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Agrobiodiversity vis-à-vis agroforestry: Cultivating a sustainable future

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Abstract
Highly diverse ecosystems are confronted with persistent challenges including conversion, deforestation, and resource depletion driven by developmental projects, intensified land use, and expanded agricultural practices. Within this context, agricultural biodiversity, known as agrobiodiversity, emerges as a subset of overall biodiversity. Agrobiodiversity encompasses the genetic, species, ecosystem and even landscape diversity that sustains essential structures, functions, and processes in and around production systems. The consequences of losing agrobiodiversity within agroecosystems are profound, leading to ecosystem degradation, resource overexploitation, habitat disruption, and adverse effects. To confront the challenge, a promising solution lies in the adoption of time-tested agroforestry practices. This review article sheds light on the remarkable conservation value of agroforestry systems, characterized by their structural complexity, diverse plant life, and their similarity to natural forest ecosystems. Agroforestry systems play a pivotal role in preserving agrobiodiversity by reducing the need for further deforestation to accommodate agriculture. They also serve as vital habitats and resource reservoirs for native plant and animal species with partial dependence on forests while fostering landscape connectivity through corridors. Furthermore, agroforestry bolsters agrobiodiversity by creating concentrated, high-density zones near trees, due to favorable soil conditions, plant interactions, water resources, and microclimatic features. Therefore, agroforestry is a powerful tool for fostering agrobiodiversity, as it promotes a harmonious coexistence between trees and traditional agricultural elements, thereby enhancing the ecological richness and sustainability of farming systems.

Keywords: Agroecosystems, biodiversity conservation, ecosystem resilience, genetic diversity, habitat disruption, land use, silvo-pastoral systems

Introduction
Complex ecosystems, such as tropical forests, are currently facing significant threats due to their conversion for developmental initiatives, intensification of land use, and expansion of agricultural activities (Pastur *et al*. 2012) [40]. This process has led to the loss of habitat, degradation, and fragmentation (Harris and Silva-Lopez 1992) [21], resulting in a substantial decline in biodiversity (Flynn *et al*. 2009) [17]. This loss of biodiversity in agroecosystems caused by many factors (as illustrated in Figure 1) carries with it a host of devastating consequences, which encompass the direct destruction, conversion, or degradation of agroecosystems, over-exploitation of resources, habitat disruption, pollution, and several other detrimental impacts. Moreover, it is important to note that this loss of agrobiodiversity has broader implications, as it can affect the resilience of agricultural systems, food security, and the overall health of ecosystems. Maintaining biodiversity within agroecosystems is crucial not only for preserving the richness of species and ecosystems but also for the sustainability of agriculture and the well-being of human societies that depend on these systems for their livelihoods and food production. Therefore, addressing the conservation of biodiversity in the face of expanding agriculture and land-use changes is a critical challenge that requires comprehensive strategies and sustainable practices to minimize the negative impacts.

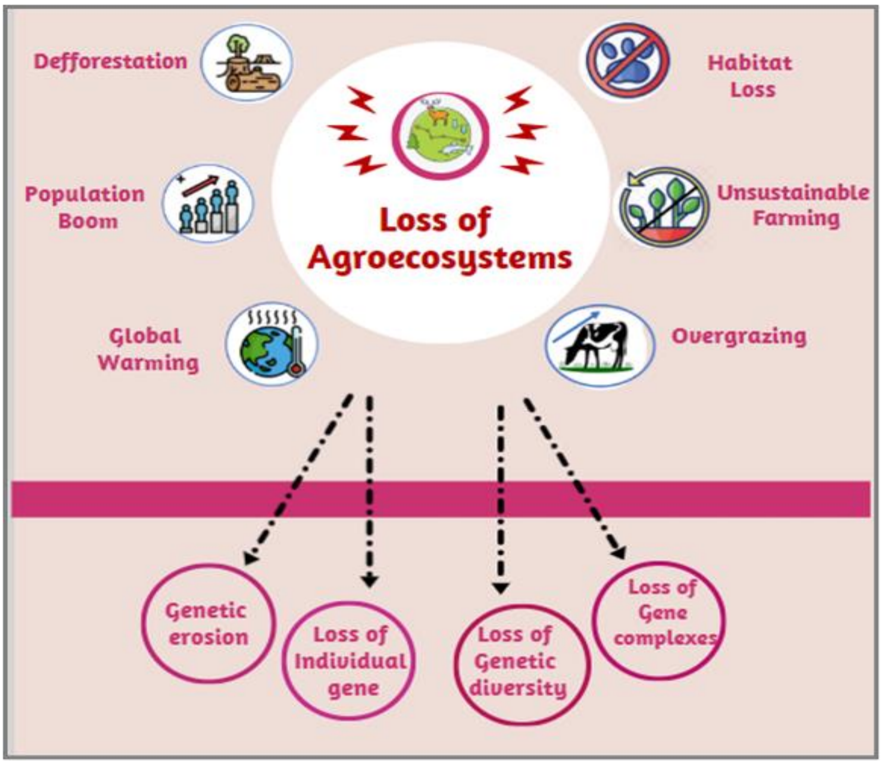

Fig 1: Factors contributing to agroecosystem decline

Agrobiodiversity, a crucial subset of overall biodiversity, it is the diverse range and differences in genetic makeup, species composition, and ecosystem presence of animals, plants, and micro-organisms. This diversity is crucial for maintaining the structures, functions, and processes of ecosystems within and around production systems. Additionally, it plays a vital role in the provision of both food and non-food agricultural products. The depletion of biodiversity within agroecosystems gives rise to a multitude of dire consequences, encompassing the degradation of agroecosystems, over-exploitation of resources, and habitat disruption, among others. The connection between the loss of agrobiodiversity and human well-being is becoming increasingly evident. This loss can compromise the resilience and sustainability of agricultural systems, impacting food security, local economies, and the broader ecological health. Therefore, it is imperative to explore effective solutions to conserve agrobiodiversity. One promising approach to mitigate the loss of agrobiodiversity involves the implementation of age-old practices such as agroforestry. This method, as proposed by Nair (1993) [35], involves integrating trees and other perennial vegetation into agricultural landscapes.

