface runoff. Agroforestry systems also contribute significant quantities of organic matter to the soil, thereby improving soil physical and chemical characteristics and providing soil coverage (Seiter *et al*., 1999). Organic matter presence alleviates soil compaction, enhances water infiltration, and increases soil porosity (del Castillo *et al*., 1994). These alterations to soil structure facilitate more effective root penetration and access to water and nutrients. Agroforestry is a land use strategy that is in between the European definitions of purely forestry and agriculture, combining aspects of both. Agroforestry systems, when correctly implemented, can assist EU governments in addressing productivity, ecological, and social concerns. Although agroforestry techniques are extensively employed and supported in tropical nations, their application in Europe is restricted to periphery where sustainable land management is crucial in the near future. Improved utilisation of resources both spatially and temporally is one of the many productive benefits of agroforestry systems. This helps the environment by reducing nutrient losses, increasing carbon sequestration, improving biodiversity, reducing soil erosion, and managing fire risk in particular areas. In addition to helping the general population, these benefits also have societal consequences at the farm level and in various biogeographic regions of Europe. This chapter will go into greater detail about these topics (Rigueiro *et al*., 2009).

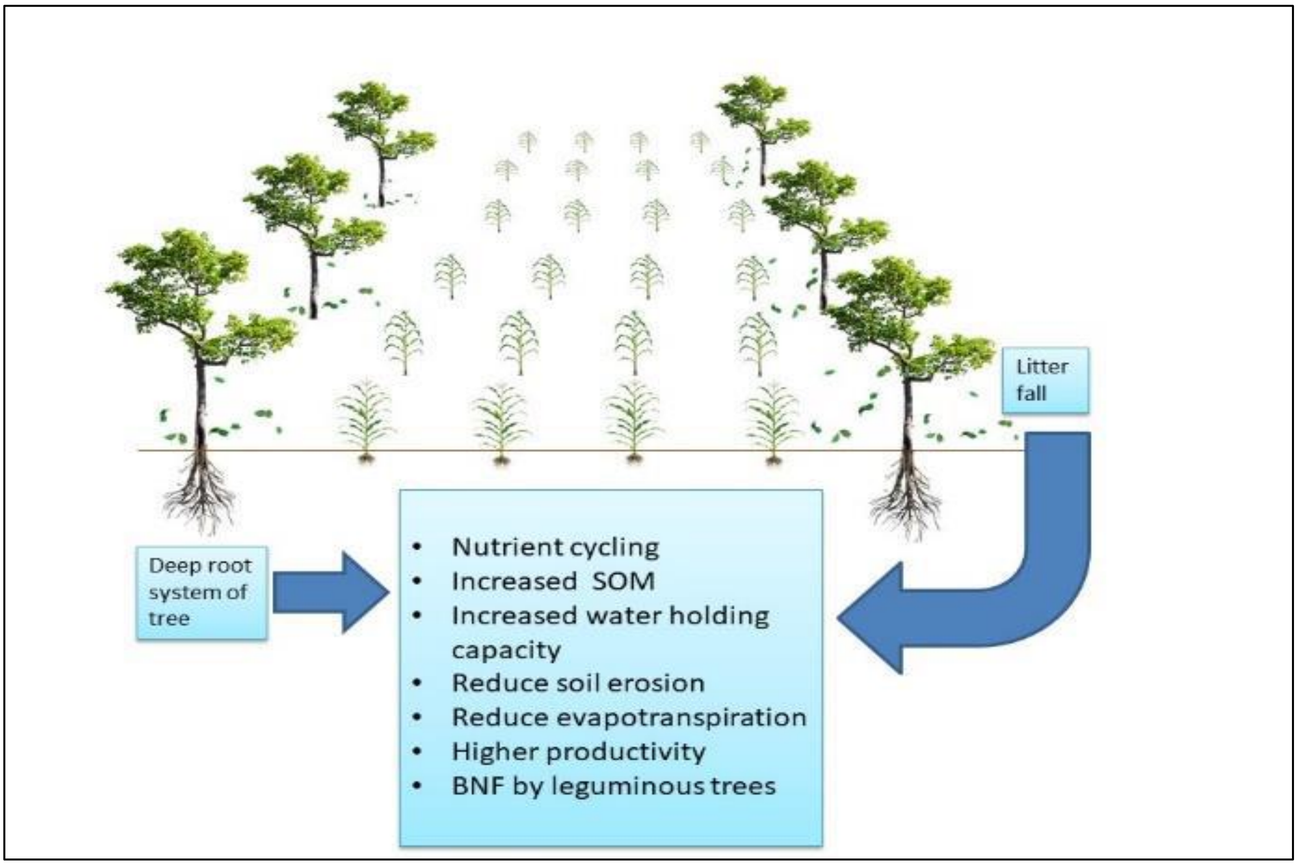

Figure7: Role of agroforestry in agriculture and soil. This figure was uploaded by Prodipto Bishnu Angon (Mondal *et al.*, 2023)

