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Agroforestry and soil carbon sequestration: Interlinkages with soil health and climate change mitigation

Muhammad Bashir Shuaib[1+]
Muhammad Murtala Sauwa[2]
Fidelis Atuanya Adigwe[3]
Ayomide Emmanuel Afolabi[4]
Mahama Musah[5]

[1,2]*Department of Soil Science and Land Resources Management, Usmanu Danfodiyo University, Sokoto, Nigeria.*
[1]*Email: shuaibmuhammadbashir751@gmail.com*
[2]*Email: sauwamm4u@gmail.com*
[3]*Texas Commission on Environmental Quality, United States.*
[3]*Email: fidelis.adigwe@tceq.texas.gov*
[4]*Department of Plant Science, University of Cambridge, Downing Street, Cambridge, CB2 3EA, United Kingdom.*
[4]*Email: aea52@cam.ac.uk*
[5]*University for Development Studies, Earth and Environmental Science, Ghana.*
[5]*Email: mahama.musah@gmail.com*


(+ Corresponding author)

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ABSTRACT

Agroforestry is recognized as a multifunctional land use system that provides numerous benefits, including improved soil quality, enhanced agricultural productivity, and reduced climate change impacts. This article explores the mechanisms behind the underground storage of soil organic carbon (SOC) in agroforestry systems, emphasizing its link to soil health and climate resilience. Trees contribute to SOC through processes such as the addition of organic matter from falling leaves and dying roots, which enhances carbon storage and initiates essential soil functions like humification, mineral association, and aggregate formation that protect against microbial decay. The organic matter's quality, particularly its lignin and nitrogen content, influences decomposition rates, affecting nutrient cycling and long-term carbon stability. Research illustrates significant increases in SOC across various agroforestry practices involving crops, livestock, and trees, with tree systems demonstrating the most substantial daily carbon deposition and biological enrichment. A global synthesis indicates that even a modest increase in agroforestry (up to 30 percent) could sequester between 12 to 19 petagrams of carbon dioxide, notably in regions like South America, sub-Saharan Africa, and Southeast Asia, which exhibit high potential. Besides carbon sequestration, agroforestry positively influences soil structure, nutrient cycling, and microbial diversity, thereby promoting ecologically resilient and productive farming. However, outcomes vary by context, influenced by climate, soil properties, species diversity, and management practices. The article concludes that agroforestry is a scientifically valid natural climate solution and sustainable agriculture alternative, with its effectiveness hinging on intentional policy support and its inclusion in climate mitigation strategies.

Contribution/Originality: This study contributes to the existing literature by integrating tree-canopy litter dynamics, mycorrhizal interactions, and deep-soil carbon stabilization into a framework for agroforestry, enhancing understanding of SOC permanence. It establishes a model linking litter quality, root processes, and microbial pathways to long-term carbon sequestration.