Agroforestry represents a deliberate and strategic approach to incorporate trees and shrubs within agricultural and animal farming systems. These systems hold profound conservation significance due to their unique attributes, including structural complexity, high floral diversity, and a remarkable resemblance to natural forest ecosystems (Schroth *et al*. 2004) [44]. Agroforestry systems play a pivotal role in the conservation of agrobiodiversity through various mechanisms. One of their fundamental contributions is the reduction of pressure to clear additional land for conventional agriculture, thus curbing deforestation. Comparative assessments have revealed that agroforestry systems typically exhibit greater diversity when contrasted with both forests and tree monoculture management. For instance, Bhagwat *et al*. (2008) [9] reported an impressive 60 percent higher mean richness of taxa in agroforestry systems compared to forests. This heightened diversity equips agroforestry systems with ecological resilience, allowing them to perform a wider range of ecological functions effectively. A comprehensive meta-analysis conducted by Udawatta *et al*. (2019) [51] revealed significantly greater floral, faunal, and soil microbial diversity within agroforestry systems when compared to monocropping, adjacent croplands, crop alleys, and even certain types of forests.

Agrobiodiversity and Agroforestry

Agricultural biodiversity is a sub-set of general biodiversity. Otherwise known as agrobiodiversity is “the variety and variability of animals, plants and micro-organisms at the genetic, species and ecosystem levels that sustain the ecosystem structures, functions and processes in and around production systems, and that provide food and non-food agricultural products.” Whereas, agroforestry is a sustainable land use management system that combines the cultivation of trees or shrubs with agricultural crops and/or livestock on the same piece of land. This approach integrates trees or woody plants with conventional agricultural practices to create a more diverse and environmentally friendly system. It is considered a multifunctional land use strategy that can help address various ecological and economic challenges while promoting sustainability. They are of high conservation importance due to their structural complexity, high floral diversity, and high similarity to natural forest ecosystems. Hence, agroforestry system is recognized as an excellent land-use practice for biodiversity conservation and sustainable development in the tropics (Lacerda *et al*. 2020) [26]. Furthermore, agroforestry practices create spatially concentrated pockets of high-density agrobiodiversity around trees. This phenomenon is a consequence of the favorable soil-plant-water-microclimate conditions created by the presence of trees. The unique combination of these factors makes agroforestry a powerful tool in the promotion of agrobiodiversity conservation and the provision of ecosystem services, ultimately contributing to sustainable and resilient agricultural landscapes.

Agroforestry Contribution to Biodiversity Conservation

Agroforestry systems, along with the diverse mosaic landscapes they constitute, have increasingly captured the attention of conservation biologists and researchers operating at the intersection of integrated natural resource management and biodiversity preservation. Agroforestry, when embraced as a sustainable alternative to more expansive and ecologically harmful land use practices, can alleviate the need to clear additional forests for agriculture. These systems offer vital habitat and resources for native plant and animal species that rely on forested environments for their sustenance and well-being. Hence, they have the potential to serve as valuable tools for biodiversity conservation when compared to other non-forest land use options, such as highly managed monocultures or extensive pasture and crop lands with minimal tree cover. Schroth *et al.* (2004) [44] proposed three hypotheses that examine how agroforestry could potentially bolster biodiversity conservation in human-impacted tropical environments (Figure 2).