Samra and Singh (2000) conducted a study revealing that the soil organic carbon content in surface soil rose significantly after five years under certain tree combinations. Specifically, under *Acacia nilotica* + *Saccharum munja*, the organic carbon content increased from 0.39% to 0.52%, and under *Acacia nilotica* + *Eulaliopsis binata*, it increased from 0.44% to 0.55%. They suggested that these tree combinations are conservative, highly productive, and less competitive with other vegetation, making them well-suited for eco-friendly conservation and land rehabilitation efforts in the Shivalik foothills of sub-tropical northern India. In the realm of agri-silviculture, the cultivation of *Albizia procera* with various pruning regimes led to a notable increase in soil organic carbon levels by 13-16% compared to initial values. This increase was significantly higher than when either sole trees or sole crops were grown, showcasing the potential of this approach for enhancing soil fertility. Additionally, the use of suitable species has been shown to restore soil fertility in shifting cultivation areas. For instance, an experiment on N2 fixation efficiency demonstrated that planting stem-cuttings and implementing flooding conditions resulted in significantly higher biological N2 fixation, with *Sesbania rostrata* and *S. cannabina* fixing 307 and 209 kg N ha-1 respectively. Therefore, *S. rostrata* can be effectively utilized as a green manure by planting stem-cuttings under flooded conditions (Patel *et al.*, 1996). Moreover, in agroforestry fallows with *Sesbania sesban*, decreased soil bulk density and improved water infiltration were observed, which contributed to better early growth of subsequent crops (Torquebiau and Kwesiga, 1996). Biodrainage plantations, as reported by Chowdhury *et al.*, (2011), can enhance soil aeration, nutrient utilization efficiency, and reduce sulphide toxicity. Furthermore, agroforestry models play a crucial role in reclaiming salt-affected soils. Eucalyptus plantations, as noted by Ram *et al.*, (2011), effectively lowered the water table and improved soil conditions, resulting in a significant increase in wheat grain yield and the reclamation of waterlogged areas. Overall, agroforestry practices contribute to increased soil organic matter through the addition of leaf litter, which sustains beneficial microorganisms and enhances biological nitrogen fixation in the soil. Microbial activity in the soil plays a vital role in nutrient cycling and other ecosystem functions, ultimately contributing to ecosystem services that support human well-being (Jhariya and Raj, 2014).

Managing pest and disease in agroforestry

Agroforestry techniques can affect the incidence and frequency of pests in two ways: first, by strengthening the natural enemies' control, and second, by affecting bottom-up elements including soil nutrients, moisture content, and microclimate. A comprehensive meta-analysis was conducted to examine the impact of agroforestry on weed abundance, natural enemies, insect pests, and plant damage caused by diseases and insects. The study also investigated the influence of crop type (annual or perennial), pest association type (above or belowground), and weed type (parasitic Striga species weeds or non-parasitic weeds) on the outcomes of agroforestry practices. The findings of the analysis revealed that agroforestry techniques led to an increase in the populations of natural enemies while simultaneously reducing the occurrences of both parasitic and non-parasitic weeds. Moreover, it was discovered that the kind of crop affected by agroforestry had an effect on invertebrate pests and illnesses differently. More specifically, agroforestry has been linked to lower insect abundances and less plant damage in annual crops such plantains, coffee, and cocoa. However, when it came to annual crops including beans, rice, and maize, these benefits were not statistically significant. Overall, this study's results indicate that agroforestry can be helpful in controlling weeds, illnesses, and pests, even with the small number of crop-pest relationships analysed (Pumarino and associates, 2015).

Integrating water and insect pest management with conservation agricultural practices showcases synergistic benefits, including enhanced pest control and improved water availability. Understanding these interactions is vital for developing novel strategies to increase plant resilience to water stress and herbivory while maintaining sustainable crop productivity. Key factors such as water use efficiency (WUE) and volatile organic compounds (VOCs) play crucial roles in shaping these relationships. Identification of these interactions is essential for devising effective and sustainable agricultural management approaches. Pest management research in agroforestry is still developing, with challenges in determining when investment in pest-related research is warranted. This study aimed to understand farmers' indigenous ecological knowledge regarding pests, prioritize pest issues affecting tree planting and maize production, and identify farmers' traditional pest management practices. Findings reveal farmers' perceptions of insects as the main cause of tree mortality and prioritize pests such as termites and stalk bores in maize production, aligning with researchers' observations. The study highlights the importance of considering farmers' perspectives and indigenous practices in pest management strategies (Sileshi *et al.*, 2008).