1. INTRODUCTION

Soil Organic Carbon (SOC) dynamics play a crucial role in regulating global climate change and the carbon budget (Herzfeld, Heinke, Rolinski, & Müller, 2021). The Earth's biosphere considers soil as the main carbon reservoir, and the carbon it holds is equal to three times the total amount of carbon found in plants and the atmosphere combined (Scharlemann, Tanner, Hiederer, & Kapos, 2014). The status of soil carbon depends on our ability to create a net situation where carbon inputs (through litter, roots, and residues) exceed carbon outputs (losses due to microbial decomposition and other processes) (Smith et al., 2016). The extent of carbon buried in soils exceeds that of the atmosphere and vegetation combined, indicating the resource's vulnerability to land use modifications and highlighting the severe negative impacts that a SOC increase or decrease might create in the context of climate change (Meena, Kumar, & Yadav, 2019). The main contributor of carbon to the soil is photosynthesis, which not only absorbs carbon dioxide from the atmosphere but also transports it underground via the roots and exudates, thereby boosting the soil's microbial activity. Thus, the only way to change the negative impact of agroecosystems on the carbon cycle to a positive one is through the adoption of sustainable land management practices that will allow the agroecosystems to turn from being carbon sources to sinks, thus reducing greenhouse gas emissions. According to the National Agrarian Institute (2019), one of the most sustainable farming systems is agroforestry, along with the science-based method of enhancing the land's production potential while allowing the sustainability features to remain unchanged by planting trees or shrubs that are not harvested as part of the existing agricultural system or next to that. This technique has a dual benefit of obtaining revenue from the timber and a lesser amount of maize and sugarcane being grown on the same land, but also creating a land use system that is more diverse, more productive, and less harmful through intercropping than that of monocropping (FAO, 2019). The occurrence of tree perennials on the farms implies that the farmers will be able to experience a variety of ecosystem services, such as the enhancement of soil physical, chemical, and biological properties, which will then make the land more suitable for crops and less prone to erosion. Furthermore, since the very nature of agroforestry practice involves more plants in the fields than conventional farming, there would be more benefits for animals that rely on plants for their habitat (Udawatta, Jose, & Garrett, 2019). The ability to generate more crops, diversify farmers' output, and at the same time keep the environment clean has caused global attention to agroforestry as a part of the development paradigm to increase. The discipline is experiencing a significant transformation where the focus is now placed on the specific mechanisms that control carbon stabilization and permanence rather than just applying rough estimates of the carbon storage potential of agroforestry. The demand for reliable, long-term climate solutions as outlined in international agreements and developing carbon markets (Chen et al., 2020; Houghton & Nassikas, 2018) is primarily responsible for the shift. The comprehensive narrative review conducted here aims primarily to enhance understanding of the influence of agroforestry systems on soil health and carbon capture. Consequently, this review also contributes indirectly to the process of determining suitable species for soil carbon dynamics planting.

1.1. Agroforestry's Multifaceted Contribution to Soil Health: System Classification and Typological Variations

Agroforestry, according to Dagar and Tewari (2018) is a science-based technique for gaining the production advantages and sustainability features of the long-established methods of integrating trees into agricultural systems for multiple purposes. Global development policies and programs have started giving agroforestry more prominence owing to its proven ability to preserve crop yields, enhance agricultural production, and provide ecosystem services while keeping the environment intact in terms of land use. Acacia, Senegal has been particularly identified as a good candidate for agroforestry systems, especially when looking at the case of shifting agriculture (Gaafar, Hanafy, Tohamy, & Ibrahim, 2006). In fact, the intercropping of A. Senegal, with several crops, including millet, sorghum, sesame, and peanuts, is common in these systems (Fadl & Sheikh, 2010). Agroforestry may be thought of as a method for managing land use whereby trees or bushes are intentionally planted within or adjacent to pasture or cropland areas. The planting of trees and shrubs is combined with farming and forestry practices in order to develop a land use system that is diverse, economically viable, environmentally friendly, and sustainable (FAO, 2019). What is more, because of the presence of two or more plant species with different requirements and growth characteristics interacting in the same area, the biodiversity of agroforestry systems is usually greater than that of monoculture crop farming. This, in turn, gives rise to a wider variety of birds, insects, and other species that inhabit the area and benefit from the diversity of the environment. Both in North America and worldwide, five types are recognized: Alley Cropping (or Silvoarable systems), Forest Farming, Silvopasture, Windbreaks (or Shelterbelts), and Riparian Forest Buffers (USDA, 2014). Alley cropping is a practice of planting crops between rows of trees, which not only provides income during the growing period of the trees but is also referred to sometimes as intercropping when the rows are indistinct (USDA, 2014). Silvopasture is a practice that combines trees with livestock and forage, aiming to create conditions beneficial for both animals and trees, such as providing shade and leaf fodder (Smith, Pearce, & Wolfe, 2022). The complexity and variety inherent in these systems have a fundamental influence on their carbon storage potential. Studies have shown that highly diversified agroforestry systems have higher mean soil carbon stocks than simple agroforestry systems, which reflects the ecological advantage of multifunctionality (Lorenz & Lal, 2014).

