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The Role of Agroforestry in Ecosystem Service and Climate Change Regulation: A Review

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Abstract: Agricultural and forest ecosystems, as well as communities' means of subsistence, have been threatened by the effects of climate change caused by complicated weather-related phenomena. Agroforestry plays a significant part in climate change adaptation through diversified land use practices, sustainable livelihoods, income sources, increased forest and agricultural productivity, and decreased weather-related production losses, which increase resilience against climate impacts. It provides a variety of ecosystem services; however, evidence in the agroforestry literature supporting these perceived benefits has been lacking until recently. This paper aimed to provide empirical information on the role of agroforestry in ecosystem maintenance and climate change adaptation and mitigation provided by agroforestry. Agroforestry has played a greater role in the maintenance of the ecosystem and mitigation of CO_2 than monocropping and open cereal-based agriculture but less than natural forest. It is important for preserving biodiversity, CO_2 sequestration, and adapting to climate change. CO_2 sequestration through above and ground biomass, offsetting CO_2 emission from deforestation and microclimate modification are major climate change mitigation effects. Provision of numerous ecosystem services such as food, fodder, fuel wood, income source, and enhancing soil productivity helps the community sustain changing climate effects. Hence, considerable attention needs to be given to agroforestry to contribute considerable benefit to the maintenance of the ecosystem, and climate change mitigation and adaptation next to a forest.

Keywords: Biodiversity Preservation, Carbon Sequestration, Air and Water Clean, Soil Improvement, Socio-economic Benefits

1. Introduction

Through the application of agroforestry, crop production can be maintained while providing an alternate solution to ecological problems [1, 2]. According to the spatial arrangement or temporal order, this system integrates tree culture, crop cultivation, and/or animal production on the same land management [3]. Through sustainable land management (including reforestation) and effective resource management, agroforestry can help conserve natural ecosystems. Additionally, agroforestry has the potential to mitigate climate change because it involves several activities that have been shown to increase carbon absorption and hence lower GHG emissions [2, 4]. Furthermore, the system can support biodiversity by incorporating several plant/crop species that could serve as homes for a variety of wildlife [5, 6]. Numerous studies have emphasized the socioeconomic advantages of agroforestry for rural populations in addition to its beneficial effects on the environment [7]. Implementing a broad agroecosystem with livestock, trees (for wood and fruit), and other crops could increase the community's economic resilience [8]. Through a variety of food sources, the system may also increase household food security [9, 10]. As a result, agroforestry may potentially help with current socio-economic problems.

Ripple et al. [11] noted that climate change is currently occurring and that immediate action is needed to keep the global temperature increase to 1.5 degrees [12]. Risks associated with climate change, such as severe droughts, flooding, and diseases, can significantly negatively influence agricultural systems, leading to soil erosion, crop failure, biodiversity loss, decreased soil moisture, insect damage, and financial losses. Farmers are already finding it challenging to plan planting and harvesting due to more extreme events and frequent drier and wetter weather [13], endangering current production systems and food availability. To reduce carbon emissions and meet the goals outlined in the Paris Agreement, agriculture, forests, and trees are essential. Farmers can adjust to the effects of climate change by replanting the proper tree species in the right location.

Although the potential contribution of agroforestry systems to ecosystem maintenance is still debated and largely unexplored [14]. Furthermore, empirical data on the relationships between agroforestry and household livelihood resilience, particularly in terms of climate change mitigation, is lacking [15, 16]. As a result, the goal of this paper is to provide empirical data on the specific contribution that agroforestry makes to ecosystem services as well as climate change solutions.

2. Agroforestry for Socio-economic Benefits

The inclusion of woody plants within the system distinguishes agroforestry from other land-use systems. By diversifying the products produced, this type of tree-based farming can increase economic resilience from an economic viewpoint [1]. The use of multipurpose trees, in particular, may increase the profitability of agroforestry since they can fulfill a variety of needs, including providing alternate sources of revenue, fodder, or food (such as wild edible fruits) during hard times among rural people [17]. In addition, some trees with the higher economic worth may be able to create cash for the community in addition to that from yearly crops. According to research on teak-agroforestry (Tectona grandis) systems in Indonesia, for instance, although having a lower recycling time (because of the plant's delayed growth phase), these systems can produce up to 12 percent of the total household income [18]. Additionally, a study on the agroforestry of damar (Agathis dammara) in Pesisir, West Sumatra, revealed that the production of damar contributed up to 50% of the household's overall revenue [19]. Furthermore, the adoption of coffee agroforestry in Wey-Besay Watershed, Lampung, contributed to more than 50% of household income as opposed to just 12% from the conventional agriculture system (non-agroforestry system) [20].