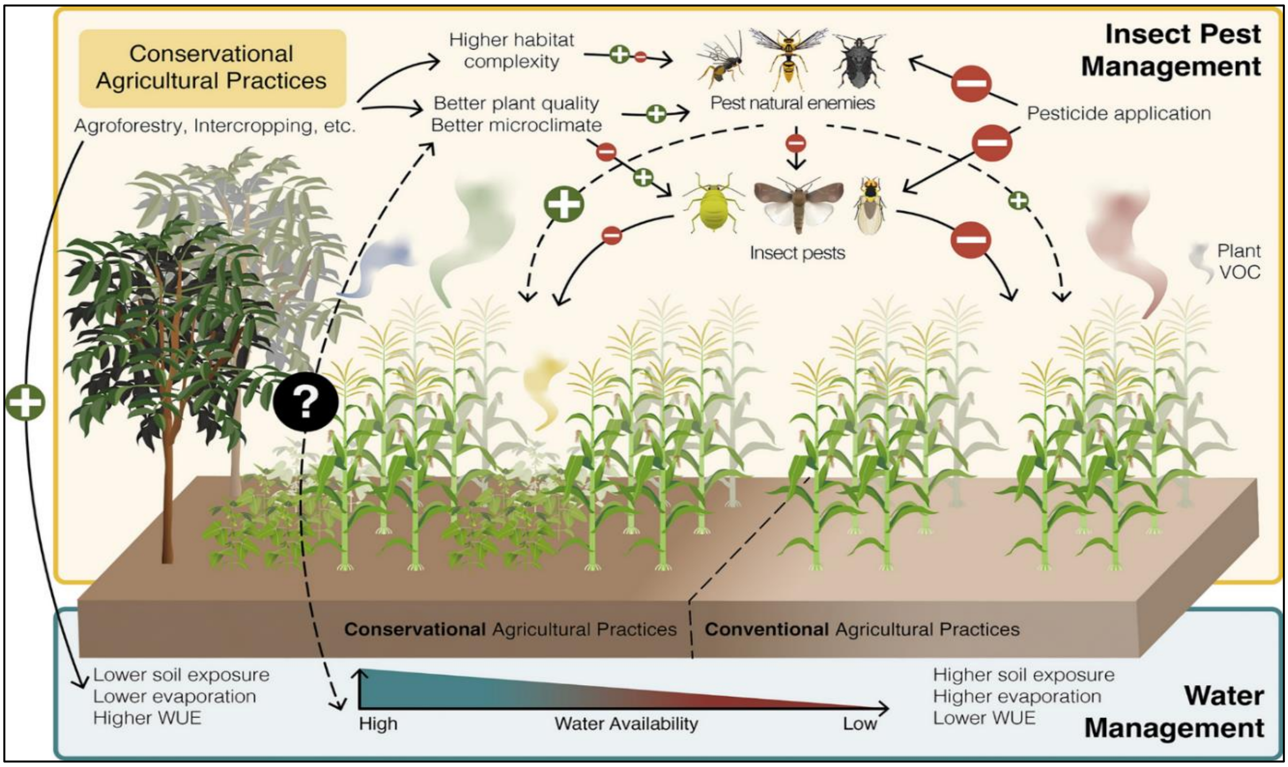

Figure 8: From: Integrating water and insect pest management in agriculture (Lin *et al.*, 2023)

This study investigates farmers' knowledge of pests and diseases affecting coffee and bananas in mid-eastern Uganda's coffee-banana agroforestry system. Findings reveal widespread awareness among respondents, with black coffee twig borer (BCTB), coffee wilt disease (CWD), banana weevils, and banana xanthomonas wilt (BXW) being the most commonly reported pests. While cultural practices are employed by over 50% of farmers to manage certain pests, limited knowledge persists regarding others, highlighting the need for increased awareness campaigns on all pests and diseases affecting these crops in the region (Judith *et al*., 2018).

Addressing plant protection challenges and phytosanitary risks, especially in tropical regions, is critical for food security and environmental sustainability. To achieve this, reducing pesticide use while controlling crop pests and diseases is imperative. An agroecological approach, emphasizing the conservation or introduction of plant diversity, offers potential solutions, although its effectiveness varies across different pathogens and pests. This review explores various mechanisms through which increasing vegetational diversity in agroecosystems can mitigate pest and disease impacts, underscoring the need for further research to optimize agroecological practices (Ratnadass *et al*., 2012).

Economic viability and socio-ecological impacts of agroforestry integration

A detailed examination was conducted on five distinct traditional agroforestry systems in the Sikkim Himalaya region, namely farm-based, forest-based, Alnus-cardamom, forest-cardamom, and Albizia-mixed-tree-mandarin systems. The aim was to assess and compare their nutrient dynamics, N2-fixation, and cost-effectiveness, considering their social and ecological resilience to climate change and other external factors. Results revealed that the Alnus-cardamom systems exhibited the highest soil nutrient availability, followed by the Albizia-mandarin systems. Among the different systems, the Alnus-cardamom systems demonstrated the highest N2-fixation rate (95 kg ha^{-1}), whereas the forest-based systems showed a moderate rate (59 kg ha^{-1}), and the forest-cardamom agroforestry systems displayed the lowest rate (9.5 kg ha^{-1}). In terms of economic returns, the Alnus-cardamom systems yielded the highest annual income (US$ 1895), followed by the forest-cardamom systems (US$ 1275), and the Albizia-mandarin systems (US$ 1166). Additionally, the output-input ratio was found to be the highest in the Alnus-cardamom systems (12.05) and the lowest in the forest-based agroforestry systems (4.21). The impact of climate change has primarily manifested in the form of unpredictable or shorter rainfall events. Agricultural areas lacking tree cover have experienced reduced soil water retention, leading to the drying up of local springs and streams at lower altitudes. Moreover, the productivity of large cardamom in traditionally suitable altitudes has declined by 10-20% over the past 3-4 years. Farmers have also observed a shift in the phenological calendar, particularly in the flowering period of plants. To ensure future socio-ecological and economic resilience, collaborative efforts are needed to design and implement integrated agroforestry schemes that incorporate the perspectives of farmers, scientists, agricultural extension agents, and policymakers (Sharma *et al.,* 2016). Adopting agroforestry has been shown to assist rural areas in numerous studies. Agroforestry has the ability to increase food security, equitable distribution of smallholders' revenue, and cultural events in rural areas from an economic standpoint. Furthermore, through better soil structure, increased storage of carbon, and improved water retention, agroforestry can support ecosystem services. Agroforestry is still not widely used in rural areas, particularly among smallholder farmers in developing nations, despite its many benefits. The potential of agroforestry to mitigate the climate catastrophe and enhance rural livelihoods has not been acknowledged due to its lack of inclusion in governmental policies. Among other things, the lack of thorough research assessing agroforestry's social, economic, and environmental effects on the community at the same time may be to blame for its slow uptake. The evidence that is now available about the features of agriculture adoption, its advantages, potential disadvantages, and adoption obstacles in poor nations is particularly highlighted in this review. The review's conclusions can help pertinent parties make decisions that will improve rural livelihoods (Mukhlis *et al*., 2022).