1.2. Role of Agroforestry in Enhancing Soil Physical, Chemical, and Biological Properties

The mixture of tree-like plants is a source of numerous soil-related ecological services that promote the sustainable and holistic use of agricultural lands to a great extent. Litter from trees and soil covered by them are the main sources of soil physical health. The presence of trees directly reduces runoff, meshes rain, and holds together soil particles, which are the cardinal mechanisms for effective control of erosion (Daoust, Kreutzweiser, Guo, Creed, & Sibley, 2019). This role is very much crucial in areas with steep or inclined land where the loss of topsoil can be critical (Wang et al., 2022). In addition, the litter of tree canopies acts as a physical shield that mitigates the impact of raindrops on the surface, thus leading to less surface runoff, less soil movement, and no soil compacting (Jourgholami, Sohrabi, Venanzi, Tavankar, & Picchio, 2022). The litter made of old and decayed organic matter contributes to water retention by soaking up water during rain and slowly releasing it through the soil over longer periods, thus providing water when the soil is dry and also making plants drought-resistant by allowing them to grow in dry areas. On the chemical side, the introduction of trees into crop farming leads to an increase in soil fertility and nutrient content compared to the case of growing crops without trees (conventional agriculture). Some trees, such as legumes, which fix nitrogen, have been used in soil fertility improvement since they increase total soil N, organic matter, and Cation Exchange Capacity (CEC) (Ma et al., 2023). For instance, the tree species Acacia senegal is very suitable for and is commonly used in intercropping with millet, sorghum, and peanuts in shifting agriculture due to its nitrogen-fixing capability and its contribution to increasing overall crop yield (Gaafar et al., 2006).

Through the presence of trees, "nutrient pumping" occurs, which is an invisible but highly beneficial service provided by agroforestry. This process involves the access of deep soil resources by roots, where nutrients are drawn up and recycled back through litterfall onto the surface soil layer (Singh, Sharma, Moon, & Park, 2024). The systems where trees and crops are together help in creating biological diversity as they attract a great variety of fauna and also contribute to the development of different microclimates (Sayer et al., 2013). Different researchers have found that there is always increased biological activity; for instance, there is a greater occurrence of earthworms in the mixed farming of crop systems than in monoculture (Fahad et al., 2022). In this regard, one of the main advantages of FDA practices is the conversion to fungal-dominated communities, which are positively associated with SOC accumulation and stability. Microbial communities that are vibrant and plentiful due to agroforestry practices are vital for the decay of organic matter, the release of nutrients, and they also play a role in the functioning of the ecosystem in general (Wang et al., 2022). Figure 1 illustrates the pathway through which tree-canopy litter contributes to improved soil physical, chemical, and biological properties, demonstrating how litterfall, decomposition, and root interactions collectively enhance soil structure, nutrient availability, and microbial activity.

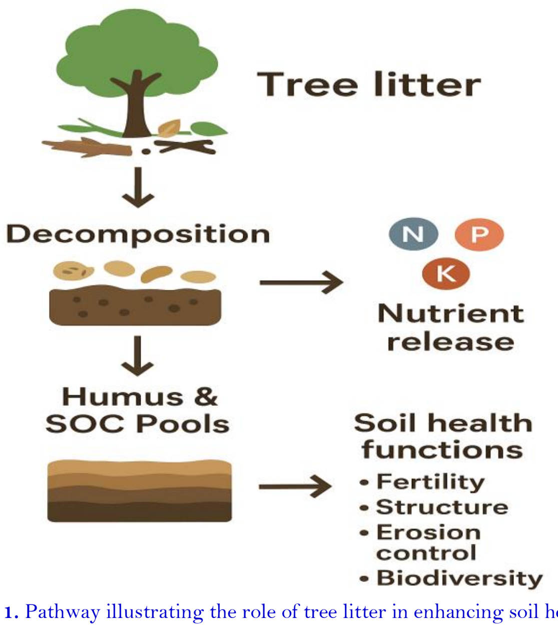

Figure 1. Pathway illustrating the role of tree litter in enhancing soil health.