Another way to increase the benefit-to-cost ratio is through agroforestry. Some techniques involve growing woody plants that require little input (chemical fertilizers, insecticides, etc.), which can reduce production costs and increase farmer revenue [21, 8]. The farmers' understanding of the procedure, particularly regarding how to choose the best plants or trees for their system, maybe a major factor in how this outcome turns out. Some trees benefit from being grown alongside crops that are complementary to them. Contrarily, the incorrect choice of tree or crop components can result in nutrient competition [22], which consequently reduces yield and, as a result, the farmers' profit. In rural areas, the implementation of agroforestry may create new employment opportunities for off-farm tasks (Table 1) [23]. Women may also benefit from more job opportunities since they can participate directly in production activities, which can increase gender equality in rural areas [10]. Additionally, the retention of jobs in rural areas may stop the rural exodus and so help the rural economy [24].

Agroforestry can boost food and nutrition security for those living near forests while also generating revenue. Ickowitz *et al.*, [25]'s analysis of spatial data revealed that children in Indonesia between the ages of one and five were consuming micronutrients at a higher rate than previously thought. Their research revealed that agroforestry raises the consumption of vitamin A-rich fruits and leafy vegetables at the regional level. Following the introduction of agroforestry, low-income farmers who had participated in agroforestry training also showed increased food output and diversity, indicating greater food availability [26]. Other studies, including those undertaken in Sub-Saharan Africa, South Asia, and Latin America, have found a positive association between agroforestry adoption and household food security [2, 27-29].

3. Agroforestry for Ecosystem Services

Agroforestry includes several ecological practices that have the potential to improve ecosystem services for rural areas. These practices include improving soil fertility, reducing erosion, improving water quality, promoting biodiversity, improving aesthetics, and sequestering carbon [29]. It is widely acknowledged that the services and benefits supplied by agroforestry methods occur at many geographical and temporal ranges.

3.1. Biodiversity Conservation

Ecosystems and species vital to human survival and the health of our planet are rapidly disappearing. Scientists and policymakers are increasingly aware of the value of agroforestry in preserving biological diversity in both tropical and temperate regions of the world. Several authors have investigated how agroforestry systems affect biodiversity [30-32]. Agroforestry serves critical functions in biodiversity conservation, including:

1) Provides habitat for species that can withstand some disturbance;
2) Aids in the preservation of sensitive species' germplasm
3) Reduces the rate of natural habitat conversion by providing a more productive, long-term alternative to typical agriculture techniques that may include destroying natural ecosystems;
4) Creates connectivity between habitat remnants, which may help to maintain the integrity of these remnants and the conservation of area-sensitive floral and faunal species; and
5) Helps to sustain biological variety by providing additional ecosystem services such as erosion control and water recharge, minimizing habitat degradation and loss.

3.2. Agroforestry for Soil Improvement

Agroforestry has a well-established role in boosting and sustaining long-term soil productivity and sustainability. Nitrogen-fixing trees and crops are widely used in tropical agroforestry systems [33]. Non-N-fixing trees can also improve soil's physical, chemical, and biological qualities in agroforestry systems by supplying a considerable amount of above and belowground organic matter and releasing and recycling nutrients [34].

Agroforestry systems have also been shown to be capable of reclaiming polluted land as well as reducing soil salinization and acidity [28]. Eco restoration and soil resource sustainability via AF are also one of the most viable strategies for managing land and soil resources. Agroforestry is thought to increase soil organic carbon (SOC) through litter fall [35, 28] and rhizospheric effects increase land productivity [36], control soil erosion [34], conserve moisture in the soil, and diversify farm income [37].

3.3. Agroforestry for Improved Air and Water Quality

The incorporation of AF improves flood control, with wider riparian buffers protecting levees and farmlands from flooding and sand deposition. Water storage and use by trees, as well as soil modification processes, all contribute to flood reduction. Green vegetation improves air quality by filtering out particulate matter, gases, vapor, volatile organic chemicals, minerals, spores, and odor. [38]. Aerosols carry the majority of odor-causing chemicals and substances (particulates). By eliminating dust, gas, and microbiological elements, vegetative buffers can filter particles from airstreams. In their comprehensive review of the subject, they focus on swine odor. According to these authors, efficiently control odor in a socioeconomically responsible manner when planted in strategic patterns. Agroforestry operations are also a tried-and-true method of providing clean water.