Best practices for designing and implementing agroforestry systems

In southern China, intercropping Ginkgo trees with other crop species has garnered increasing interest due to its potential benefits in enhancing cultivation sustainability, augmenting farmers' income, and optimizing resource utilization. To thoroughly assess the competitive dynamics cbetween different species and the commercial viability of such intercropping systems, we conducted a comprehensive 2-year field study. This study involved combinations of Ginkgo with wheat, broad beans, and rapeseed. A systematic approach was adopted, employing a two-way density matrix comprising three monoculture densities and nine intercropping combinations to manipulate the densities of Ginkgo and crop species. Various intercropping indices, including vector competitive analysis, relative population coefficient, land equivalent ratio, and comparable competition intensity, were employed to evaluate the intercropping systems. The results indicated that compared to conventional monoculture crops (Ginkgo, broad beans, wheat, and rapeseed), the combined biomass production of component crop varieties was significantly higher in the Ginkgo crop combinations. Specifically, the Ginkgo:rapeseed ratio of 24:12, the Ginkgo:broad bean ratio of 24:5, and the Ginkgo:wheat ratio of 24:200 demonstrated the highest overall biomass output. Moreover, the Ginkgo:rapeseed (and broad bean) ratio of 24:5 and the Ginkgo:wheat ratio of 24:200 in their respective Ginkgo/crop mixes yielded the greatest economic returns. Vector comparisons revealed an antagonistic relationship in the Ginkgo/rapeseed combination, suggesting its unsuitability for intercropping. However, among the three intercropping schemes, the Ginkgo/broad bean combination yielded the most favorable outcomes (Cao *et al.,* 2012).

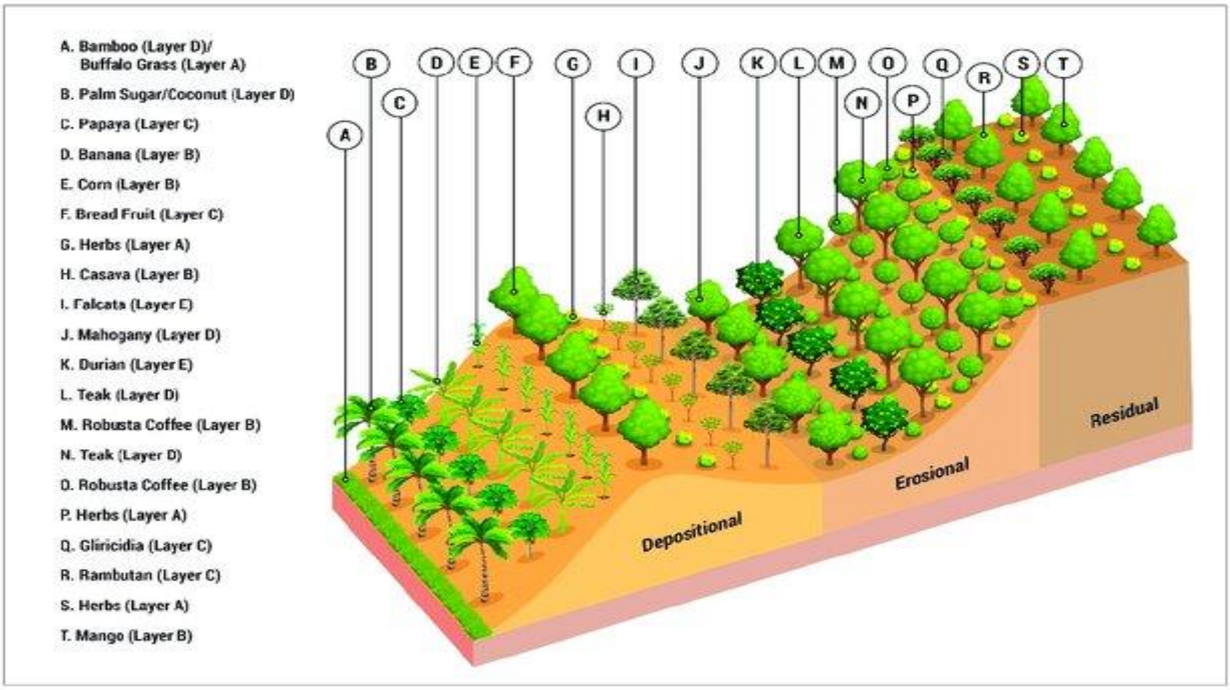

Figure 9: Illustration of Plant Layout Model of Agroforestry Systems to Control Landslides following three succession slope units of landslide (Purwaningsih *et al*., 2020)

Alley cropping has been impacted by the socioeconomic and social settings in which it has been used, just like other agricultural techniques. Alley cropping has naturally evolved to high-input, massive production and, more recently, environmental sustainability in temperate zones, where farmland has mostly focused on these methods. Alley cropping is still a unique method in temperate zones, while having its roots mostly in tropical zone uses. In contrast to tropical systems, temperate agroforestry systems typically feature wider tree spacing, facilitating mechanical crop cultivation within strips or alleys (Gillespie *et al.*, 2000). Additionally, to maintain soil fertility and productivity, temperate systems often do not rely on directly incorporating prunings from trees or shrubs (Garrett and McGraw, 2000).

