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AGROFORESTRY AS A POLLINATOR CONSERVATION AND IMPROVED AGRICULTURAL PRODUCTIVITY STRATEGY: A REVIEW

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ABSTRACT

Pollinators are critical for food security at the international level, the conservation of biodiversity, and sustainable agriculture. Unfortunately, their numbers are dwindling because of habitat destruction, the use of pesticides, climate change, and monoculture agriculture. Agroforestry which involves tree-crop/or livestock integration presents itself as a sustainable land management system that favors pollinator diversity and productivity in crops. This review examines the ways in which agroforestry systems provide essential habitats for pollinators, enhance pollination services, and ultimately lead to increased agricultural production. The article also addresses mechanisms through which agroforestry enhances pollinator health and synergies between conservation of ecosystems and profitability at the farm level.

***Keywords*:** Climate Change, Agroforestry, Pollinators, Conservation biodiversity

Introduction

Pollinators like bees, butterflies, birds, and bats are essential for the reproduction of over 75% of all food plants in the world (Saha *et al*., 2023). Such organisms ensure the exchange of pollen from the male structures of flowers to the female structures, supporting fertilization and fruit growth. Yet, in recent decades, there has been a widespread reduction in pollinator populations all over the world due to issues like habitat loss, extensive pesticide application, climate change, and intensification of monoculture agriculture (Nicholls, and Altieri, 2013). This reduction threatens food security and ecosystem stability across the globe.

To counter these challenges, agroforestry has risen as an attractive option to traditional farm systems. Through its ability to replicate natural landscapes, agroforestry increases biodiversity while offering a multifaçade land use strategy. In addition to farm income diversification, agroforestry provides crucial ecosystem services such as pollination, soil protection, and climate control (Plieninger *et al*., 2020). Agroforestry involves incorporating trees, crops, and in some instances, livestock in a manner that enhances more stable and sustainable agricultural landscapes (Raj *et al*., 2019).

Table 1 : Agroforestry pollination conservation

Aspect	Description
Definition of Agroforestry	A sustainable land-use system integrating trees/shrubs with crops and/or livestock to create productive and ecologically balanced environments.
Pollinator Role	Pollinators like bees, butterflies, birds, and bats are vital for over 75% of global food crop reproduction and biodiversity maintenance.
Pollinator Benefits of Agroforestry	Agroforestry offers habitat, floral resources, shelter, and nesting sites for pollinators, supporting their year-round survival and activity.
Major Agroforestry Systems	**Silvopasture:** Trees + Livestock **Agrosilviculture:** Trees + Crops **Agrosilvopastoral:** Trees + Crops + Livestock **Homegardens:** Multi-layered cropping
Mechanisms for Pollinator Support	**Habitat provision** through diverse plant species **Reduced pesticide exposure** **Continuous forage availability** **Microclimate regulation**
Impact on Crop Productivity	Enhanced pollination efficiency and crop yields Improved pest control through natural predators Better soil fertility and moisture retention
Evidence from Case Studies	**India:** Homegardens in Kerala/Uttarakhand show increased bee diversity and fruit yield **Mexico:** Coffee agroforestry boosts pollinators and quality **Africa:** Indigenous trees in maize fields increase bee visits and yield
Challenges	Lack of awareness/training Land tenure issues Crop-tree competition Limited research on specific interactions
Policy Recommendations	Promote research on tree-pollinator-crop links Use native flowering species and minimize pesticides Offer incentives and training Integrate pollinator focus in agroforestry policies
Conclusion	Agroforestry is a win-win system for both nature and farmers. It strengthens pollinator conservation and supports resilient, productive agriculture.

Animal pollination is a major determinant of maintaining ecological balance and promoting biodiversity worldwide. It is estimated that 85% of the world's flowering plants are dependent on pollination by animals, of which the overwhelming majority are insects, notably bees (Ollerton, 2017). This process is not just critical for the reproduction of wild plant species but has significant ramification for food production agriculture and world food security. It has been estimated that approximately 35% of world crop production not to mention many fruits, vegetables, nuts, and oilseeds directly relies on animal-mediated pollination (Van der Sluijs *et al*., 2016).

Yet, the worldwide population of insect pollinators is facing a serious decline. Scientific research projects that almost 40% of animal pollinator species are under threat of extinction. This trend is being fueled by numerous factors, such as habitat degradation and fragmentation, extensive use of deadly pesticides, introduction of disease and parasites, and global warming (Nath *et al*., 2023). Loss of pollinators is not only endangering ecosystem resilience but also the stability of global food systems (Kluser, and Peduzzi, 2007).

To this escalating crisis, new approaches to land use like agroforestry are emerging as successful means of conserving pollinators. Agroforestry is the integration of trees and shrubs into crops and/or livestock on the same land, managed on a single agricultural unit (Dagar, and Tewari, 2017). Agroforestry increases landscape diversity and produces structurally complex habitats for pollinators by providing foraging resources, nesting places, and shelter from environmental stresses (Kay *et al*., 2020).

Shrubs and trees, especially early-season bloomers, are significant food sources for early-emerging pollinators (Tarbill, 2022). Through the integration of many plant species in various vertical and horizontal farmland layers, agroforestry extends floral season length so that pollinators can access nectar and pollen on a year-round basis during the growing season (Keerthika *et al*., 2024).

In addition, agroforestry offers significant ecosystem services in addition to pollination. It helps in conservation of soil, erosion control, and topsoil protection (Kuyah, 2018). It also enhances water holding capacity, improves nutrient cycling, and facilitates effective use of water in farming systems (Li, 2009). All these results in higher productivity of crops and livestock and improving the resilience of agricultural landscapes to stresses caused by the environment (Lin, 2011).

Furthermore, agroforestry systems sequester carbon, thereby mitigating climate change. The systems also support a wide variety of plants and animals, thereby promoting biodiversity and cleaner air and water.

Table 2 : Crops produced in forested areas in the Brazilian Legal Amazon, their dependence on pollinators, and their pollination service value in the study region.