Crops absorb less than half of the nitrogen and phosphorus fertilizer used in conventional farming methods. Surplus fertilizer is either transported away from agricultural fields by surface runoff or leached into the subsurface water supply, contaminating water sources and reducing water quality [39]. Agricultural surface runoff, for example, can contribute significantly to eutrophication in the Gulf of Mexico by delivering excessive silt, fertilizer, and pesticides to recipient water bodies. Riparian buffers, for example, have been suggested as a solution to reduce non-point source pollution from agricultural areas. Riparian buffers aid in the cleaning of runoff water by slowing it down, allowing for greater infiltration, sediment deposition, and nutrient retention. In agroforestry systems, trees with deep root systems can help enhance groundwater quality by acting as a "safety net," collecting excess nutrients leached below the rooting zone of agronomic crops. These nutrients are then recycled back into the system through root turnover and litterfall, increasing the nutrient consumption efficiency of the system [40].

4. Agroforestry Solutions for Climate Change

4.1. Agroforestry for Climate Change Mitigation

Without a doubt, different AF methods can lower atmospheric CO_2 levels as fossil fuels are substituted. AFS may collect ambient carbon and store it in many components, including the bole, branch, foliage, and root. As a result, agroforestry is a form of a low-carbon farming system that combines the provision of food security in a changing climate with the sequestration of ambient carbon in soil and vegetation through the management of natural resources such as light, land, water, and nutrients [41, 42]. Short rotation forestry programs that use fast-growing, high-yield trees result in larger biomass because they absorb more CO_2. Raj et al. [43] estimate, that the global storage capacity for C under AFS ranges from 0.3 to 15.2 mega C/ha/year, and according to Nair et al. [44], the storage capacity was shown to be highest in humid tropics in comparison to other high-rainfall regions.

There are numerous ways to calculate how much carbon is stored in agroforestry systems; some of them are based on in-situ measurements, but the use of various assumptions causes significant variations in the data [45]. The reported carbon stocks and carbon sequestration vary greatly among African agroforestry systems. Agro-silver-pastoral systems, for example, combine rich carbon stocks with a high potential for sequestration (Table 2). Agroforestry systems can also significantly reduce the demand for wild forests for energy. According to some authors, increased demand for tree products might encourage farmers to undertake agroforestry [46], especially in areas where the supply of fuel wood is dwindling. The growth of agroforestry for sustainable fuelwood can help replace energy sources and evolve into a significant carbon offset option [47].

Table 2. *Potential C stock and C sequestration of some AFS in Africa.*

Description (source)	C sequestration (Mg C/ha/yr) [range]	C stock (Mg C /ha)	Max rotation period (yr)	Reference
Parklands dominate AFS (Faidherbia albida)	0.2–0.8	5.7–7	50	[48, 49, 50]
Rotational woodlots	2.2–5.8	11.6–25.5	5	[48, 49, 50, 51]
Tree planting-windrows-home gardens	[0.4–0.8]	19.0	25	[48, 52]
Long-term fallows, regrowth of woodlands in abandoned farms	0.22–5.8	15.7	25	[48, 53]
AFS and integrated land use	1.0–6.7	12–228	50	[50, 54, 55]
Soil C in AFS	0.25–1.6	13–300	Ns	[45, 56]

Note: ns: not specified. Source Mbow et al. [2]

4.2. Agroforestry for Climate Change Adaptation

Climate change threatens tropical agriculture, particularly subsistence agriculture [57]. Due to declining soil fertility, water availability, and biodiversity loss, Africa's agricultural production faces sustainability issues, and yields of significant cereal crops, such as maize, have plateaued at 1 ton ha-1 [58]. Smallholder farmers' livelihoods are thus seriously threatened by insufficient food production for household consumption, particularly in areas characterized by more changing climate and fluctuation. Agroforestry can help smallholder farmers adapt to changing climates because they lack the resources to do so [59].

Agroforestry can increase smallholders' resilience to present and future climatic hazards, such as future climate change, both at the farm and landscape scales [60, 59]. Even in areas where the water, soil, and biodiversity are damaged, they are essential to maintaining homes. Through the provision of several direct and indirect ecosystem goods and services, the trees component of farming has significantly improved land productivity and livelihoods [28]. In the highlands of Eastern Africa, fodder trees in agroforestry systems are especially crucial, according to Franzel et al. [61], primarily to feed dairy cows and satisfy output shortages during periods of harsh climatic circumstances, such as droughts. These fodder trees are simple to grow, need little land, labor, or capital, produce a variety of byproducts, and frequently supply feed within a year of planting. However, several major obstacles prevent the widespread use of fodder trees, including the lack of species suitable for different agroecological zones, a lack of seed, and farmers' lack of knowledge and expertise required to grow them.