Case studies: Successful applications of agroforestry-agronomy integration

Africa has many complex issues to deal with, such as a serious lack of food, fuelwood, and fodder, which is mostly caused by an increase in the number of people and animals as well as subsistence farming. The three most important signs of land degradation are deforestation, decreasing soil fertility, and soil erosion. Low crop yields in nutrient-depleted soils cause a food shortfall in the majority of dry regions. In order to remove the forests, farmers are compelled to expand farming to marginal and erosive soil. In most of Sub-Saharan Africa (SSA), the conventional fallow and shifting cultivation methods have been replaced by continuous cultivation as a means of restoring soil fertility. Since the establishment of the International Centre for Research in Agroforestry (ICRAF) in 1987, new farming innovations are being tested at labs and on farms, primarily in tropical countries across the world. Traditional agroforestry methods have been meticulously documented during the diagnosis and design phase in the late 1980s. In SSA, resource-poor farmers are currently distributing and utilizing a wide range of improved agroforestry solutions. This chapter provides a brief overview of the traditional and enhanced agroforestry systems in SSA, which are the foundation for food security for farmers with limited resources.

The goal has been made to report the current status of indigenous woodland and fruit tree species, cultivating of indigenous fruits, utilization and nutritional characteristics of tree products, and fruit transformation into marketable goods as reported in various studies, in order to trace the links and prospects of agricultural forests to enhance food security. The status of research on various agroforestry systems, the value of trees in restoring degraded areas, soil and water conservation, hydrological advantages, microclimatic changes, and biodiversity preservation are all highlighted in this study. We also highlighted barriers, problems with the implementation of agroforestry, and technical areas that still need scientific input. Agroforestry holds great promise for improving livelihood security, increasing crop yields, and ensuring food security, especially in SSA's dry and degraded regions. This is according to a summary of research trends and new challenges. In various African regions, the broad implementation of agroforestry technology coupled with ongoing collaborative research and dissemination can play a pivotal role in accomplishing the objectives of poverty reduction, food sovereignty, soil preservation, and ecological sustainability, especially in light of the impending climate change (Dagar *et al.*, 2020).

Addressing growing demands for food grains amid limited resources and climate change challenges, integrating millets into agroforestry systems offers efficient resource management and resilience against climate impacts. Farmers are increasingly transitioning to sustainable practices like agroforestry due to benefits such as higher yield, production, and diversity, alongside lower crop failure. This review focuses on the significance of Millet-based Agroforestry (MbAF) in India and Africa, highlighting successful models and providing recommendations to policymakers for improving income and stabilizing farming conditions in arid and semi-arid regions (Teli *et al.*, 2023).

Smallholder coffee farms, which produce 60% of global coffee, often fail to generate a living income, prompting the adoption of agroforestry for cost reduction and income diversification. This study proposes a shift in coffee agroforestry management towards active species management and stem turnover to sustain ecosystem-based benefits, using a three-phase analysis approach. Results highlight the need for targeted shifts in coffee varieties and associated trees to address challenges like decreasing margins, labor scarcity, and climate variability, with data-driven management strategies becoming increasingly important (Siles *et al.*, 2022).

CONCLUSION

Agroforestry is not a recent development. It's a relatively recent term for a group of traditional farming methods. Agroforestry consists of woody perennials (tree crops/forest plants), animals, and agricultural crops (herbaceous plants). In accordance with the principles of agroforestry, enhancing yield productivity, soil nutrient status, and microbial population dynamics—key factors in nutrient cycling and ecosystem maintenance—necessitates an appropriate combination of nitrogen-fixing and multipurpose trees alongside field crops. The environment, national economies, and rural residents all greatly benefit from trees and agroforestry in emerging nations. Thus, the agroforestry system promotes diversity, increases nutrient uptake, produces green cover for carbon sequestration, and their utilization management practices that result in an improved soil's organic matter status will inexorably improve soil productivity and nutrient cycling.

Acknowledgment

We express our gratitude to our exceptional team for their collaborative teamwork and dedication, which significantly contributed to the success of this paper. Special thanks to Rida Pervaiz for her invaluable support, dedication, and outstanding contributions to our research efforts.