Crop (English/Portuguese/ product)	Scientific name	Family	Dependence on pollinators	Dependence rate	Crop production value (2017) (US $1000)	Economic value of pollination service (2017) (US$1000)
1. Assai palm/Açaí/fruit	*Euterpe oleracea* Engel	Arecaceae	Great	0.65	197,602	128,441
2. Brazil nut/Castanha-do-Para/almond	*Bertholletia excelsa* Bonpl	Lecythidaceae	Essential	0.95	20,699.4	19,664.4
3. Babassu palm/Babaçu/ coconut	*Orbignya phalerata* (Mart).	Arecaceae	Modest	0.25	10,257.1	2564.28
4. Babassu palm/Babaçu/ almond	*Orbignya phalerata* (Mart).	Arecaceae	Modest	0.25	7526.13	1881.54
5. Tucuma palm/Tucum˜a/ fruit	*Astrocaryum vulgare*(Mart.)	Arecaceae	Essential	0.95	1160	1102
6. **/Pequi/fruit	*Caryocar brasiliense*(Cambess.)	Caryocaraceae	Essential	0.95	887.101	842.736
7. Bacaba palm/Bacaba/fruit	*Oenocarpus bacaba* (Mart.)	Arecaceae	Great	0.95 *	901.943	586.251
8. Buriti palm/Buriti/ coconut	*Mauritia flexuosa* (L.f.)	Arecaceae	Essential	0.95	741.288	704.219
9. **/Bacuri/fruit	*Platonia insignis* (Mart.)	Clusiaceae	Essential	0.95	589.034	559.582
10. Cocoa/Cacau/almond	*Theobroma cacao* (L.)	Malvaceae	Essential	0.95	368.708	350.281
11. Peach palm/Pupunha/ coconut	*Bactris gasipaes (*Kunth.)	Arecac ae	Essential	0.95	305.167	289.897
12. Cupuassu/Cupuaçu/fruit	*Theobroma grandiflorum (*Willd. ex Spreng.) K. Schum.	Malvaceae	Essential	0.95	229.673	218.185
13.**/Andiroba/seed	*Carapa guianensis* (Aubl.)	Meliaceae	Essential	0.95	201.292	191.231
14.Nance/Murici/fruit	*Byrsonima crassifolia* (L.) Kunth.)	Malpighiaceae	Essential	0.95	179.35	170.395
15. **/Cajarana/fruit	*Spondias dulci*s (Parkinson)	Anacardiaceae	Essential	0.95 *	125.156	118.895
16. **/Cumaru/seed	*Dipteryx odorata* (Aubl.) Forsyth f.	Fabaceae	Essential	0.95	82.5754	78.4546
17.**/Baru/almond	*Dipteryx alata* (Vog.)	Fabaceae	Essential	0.95	46.1309	43.8297
18. **/Copaíba/oil	*Copaifera langsdorffii(Desf.)*	Fabaceae	Essential	0.95	41.6177	39.5306
19. **/Mangaba/fruit	*Hancornia speciosa(Gomes)*	Apocynaceae	Essential	0.95	21.6205	20.5324
20. **/Ucuuba/almond	*Virola surinamensis* (Rol ex Rottb.) Warb..	Myristicaceae	Essential	0.95	12.5763	11.9519
21. Murumuru palm/ Murumuru /seed	*Astrocaryum murumuru(Mart.)*	Arecacae	Essential	0.95 *	7.742	7.34955
22. **/Cagaita/fruit	*Eugenia dysenterica* (Mart.) DC.)	Myrtaceae	Great	0.65	4.1921	2.72932
23. Macauba palm/ Macaúba/fruit	*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.)	Arecaceae	Great	0.65	0.64219	0.42813
24.**/Camucamu/fruit	*Myrciaria dubia* (Kunth) McVaugh	Myrtaceae	Modest	0.25	0.96329	0.24974
25. Assai palm/Açaí /Heart of palm	*Euterpe oleracea* Engel	Arecaceae	No increase	0	2295.81	0

26. Piassava/Piaçava/fiber	*Attalea funifera* (Mart.)	Arecaceae	No increase	0	302.259	0
27. Rubber tree/ Seringueira/ clotted latex	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.	Euphorbiaceae	No increase	0	297.746	0
28. Buriti palm/Buriti/straw	*Mauritia flexuosa* L.f	Arecaceae	No increase	0	130.972	0
29. Rubber tree/ Seringueira/liuid latex	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg	Euphorbiaceae	No increase	0	23.5471	0
30. **/Sorva/none/lastic gum	*Couma utilis* ((Mart.) Muell. Arg.)	Apocynaceae	No increase	0	2.26552	0
31. **/Jambu/leaf	*Acmella oleracea* ((L.) R. K. Jansen)	Asteraceae	No increase	0	0.64219	0
32.Cassava/Maniçoba/ elastic gum	*Manihot esculenta* Crantz	Euphorbiaceae	No increase	0	0.64219	0
33. **/Maçaranduba/ nonelastic gum	*Manilkara huberi* (Ducke) A.Chev.	Sapotaceae	No increase	0	0.3211	0

*based on genus; ** no correspond name was found in English.

A study by the USDA Forest Service's National Agroforestry Center in partnership with the Xerces Society for Invertebrate Conservation has indicated the various benefits of agroforestry (Forest, and Station 2024). Their research shows that agroforestry practice not only creates pollinator habitats of high quality, but also maintains connectivity among fragmented habitats, which is important for the movement and survival of pollinator populations (Bentrup 2021). Agroforestry also serves as a buffer to limit pollinators' exposure to toxic agrochemicals and thereby enhance their survival and reproductive probabilities (Bentrup, 2021).

Today, over 30,000 farms in the United States have integrated agroforestry systems. These farms are proving that agriculture and environmental stewardship can coexist (Bishaw, 2013). By adopting agroforestry, farmers can produce landscapes that are productive and pollinator-supportive, opening the door to a more sustainable and resilient agricultural future (Wilson, and Lovell, 2016).

This article explores how agroforestry systems have the capacity to enhance and conserve pollinator populations by providing diverse floral resources, nesting sites, and protection from agricultural disturbances (Bentrup, 2021). Through constant blooms, structural complexity, and minimized chemical exposure, agroforestry establishes favorable microhabitats that favor both generalist and specialist pollinators (Lee-Mäder, 2020). Furthermore, the paper also analyzes how enhanced pollination services in agroforestry systems may result in enhanced crop yields, fruit quality, and farm productivity as a whole. Case studies and empirical data from various agro-ecological regions are discussed to showcase effective integration techniques and results (Workman *et al.*, 2003).