1.3. Soil Quality Index and Contextual Restoration in Agroforestry Systems

The comparative assessment of land-use systems through the Soil Quality Index (SQI) provides significant information regarding soil health outcomes. In India's semiarid context, Uthappa et al. (2024) shared SQI figures ranked as follows: natural forest (0.973) > Swietenia macrophylla plantation (0.756) > agroforestry (0.737) > agriculture (0.556). Though the conversion of forest to other land uses results in the loss of soil quality, agroforestry systems still retain a significant portion of soil health compared to traditional farming. Long-term studies indicate that the introduction of agroforestry leads to an increase in soil organic carbon (SOC) as well as labile carbon pools, even in deeper soil layers, particularly when established on degraded or low-biomass land (Barman et al., 2025).

Global syntheses strengthen these assertions. A fresh meta-analysis makes known that agroforestry is a positive factor for SOC stocks, microbial biomass, and soil nutrients, with the strongest impact in the regions of arid and semi-arid climate (Pan et al., 2025). Reports from the studies done in a particular region show the same results: agroforestry is a rising force in the soil health of arid ecosystems of western Rajasthan, India (Pareek & Adhana, 2024), alongside the major gain of SOC in the case of Brazilian integrated crop-livestock-forestry systems after the first decade of their implementation (Madari et al., 2024). Not only mitigation, but agroforestry is also a means of adaptation. Climate modeling in the temperate zones indicates that the diversified systems of agroforestry, through their ability to maintain yields and SOC, are less affected by climate change than continuous arable practices (Cardinael et al., 2018; Hunde, Smith, & Kumar, 2015). This body of evidence establishes agroforestry as a dual tool, that is, soil quality restoration along with the building of capacity against climate-driven aridification and degradation.

1.4. Classification and Primary Soil Carbon Benefits of Major Agroforestry Systems

1. Silvoarable and alley cropping systems are also known as Silvoarable systems, which involve the cultivation of trees in rows along with annual crops such as walnut-wheat or Erythrina-maize. The principal pathway for soil organic carbon (SOC) in these systems is through aboveground litter and prunings, fine root turnover, and root exudates. SOC usually builds up specifically around tree rows where the inputs are high. The visible effects of SOC on the soil generally take about ten years of management before they become apparent.

2. Silvopastoral systems are those systems that combine trees with pastures and livestock, including fodder banks, live fences, or pastures with dispersed trees. There are various ways through which soil organic carbon (SOC) is increased in these systems: addition of tree litter, trees with deeper roots, and nutrient cycling facilitated by inputs from manure and grazing. Evidence from Mexico indicates that these systems can be highly effective, as total carbon stocks in above- and belowground pools in silvopastoral landscapes and forest remnants were reported to be 26% to 163% higher than in open pastures. However, the area and soil depth also play a critical role in the SOC response, highlighting the context-specific nature of these benefits. Figure 2 illustrates the distribution and functioning of soil organic carbon pools within agroforestry systems, showing how carbon enters active, slow, and passive fractions through above- and below-ground inputs and is stabilized through aggregation and mineral association.

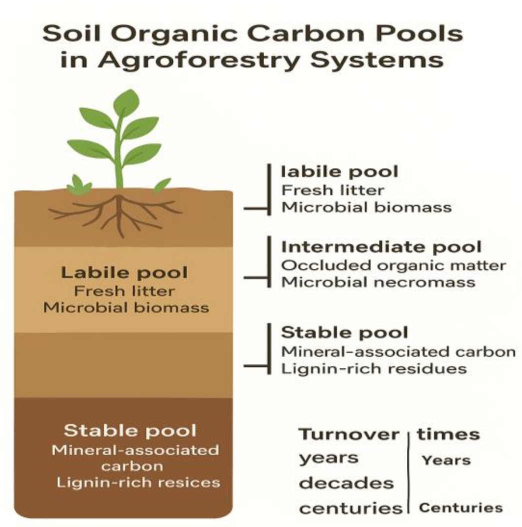

Figure 2. Soil organic carbon pool in agroforestry system.