REFERENCES

- Baah-Acheamfour, M., Carlyle, C. N., Bork, E. W., & Chang, S. X. (2014). Trees increase soil carbon and its stability in three agroforestry systems in central Alberta, Canada. *Forest Ecology and Management*, 328, 131–139.
- Barrios, E., Sileshi, G. W., Shepherd, K., & Sinclair, F. (2012). Agroforestry and soil health: linking trees, soil biota and ecosystem services. *Soil Ecology and Ecosystem Services*, 315–330.
- Bayala, J., Sanou, J., Teklehaimanot, Z., Kalinganire, A., & Ouédraogo, S. (2014). Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. *Current Opinion in Environmental Sustainability*, 6, 28–34.
- Bayala, J., Sanou, J., Teklehaimanot, Z., Ouedraogo, S., Kalinganire, A., Coe, R., & van Noordwijk, M. (2015). Advances in knowledge of processes in soil–tree–crop interactions in parkland systems in the West African Sahel: A review. *Agriculture, Ecosystems & Environment*, 205, 25–35.
- Bayala, J., Sileshi, G. W., Coe, R., Kalinganire, A., Tchoundjeu, Z., Sinclair, F., & Garrity, D. (2012). Cereal yield response to conservation agriculture practices in drylands of West Africa: A quantitative synthesis. *Journal of Arid Environments*, 78, 13–25.
- Bene, J. G., Beall, H. W., & Cote, A. (1977). Trees, Foods and people. Ottawa, Canada: IDRC.
- Bhardwaj, D. R., Navale, M. R., & Sharma, S. (2017). Agroforestry practices in temperate regions of the world. In D. K. Singh & B. P. Singh (Eds.), Agroforestry: anecdotal to modern science (pp. 163-187).
- Cao, F. L., Kimmins, J. P., & Wang, J. R. (2012). Competitive interactions in Ginkgo and crop species mixed agroforestry systems in Jiangsu, China. *Agroforestry Systems*, 84, 401-415.
- Caron, B. O., Sgarbossa, J., Schwerz, F., Elli, E. F., Eloy, E., & Behling, A. (2018). Dynamics of solar radiation and soybean yield in agroforestry systems. *Anais da Academia Brasileira de Ciências*, 90, 3799-3812.
- Chowdhury, S. R., Kumar, A., Brahmanand, P. S., Ghosh, S., Mohanty, R. K., Jena, S. K., ... & Panda, G. C. (2011). Application of BioDrainage for Reclamation of Waterlogged Situations in Deltaic Orissa (Research Bulletin no. 53). Directorate of Water Management (Indian Council of Agricultural Research).
- Cristo, E. D., Sgarbossa, J., Schwerz, F., Nardini, C., Tibolla, L. B., & Caron, B. O. (2020). Growth and yield of soybean cultivated in agroforestry systems. *Revista Ceres*, 67, 165-175.
- Dagar, J. C., Sileshi, G. W., & Akinnifesi, F. K. (2020). Agroforestry to enhance livelihood security in Africa: research trends and emerging challenges. In F. K. Akinnifesi, R. R. B. Leakey, O. C. Ajayi, G. Sileshi, Z. Tchoundjeu, & P. Matakala (Eds.), Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges-Vol. 1 (pp. 71-134).
- Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., & Liebman, M. (2012). Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. PLoS ONE, 7, e47149.
- del Castillo, R. A., Dalmacio, R. V., Lasco, R. D., & Lawas, N. R. (Eds.). (1994). Agroforestry Production and Postproduction Systems: A Training Manual. University of the Philippines Los Baños Agroforestry Program.
- Dhyani, S. K., Newaj, R., & Sharma, A. R. (2009). Agroforestry: its relation with agronomy, challenges and opportunities. Indian Journal of Agronomy, 54(3), 249-266.
- Dupraz, C., Newman, S. M., & Gordon, A. M. (1997). Temperate agroforestry: the European way. In A. M. Gordon & S. M. Newman (Eds.), Temperate agroforestry systems (pp. 181–236). CAB International.
- Evans, J. (1992). Plantation Forestry in the Tropics (2nd ed.). Carendon Press.
- Fanish, S. A., & Priya, R. S. (2013). Review on Benefits of Agro Forestry System. International Journal of Education and Research, 1(1), 1-12.
- Garrett, H.E., & McGraw, R.L. (2000). Alley cropping practices. In H.E. Garrett, W.J. Rietveld, & R.F. Fisher (Eds.), North American Agroforestry: An Integrated Sand Practice (pp. 149–188). Madison, WI: American Society of Agronomy.
- Garrity, D.P., Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M., & Bayala, J. (2010). Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Security, 2(3), 197–214.
- Ghaley, B.B., Vesterdal, L., & Porter, J.R. (2014). Quantification and valuation of ecosystem services in diverse production systems for informed decision-making. Environmental Science & Policy, 39, 139–149.
- Gillespie, A.R., Jose, S., Mengel, D.B., Hoover, W.L., Pope, P.E., Seifert, J.R., ... & Benjamin, T.J. (2000). Defining competition vectors in a temperate alley cropping system in the midwestern USA. 1. Production physiology. Agroforestry Systems, 48, 25–40.
- Glover, J.D., Reganold, J.P., & Cox, C.M. (2012). Agriculture: plant perennials to save Africa's soils. Nature, 489(7416), 359–361.

