Review Article

Agroforestry for Carbon Neutrality: AnEffectivePathway to Net Zero

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ABSTRACT

Agroforestry is a promising strategy to achieve carbon neutrality and net zero emission, aiming towards the balance between greenhouse gas emissions and equal amount of carbon removal through sequestrationAmong several methods of carbon sequestration, agroforestry stands out for itsunique ability to simultaneously sequester carbon while reducing greenhouse gas emissions, particularly nitrous oxide (N_2O) emissions associated with chemical fertilizer use in conventional agriculture. These systems store carbon through multiple pathways like, in above-ground biomass, below-ground root systems, and enhanced soil organic carbon accumulation while maintaining the agricultural productivity.Acknowledged under the afforestation and reforestation programs of the Kyoto Protocol, agroforestry has attracted interest for its several advantages from both industrialized and developing countriesfor its multifaceted benefits, including its potential to combat desertification and reduce anthropogenic emissions.Beyond carbon sequestration, it enhances soil fertility, supports biodiversity conservation, and provides economic diversification for farmers through multiple income streams.The role of REDD+ (Reducing Emissions from Deforestation and Forest Degradation) negotiations in extending the Kyoto Protocol's second commitment period has further strengthened agroforestry's position in global climate action, particularly through the development of REDD offset credits in compliance carbon markets.The World Agroforestry Centre defines agroforestry as a dynamic, ecologically based natural resources management system that integrates trees on farms and in the agricultural landscape, diversifying and sustaining production for increased social, economic, and environmental benefits. The Association for Temperate Agroforestry (AFTA) defines it as an intensive land management system that optimizes the benefits from biological interactions created when trees and/or shrubs are deliberately combined with crops and/or other natural resources.This review article critically examines agroforestry's crucial role as an effective pathway toward achieving carbon neutrality and net zero goals, synthesizing current knowledge and future prospects.

Keywords: Agroforestry system, Green House gas, Kyoto Protocol, Carbon Sequestration, Intensive land management system

1. INTRODUCTION

Net zero emissions and carbon neutrality have become fundamental principles in the global struggle against climate change. In a world increasingly afflicted by environmental deterioration and the imminent risk of catastrophic climatic catastrophes, attaining net zero emissions and carbon neutrality has emerged as a critical objective for governments, organisations, and individuals alike. Net zero emissions denote the equilibrium between the quantity of greenhouse gases emitted and the volume extracted from the atmosphere.

Carbon neutrality is compensating for carbon dioxide emissions by strategies such as carbon capture and storage, reforestation, or the use of renewable energy sources. These principles represent a significant transition towards sustainable practices and renewable energy sources, with the objective of alleviating the detrimental effects of climate change and preserving the earth for future generations. The escalating urgency of climate change necessitates the attainment of nett zero emissions and carbon neutrality, which are essential benchmarks in the collective endeavour to mitigate environmental degradation and ensure a sustainable future, wherein agroforestry can significantly contribute to these objectives.

Although carbon dioxide (CO_2) is a vital component of the atmosphere, its increasing concentration designates it as a significant greenhouse gas (GHG). The persistent rise in atmospheric concentration is thought to be expedited by anthropogenic activities, including fossil fuel combustion and deforestation [1]. Carbon sequestration is a method for diminishing atmospheric CO_2 levels by extracting carbon from the atmosphere and storing it in a reservoir. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC)—the inaugural and, to date, the most extensive international accord aimed at stabilising greenhouse gas concentrations—permits carbon sequestration by afforestation and replanting. The equilibrium between greenhouse gas emissions and their removal from the atmosphere involves balancing carbon dioxide emissions by strategies such as carbon capture and storage, reforestation, or the adoption of renewable energy. Agroforestry has emerged as a promising solution, combining agricultural and forestry practices to create sustainable land-use systems.In light of the acknowledgement of trees' vital function in sequestering and storing atmospheric CO_2 in vegetation, soils, and biomass products [2], agroforestry has been recognised as a carbon sequestration practice. This was especially applicable to afforestation and reforestation initiatives, which the Kyoto Protocol endorsed as techniques for decreasing greenhouse gas emissions. As a result, both industrialised and developing nations started prioritising agroforestry systems as a carbon sequestration approach [3, 4]. Consequently, there are elevated expectations concerning the function of agroforestry as a method for carbon sequestration. As The IPCCreport [1] emphasizes the urgency of implementing such nature-based solutions (NbS), highlighting their role in ecosystem resilience and climate change adaptation,it is appropriate to reassess our current comprehension of the subject and evaluate the feasible potential of agroforestry as a biological method for carbon sequestration. This study aims to assess the function of agroforestry as a method for carbon sequestration and to emphasise its scientific foundations. This study concentrates on application-oriented scientific advancements in carbon sequestration, particularly in soils [5,6], in light of the growing body of outstanding papers on the mechanisms and processes involved.