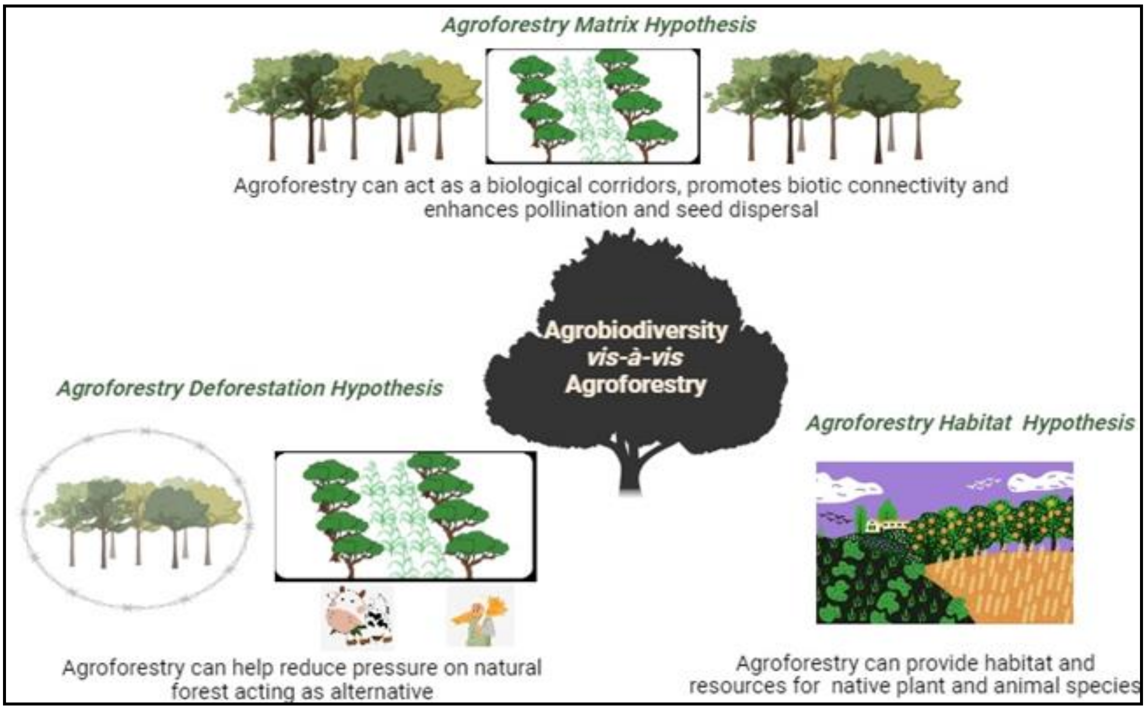

Fig 2: Agroforestry Contribution to Biodiversity Conservation

The Agroforestry-Deforestation Hypothesis

As proposed by Schroth *et al.* (2004) [44], this hypothesis suggests that certain profitable and sustainable agroforestry practices have the potential to efficiently utilize available labor resources and meet the needs of local populations on smaller land areas, as opposed to extensive land use methods like cattle pasture that often lead to additional deforestation. Regions with low land prices and limited market access frequently witness the prevalence of extensive land use practices. Although more intensive agricultural approaches may reduce land requirements per household or unit of produce in comparison to agroforestry, they can subject farmers to elevated economic and ecological risks. Agroforestry practices, on the other hand, exhibit greater sustainability, allowing for the extended utilization of previously deforested plots when compared to alternative methods like annual cropping, which can rapidly degrade soil, or monocultures of tree crops, which may be more susceptible to pest and disease outbreaks (Somarriba and Sampson 2018) [49]. Consequently, the adoption of agroforestry holds promise for reducing the imperative for further deforestation (Desta 2015) [16]. It is essential to highlight that the sustainability of agroforestry practices is not an inherent characteristic (Nair and Toth 2016) [34]. Sustainability encompasses both biological and socioeconomic dimensions, and even when it is technically feasible to manage a particular land use system sustainably, it may not be advantageous for a farmer to do so if new land is readily available or if there are advantages to occupying a larger land area, such as property acquisition or land use rights.

The Agroforestry-Habitat Hypothesis

Agroforestry systems, like agrobiodiversity in general, encompass both planned and unplanned biodiversity components. Agroforestry inherently comprises more planned diversity, with a greater variety of planted and selected plant species than monoculture crops, although this diversity may not surpass some traditional mixed cropping systems. Notably, tropical homegardens, a specific form of agroforestry, can serve as significant repositories of tropical tree and crop germplasm due to their diverse assemblage of tree and crop species. However, the value of agroforestry systems in terms of biodiversity conservation extends beyond their planned diversity. Unplanned diversity, including the plants and animals that colonize or utilize the habitat formed by the planted species, is equally crucial. The structural complexity of perennial vegetation in agroforestry provides more niches for native flora and fauna compared to structurally simpler monocultures and pastures (Schroth *et al*. 2004) [44]. In addition, the presence of a humus-rich soil undisturbed by regular tillage and a permanent litter layer beneath agroforestry systems creates suitable habitat for diverse soil fauna and microflora (Pande and Tarafda 2004; Beule *et al*. 2020; Singh *et al*. 2020) [39, 8, 48], aspects that are not well understood in simpler agricultural systems. Agroforestry systems can play a crucial role as refuges for forest-dependent species, particularly in landscapes largely devoid of natural vegetation. In such deforested and densely populated areas, agroforestry systems may harbour a broader array of species from original ecosystems compared to agricultural monocultures and pastures. This makes them a potential compromise between production objectives and biodiversity conservation. However, it is essential to assess whether forest-dependent and endangered species inhabit agroforestry areas, the extent of their reliance on these habitats for sustenance, and the viability of their populations over the long term, rather than simply tallying the species present.

The Agroforestry-Matrix Hypothesis

This hypothesis focuses on the broader landscape-level impacts of agroforestry elements on their suitability as habitats for native fauna and flora. In tropical landscapes with mixed land use, agroforestry components can significantly affect ecological processes and characteristics such as microclimate, water and nutrient flows, pest and disease dynamics, and the presence and movement of flora and fauna. For instance, strategically placed agroforestry systems can function as biological corridors (Laurance 2004) [27] or stepping stones that facilitate the movement of animals between patches of natural vegetation. This promotes biotic connectivity and enhances pollination (Bentrup *et al*. 2019; Bentrup *et al*. 2021) [6-7] and seed dispersal (Schroth *et al*. 2013) [43]. Agroforestry systems adjacent to forests can also act as buffers, shielding them from strong winds and harsh microclimates, thereby expanding the core area available to sensitive forest species. Additionally, these buffer zones can protect forests from fire (Suyanto *et al*. 2005; Damianidis *et al*. 2021) [50, 13], a common management practice in open agricultural fields but detrimental to valuable tree crops and timber trees. While underexplored, the potential of agroforestry to enhance the conservation value of fragmented landscapes at a larger scale could be pivotal for landscape conservation efforts in partially deforested regions.

Agrobiodiversity components of Agroforestry systems

The biodiversity within Agroforestry Systems can be categorized based on their contributions to agroforestry system functionality (Figure 3). Productive biota encompasses the crops, trees, and animals deliberately selected by farmers, significantly influencing agroecosystem diversity and intricacy. Resource biota comprise the organisms that enhance productivity through functions like pollination, biological pest control, decomposition, and other similar roles. Conversely, destructive biota encompasses elements like weeds, insect pests, microbial pathogens, which farmers aim to minimize through cultural management practices.

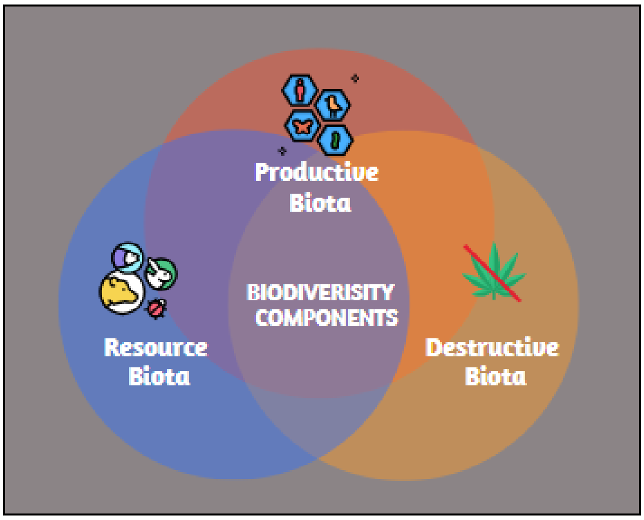

Fig 3: Agrobiodiversity components of Agroforestry systems

Asigbaase (2012) [3] delineated these elements into planned biodiversity and associated biodiversity. The first element, planned biodiversity, encompasses the crops and livestock intentionally integrated into AFS by farmers, the composition of which varies according to management inputs and crop spatial or temporal arrangements. The second element, associated biodiversity, encompasses all the soil flora and fauna, herbivores, carnivores, decomposers, and more, which migrate into the agroecosystem from the surrounding environments and adapt their presence based on the agroecosystem's management and structure. Whereas, all these components of agrobiodiversity within agroforestry systems can be categorized into three main groups: floral diversity, faunal diversity, and soil microbial diversity (Fig 4).