Agroforestry techniques, such as parklands, are crucial because they provide soil cover with trees and shrubs, which prevents erosion and mitigates the effects of climate change. In risky regions like the Sahelian zone of West Africa, they give green fodder to supplement crop wastes for livestock feeds, fruits, and leaves for human consumption, as well as help farmers, generate cash. The interactions between diverse agroforestry system components have an impact on the ecosystem service functions of parkland trees (providing, regulating, and sustaining services) in several different ways [62]. By providing woodfuels, agroforestry has also played a significant part in SSA's energy provision and is expected to continue to dominate the region's population's energy portfolio in the future decades [63]. For instance, Asase and Tetteh [64] stated that of the 20 species identified in Ghana's agroforestry, 100% of them were used as fuel wood and 83% as medicines. According to a study conducted in western Kenya, the existence of trees on farms provides a more readily available, secure, and stable source of fuelwood for energy and income, notably to the benefit of women [65].

According to Syampungani et al. [66], well-designed and well-managed agroforestry have some positive effects on yield and income as well as the possibility of continued production. For example, home garden species are crucial to small-scale household honey production for income [67]. Similar to this, Bachi [68] found that about 24.4 percent and 10% of respondents, respectively, utilized woody plants for income, and beekeeping helped them to acquire market-priced food for subsistence. Agroforestry adopters have improved cash income and food security, according to numerous reports [68-70]. According to Tadesse [71], 46% of the honey marketed in 2010 in southwest Ethiopia came from agroforestry based on coffee. Mekonen et al. [72] indicate that, in Ethiopia, around 25% of plant species were used for food, 13% for medicine, and 10% for household tools. Fertilized tree species (FTS) are well known to significantly boost maize yields when compared to maize farming without fertilizer in Zambia [73].

The use of trees in agroforestry, which provides social and environmental advantages as a part of farming livelihoods, also contributes to food security in Africa in the face of climate change and variability [2]. The amount of shade has a direct effect on reducing microclimate fluctuation and preserving soil moisture. This reduces the risk of crop failure or a decline in crop output by shielding the crop of interest from extreme climate occurrences [74]. According to Lin [75], crops cultivated in open spaces lose between 31 and 41 percent of their moisture from soil evaporation and plant transpiration. Additionally, it was noted that coffee beans grew larger under agroforestry (under trees) than they did in full light, even though the full sun produced more fruiting and beans per cluster [76]. Additionally, coffee production and biodiversity preservation under the influence of climate change may be reconciled through the use of agroforestry systems, which may also contribute to some regulating and supporting ecosystem services [77]. The varied traditional cocoa forest gardens may aid in controlling pests and illnesses and enable effective adaptability to shift socioeconomic conditions, according to a study [78].

Kebebew and Urgessa [79] argue that tree-based agricultural systems are more lucrative and less dangerous than other agricultural options because they provide a wider range of goods and are less likely to be infected by pests, allowing farmers to avoid dangers. Through its naturally occurring side effects, such as improved nutrient cycling, integrated pest management, and higher disease resistance, agroforestry can safeguard farm productivity. Agroforestry methods also frequently improve crop diversity inside the systems, which increases the variety of food, fuel, and fodder products produced for smallholder farmers and reduces wind damage by up to twice the height of the windbreak [75]. As a result, a variety of agroforestry systems may enable numerous different kinds of adaptation to take place under a variety of climatic conditions. However, the degree of diversity incorporated into the system will determine the co-benefit levels, with more diversity within the agroforestry system resulting in more co-benefits [80]. As a result, the ecosystem services offered by agroforestry help people and other ecosystems become more resilient to the effects of climatic fluctuation and change.

5. Conclusion

Agroforestry is a land-use system that helps to conserve the environment, reduce CO_2 emissions, and improve livelihood resilience to climatic variability and change. It reduces emissions from deforestation and soil erosion while also relieving pressure on natural forestation by storing CO_2 in living biomass and soil. Recognizing and successfully managing the various socioeconomic and environmental constraints that prevent agroforestry from realizing its full potential for maintenance, conservation, and CO_2 reduction is critical. The potential of agroforestry must also be understood by decision-makers and the general public, and landowners must be assisted in terms of technical know-how, access to and selection of appropriate planting species, and management. Future research should focus on determining the optimal ways to combine multiple agroforestry components, diversifying agroforestry components and management strategies, assessing the multitude of ecosystem services given by various agroforestry systems, and the contributions of urban agroforestry to ecosystem preservation and climate change management.

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