2. DEFINITION OF AGROFORESTRY

Agroforestry encompasses several definitions. The World Agroforestry Centre (www.icraf.cgiar.org) characterises it as "*a dynamic, ecologically grounded natural resource management system that integrates trees within farms and agricultural landscapes, thereby diversifying and sustaining production to enhance social, economic, and environmental benefits for land users at all levels.*" The Association for Temperate Agroforestry (AFTA: www.aftaweb.org) defines it as "*an intensive land management system that maximises the advantages derived from the biological interactions established when trees and/or shrubs are intentionally integrated with crops and/or livestock*." Essentially, they all denote the intentional cultivation of trees, crops, and/or animals in synergistic combinations across nations, for diverse advantages and services [7].

Agroforestry relies on land-use systems that exhibit higher structural and functional complexity than monocultures of crops or trees, leading to enhanced efficiency in the collection and utilisation of resources (nutrients, light, water) and increased structural variety, which promotes tighter nutrient cycles. The diversity of both aboveground and belowground organisms contribute to system stability and resilience at the site level, while also facilitating connection with forests and other landscape elements at the landscape and watershed levels [8].

Agroforestry has now developed into a comprehensive forestry discipline with the capacity to address land management and environmental issues globally, regardless of varying levels of development. Numerous conventional and enhanced agroforestry systems have been identified in various regions worldwide [9]. A multitude of varied agroforestry systems exists in the tropics, attributable to both favourable climatic conditions and socio-economic factors, including human population pressure, increased labour availability, reduced land-holding size, intricate land tenure, and greater distance from markets [10].

In addition to the protective and productive foundations, the economic side of agroforestry is the primary motivating factor for industrialised nations. In North America, the five principal agroforestry methods identified are alley cropping, forest farming, riparian buffer strips, silvo-pasture, and windbreaks. Additional temperate-zone agroforestry systems encompass traditional tree-based agriculture with many multifunctional species, including Chestnuts (*Castanea* spp.), Oaks (*Quercus* spp.), Carob (*Ceratonia siliqua*), Olives (*Olea europaea*), and Figs (*Ficus* spp.) in the Mediterranean regions [11]. The *Dehesa* system, characterised by grazing beneath oak trees and closely associated with cyclical cereal cultivation in rangelands, is an ancient European practice [12].

The evolution of agroforestry as a climate mitigation strategy gained significant momentum under the Kyoto Protocol, which recognized afforestation and reforestation as legitimate carbon sequestration activities. The theoretical underpinning of carbon capture in agroforestry systems involves complex interactions between trees, crops, and soil systems, under various agroforestry practices, including silvo-pastoral systems, alley cropping, and forest farming.

3. CARBON SEQUESTRATION AND CARBON NEUTRALITY POTENTIAL OF THE AGROFORESTRY SYSTEM

Carbon sequestration entails the net extraction of CO_2 from the atmosphere through photosynthesis and its subsequent storage in enduring carbon reservoirs. These pools encompass aboveground plant biomass, belowground biomass including roots and soil microbes, stable forms of organic and inorganic carbon in soils and deeper underground habitats, as well as durable products created from biomass, such as timber. Agroforestry systems are considered to possess greater carbon sequestration capacity than grasslands or field crops. This assumption posits that the integration of trees into agricultural fields and pastures would yield enhanced net carbon sequestration both aboveground and belowground [13,14].