3. Forest-Farming and Multistrata Agroforestry: Multistrata systems, including tropical homegardens and shaded coffee, are distinguished by their layered tree crop arrangements. In the case of the latter, silviculture is the main method of enhancing soil organic carbon (SOC) since it provides different inputs of organic matter, mainly through litter, and the rooting system is deeper. Additionally, a microclimate is created that supports fungi and microbes with higher biomass carbon. Soil carbon fractions and soil biological indicators, such as earthworm numbers and microbial activity, have been consistently reported as higher in multilayered systems through recent meta-analyses and global syntheses. Gains in soil carbon have been reported in some studies to be even greater than those obtained from planting trees in non-deforested areas or cropland conversion.

1.5. Ecological Mechanisms of Soil Carbon Sequestration in Tree-Based Systems: The Aboveground and Belowground Carbon Inputs: Quantifying Litter Dynamics

According to studies, the long-term efficacy of agroforestry systems in carbon dioxide mitigation is based on the specific ecological mechanisms responsible for carbon's entering the soil, its turnover, and its stability in the soil (Lal, Follett, Stewart, & Kimble, 2007; Regnier et al., 2013). Soil carbon accumulation occurs when the carbon flux from plant inputs (leaf, stem, and root litter) exceeds the rate of loss through decomposition by soil microbes and leaching, leading to an imbalance.

The primary input of trees to soil organic carbon (SOC) in agroforestry systems is the matter of leaf, twig, and root mixing from aboveground parts (Cardinael et al., 2018). The accumulation of organic substances on the ground is among the most important soil enrichment processes because, in addition to direct contribution to humus formation, they are also responsible for chemical fertility and moisture, plus nutrient holding capacity. Besides being beneficial for soil chemical enrichment, good management of aboveground residues is vital for the maximization of carbon accumulation. Research on harvest residue management in various systems, including eucalyptus plantations, concluded that leaving all the forest residues on the surface of the soil practically doubled the SOC levels compared to practices where residues were removed, thus confirming the important role played by litter retention in maintaining and even enhancing stocks (De São José et al., 2023).

While the aboveground litter is protecting the surface and enabling nutrient cycling, the plant's root system is the main pathway through which atmospheric carbon is going into stable soil pools, especially the deep ones (Panchal, Preece, Peñuelas, & Giri, 2022). In the same report, Panchal et al. (2022) indicated that different root systems of trees deposit carbon in the soil through senescence (root cycling) and the constant release, which are organic substances that soil microbes feed on. These different root systems will release different amounts and at different depths of exudates, thereby enabling more efficient exploitation of soil resources. The input of belowground root litter usually results in greater production of litter-derived carbon as well as soil aggregation compared to aboveground inputs, which highlights the peculiar role of belowground input in carbon stabilization (Solly et al., 2020). This physical input is the one that directly influences the stable soil organic matter (SOM) formation.

1.6. The Role of Litter Quality and Decomposition Kinetics

Which plant materials have the chemical composition of their respective nature, thereby determining their rate of decomposition and contribution to carbon storage in the long run? The decomposition process itself is primarily influenced by lignin and nitrogen present in the litter as its main contributors.

1. C: N Ratio and Recalcitrance: Generally, the litter rich in lignin becomes less and less decomposed with time. Lignin, together with tannins and polyphenols, creates the so-called chemically recalcitrant substances that are hard for microorganisms to decompose, hence the long-lasting presence of these materials (Lima et al., 2009). This high C: N ratio has a very strong negative impact on soil microorganisms' reaction to organic matter mineralization, thus positively affecting the slow-turnover pools where organic material accumulates. The recalcitrant materials formed are very important for the passive soil organic matter fraction, which is the major provider of the long-term stability needed for climate change mitigation (Averill & Hawkes, 2016). On the other hand, nitrogen-rich litter decomposes at a fast rate, which in turn leads to a quick nutrient cycle that is favorable for crop production but might cause lower long-term carbon storage.