- Goenster, S., Wiehle, M., Kehlenbeck, K., Jamnadass, R., Gebauer, J., & Buerkert, A. (2009). Indigenous fruit trees in homegardens of the Nuba Mountains, Central Sudan: tree diversity and potential for improving the nutrition and income of rural communities. Acta Horticulturae, 911, 355–364.
- Hairiah, K., Sardjono, M.A., & Sabarnurdin, S. (2002). Pengantar Agroforestri [Introduction to Agroforestry]. World Agroforestry Centre ICRAF.
- IPCC. (2000). Special report on land Use, Land Use Change and Forestry. Summary for Policy Makers. Geneva, Switzerland.
- Jhariya, M.K., & Raj, A. (2014). Human welfare from biodiversity. Agrobios Newsletter, 12(9), 89-91.
- Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. Agroforestry Systems, 76, 1–10.
- Jose, S., Gold, M.A., & Garrett, H.E. (2012). The Future of Temperate Agroforestry in the United States. In P.K.R. Nair & D. Garrity (Eds.), Agroforestry—The Future of Global Land Use (pp. 217–245). Springer.
- Judith, K., Godfrey, K.H., Abisagi, K., Patrick, K., Lilian, N., Ivette, P., & William, W.W. (2018). Farmers' knowledge of pests and diseases in the coffee-banana agroforestry systems of mid-eastern Uganda. Journal of Agriculture and Environmental Sciences, 7(2), 109-119.
- Kulp, J. J. (1990). The photosystem as a sink for carbon dioxide. EPRI Report EN-6786. Electrical Power Research Institute, Palo Alto, CA, USA.
- Kuyah, S., Dietz, J., Muthuri, C., & van Noordwijk, M. (2013). Allometry and partitioning of above-and below-ground biomass in farmed Eucalyptus species dominant in Western Kenyan agricultural landscapes. Biomass Bioenergy, 55, 276–284.
- Lal, R. (2010). Managing Soils and Ecosystems for Mitigating Anthropogenic Carbon Emissions and Advancing Global Food Security. Bioscience, 60, 708–721.
- Lin, P. A., Paudel, S., Lai, P. C., Gc, R. K., Yang, D. H., & Felton, G. W. (2023). Integrating water and insect pest management in agriculture. Journal of Pest Science, 1-18.
- Luedeling, E., & Buerkert, A. (2008). Effects of land use changes on the hydrological sustainability of mountain oases in northern Oman. Plant and Soil, 304(1–2), 1–20.
- Luedeling, E., Huth, N.I., Kindt, R., & König, K. (2014). Agroforestry systems in a changing climate — challenges in projecting future performance. Current Opinion in Environmental Sustainability, 6, 1–7.
- Matocha, J., Schroth, G., Hills, T., & Hole, D. (2012). Integrating climate change adaptation and mitigation through agroforestry and ecosystem conservation. In Agroforestry-the future of global land use (pp. 105-126).
- Mondal, S., Angon, P. B., & Roy, A. R. (2023). Ecological Advancements and Developments of Agroforestry. Turkish Journal of Agriculture-Food Science and Technology, 11(12), 2476-2480.
- Mukhlis, I., Rizaludin, M. S., & Hidayah, I. (2022). Understanding socio-economic and environmental impacts of agroforestry on rural communities. Forests, 13(4), 556.
- Nair, P. R. (2011). Agroforestry systems and environmental quality: introduction. Journal of Environmental Quality, 40(3), 784-790.
- Nair, P.K.R. (1987). Soil productivity under agroforestry. In H.L. Gholz (Ed.), Agroforestry: Realities, Possibilities and Potentials (pp. 21–30). Dordrecht, the Netherlands: Martinus Nijhoff Publishers.
- Nair, P.K.R. (1991). State-of-the-art of Agroforestry Systems. In P.G. Jarvis (Ed.), Agroforestry Principles and Practices (pp. 5-10). The Netherlands: Elsevier Science Publishing Company.
- Nair, P.K.R., & Garrity, D. (2012). Agroforestry—The Future of Global Land Use (Advances in Agroforestry; Vol. 9). Springer.
- Nasielski, J., Furze, J. R., Tan, J., Bargaz, A., Thevathasan, N. V., & Isaac, M. E. (2015). Agroforestry promotes soybean yield stability and N2-fixation under water stress. Agronomy for Sustainable Development, 35, 1541-1549.
- Odhiambo, H. O., Ong, C. K., Deans, J. D., Wilson, J., Khan, A. A. H., & Sprent, J. I. (2001). Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya. Plant and Soil, 235, 221-233.
- Ong, C. K., Corlett, J. E., Singh, R. P., & Black, C. R. (1991). Above and below ground interactions in agroforestry systems. Forest Ecology and Management, 45(1-4), 45-57.
- Ong, C.K., & Kho, R. (2015). A framework for quantifying the various effects of tree-crop interactions. In C. Black, J. Wilson, & C.K. Ong (Eds.), Tree–Crop Interactions: Agroforestry in a Changing Climate (pp. 1–23). CABI.
- Pagella, T.F., & Sinclair, F.L. (2014). Development and use of a typology of mapping tools to assess their fitness for supporting management of ecosystem service provision. Landscape Ecology, 29(3), 383–399.
- Palma, J., Graves, A., Burgess, P., van der Werf, W., & Herzog, F. (2007). Integrating environmental and economic performance to assess modern silvoarable agroforestry in Europe. Ecological Economics, 63(4), 759–767.
- Pantera, A., Mosquera-Losada, M. R., Herzog, F., & Den Herder, M. (2021). Agroforestry and the environment. Agroforestry Systems, 95(5), 767-774.