The improved carbon sequestration and diminished emissions can result in net carbon neutrality, a goal adopted by several nations during the Glasgow Agreement (COP-26) as part of their environmental objectives. Numerous assessments of carbon sequestration and carbon losses across various land-use regimes exist. CAB Abstracts (http://www.cabi.org) catalogues 266 publications pertaining to agroforestry, predominantly published in the last 15 years, with the keywords "*agroforestry*" and "*carbon sequestration*." The estimations are obtained by integrating data on the aboveground, time-averaged carbon stocks (50% of the system's carbon stock at its maximum age or rotation duration for plantations) and the soil carbon values of the system [15].

3.1 Aboveground (vegetation) carbon sequestration

Forests worldwide are estimated to harbour up to 80% of all aboveground carbon and 40% of all belowground terrestrial carbon, including soils, litter, and roots. The evaluation of accumulated biomass in the forest ecosystem is crucial for determining the productivity and sustainability of the forest [16]. Estimates of aboveground carbon sequestration potential (CSP) indicate that 46% to 52% of branch dry weight and 32% of leaf dry weight comprise carbon [17]. The total estimates for above-ground biomass, carbon stock, and carbon equivalent from all the listed roadside trees were 154.53 metric tonnes, 72.63 metric tonnes, and 266.55 metric tonnes, respectively. The findings indicate that the roadside trees possess a significant carbon stock that can aid in climate change mitigation via carbon sequestration [18]. The table demonstrates that the estimations of CSP in agroforestry systems exhibit significant variability. These values directly reflect the ecological production capacity of the system, influenced by several aspects like as site characteristics, land-use types, species composition, stand age, and management strategies. Agroforests in arid, semiarid, and degraded areas exhibit a lower CSP than those in fertile wet regions; also, temperate agroforestry systems demonstrate comparatively reduced vegetation CSP relative to tropical systems. Intensive continuous cropping and short-term fallow systems in sub-humid tropics, characterised by relatively brief growing cycles or rotation intervals, exhibit reduced CSP in vegetation compared to the slash-and-burn systems prevalent in humid tropical regions [19].Table 1 summarizes mean aboveground carbon sequestration potential of different agroforestry systems from several studies performed till date.

Table 1. Aboveground carbon sequestration by different agroforestry systems

Sl. No.	Agroforestry/land-use system	Mean vegetation C	Source
1	Fodder Trees of the Lower and Middle Ouémé Valley, Benin	0.21 to 54.17 Mg ha^{-1} y^{-1}	[20]
2	Coconut based intercropping System	0.037 to 0.0 56 Mg ha^{-1} y^{-1}	[21]
3	Agroforestry at Different Altitudes in the Garhwal Himalayas	353.48 to 373.23 t ha^{-1}	[22]
4	Forests at Different Altitudes in the Garhwal Himalayas	1023.48 to 1099.35 t ha^{-1}	[23]
5	Agroforestry food crop system for C stock and sequestration (case study on Saobi Island Madura)	11.59 -14.97 t ha^{-1}	[24]
6	Indigenous Agroforestry Systems in SilteWereda, Southern Ethiopia	1.28 to 7 Mg ha $^{-1}$	[25]
7	Coffee agroforests in the western highlands of Guatemala	74.0 to 259.0 Mg C ha^{-1}	[26]
8	Sesbania alley cropping based rainfed food - fodder systems	1.72 Mg ha^{-1} y^{-1}	[27]
9	The Tropical Seagrass Meadows in Indonesia	1.6–7.4 Mt C y^{-1}	[28]
10	urban afforestation in Prato municipality Italy	33.1 kt CO_2 yr^{-1}	[29]
11	Mangroves in Sukol river Philippines	10,187.05 Mg ha^{-1}	[30]
12	prominent agroforestry systems in north-western Himalaya, India	66.55 t ha^{-1} to 34.87 t ha^{-1}	[31]