2. Balancing Storage and Fertility: The contrasting properties of litter quality, on the one hand, its contribution to long-term carbon stabilization, and on the other hand, its effect on quick nutrient cycling, represent the main factor for considering agroforestry design. A prerequisite, as far as the maximization of carbon permanence is concerned, is the identification of tree species with a litter composition that is highly resistant to biotic attack, either lignin- or polyphenol-rich, and hence chemically recalcitrant. However, a high level of agricultural productivity will not be possible if nutrients are not supplied in ample quantities either. Therefore, the optimal system will require a diversity of species, with the plants producing high lignin material, which is responsible for good SOC, combined with nitrogen-fixing plants, such as legumes in particular, the tree species Acacia senegal, as indicated by Regnier et al. (2013).

3. Stabilization Pathways: Carbon sequestration is a process that involves not just an increase in inputs, but rather a complex physicochemical process by which organic material becomes resistant to biodegradation (Kavya, Rani, Banu, & Jabin, 2023). The hierarchical stabilization process demonstrates how carbon is protected physically and chemically against release via biodegradation in the soil system.

4. Humification and Mineral Protection: The first process involved in the decomposition of biomass is humification, whereby complex organic matter is converted into humus. The next process involves the formation of organo-mineral complexes, whereby SOM interacts with minerals present in the soil, making it less accessible to decomposers (Dwivedi et al., 2019). The formation of aggregates through SOM, particularly microaggregates, is vital to the long-term storage of SOC.

5. Physical protection by aggregation: The physical protection of organic carbon by soil aggregation involves encapsulating SOM and holding it reserved for functioning in the slower turnover pool. The substantial enhancement in root litter input to the below-ground pool significantly facilitates soil aggregation, hence the formation of physical components involved in the storage of carbon. On the other hand, macroaggregates that are more susceptible to management variations greatly mirror the impact of plant roots and coarse particulate organic matter. Consistent root inputs are the reason for the continuous generation and upkeep of these stabilizing macroaggregates (Semenov et al., 2020). Therefore, soil disturbance must be kept to a minimum, such as the traditional practice of tillage, which is harmful because it destroys these aggregates and hence, carbon stability.

6. Mycorrhizal Fungi, Glomalin, and Rhizosphere Dynamics: The processes occurring in the rhizosphere, the area around the root system directly affected by it, are essential for carbon fixation. Mycorrhizal associations are pivotal in connecting tree species to SOC stock (Mayer et al., 2020). Findings indicate that arbuscular mycorrhizal (AM) trees are more likely to increase soil carbon stock than ectomycorrhizal (EM) trees due to their impact on litter dynamics and root interactions (Soudzilovskaia et al., 2019). Furthermore, mycorrhizal fungi synthesize glomalin-related soil proteins (GRSPs), which serve as the 'glue' binding soil aggregates, thus benefiting the soil structure and quality of SOC stability. Moreover, the advancement of a community of microbes dominated by fungi is inevitably associated with increased SOC in agroforestry systems.

7. Root exudates and microbial activity: The roots are the source of various organic compounds, which are called exudates, and they serve to promote microbial activity. Although increased microbial activity often results in increased respiration and potential carbon loss, these exudates also play a direct role in the formation of stable soil organic matter (SOM) through long-lived carbon pools, acting as precursors. Table 1 presents the key ecological and biochemical mechanisms that govern soil carbon stability and permanence in agroforestry systems, highlighting how litter quality, root dynamics, soil aggregation, and microbial associations influence the distribution and protection of SOC pools.

