

Agroforestry: An effective technique for carbon sequestration and achieving net zero carbon neutrality

ABSTRACT

Agroforestry is a promising strategy for carbon sequestration and net zero carbon neutrality, aiming to balance greenhouse gas production and removal from the atmosphere. Measures such as carbon capture and storage, reforestation, or the adoption of renewable energy help achieve this. Agroforestry systems have gained attention as a carbon sequestration strategy, particularly under the Kyoto Protocol's afforestation and reforestation activities. The Kyoto Protocol allows for carbon sequestration through afforestation and reforestation, which are considered GHG-mitigating strategies. Agroforestry systems have attracted attention from both industrialized and developing countries, and there is a growing expectation of their role in carbon sequestration. 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.

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 net 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 (CO₂) 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 CO₂ 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. In light of the acknowledgement of trees' vital function in sequestering and storing atmospheric CO₂ 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. Consequently, 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].

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

Carbon sequestration entails the net extraction of CO₂ 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 vegetation carbon sequestration potential from several studies performed till date.

Table 1. Aboveground carbon sequestration by different agroforestry systems

SI. 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 0.056 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	Mangrooves 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 = 10¹⁵ 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 CO₂ by 0.47 ppmv. Consequently, any alteration in the soil carbon pool would substantially impact the global carbon budget. The historical emission of CO₂-C into the atmosphere from terrestrial ecosystems is estimated to be between 136 to 55 Pg, with soils contributing approximately 78 to 12 Pg.

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 [34]. 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 CO₂ emissions is also being contested [35]. Experiments in loblolly pine (*Pinustaeda*) 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 [36]. In two trials with *Pinustaeda* trees subjected to high atmospheric CO₂, the increase in biomass carbon due to CO₂ 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 CO₂ 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 CO₂-enriched environment, the decomposition rate also accelerated, leading to the release of carbon back into the atmosphere instead of its incorporation into the soil [37]. 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 [38]. 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.

4. CONCLUSION

Agroforestry systems that combine tree production with crop and livestock systems are considered to possess a greater capacity for carbon sequestration than pastures or field crops, which involve just agricultural components. This assumption posits that the integration of trees into agricultural and pastoral regions would enhance net carbon sequestration both above and below ground. While some assessments of the "C-sequestration potential" of agroforestry systems exist, they primarily consist of estimations of carbon stocks, and the total data lack rigour. Methodological challenges in quantifying biomass carbon stock and assessing soil carbon storage under diverse conditions, coupled with the absence of credible

estimates of land area dedicated to agroforestry systems, significantly hinder the use of this cost-effective environmental advantage of agroforestry.

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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.

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