3.2 Belowground (soil) carbon sequestration

Soils are essential to the global carbon cycle [32]. Significant geographic variations in forest soil carbon sequestration were observed across several regions of China [33]. The forest soil in Jiangxi, Hunan, Zhejiang, Fujian, Anhui, Shanxi, Shaanxi, Guangxi, and Liaoning acted as carbon sources, releasing around 25.507 Tg C each year. The remaining 22 provinces functioned as carbon sinks, with an average carbon sequestration by forest soil totalling 103.300 Tg C per year. The total soil carbon pool of 2,300 Pg (1 petagramme = 10^15 g = 1 billion tonnes) is threefold the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg; a decrease in the soil carbon pool by 1 Pg corresponds to an increase in atmospheric CO_2 by 0.47 ppmv. Consequently, any alteration in the soil carbon pool would substantially impact the global carbon budget. The historical emission of CO_2 into the atmosphere from terrestrial ecosystems is estimated to be between 136 to 55 Pg, with soils contributing approximately 78 to 12 Pg.Table 2 summarizes mean belowground carbon sequestration potential of different agroforestry systems from different studies.

Table 2. Belowground carbon sequestration by different agroforestry systems

Sl. No.	Agroforestry/land-use system	Mean vegetation C	Source
1	Caragana Korshinskii Kom plantations on the Loess Plateau	20.52 Mg ha−1	[34]
2	Mangroves in eastern Niger Delta	732,595.71 ± 55.64 Mg CO_2	[35]
3	Shelterbelt Trees in Canada	20.8 g C kg^{-1}	[36]
4	Commercial Willow Plantation	0.07 to 0.99 Mg ha^{-1} y^{-1} C	[37]
5	Tankawatinaturalforest in Bangladesh	36.26 to 522.24 kg·ha−1	[38]
6	Carbon storage in old hedgerows	43.23 Mg ha^{-1}	[39]
7	Typical steppe of Nei Monggol inNorth China	277.35 to7307.59 g m^{-2}	[40]

The interaction between vegetation and soil microorganisms plays a vital role in long-term carbon storage. Beyond its carbon sequestration potential, agroforestry offers numerous environmental and socioeconomic benefits. The IPCC report [1] highlights its contribution to biodiversity conservation and ecosystem resilience. Economic advantages include diversified income streams for farmers through multiple products (timber, fruits, crops) and enhanced farm productivity. It also documents improved soil fertility, water retention, and microclimate regulation as additional environmental benefits.

4. TREE-SPECIES SELECTION AND SILVICULTURAL MANAGEMENT

The "native vs. exotic"–species controversy and growth-rate differences among tree species are among the biological issues that are extensively debated but have not yet been resolved in relation to the sequestration of carbon by trees in agroforestry systems [41]. Many of these discussions stem from publications on carbon sequestration in tropical tree plantations, where carbon sequestration is sometimes equated with carbon stock, a notion that is not entirely accurate. Despite occupying merely a fraction (5%) of tropical forests these plantations may gain significance as their extent is projected to expand in the coming decades and numerous species advocated for tropical plantations are anticipated to be cultivated in agroforestry systems as well [1]. It is uncertain if native species, purportedly more adaptable to local conditions, will outperform exotic species in such plantations. The notion that afforesting could serve as an economical method for sequestering CO_2 emissions is also being contested[42]. Experiments in loblolly pine (*Pinus taeda*) forests in North Carolina, USA, revealed that following an initial growth spurt, trees exhibited reduced growth rates and absorbed less excess carbon from the atmosphere than anticipated[43]. In two trials with *Pinus taeda* trees subjected to high atmospheric CO_2, the increase in biomass carbon due to CO_2 was undetectable at a nutritionally deficient site, while the stimulation observed at a nutritionally adequate site was temporary, stabilising at a minimal gain after three years. A significant synergistic benefit from increased CO_2 and nutrients was observed with nutrient addition, with the benefit being more pronounced at the poor site compared to the moderate location. The scientists concluded that the evaluation of future carbon sequestration is constrained by soil fertility and its interactions with nitrogen deposition. Another study investigated the decomposition of leaves and roots on the forest floor of experimental pine-forest plots, revealing that while the total quantity of litter increased in a CO_2-enriched environment, the decomposition rate also accelerated, leading to the release of carbon back into the atmosphere instead of its incorporation into the soil[44]. The findings indicate that while planting trees is significant, it may not sufficiently replace the need to reduce heat-trapping greenhouse gas emissions. Another facet of ambiguity pertains to the variations in wood quality among species and their carbon accumulation rates.