In addition, the review addresses the ecological and socio-economic synergies between pollinator conservation and agricultural production, with a focus on how agroforestry enhances ecosystem services, climate resilience, and rural livelihoods. Policy implications, research gaps, and practical recommendations for mainstreaming agroforestry into pollinator-friendly farming systems are also presented (Centeno-Alvarado *et al.*, 2023). Overall, this paper places agroforestry in context as a viable and multifunctional solution to balance conservation objectives with productive land use, thus supporting sustainable food systems and environmental stewardship.

Fig. 1 : Pollination done by honeybee

Role of Pollinators in Agriculture

Pollinators play a crucial role in agricultural production because they directly impact the quality and quantity of a vast array of crops, such as fruit, vegetables, nuts, and seeds. Successful pollination leads to increased fruit setting, increased yields, enhanced nutritional value, and extended shelf life of the produce (Krishnan, 2020). Thus, the abundance and well-being of pollinator populations have direct implications on the success of agricultural systems (Potts *et al.*, 2016).

In addition to their contribution to food production, pollinators also play essential ecosystem services that support plant reproduction and preserve plant population genetic diversity. Maintaining a diverse array of wild plants, pollinators enhance ecosystem resilience, enabling natural and agricultural ecosystems to resist environmental stresses and bounce back from perturbations (Maggi, *et al.*, 2023).

The economic value of insect pollinators is impossible to exaggerate. Insect pollinators are estimated to provide more than $200 billion each year to world agriculture, reflecting their value to food production and rural economies on a massive scale (Khalifa *et al.*, 2021). The loss of these critical species could thus have serious economic implications, and the protection of pollinators should be a high priority for sustainable agriculture globally.

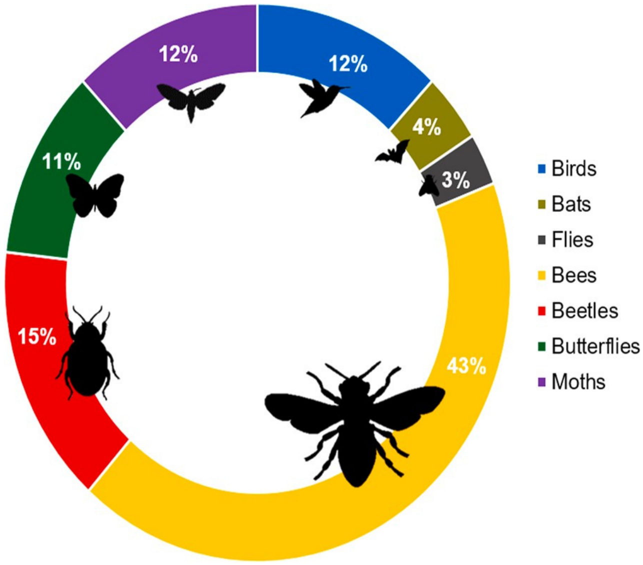


Fig. 2 : Image percentage of different insect in pollination

Table 3 : Strategies for Pollinator Conservation and Enhanced Agricultural Productivity

Category	Strategy/Practice	Purpose/Benefit
Agroforestry Systems	Silvopasture, Agrosilviculture, Agrosilvopastoral, Homegardens	Provide habitat, floral resources, and microclimatic regulation for pollinators
Native Flowering Plants	Planting diverse, nectar- and pollen-rich native species	Continuous food supply for pollinators across seasons
Pesticide Management	Reduce chemical use, adopt Integrated Pest Management (IPM)	Minimize harm to pollinators and support healthy ecosystems
Habitat Restoration	Maintain hedgerows, flowering strips, and nesting sites	Shelter and breeding grounds for wild pollinators
Landscape Diversity	Promote polycultures and mixed cropping systems	Enhance biodiversity and pollinator movement
Microclimate Regulation	Plant shade trees, use mulching, conserve moisture	Create favorable conditions for pollinator activity
Water Provision	Provide clean, shallow water sources	Essential for pollinator hydration and thermoregulation
Beekeeping (Apiculture)	Integrate managed honey bee hives	Enhance crop pollination and provide additional income
Crop Diversification	Rotate and intercrop with pollinator-attractive plants	Support pollinators and improve crop health and yield
Pollinator-Friendly Certification	Eco-labeling, market recognition for safe practices	Incentivizes conservation through market access and premium pricing
Farmer Training & Awareness	Workshops, field schools, community outreach	Builds capacity for adopting pollinator-supportive agricultural practices
Policy Integration	Include pollinators in agroforestry, biodiversity, and agri-environmental policies	Supports large-scale implementation and funding of conservation strategies
Research & Innovation	Study pollinator-tree-crop interactions, develop new agroforestry models	Strengthen scientific understanding and practical solutions for sustainable farming

Crop Pollinator Dependency and Pollination Service Valuation

In the Amazon, a large percentage of cultivated crops nearly 73% rely on pollinators for productive cropping (Borges, *et al.*, 2020). This emphasizes the importance of pollination as an ecosystem service that has direct support for agriculture in forested mosaics. Our results illustrate how crucial pollinators are to maintaining crop yields and species diversity in these biomes (Campbell *et al.*, 2022).

Other research has also illustrated the agricultural and economic importance of pollination. For example, Giannini *et al.* (2015a) revealed that pollination services contributed 30% of Brazil's overall crop production in 141 crops. A similar percentage was witnessed in the state of Pará, where pollination played a crucial role for 36 crops, as revealed by Borges *et al.* (2020). At the world level, Klein *et al.* (2007) reported that 48 of the 67 major crops five of the globe's top commodities are benefited by higher yields through the use of animal pollinators.

Among the 24 pollinator-dependent crops assessed in our study, 18 were recently identified as native species of socio-biodiversity significance (Brasil, 2021). These crops are especially valuable for their high nutritional content and cultural importance. In addition to supporting food diversity, they contribute to sustainable livelihoods, income generation, and improved quality of life for family farmers and traditional forest communities. As such, pollination supports not only agriculture but also social and economic resilience in the Amazon.

Crop Pollinator Species

As expected, bees turned out to be the prevalent pollinators for crops under scrutiny in this study. Bees are known internationally as the most important pollinators of agricultural systems, especially in tropical ecosystems (Giannini *et al.*, 2015b, 2020a; Wolowski *et al.*, 2019; Aizen *et al.*, 2019). The worldwide loss of bee populations (Potts *et al.*, 2016b), however, highlights the importance of conserving natural habitats, which provide important havens for many bee species (Brosi *et al.*, 2008).