- Patel, L.B., Sidhu, B.S., & Beri, V. (1996). Symbiotic efficiency of Sesbania rostrata and S. cannabina as affected by agronomic practices. Biology and Fertility of Soils, 21, 149-151.
- Prinsley, R.T. (1990). Agroforestry for Sustainable Production: Economic Implications. Commonwealth Science Council, London.
- Pumariño, L., Sileshi, G.W., Gripenberg, S., Kaartinen, R., Barrios, E., Muchane, M.N., ... & Jonsson, M. (2015). Effects of agroforestry on pest, disease and weed control: A meta-analysis. Basic and Applied Ecology, 16(7), 573-582.
- Purwaningsih, R., Sartohadi, J., & Setiawan, M.A. (2020). Trees and crops arrangement in the agroforestry system based on slope units to control landslide reactivation on volcanic foot slopes in Java, Indonesia. Land, 9(9), 327.
- Ram, J., Dagar, J.C., Lal, K., Singh, G., Toky, O.P., Tanwar, V.S., Dar, S.R., & Chauhan, M.K. (2011). Bio-drainage to combat water logging, increase farm productivity and sequester carbon in canal command areas of northwest India. Current Science, 100(11), 1673-1680.
- Rao, K.P.C., Verchot, L.V., & Laarman, J. (2007). Adaptation to Climate Change through Sustainable Management and Development of Agroforestry Systems. An Open Access Journal published by ICRISAT, 4(1), 1-30.
- Ratnadass, A., Fernandes, P., Avelino, J., & Habib, R. (2012). Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agronomy for Sustainable Development, 32, 273-303.
- Rigueiro-Rodríguez, A., Fernández-Núñez, E., González-Hernández, P., McAdam, J.H., & Mosquera-Losada, M.R. (2009). Agroforestry systems in Europe: productive, ecological and social perspectives. In Agroforestry in Europe: current status and future prospects (pp. 43-65).
- Rosenstock, T., Tully, K., Arias-Navarro, C., Neufeldt, H., & Butterbach-Bahl, K. (2014). Agroforestry with N2-fixing trees: sustainable development's friend or foe? Current Opinion in Environmental Sustainability, 6, 15–21.
- Samra, J.S., & Charan, S.S. (2000). Silvipasture systems for soil, water and nutrient conservation on degraded lands of Shivalik foot hills (subtropical northern India). Indian Journal of Soil Conservation, 28(1), 35-42.
- Santos-Martin, F., & van Noordwijk, M. (2009). Trade-offs analysis for possible timber-based agroforestry scenarios using native trees in the Philippines. Agroforestry Systems, 76(3), 555–567.
- Schultz, R.C., Isenhart, T.M., Colletti, J.P., Simpkins, W.W., Udawatta, R.P., Schultz, P.L., & Garrett, H.E.G. (2009). Riparian and upland buffer practices. In ACSESS Publications; American Society of Agronomy: Madison, WI, USA.
- Seiter, S., William, R. D., & Hibbs, D. E. (1999). Crop yield and tree-leaf production in three planting patterns of temperate-zone alley cropping in Oregon, USA. *Agroforestry Systems*, 46, 273–288.
- Sharma, G., Hunsdorfer, B., & Singh, K.K. (2016). Comparative analysis on the socio-ecological and economic potentials of traditional agroforestry systems in the Sikkim Himalaya. *Tropical Ecology*, *57*(4), 751-764.
- Sheppard, J. P., Bohn Reckziegel, R., Borrass, L., Chirwa, P. W., Cuaranhua, C. J., Hassler, S. K., ... & Kahle, H. P. (2020). Agroforestry: an appropriate and sustainable response to a changing climate in Southern Africa? *Sustainability*, *12*(17), 6796.
- Siles, P., Cerdán, C. R., & Staver, C. (2022). Smallholder Coffee in the Global Economy—A Framework to Explore Transformation Alternatives of Traditional Agroforestry for Greater Economic, Ecological, and Livelihood Viability. *Frontiers in Sustainable Food Systems*, 6, 808207.
- Sileshi, G., Akinnifesi, F. K., Ajayi, O. C., & Place, F. (2008). Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant and Soil*, *307*(1–2), 1–19.
- Sileshi, G. W., Kuntashula, E., Matakala, P., & Nkunika, P. O. (2008). Farmers' perceptions of tree mortality, pests and pest management practices in agroforestry in Malawi, Mozambique and Zambia. *Agroforestry Systems*, 72, 87-101.
- Sinclair, F. L. (1999). A general classification of agroforestry practice. Agroforestry Systems, 46, 161-180.
- Teli, S. B. (2023). Millet-based agroforestry: a nature-positive farming to achieve climate-resilience and food security in India and Africa.
- Tiwari, T., Virk, D., & Sinclair, F. (2009). Rapid gains in yield and adoption of new maize varieties for complex hillside environments through farmer participation: I. Improving options through participatory varietal selection (PVS). *Field Crop Research*, *111*(1), 137–143.
- Torquebiau, E. F. (2000). A renewed perspective on agroforestry concepts and classification. Comptes Rendus de l'Académie des Sciences-Series III-Sciences de la Vie, 323(11), 1009-1017.
- Torquebiau, E., & Kwesiga, F. (1996). Root development in a Sesbania sesban-maize system in Eastern Zambia. *Agroforestry Systems*, *34*(3), 193-211.
- Trexler, M. C. (1993). Mitigating Global Warming Through Forestry: A Partial Literature Review. Report to GTZ for Enquette Commission, German.
- Tsonkova, P., Böhm, C., Quinkenstein, A., & Freese, D. (2012). Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: a review. *Agroforestry Systems*, 85, 133-152.
- Udawatta, R. P., Garrett, H. E., & Kallenbach, R. L. (2010). Agroforestry and grass buffer effects on

water quality in grazed pastures. In Agroforestry Systems (Vol. 79, pp. 81–87). Springer: Dordrecht, The Netherlands.

- Udawatta, R. P., Krstansky, J. J., Henderson, G. S., & Garrett, H. E. (2002). Agroforestry practices, runoff, and nutrient loss: A paired watershed comparison. *Journal of Environmental Quality*, 31, 1214–1225.
- Watson, R. T., Noble, I.R., Bolin, B., Ravindranath, N. H., Verardo, D. J., & Dokken, D. J. (Eds.). (2000). Land Use, Land Use Changes and Forestry: A Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, NY.
- Widianto, K. H., Suharjito, D., & Sardjono, M. A. (2003). Fungsi dan Peran Agroforestri ICRAF. Bogor.
- Yamani, A. (2010). Analisis kadar hara makro dalam tanah pada tanaman agroforestri di Desa Tambun Raya Kalimantan Tengah. *Jurnal Hutan Tropika*, 11, 37–46.
- Zhu, X., Liu, W., Chen, J., Bruijnzeel, L. A., Mao, Z., Yang, X., ... & Jiang, X. J. (2020). Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes. Plant and Soil, 453, 45-86.