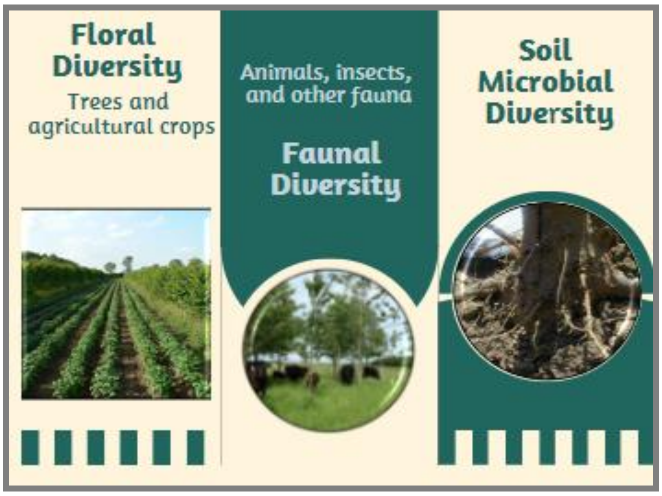

Fig 4: Categorizing Agrobiodiversity in Agroforestry Systems

Floral Diversity

Agroforestry practices serve as effective means to enhance floral biodiversity on agricultural lands, functioning as in-situ conservation methods Mulatu and Hunde (2019) [32]. The extent to which agroforestry contributes to conservation varies depending on the specific type and management of agroforestry systems. Traditional agroforestry systems, such as home gardens and cocoa or coffee-based agroforestry, are designed to mimic natural ecosystems. Home gardens stand out as ecologically sustainable systems that simultaneously diversify the livelihoods of local communities. They are regarded as powerful tools for biodiversity conservation due to their ability to maintain a wide array of plant species, including native and exotic varieties. Studies have shown that different agroforestry practices exhibit varying potentials for the conservation of native species (Rendón-Sandoval, 2020; Udawatta *et al*. 2021; Singh *et al*. 2021a) [41, 46, 52]. For instance, coffee-based agroforestry systems have demonstrated promise in safeguarding native plant species, emphasizing the importance of the choice of agroforestry approach in biodiversity preservation efforts (Kusumawati *et al*. 2022) [25]. These findings highlight the multifaceted role of agroforestry in promoting floral biodiversity and contributing to conservation across diverse landscapes.

Faunal Diversity

Agroforestry practices offer the opportunity to establish a diverse range of habitats, promoting the conservation of wild animal species (Moore *et al*. 2016; Yashmita-Ulman *et al*. 2021) [31, 55]. Within these agricultural landscapes, the presence of specific tree species plays a pivotal role in providing various ecosystem services that enhance animal diversity, encompassing shelter, sustenance, and pathways for unhindered movement. These trees serve as nesting sites for numerous avian species and provide shelter against potential predators. They also facilitate access to breeding territories and ensure a consistent supply of food sources throughout the year (Singh *et al*. 2021b) [47]. Furthermore, they encourage the presence of beneficial species like pollinators (Udawatta *et al*. 2019) [51], which is essential for both agricultural productivity and the broader ecosystem. The inherent complexity and suitability of multi-strata agroforestry systems are particularly conducive to a greater diversity of insect species (Bos *et al*. 2007; Dagar and Gupta 2020; Nair *et al*. 2021) [10, 12, 33] when compared to monocropping fields. This ecological richness in turn supports ecosystem health and resilience, as a diverse insect community is often indicative of a balanced and functioning ecosystem. Additionally, agroforestry practices are instrumental in preserving the diversity and abundance of soil invertebrates, which are crucial to soil health and nutrient cycling. Their presence contributes to the overall ecological integrity of agroecosystems, underlining the multifaceted benefits of agroforestry in promoting both above-ground and below-ground biodiversity.

Soil microbial Diversity

A mechanistic link between plant diversity and ecosystem function becomes evident when delving into soil diversity within agroforestry systems. This encompasses the entire ecological spectrum of the soil ecosystem, featuring microorganisms, earthworms, and various other soil-dwelling organisms. Research has compellingly established the profound influence of plant diversity on soil microorganisms in the context of agroforestry systems (Beule *et al*. 2020) [8]. In agroforestry, diverse plant species contribute to the expansion of soil microbial diversity, largely through the release of exudates from their roots (Pande and Tarafda 2004) [39]. These microbial communities, particularly the heterotrophic ones, serve as critical mediators in governing essential processes that control ecosystem-level carbon and nitrogen cycling. The presence of a multitude of plant species fosters a more complex and interconnected network of soil microorganisms, resulting in enhanced nutrient cycling and overall soil health. Consequently, this intricate relationship between plant diversity and the thriving soil microbial community stresses the vital role that agroforestry plays in sustaining the fundamental processes underpinning ecosystem function and resilience. The presence of a mix of tree crop species within a system had a notable impact on the movement and changes in soil nutrients, as well as the activity of soil microorganisms (Singh *et al*. 2020) [48]. For example, when investigating the diversity of Arbuscular Mycorrhizal (AM) fungal populations in agroforestry systems centered around neem trees, the study revealed a higher level of colonization in neem trees compared to agricultural crops. This phenomenon might be attributed to the obligatory dependency of AM fungi on living roots, as suggested by Pande and Tarafda (2004) [39].

Agrobiodiversity within different Agroforestry Practices

It is evident from the preceding discussion that agroforestry systems supporting agrobiodiversity components possess the potential to act as biodiversity repositories. Consequently, practices incorporating mixed farming systems, a variety of structurally complex elements, biodiversity-friendly farming techniques, and the provision of multiple ecosystem services are of utmost significance in terms of biodiversity conservation (Figure 5). Here, are four agroforestry practices that exemplify the distinctive characteristics mentioned earlier.