Studies in the Amazon have shown that greater forest fragmentation correlates with decreased abundance and native bee diversity (Brown and Albrecht, 2001). Within açaí plantations, fragmentation has been found to shift the functional structure of the bee community, with smaller-bodied bees most at risk from habitat loss (Campbell *et al.*, 2022).

In spite of the high dependence of most crops on wild pollinators, pollinator management is under-exploited in the region (Venturieri, 2014; Campbell *et al.*, 2018). Additionally, climate change will also decrease the habitat available for bees, particularly in the Eastern Amazon (Giannini *et al.*, 2020b), building upon existing pressures.

Agroforestry systems (AFSs) offer an effective means of resolving these challenges. Such systems offer necessary foraging resources as well as nesting sites that aid the survival and reproduction of pollinators (Kay *et al.*, 2020). Agroforestry, therefore, not only maintains farm productivity but also has an important role in bee population conservation and forest ecosystems.

It is interesting to mention here that intensive management in açaí plantations especially in floodplains has resulted in a reduction in the diversity of pollinators and greater antagonistic interactions, e.g., elevated ant densities on inflorescences, particularly in upland plantations (Campbell *et al.*, 2018). Hence, the effective implementation of agroforestry practices is required to facilitate environmentally sustainable and productive agriculture.

Finally, research has established that both extensive farming practices and the maintenance of neighboring unmanaged forest patches are crucial in preserving a rich florally visited species guild within Amazonian ecosystems (Campbell *et al.*, 2018). These research findings further buttress the incorporation of ecological practices, such as agroforestry, into the conservation of pollinators and sustainable development in the Amazon.

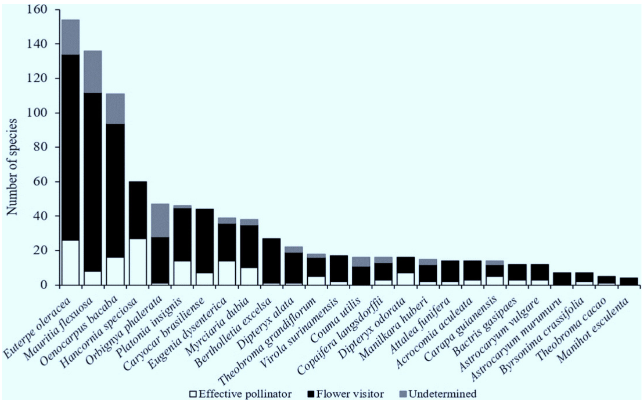


Fig. 3 : Number of species of effective pollinators, floral visitors, and species of indeterminate behavior (i.e., cases where the study does not clearly specify whether the species is a pollinator or merely a visitor) associated with crops present in forested areas within the Brazilian Legal Amazon. For each crop, the number of reported pollinator species is indicated, highlighting the diversity and role of pollinators in agroecosystems adjacent to or within forested landscapes.

Agroforestry

Agroforestry is a land-use management technique that utilizes trees or shrubs deliberately cultivated in association with crops and/or animals on the same land (Raj, and Lal, 2014). This combined technique mixes agricultural and forest technologies to provide more diverse, productive, and resilient agroecosystems. Agroforestry replicates nature by promoting interactions between animals, plants, and trees, and thus amplifying ecological functions like nutrient cycling, water replenishment, and wildlife habitat creation (Nungula *et al.,* 2024).

There are a number of principal agroforestry types, differentiated by the mix of components involved:

Silvopasture: This combines trees with grazing by animals. Trees shade, shelter, and offer forage to animals, while animals may gain improved microclimates and diversified feeds. Together, they increase land productivity and animal welfare (Jose, and Dollinger, 2019).

Agrosilviculture: Trees and crops are grown together in this system. Trees can enhance soil fertility by leaf litter and nitrogen fixation, suppress soil erosion, and serve as habitat for beneficial organisms, including pollinators. This intercropping method tends to increase the overall productivity of the farm (Barros, 2003).

Agrosilvopastoral: This is a combination of trees, crops, and livestock in the same area. It makes maximum utilization of resources and space and encourages synergistic relationships between the various elements. Agrosilvopastoral is highly diversified and can enhance environmental stress resistance (de Freitas, 2020).

Homegardens: Multi-story, diverse cropping systems usually located around homesteads. Homegardens are a mixture of diverse trees, shrubs, herbs, and vegetables cropped in layered stands. Homegardens offer diversified food, medicinal crops, and income-generating products while enhancing biodiversity and ecosystem services within small parcels of land (Huai, and Hamilton, 2009)

All of these agroforestry systems play unique roles in sustainable agriculture by increasing biodiversity, resource-use efficiency, and socio-economic returns for farmers (Murthy *et al*., 2016). Agroforestry refers to a land-use management system that intentionally combines trees and shrubs with crops and/or livestock within a spatial or temporal arrangement. It aims to maximize the ecological and economic interactions among the components of the system (Veste *et al*., 2024). The practice of agroforestry is based on traditional agricultural knowledge but has been increasingly acknowledged and supported in contemporary sustainable agriculture because of its environmental, economic, and social advantages (Plieninger *et al*., 2020). These systems have several advantages such as enhanced soil health, increased biodiversity, improved microclimate control, carbon sequestration, and diversity of farm products. Notably, agroforestry provides a structurally and biologically varied habitat that is favorable for the survival and abundance of pollinators (Udawatta *et al*., 2019).