Mixed plantings of nitrogen-fixing tropical species and commercial wood trees have been shown to yield more aboveground biomass or volume production than monoculture stands. Species mixes provide enhanced resistance to pest infestations and disease outbreaks. A recent study indicated that integrating trees into vineyard designs as vineyard agroforestry systems may enhance an effective arthropod integrated pest management method[45]. Additional silvicultural factors, including stand density and rotation duration, may also affect biomass production and the perceived carbon sequestration potential of species. In general, high-density stands sequester more quantities of carbon than low-density stands. While these findings do not inherently negate the significance of mixed species planting, they indicate that the selection of species and its management are essential for enhancing carbon sequestration. This may, however, generate conflicts with plantation management objectives, like as lumber production, underscoring the necessity for stand density regulation strategies that align with land management goals. The design of planting schemes to balance the provision of ecological services (e.g., carbon sequestration) and products (e.g., timber) presents a significant silvicultural problem.The implementation of agroforestry varies significantly across regions, adapting to local conditions and needs. Diverse case studies from both developed and developing nations, demonstrate successful adaptation strategies. These examples showcase how different regions have modified agroforestry practices to suit their specific environmental and socioeconomic contexts. Despite its potential, agroforestry faces several implementation challenges. These include initial establishment costs, long waiting periods for returns on investment, and technical knowledge requirements. Institutional barriers and policy gaps are also recognized as significant obstacles. Limited land availability and competing land-use demands also pose significant challenges.

The integration of animals into agroforestry systems presents another crucial dimension in carbon sequestration dynamics and sustainable agriculture. Bussoni et al. [46], in their comprehensive review, demonstrated how silvo-pastoral systems can enhance soil carbon sequestration through improved manure distribution and grazing management. The choice between exotic and native livestock breeds significantly influences system efficiencyand it is suggested that native breeds, better adapted to local conditions, often result in more sustainable carbon sequestration patterns and enhanced biodiversity conservation [47]. Regarding crop productivity, Garrett et al. [48] identified that alley cropping with nitrogen-fixing trees shows optimal crop yields while maintaining significant carbon sequestration benefits. Several studies further emphasized how certain agroforestry configurations naturally suppress pest populations through enhanced predator diversity, potentially reducing the need for chemical pesticides, which is particularly significant in the context of transitioning from monocropping systems [49, 50].Their researchesultimately recommend gradual conversion of monocropping systems to diverse agroforestry arrangements, suggesting a phased approach that maintains food security while enhancing ecosystem services.

5. POLICY RECOMMENDATIONS AND FUTURE DIRECTIONS

Advancing agroforestry implementation requires coordinated policy actions and research initiatives. Standardizing carbon measurement protocols is a must to facilitate carbon credit systems worldwide. Policy recommendations include developing financial incentives for farmers, strengthening research and extension services, and creating supportive institutional frameworks for agroforestry adoption.Recent work on agroforestry implementation and obstacles indicates a complex interaction of socio-economic, technical, and policy elements across various locations. Franzel et al. [51] identified significant obstacles in Sub-Saharan Africa, specifically noting that land tenure insecurity and insufficient financial resources impede widespread adoption, while proposing legislative measures to improve climate resilience. This corresponds with the findings of Jahan et al. [52] in Northern Bangladesh, where cultural obstacles and institutional constraints substantially affect adoption rates, albeit evident potential advantages. The meta-analysis conducted by Santos et al. [53] in the Brazilian Atlantic Forest offers quantitative evidence of the beneficial effects of agroforestry on biodiversity and ecosystem services, illustrating effective regional adaptation despite implementation obstacles. Rosenstock et al. [54] examined a vital technical issue by suggesting standardized measurement and verification methods inside the Paris Agreement, emphasizing the necessity for uniform monitoring strategies across various geographical contexts. Several researchersconducted thorough global systematic reviews that consolidate these themes, revealing common patterns in adoption barriers and success factors across various regions [55 – 57]. The reviews underscore that although challenges differ by context, certain fundamental issues—such as initial investment costs, technical knowledge prerequisites, and policy support—consistently affect adoption rates globally. These studies effectively emphasized that effective agroforestry implementation necessitates a comprehensive awareness of local circumstances, with the requirement for supportive policy frameworks, technical help, and financial channels to address adoption obstacles.