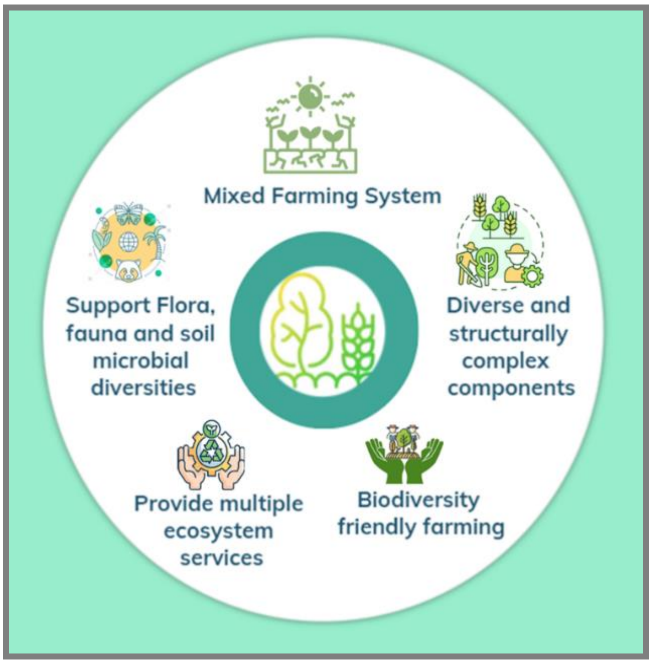

Fig 5: Agroforestry Paradigms: Nurturing Agrobiodiversity through Distinctive Practices

Homegardens

Homegardens, scientifically known as agroforestry homegardens, represent miniature agroecosystems cultivated in and around households. These unique and intricate agroforestry systems are remarkably rich in biodiversity, making them ecologically significant. The abundance and diversity of plant and animal species within homegardens contribute to their ecological and environmental value. Within the confines of a homegarden, one can find a variety of fruit trees, herbs, vegetables, and ornamental plants, often grown in a harmonious arrangement (Bagarinao 2023) [4]. These systems are meticulously tended to by household members for their personal needs as well as for commercial purposes. Moreover, rural home gardens actively contribute to the overall functioning and sustainability of the broader agricultural ecosystem (Bardhan *et al*. 2012; Gariya *et al*. 2020) [5, 18].

Generally, these ecosystems offer shelter and foraging opportunities for numerous bird species, insects, and even small mammals. Homegardens, with their multifunctional and diverse composition, serve as microcosms of natural biodiversity, promoting sustainable land use practices and contributing to overall landscape-level biodiversity conservation. Das and Das (2005) [14] found 122 species in a typical homegarden in Barak Valley, Assam, emphasizing the role of homegardens as crucial sites for conserving plant diversity and preserving indigenous tree species. Various agroforestry systems, as highlighted by Yashmita-Ulman *et al*. (2016) [54], provide habitats suitable for generalist bird species. In another study conducted in Puttalam District, Sri Lanka, Karunarathna *et al*. (2012) [24] discovered a moderate diversity of butterflies in a Home Garden habitat, ranking second only to forest habitats. Furthermore, the agroforestry system in home gardens offers an improved belowground environment, leading to increased proliferation and activity of soil macrofauna, as evidenced by higher biomass and abundance (Asfaw and Zewudie 2021) [2].

Coffee-based agroforestry

Coffee-based agroforestry systems, characterized by the cultivation of coffee plants within a diverse canopy of trees and other vegetation, are known for their remarkable biodiversity (Figure 6). The management of tree species richness, vertical complexity, and canopy structure has demonstrated its significance in the conservation of avian populations. The presence of diverse and structurally intricate tree components is highly advocated as an alternative approach for environmental conservation and protection. These agroecosystems offer a conducive environment for a wide range of flora and fauna. The shade-providing tree canopy not only benefits coffee growth but also provides habitat and sustenance for various plant species, insects, birds, and mammals. The complex structure of these agroforestry systems promotes ecological balance, nutrient cycling, and pest control. Furthermore, the presence of multiple vegetation layers in coffee-based agroforestry systems creates a diverse microclimate, resulting in increased species richness and enhanced ecosystem resilience, making them important contributors to biodiversity conservation in agricultural landscapes. As stated by Maheshwarappa *et al*. (2021), certain native trees in coffee-based agroforestry demonstrated effective roles in soil and moisture conservation, contributing to the protection of the environment. Additionally, they played a vital role in pollinating coffee plants and provided a sustainable supply of timber, small-scale timber, and firewood.

In the Western Ghats of India, the comparison between native coffee agroforestry and exotic agroforestry revealed that shade tree species diversity, measured by species richness, showed similar values in forest and native agroforestry plots but was significantly lower in exotic setups (Guillemot *et al*. 2018) [20]. In Kodagu, Karnataka, India, small mammal diversity in coffee-based agroforestry emphasized the importance of maintaining shade tree richness, mature trees, and herbaceous ground cover within coffee farms, along with preserving forested areas in the landscape to enhance the habitat for non-volant mammals (Caudill *et al*. 2014) [11]. Bat richness in coffee agroforestry systems identified nine species across 29 sites, with a notable presence in the families Rhinolophidae and Hipposideridae (Ongole *et al*. 2018) [37]. Meanwhile, in the Eastern Ghats of southern Odisha, India, a study on butterfly diversity indicated that coffee plantations stood out as the most favorable habitat among three agroforestry types, attributed to the habitat heterogeneity supporting exclusive butterfly species and minimal human influence (Mahata *et al*. 2018) [28]. The importance of diverse overstory tree management in coffee-based agroforestry, such as the number of tree species, flowering tree species, and canopy cover, in influencing bee abundance and species richness (Jha and Vandermeer 2010) [23]. Numerous studies across different regions accentuate the significance of maintaining shade tree diversity for overall habitat quality, emphasizing the broader positive impact of diverse overstory tree management in coffee-based agroforestry.