Table 4 : Forest Trees and Their Roles in Fruit Pollination

Tree Species	Role in Fruit Pollination
Syzygium cumini **(Jamun)**	Early-season nectar source for bees; supports bee populations important for mango, guava, and citrus pollination.
Albizia lebbeck (Siris)	Offers nectar and pollen to bees and butterflies; enhances pollinator diversity in orchards.
Moringa oleifera **(Drumstick tree)**	Attracts bees and hoverflies; blooms throughout the year in warm climates, maintaining pollinator activity.
Grevillea robusta **(Silky oak)**	A major nectar source for honeybees and sunbirds; often planted on orchard boundaries to enhance pollination.
Butea monosperma **(Flame of the Forest)**	Attracts a wide range of pollinators including birds and bees; blooms when few other trees do.
Terminalia bellirica **(Bahera)**	Provides nesting and foraging habitat for wild bees, critical for wild fruit tree pollination.
Schleichera oleosa **(Kusum)**	Rich pollen source in early season; supports bee health before orchard bloom periods.
Tectona grandis **(Teak)**	Indirect role—provides nesting hollows for cavity-nesting pollinators like solitary bees and birds.
Ficus spp. **(Fig trees)**	Mutualistic pollination with fig wasps; also supports other generalist pollinators used in nearby fruit crops.
Madhuca longifolia **(Mahua)**	Attracts bats and bees; important for nocturnal pollination of some tropical fruit trees.
Eucalyptus spp.	Major source of nectar and pollen; promotes honeybee health, especially near citrus and apple orchards.
Acacia spp.	Support pollinator populations during dry seasons when other floral resources are scarce.
Cassia fistula **(Golden Shower Tree)**	Provides nectar for butterflies and bees; enhances biodiversity in agroforestry fruit systems.
Azadirachta indica **(Neem)**	Supports insect biodiversity; serves as a shade tree in orchards where it improves pollinator habitat.
Melia dubia	Not a direct nectar source, but used in agroforestry for habitat connectivity and buffer zones.

General Roles of Forest Trees in Pollination

Nectar and Pollen Source

Forest trees are important sources of nectar and pollen, which are crucial for the survival and health of a diverse array of pollinators like bees, butterflies, birds, and bats. Most forest flora blooms at various intervals during the year, thus providing a constant source of floral materials. Such constant provision makes it possible to maintain pollinator populations throughout the year even when agricultural crops are not flowering (Ulyshen *et al*., 2023).

Habitat and Nesting Sites

Trees in forests offer vital nesting and habitat for pollinators. Trunks with hollows, bark crevices, deadwood, and canopies of trees provide habitat and breeding ground for solitary bees and social bees and other beneficial insects and birds (Free, 1960). Such safe nesting sites are invaluable in the conservation and maintenance of healthy and stable populations of pollinators, particularly within agricultural ecosystems where such natural formations are seldom present (Potts *et al*., 2016).

Creation of Pollination Corridors

By forming unbroken or linked patches of plants, forest trees function as ecological corridors that support the foraging and movement of pollinators between discontinuous landscapes. Such corridors are particularly vital in regions where agricultural development has fragmented natural habitats. The corridors enable pollinators to move between nesting areas and sources of food in safety, thus ensuring efficient pollination across wide distances (Kormann *et al*., 2016).

Microclimate Regulation

Tree canopies in the forest help regulate local microclimates. Canopies cast shade, slow down wind speeds, and retain humidity. Such climatic conditions are advantageous not just for pollinators, who forage more effectively at cooler, wetter temperatures, but also for the flowers themselves since it enhances flower viability and secretion of nectar, leading to increased pollination success (Zimmerman, 1988).

Supporting Biodiversity

The floral and structural complexity of forest trees adds to the biodiversity of the ecosystem as a whole. Through the attraction of diverse populations of pollinators, forest trees serve to support a stable and strong ecological community (Scaven, and Rafferty, 2013). The resulting biodiversity provides redundancy in the pollination service such that if one declines, others will continue to provide the pollination function, enhancing the reliability and stability of pollination for both wild and crop plants (Allen-Wardell *et al*., 1998).

By including flowering trees, shrubs, and understory vegetation with flowers occurring at various times of the year, agroforestry systems provide a steady flow of nectar and pollen. Temporal and spatial heterogeneity offers a refuge for pollinators, decreases the effects of pesticide drift, and lessens the detrimental influences of habitat fragmentation prevalent in monoculture agriculture (Bruhl, 2019). Agroforestry practice also frequently involves reduced tillage and chemical use, further maintaining the ecological integrity necessary to sustain pollinator populations (Nicholls, and Altieri, 2013).

Agroforestry and Conservation of Pollinators

(a) Provision of Habitat

Agroforestry habitats offer vital sites for pollinators by including trees and shrubs, which provide varied sites for nesting and shelter during different seasons (Kay, 2020). These woody plants offer vital floral resources like nectar and pollen, which meet the nutritional requirements of pollinators. The heterogeneous and complex vegetation structure of agroforestry landscapes encourages higher pollinator species richness and abundance by creating diverse microhabitats accommodating pollinator species (Bożek *et al*., 2023). This ensures that specialist and generalist pollinators are supported, which ensures that pollinator populations remain stable.

(b) Reduction in Pesticide Use

Relative to traditional monoculture agriculture, agroforestry systems tend to use fewer synthetic chemical inputs, such as pesticides and herbicides (Akinsorotan, *et al*.,2023). By reducing use of pesticides, the risk of pollinator exposure to toxic chemicals that can induce acute toxicity, behavioral alterations, and chronic population reductions is lowered (Ara, 2021). Through biodiversity, agroforestry maintains healthier and more resilient pollinator populations.

(c) Temporal and Spatial Forage Availability

One of the most important benefits of agroforestry is the staggered flowering of trees and shrubs during the course of the year. This phenological complexity provides a constant and consistent source of nectar and pollen for pollinators at all times, even when crop flowers are not present (Viswanath, and Lubina, 2018). The spatial arrangement of floral resources over the agroforestry landscape also maximizes foraging efficiency and allows pollinators to find a variety of food sources in a relatively small area.

(d) Microclimatic Regulation

Trees in agroforestry systems are essential in microclimate regulation through tempering extreme temperature fluctuation and enhancing humidity levels. The moderated microclimatic conditions thus promote excellent habitats for pollinators that shield them from heat and desiccation stress. The protective sheltered and shaded environment further promotes pollinator activity under less-than-optimal weather, thus extending foraging periods and enhancing overall pollination services (Liu *et al*., 2019).