Future directions for agroforestry policy implementation necessitate a comprehensive approach that incorporates technology innovation, financial mechanisms, and institutional support. Nair et al. [58] underscored the necessity for unified carbon credit systems and streamlined verification methods to encourage farmer engagement. Whereas, Cechinet al. [59] emphasized the importance of developing innovative financing mechanisms, including blended finance models and green bonds tailored for agroforestry projects. Azlan et al. [60] asserted that the incorporation of digital technologies, such as remote sensing and blockchain for transparent carbon monitoring, may enhance the efficiency of policy implementation and verification processes. Besides, many authors in their study advocated for the enhancement of institutional capacities at both local and national levels, proposing the creation of specialized agroforestry units within agricultural ministries [61 – 65]. Going beyond the forestry science, Kiptot [66]remarked about the necessity of gender-responsive policies in agroforestry, highlighting that gender-sensitive policy design can improve adoption rates and project efficacy. These studies collectively indicate that future policy approaches for implementation of a successful agroforestry model should prioritize the development of integrated frameworks that amalgamate technology innovation, financial incentives, institutional support, and social inclusion, while ensuring flexibility for local adaptation.

6. CONCLUSION

Agroforestry represents a pivotal strategy in the global pursuit of net-zero, offering a unique combination of climate mitigation and adaptation benefits. The integration of trees with crop and livestock systems demonstrates superior carbon sequestration potential compared to conventional agricultural systems, fundamentally transforming our approach to agricultural carbon management. Agroforestry systems significantly contribute to carbon sequestration through their multi-layered approach, storing carbon in above-ground biomass, root systems, and soil organic matter. This enhanced sequestration capacity stems from the synergistic interactions between woody and non-woody components. While the theoretical foundation for agroforestry's superior carbon sequestration potential is strong, current assessments primarily focus on carbon stock estimations, often lacking the rigor needed for definitive conclusions. There lie several methodological challenges in precisely quantifying the benefits which can be acquired from agroforestry systems across diverse conditions. The versatility of agroforestry in different geographical and socio-economic contexts positions it as a globally applicable solution for climate change mitigation, despite some challenges. Agroforestry systems are far more cost-effective compared to other nature-based solutions to achieve carbon neutrality and it also has potential to generate multiple environmental and socioeconomic co-benefits. Realizing agroforestry's full potential in achieving net-zero targets requires standardized measurement protocols, policy support, financial accessibility, technical knowhow and accurate assessment of land use area under agroforestry systems. The synthesis of current research underscores that agroforestry, when properly implemented and supported, offers a sustainable pathway toward carbon neutrality while simultaneously enhancing agricultural productivity, ecosystem health, and rural livelihoods. Moving forward, developing robust monitoring systems will be crucial for leveraging this cost-effective environmental advantage. As the global community intensifies efforts to address climate change, agroforestry emerges as a crucial component of the solution, warranting increased attention, investment, and policy support at local, national, and international levels, alongside continued research to strengthen the scientific understanding of its carbon sequestration dynamics.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Indian Council of Forestry Research and Education (ICFRE) and Director, ICFRE-Institute of Forest Productivity, Ranchi for providing institutional support.

COMPETING INTERESTS

The authors have no competing interests to declare that are relevant to the content of this article.

AUTHORS' CONTRIBUTIONS

Authors AT and RK have contributed towards the conceptualization of the study.Authors AT, RK and AM reviewed the literatures. Author RSP supervised the study. Author AT and RK prepared the first draft of the manuscript and Author AM edited and finalized the manuscript. All authors approved the final manuscript to be submitted.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that the following generative AI technologies and Large Language Models (LLMs) have been used only to check grammatical errors and improve theoverall quality of the submitted manuscript. The outputs have thoroughly been checked and revised by the authors before inclusion in the manuscript.

1. Claude 3.5 Sonnet (https://claude.ai/)
2. Quillbot (https://quillbot.com/)

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