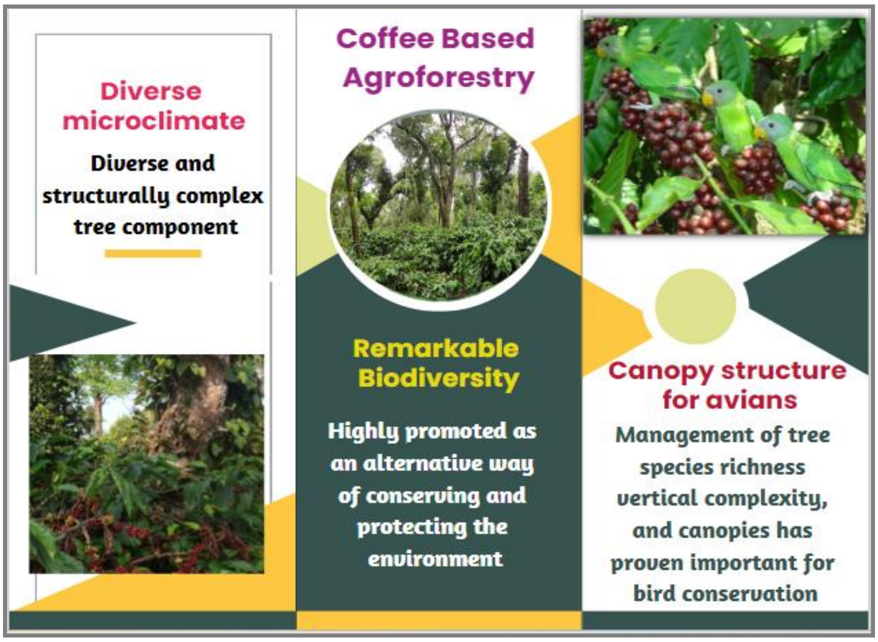

Fig 6: The Ecological Symphony of Coffee Agroforestry Systems

Cocoa-based agroforestry

Cacao-based agroforestry practices are regarded as environmentally friendly agricultural approaches, as they sustain diverse habitats that support a wide range of species. They play a significant role in the conservation of avian diversity due to the structural similarities between cocoa farms and forests, arising from the variability in habitat characteristics (Figure 7). The shade provided by the tree canopy enhances cocoa growth while fostering habitat for various plant species, insects, birds, and mammals. The structural complexity of cocoa-based agroforestry systems promotes ecological stability, nutrient cycling, and pest regulation. Moreover, the layered vegetation in these systems results in diverse microclimates, driving increased species diversity and ecological resilience.

In exploring cocoa-based agroforestry, researchers have delved into various aspects across different regions. Wartenberg *et al*. (2017) [53] conducted a study comparing tree density in cocoa agroforestry with secondary growth, revealing notable distinctions. Shifting to the Peruvian Amazon, Arévalo-Gardini (2020) [1] investigated the effects of cacao agroforestry management on soil fungi diversity, finding that different years of cacao management influenced both soil fungal diversity and functional groups. In Africa, Jarrette *et al*. (2021) concluded that cocoa farms can harbor bird assemblages similar to forests, despite variations in habitat characteristics within cocoa farms, ranging from full-sun plantations to shaded areas resembling forests. Turning to Brazil, Rocha *et al.* (2019) [42] explored bird species richness in cocoa-based agroforestry and natural forests, discovering that cacao agroforestry systems exhibited diversity comparable to nearby forests, especially when considering the entire bird community. These studies collectively contribute insights into the multifaceted dynamics of cocoa agroforestry across different geographical contexts.

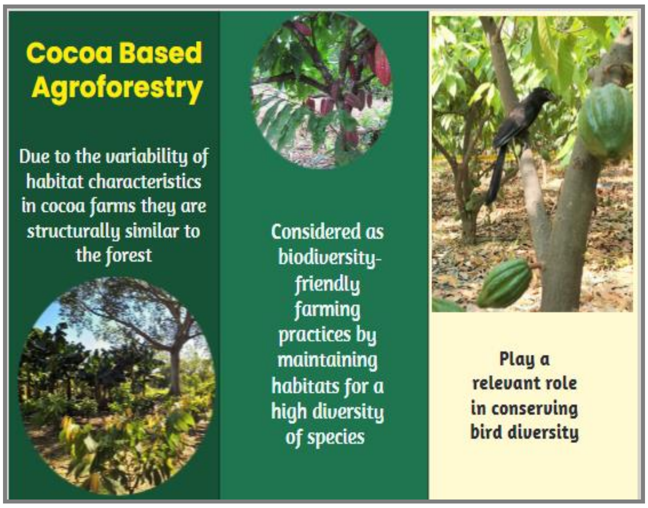

Fig 7: Cacao Canopies: Nurturing Biodiversity in Agroforestry Practices

Silvo-pastoral system

Silvo-pastoral systems, characterized by the integration of trees or woody vegetation into pastureland for livestock grazing, are ecologically significant due to their remarkable biodiversity (Figure 8). Specially the Domesticated" biodiversity (domestic animal breeds). High level of genetic diversity within the major species used for "food": many breeds of livestock originate from a single species. These systems create a dynamic landscape that supports a diverse array of plant and animal species. The presence of trees provides shade and shelter for livestock, while simultaneously offering habitat for various bird species, insects, and small mammals. The structural complexity of silvo-pastoral systems promotes ecological stability, nutrient cycling, and pest control. Additionally, the combination of grassland and woody vegetation encourages a variety of microhabitats, resulting in heightened species diversity and enhanced ecosystem resilience. Silvo-pastoral systems thus play a vital role in biodiversity conservation within agricultural contexts.

The intricate dynamics of land use on biodiversity are underscored by a synthesis of studies, particularly within the framework of silvopastoral systems. Examining the Bird Monitoring Project (BMP) in Costa Rica reveals distinct ecological niches associated with different land uses. Pristine forests, characterized by rich lichen diversity, stand in contrast to disturbed forest patches harboring pyrophytes, while forest edges host game ungulates. The study by Paiva *et al.* (2020) [38] in Southeastern Brazil adds a crucial layer to this narrative, focusing on insect fauna in a monocultural pasture and a silvopasture. Remarkably, the silvopastoral system exhibits a total abundance of 48,338 individuals, surpassing the 46,275 individuals collected in the monocultural pasture. This emphasizes the positive impact of integrating trees into pasturelands, aligning with the findings of DeClerck and Salinas (2014) [15]. Their research indicates that forests have the lowest bird species richness, whereas pastures, particularly those within a silvopastoral context, boast the highest diversity and second-highest abundance values. Together, these studies underscore the significance of sustainable land management practices, such as silvopastoral systems, in promoting biodiversity and ecological resilience across various ecosystems.