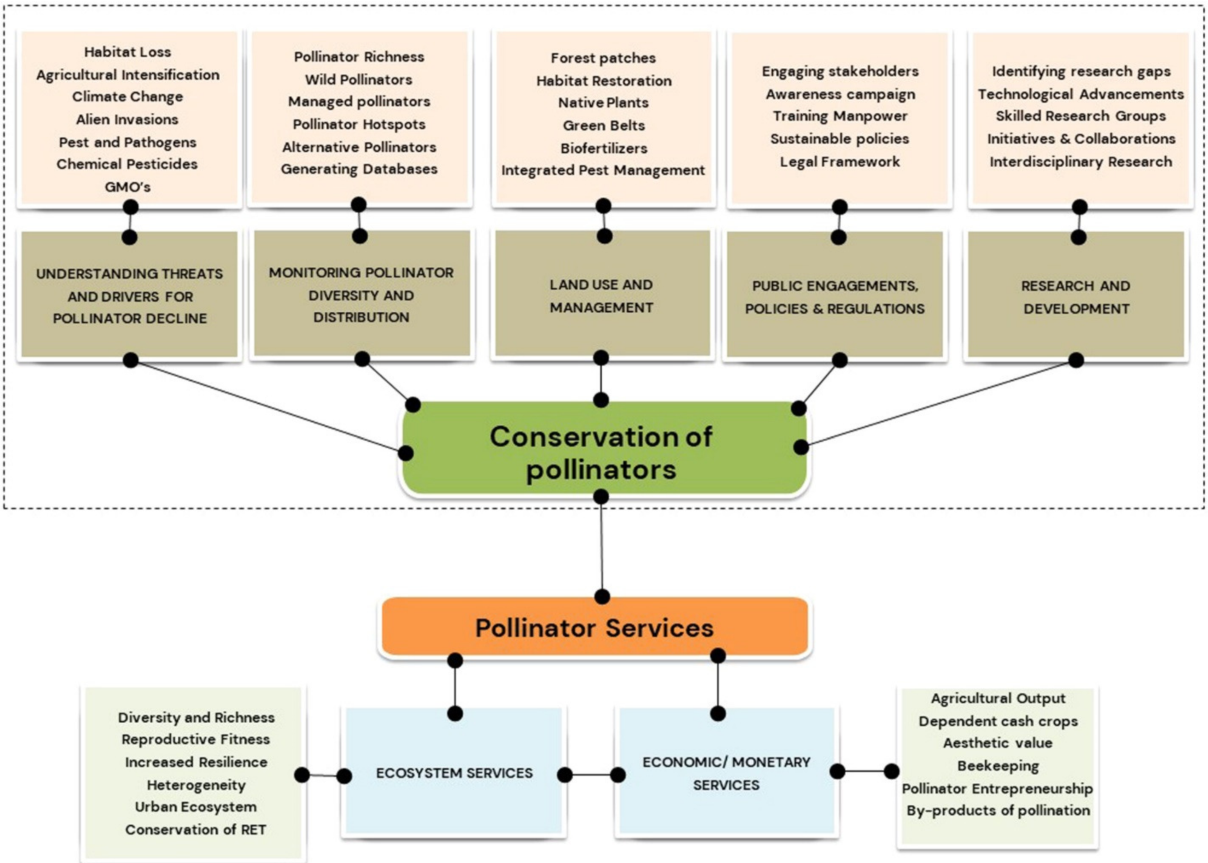


Fig. 4 : Image of conservation of pollinators

(Source, Adit *et al*., 2024)

Impact of Agroforestry on Agricultural Productivity

Agroforestry has positive impacts on farm productivity through several direct and indirect pathways, with increased pollination being one of the most important (Castle, 2021).

Secondly, with increased pollination efficiency through better diversity and abundance of pollinators, directly higher fruit set, seed yield, and overall crop yield are obtained. With enhanced pollination, also the quality characteristics of the fruits and seeds are commonly enhanced in size, weight, and nutrition, with increased value to farmers and consumers (Woodcock *et al*., 2019).

Secondly, the biodiversity in agroforestry promotes natural pest control. The diverse species in these systems create habitat and alternate food sources for natural enemies and parasitoids of pests of crops. This natural biological control minimizes damage to crops and reduces the use of chemical pesticides, promoting sustainable pest control.

Thirdly, agroforestry enhances soil fertility and water use efficiency, which indirectly increases crop productivity. Forests add organic material via leaf fall and root turnover, improving soil structure and nutrient cycles. Deep roots in trees recycle nutrients from layers of subsoil and enhance soil water storage, making water more accessible to crops during drought. These enhanced soil conditions and water storage favor optimal growth conditions for crops, leading to increased productivity and environmental stress resistance (Soni *et al*. 2017).

Different method to Conservation Agroforestry plant for Improved Agricultural Productivity

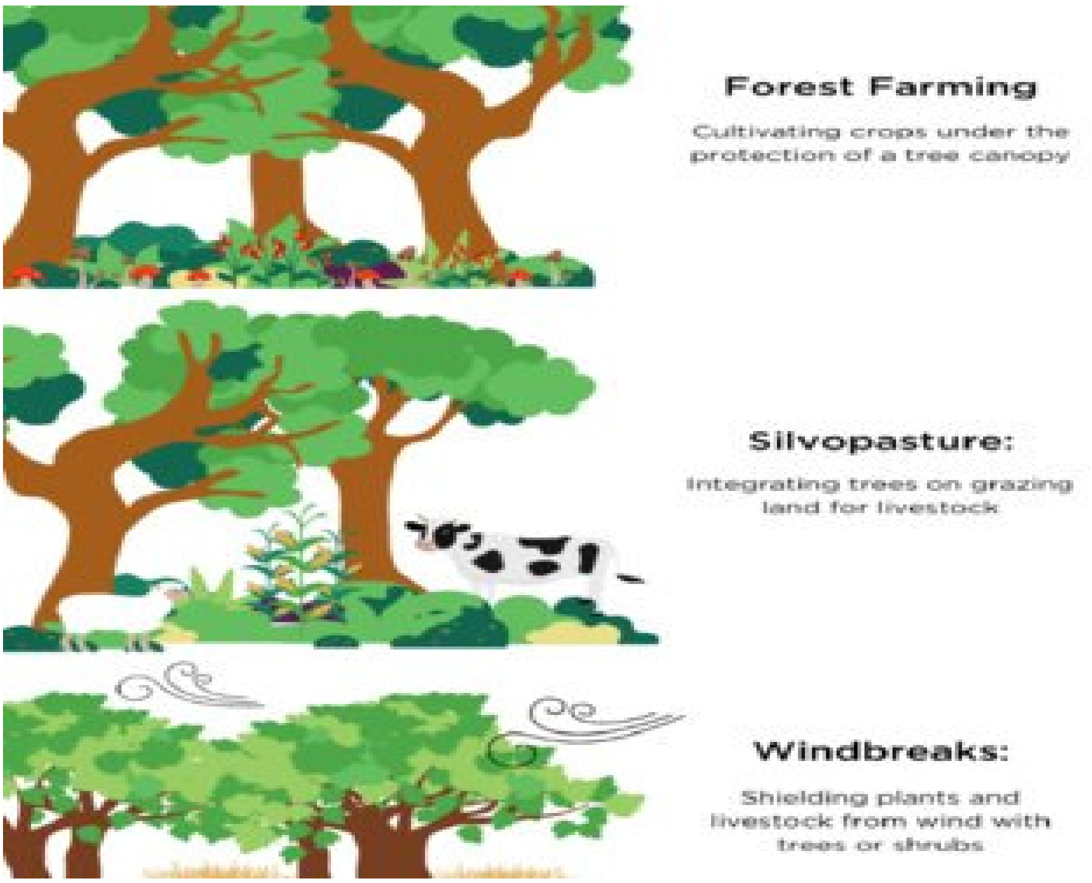
Agroforestry Design and Planting Strategies

Agroforestry systems ought to be designed and planted in a way that integrates pollinator-friendly species to save pollinators and maximize agricultural productivity (Young, 1989). This would entail the inclusion of indigenous flowering trees, shrubs, and herbaceous plants that offer rich nectar and pollen resources across various seasons.

Multistrata agroforestry systems that combine upper canopy trees, midstory shrubs, and understory crops assist in producing structurally diverse environments rich in habitats for a variety of pollinators through the provision of diverse nesting and foraging sites (Keerthika *et al.*, 2024). Temporal planting diversity is another valuable strategy, such that there is a succession of flowering periods throughout the year, thus providing continuous sources of food to pollinators. The deployment of live fencing with flowering hedges not only acts as a barrier but also as foraging corridors and nesting sites for pollinators. Integrating alley cropping systems with flowering cover crops, including legumes, between the rows of main crops can further increase floral diversity and promote pollinator health.

Conservation of Habitat and Nesting Sites

Preservation and restoration of natural habitats around and within agroforestry systems are important for maintaining wild pollinator populations. Forest patches, original grasslands, and fallows must be conserved because they offer protection, nesting, and foraging sites (Skórka *et al.*,2006). Artificial nest sites in the form of bee hotels and nesting blocks may be added to benefit solitary bees and other pollinators that need specialized nesting substrates. Moreover, the retention of deadwood, logs, stumps, and unturned areas of soil helps to preserve vital ground and wood-nesting habitats, specifically for native bee populations (Smith, 2021).



(Source- Smith, 2021)

Fig. 5 : Image of different Agroforestry system

Reducing Agrochemical Impact

Limiting or avoiding the use of toxic agrochemicals, notably insecticides such as neonicotinoids, is imperative in terms of conserving pollinators. They have been extensively documented to have a detrimental impact on pollinator health, behavior, and reproductive fitness (Nicholls *et al.*, 2022). Embracing biopesticides and encouraging Integrated Pest Management (IPM) methods can greatly reduce the threat to pollinators by using safer, environmentally friendly options for pest management (Mukhtar, and Shankar, 2023).

Farmer Awareness and Training

Awareness among farmers regarding the ecological and economic importance of pollinators is a basic step towards encouraging their conservation. Training programs and workshops can educate farmers with knowledge to follow pollinator-friendly approaches in agroforestry management. Setting up demonstration farms and farmer field schools demonstrating successful models of pollinator-friendly agroforestry can induce greater uptake of these measures among farming communities (Rudebjer, 2001).

Sustainable Land Management Practices

Organic and low-input agricultural systems promoted in agroforestry lower chemical exposure and increase on-farm biodiversity, thereby supporting healthy populations of pollinators. Biodiversity conservation efforts are facilitated by integrating measures for soil and water conservation, which uphold ecosystem integrity and provide natural resources that indirectly assist pollinator species by facilitating beneficial microhabitats (Ogwu, and Kosoe, 2025).

Policy and Institutional Support

Policy and institutional support is crucial to perpetuate agroforestry-based pollinator conservation initiatives. Financial subsidies, eco-certifications, or payment for ecosystem services (PES) can be used to incentivize farmers to implement and maintain pollinator-conserving agroforestry systems.

In addition, mainstreaming agroforestry and pollinator conservation into national agricultural development and biodiversity strategies guarantees policy coherence and resource management over the long term.

Monitoring and Research

Continuing research and monitoring are necessary to determine the interactions between agroforestry systems and pollinators. Long-term biodiversity monitoring programs may be useful to monitor pollinator population changes and guide conservation efforts (Nair *et al.*, 20210.

Besides, studies on the interplay between crop yields and pollinator activity in agroforestry systems are able to generate useful information on the economic returns from the conservation of pollinators, hence strengthening the argument for sustaining such systems.

Research Evidence and Case Studies

Various research studies conducted in the world's different regions present strong evidence for the advantages of agroforestry systems for conserving pollinators as well as promoting agricultural production.

In India, studies in homegardens of Kerala and Uttarakhand have found high bee diversity in agroforestry ecosystems compared to single-crop cultivation systems. Such diverse pollinator assemblages are correlated with better fruit yield and quality, reflecting the beneficial role of including trees and shrubs in agricultural systems. The complexity of structure and perpetual floral provision in these homegardens provide perfect conditions for maintaining diverse pollinator populations throughout the year (Augash, 2024).

Latin American coffee agroforestry systems in Mexico have been demonstrated to maintain rich and diverse pollinator communities, such as native bee species important for the pollination of coffee. They not only provide biodiversity but also increase coffee yields and bean quality. Shade trees and florally diverse resources in coffee farms promote strong pollinator populations, which in return ensure effective pollination services important for better yields.

In Africa, research conducted on the inclusion of indigenous fruit trees in maize farms shows an increased abundance of bees. The elevated abundance is related to increased maize yield, suggesting agroforestry management has positive effects on native pollinator conservation as well as staple crop productivity. Integrating fruit trees provides a steady supply of nectar sources and nesting sites that draw and maintain populations of pollinators even throughout the off-flowering seasons for maize.

These case studies together demonstrate the multifunctional advantages of agroforestry systems in various agro-ecological zones. They highlight the potential of agroforestry in promoting pollinator diversity, enhancing ecosystem services, and increasing agricultural productivity and therefore making it a potential approach to sustainable farming globally.