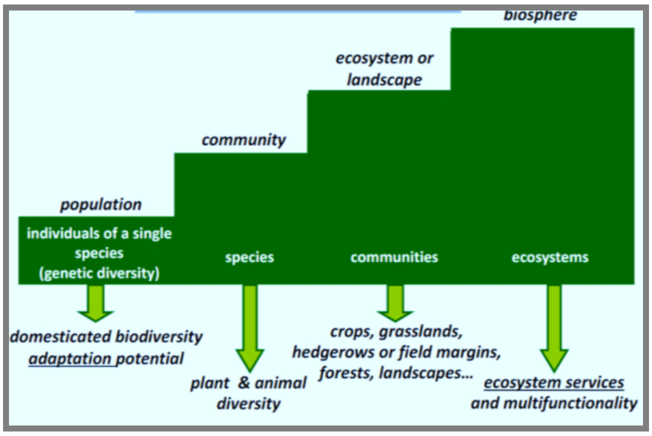

Fig 8: Biodiversity levels in SPS (Source: Gorlierand Vacchiano 2012)

Agroforestry for Sustainable Development Goals in Agrobiodiversity Conservation

Exploring the crucial role of agroforestry in agrobiodiversity conservation demands a recognition of the significant contribution this practice makes to achieving various Sustainable Development Goals (SDGs). Agroforestry stands as a multifaceted solution that not only preserves biodiversity within agroecosystems but also aligns with broader global development objectives) (Montagnini and Metzel 2017; Sharma *et al.* 2022; Ntawuruhunga *et al.* 2023) [30, 45, 36]. Here is how agroforestry aligns with key SDGs:

1. **Zero Hunger (SDG 2):** Diversification of Food Sources: Agroforestry enhances food security by introducing a variety of crops, fruits, and nuts alongside traditional agricultural practices, ensuring a more resilient and diversified food supply.
2. **Good Health and Well-being (SDG 3):** Medicinal Plants in Agroforestry: Many agroforestry systems incorporate medicinal plants, contributing to traditional healthcare practices and supporting community health, aligning with SDG 3.
3. **Climate Action (SDG 13):** Carbon Sequestration: Agroforestry's capacity for carbon sequestration aids in climate change mitigation, directly addressing SDG 13 by reducing greenhouse gas emissions and promoting climate resilience.
4. **Life on Land (SDG 15):** Biodiversity Conservation: Agroforestry systems serve as biodiversity hotspots, contributing to the conservation of various plant and animal species. This directly supports SDG 15, aiming to protect and restore terrestrial ecosystems.
5. **Clean Water and Sanitation (SDG 6):** Water Quality Improvement: Agroforestry helps improve water quality by reducing runoff, preventing soil erosion, and acting as natural filters, contributing to achieving SDG 6 on clean water and sanitation.
6. **Decent Work and Economic Growth (SDG 8):** Income Diversification: Agroforestry provides additional sources of income for farmers through the sale of timber, fruits, nuts, and non-timber forest products, aligning with SDG 8 on decent work and economic growth.
7. **Responsible Consumption and Production (SDG 12): Sustainable Resource Use:** Agroforestry promotes

sustainable land use practices by integrating trees with agricultural activities, reducing the need for deforestation and aligning with SDG 12 on responsible consumption and production.

8. **Gender Equality (SDG 5):** Empowering Women: Agroforestry projects can empower women by involving them in decision-making processes, providing them with access to resources, and creating opportunities for income generation, contributing to SDG 5 on gender equality.
9. **Affordable and Clean Energy (SDG 7):** Renewable Energy: Agroforestry systems can include the cultivation of energy crops, such as bioenergy trees, contributing to the production of affordable and clean energy as outlined in SDG 7.

By addressing these SDGs, agroforestry emerges as a holistic and sustainable approach to land management, promoting environmental conservation, social well-being, and economic development. As the world strives to achieve the 2030 Agenda for Sustainable Development, the integration of agroforestry practices becomes paramount in fostering a sustainable and resilient future.

Enhancing Agrobiodiversity in Agroforestry through Key Features

To optimize agrobiodiversity within agroforestry systems, a multifaceted approach is essential, incorporating key features that foster ecological richness and resilience (Figure 9). High structural and floristic diversity form the cornerstone, promoting a varied habitat that supports a wide array of plant and animal species. Embracing minimal management intensity is crucial, allowing natural processes to thrive and reducing the ecological footprint associated with intensive agricultural practices. Extending rotation periods provides a conducive environment for species to establish and flourish over extended periods, fostering a more robust ecosystem. Embracing a natural disturbance regime, when feasible, ensures ecological processes are maintained, contributing to the overall health of the agroforestry system. Strategic placement of these systems within the landscape is pivotal, as it can enhance connectivity between habitats and promote the movement of species, thereby fostering biodiversity at a larger scale. Agroforestry interventions are particularly potent when implemented on degraded agricultural and pasture lands with limited biodiversity value. By transforming these areas, agroforestry not only mitigates environmental degradation but also catalyzes the restoration of biodiversity, offering a sustainable and harmonious coexistence between agricultural productivity and ecological health. Through these integrated strategies, agroforestry emerges as a potent tool in the conservation and enhancement of agrobiodiversity, embodying a holistic approach to sustainable land management.

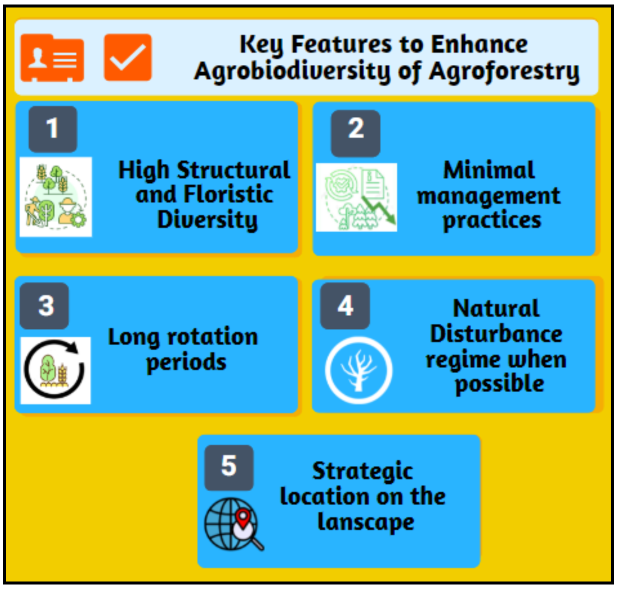

Fig 9: Key Features to Enhance Agrobiodiversity of Agroforestry

A Way forward

The way forward to a sustainable future hinge on strategic interventions across educational, policy, research, capacity building, market access, community engagement, integrated landscape management, and international collaboration fronts (Figure 10).

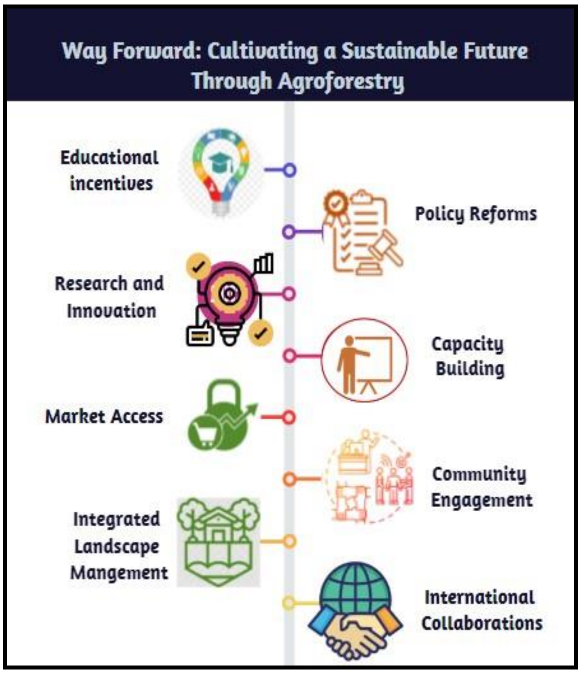

Fig 10: Infographic representation for Cultivating a Sustainable Future through Agroforestry

Educational initiatives play a pivotal role in cultivating a sustainable future by promoting awareness and providing education to diverse stakeholders on the significance of agrobiodiversity, the consequences of its loss, and the benefits of adopting sustainable practices like agroforestry. In this regard, efforts should be directed towards farmers, policymakers, and local communities. Educational programs can highlight the interdependence of agrobiodiversity, agricultural resilience, and overall ecosystem health. Farmers need to understand the long-term benefits of maintaining diverse ecosystems on their lands, not only for the health of their crops but also for sustainable livelihoods. Policymakers should be informed about the ecological and economic advantages of agroforestry, and how it aligns with broader environmental and agricultural goals. Communities, especially those directly affected by land-use changes, should be educated about the interconnectedness of agrobiodiversity with their well-being.

Policy reforms are integral to fostering agroforestry practices on a broader scale. Advocating for policies that incentivize and support agroforestry is crucial. This can include measures such as subsidies, tax breaks, or certification programs that acknowledge and reward farmers for adopting sustainable and biodiversity-friendly approaches. These policies should be designed to create a conducive environment for the widespread adoption of agroforestry, aligning economic incentives with environmental conservation goals. By influencing policy changes, there is a greater likelihood of encouraging farmers to transition towards more sustainable agricultural practices.

Research and innovation are essential components of advancing agroforestry practices. Investment in research is needed to better understand the ecological and economic benefits of agroforestry. This includes studying the interactions between trees and crops, identifying best practices, and developing technological innovations that enhance the effectiveness of agroforestry systems. The dissemination of this knowledge is critical to empowering farmers with the information they need to implement and manage agroforestry systems effectively. By staying at the forefront of research and innovation, the agricultural sector can evolve towards more sustainable and environmentally friendly practices. Capacity building is another key aspect that complements educational initiatives and policy reforms. Farmers need practical training on implementing and managing agroforestry systems. This includes understanding the dynamics of tree-crop interactions, sustainable land management practices, and effective biodiversity conservation measures. Building the capacity of farmers ensures that they have the necessary skills and knowledge to adopt and sustain agroforestry practices in the long run.

Market access is crucial for incentivizing producers to adopt agrobiodiversity-friendly practices. Developing markets that reward producers for sustainable and agrobiodiversity-friendly approaches is essential. This can be achieved by creating labels or certifications that highlight products originating from agroforestry systems. Such labelling makes these products more appealing to environmentally conscious consumers, driving market demand and encouraging more farmers to adopt sustainable practices. Community engagement is fundamental for the success of agroforestry initiatives. Involving local communities in decision-making processes related to land use and agroforestry fosters a sense of ownership and responsibility. Community-based conservation efforts can be particularly effective in ensuring that the benefits of agroforestry are shared equitably among community members.

Integrated landscape management emphasizes the strategic incorporation of agroforestry systems into broader landscape management plans. This involves considering the connectivity between different habitats, strategically placing agroforestry systems to enhance biodiversity at a landscape scale, and contributing to overall ecosystem health. By integrating agroforestry into larger landscape management strategies, the potential for biodiversity enhancement and sustainable land use practices is maximized. International collaboration is essential for addressing global challenges related to agrobiodiversity loss. Fostering collaboration and knowledge exchange on successful agroforestry models, policies, and experiences can contribute to a shared understanding and a unified global effort to promote sustainable agricultural practices. By learning from each other's successes and challenges, countries can collectively work towards mitigating the threats to agrobiodiversity and fostering a more sustainable future for agriculture on a global scale.

Conclusion

In the last few decades, increasing awareness has emerged regarding the interconnections between agrobiodiversity loss and human well-being. These realizations have given rise to the concept of multi-functional ecosystems designed to preserve and enhance agrobiodiversity while simultaneously meeting other consumption-related objectives. An approach that demonstrates significant potential in achieving this dual purpose is the promotion of agroforestry systems. Agroforestry, as a multifunctional working ecosystem, has unequivocally proven its effectiveness in conserving and enriching biodiversity, spanning from the farm to the landscape levels. Therefore, the endorsement of agroforestry systems can effectively contribute to the preservation and enhancement of agrobiodiversity while fulfilling other consumptive requirements.

Competing Interests

The authors declare that there are no competing interests associated with the publication of this article. There are no financial or non-financial interests that could be perceived as influencing the content or interpretation of the research findings. The authors affirm that the research and its outcomes are conducted and presented with integrity and objectivity.

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