Challenges and Limitations

Though many advantages are linked with agroforestry systems, a number of challenges and limitations discourage their adoption and utilization on a large scale for pollinator conservation and agriculture productivity. One of the key challenges is that farmers are not aware or trained about the ecological and economic benefits of agroforestry. Most of the farmers are not aware of designing and managing the agroforestry system to derive maximum benefits for pollinators and crops. Without proper extension services and capacity-development initiatives, the promise of agroforestry goes untapped.

Also, land tenure problems cause major challenges, particularly in areas where farmers lack secure or permanent rights to their land. Uncertainty of land ownership frequently discourages investment in agroforestry development and tree planting. In addition, there is often resistance to shifting traditional farming practices since farmers might be reluctant to experiment with new approaches due to perceived risk, cultural factors, or short-run economic reasons.

Another ecological constraint is the competition that exists between crops and trees for critical resources like water, nutrients, and sunlight. Unplanned agroforestry systems can result in decreased crop yields if appropriate tree species or planting densities are not optimally chosen and controlled to reduce competition.

Lack of Training and Awareness among Farmers Weeds are aware of the ecological and economic advantages of agroforestry, especially pollinator conservation and improvement in crop yield. Lack of formal training programs, demonstrations, and extension services constrains awareness and use of pollinator-friendly agroforestry practices.

Land Tenure Problems and Resistance Weeds are resistant to adopting novel approaches to management of land, which is a limitation of practicing agroforestry.

In most areas, particularly in developing countries, uncertain or insecure land tenure deters long-term investment such as planting trees. Farmers also resist the adoption of agroforestry because of ingrained cultural preferences, distrust of new techniques, and fear of initial losses or higher labor requirements.

Possible Competition among Trees and Crops for Resources

If managed poorly, trees and crops in agroforestry systems can compete with each other for sunlight, water, and nutrients. This results in inferior crop performance in situations where soil fertility or rainfall is limited. The success of agroforestry is largely reliant on species compatibility and maximization of spatial arrangements.

Limited Research on Specific Tree-Pollinator-Crop Interactions

There are no in-depth, location-specific investigations of how various tree species drive pollinator behavior and how this then impacts pollination services to neighboring crops. Without this information, it is impossible to plan scientifically based agroforestry systems to optimize both biodiversity and crop yields.

Future Directions and Policy Recommendations

To maximize the benefits of agroforestry for conserving pollinators and increasing agricultural yields, future initiatives should target research and policy support. Encouraging thorough research on plant-pollinator interactions across varied agroforestry systems is crucial to grasp the ecological mechanisms maximising pollination services. Such research will deliver essential information in choosing optimal tree and crop species mixtures that double benefits for both pollinators and farmers. Integrating pollinator-supportive practices into agroforestry planning needs to be prioritized. These include planting indigenous flowering crops that offer year-round sources of nectar and pollen, eliminating or reducing pesticide applications, and preserving habitat structures that meet pollinator nesting and shelter requirements. These practices will facilitate robust ecosystems that maintain healthy pollinator populations and enhance crop yields. Offering financial incentives, technical education, and extension services is crucial to motivate farmers to practice and sustain agroforestry. The government and development organizations must work together to provide affordable education programs and subsidies that lessen the initial investment and risks involved in shifting to agroforestry.

In addition, mainstreaming pollinator conservation in national agroforestry and biodiversity policies will establish an enabling framework for sustainable land management. Policies must encourage cross-sectoral coordination between agriculture, forestry, and environmental departments to ensure pollinator-friendly agroforestry is established as a holistic part of national food security and environmental conservation strategies.

By focusing on these future directions, stakeholders can promote agroforestry as a viable and effective strategy for conserving pollinators while simultaneously enhancing agricultural productivity and rural livelihoods.

Encourage Research on Plant-Pollinator Interactions in Agroforestry Systems

Region- and crop-specific research is urgently needed to determine how various agroforestry components (tree species, floral diversity, spatial configuration) affect pollinator diversity and pollination efficiency. This research will inform the development of optimized agroforestry models that balance agricultural productivity with pollinator well-being.

Include Pollinator-Friendly Practices in Agroforestry Design

Agroforestry systems must be deliberately planned to favor pollinators by incorporating indigenous, nectar-dense flowering trees and shrubs that flower at various intervals throughout the year. Pesticide avoidance or elimination and the preservation of natural vegetation strips or hedgerows will improve habitat quality and resource availability for pollinators as well.

Offer Incentives and Extension Support for Embracing Agroforestry

Aid agencies and governments must provide financial incentives like subsidies, credits, or payments for ecosystem services to promote agroforestry practice. Concurrently, agricultural extension services need to be strengthened for educating and assisting farmers in effectively putting pollinator-friendly agroforestry practices into action.

Incorporate Pollinator Conservation in National Agroforestry and Biodiversity Policies

Pollinator conservation needs to be an integral part of national and regional agroforestry, agricultural, and biodiversity policies. This entails policy structures that acknowledge the ecological service value of pollinators, facilitate habitat restoration programs, and enable land-use planning that balances agricultural development with biodiversity conservation.

Conclusion

Agroforestry is a robust and ecologically friendly farming system that serves as an important measure for pollinator population conservation while at the same time increasing agricultural production. Through a combination of trees, crops, and livestock, agroforestry produces diverse microhabitats with necessary nesting places, protection, and floral resources for pollinators all year round. Such a system lowers dependence on chemical pesticides, thus lessening pollinator exposure to harmful chemicals. Furthermore, temporal and spatial continuity of forage in agroforestry landscapes guarantees the maintenance and well-being of pollinator communities.

In these ways, agroforestry not only ensures biodiversity conservation but also facilitates greater crop yields and quality through increased pollination efficiency. Its multiple advantages include soil health, pest regulation, and microclimate management, making it an integrated approach to sustainable agriculture.

Upscaling agroforestry practices with a specific intent towards pollinator conservation presents a potential solution to address critical food security, environmental degradation, and ecosystem resilience issues. Fostering synergies between ecological sustainability and farm profit, agroforestry represents a double-win situation for farmers and nature alike, playing a major role in agricultural sustainability and ecological stability in the long term.

Finally, there is little empirical work on individual tree-pollinator-crop interactions, which limits the possibility of designing agroforestry systems to maximize pollination services. It is essential to know the intricate interactions among various tree species, pollinating communities, and crop crops to maximize both biodiversity conservation as well as agricultural yield.

Mitigating these challenges with specific research, policy assistance, farmer training, and participatory efforts will be critical to the full potential of agroforestry as a means of pollinator conservation and sustainable agriculture.

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