Table 1. Mechanisms Influencing Soil Carbon Stability and Permanence in Agroforestry

Factor	Mechanism of Action	Impact on SOC Pools	Implication for Management
Litter quality (High Lignin/polyphenol)	Increases microbial resistance, slowing decomposition and mineralization	Promotes accumulation in stable SOM fractions, ensuring long-term carbon storage	Select tree species with chemically recalcitrant litter (e.g., certain conifers or hardwood species)
Root systems (Depth/Diversity)	Differential root morphology and depth; release of labile carbon via exudates	Enhances labile carbon pools in the rhizosphere; improves physical protection and deep carbon translocation	Encourage diverse species (e.g., deep-rooting perennials) to maximize vertical carbon distribution and microbial interactions
Soil aggregation and mineral interaction	Physical encapsulation of organic matter; interaction of SOM with minerals	Protects carbon from microbial attack; increases aggregate stability, especially through root inputs	Reduce tillage intensity; promote aggregation through biological activity
Microbial association (e.g., Glomalin)	Glomalin and other microbial byproducts act as binding agents in soil aggregates.	Increases physicochemical stability and longevity of SOC, fostering a fungal-dominated community	Manage systems to support diverse mycorrhizal fungi populations

1.7. Influence of Tree Canopy Litter on Soil Carbon Stock and Carbon Sequestration

Nevertheless, the influence of tree canopy litter on both soil carbon stock and carbon sequestration remains a major field of research, particularly with the current global climate changes and the necessity for efficient carbon management strategies (Mayer et al., 2020). Tree litter is made up of leaves, twigs, and other decomposed organic matter, and its role in the soil's improvement and forest ecosystems' nutrient cycling and carbon levels is enormous (Rawat, Dixit, Gulati, Gulati, & Gulati, 2021). Tree litter, through the processes of decomposition and humification, contributes to the nutrient cycling in ecosystems, and the conditions under which litter decomposes are determined by several factors that include litter chemical composition, environmental conditions, and microbial activity. Giweta, Dyck, Malhi, Puurveen, and Quideau (2020) found that even within the same tree family, different species have litter with varying nitrogen and lignin content, which directly affects decomposition rates. Young trees with high lignin content are typically associated with lower decomposition rates and thus enable greater organic matter to accumulate in the soil (Hall, Huang, Timokhin, & Hammel, 2020). On the other hand, the litter with the highest nitrogen content is usually fast in the decomposition process; thus, there is a rapid cycling of nutrients, but this may not be enough for the storage of carbon over a long period (Fernández-Alonso, Yuste, Kitzler, Ortiz, & Rubio, 2018).

Peng et al. (2020) elaborated that the involvement of mycorrhizal associations is a very crucial phenomenon as they act as a mediator between tree species and soil carbon stocks. The results indicated that the soil respiration rate and fine roots of the arbuscular mycorrhizal trees were greater than ectomycorrhizal trees (Lang, Jevon, Ayres, & Hatala Matthes, 2020). This suggests that the arbuscular mycorrhizal trees are presumably the better trees among all types as far as soil carbon stock is concerned, as their interactions between litter and roots have been positively affected by microbes. The outcomes show that the strategy involving earth tree types according to their mycorrhizal associations may be an admirable approach towards arresting carbon at the site via reforestation activities. The tree-specific effects are not the only driver regarding forest floor management, as the gross soil carbon quantity will be measured by this process as well. The eucalyptus cutting residues can be well-managed as indicated by the desk-reviewed article by De São José et al. (2023). They suggested that the upper limits of soil organic carbon levels were significantly greater when all forest residues of the cutting were retained at the soil surface compared to when all residues were removed completely. As indicated by the results of De São José et al. (2023), even greater rates of carbon retention could be achieved when all residues were retained, thus proving once again the momentous role of proper forest floor management in retaining as well as increasing carbon stocks at this site. It may be fruitful to consider a forest operation involving a healthy and effectively sustaining approach involving floor retention, as this will culminate in a better forest floor as well as a better carbon sink at the site. Figure 3 illustrates the major carbon sequestration pathways operating within terrestrial ecosystems, highlighting how vegetation, litter inputs, root processes, and microbial activity drive the transfer, stabilization, and long-term storage of carbon in soils.

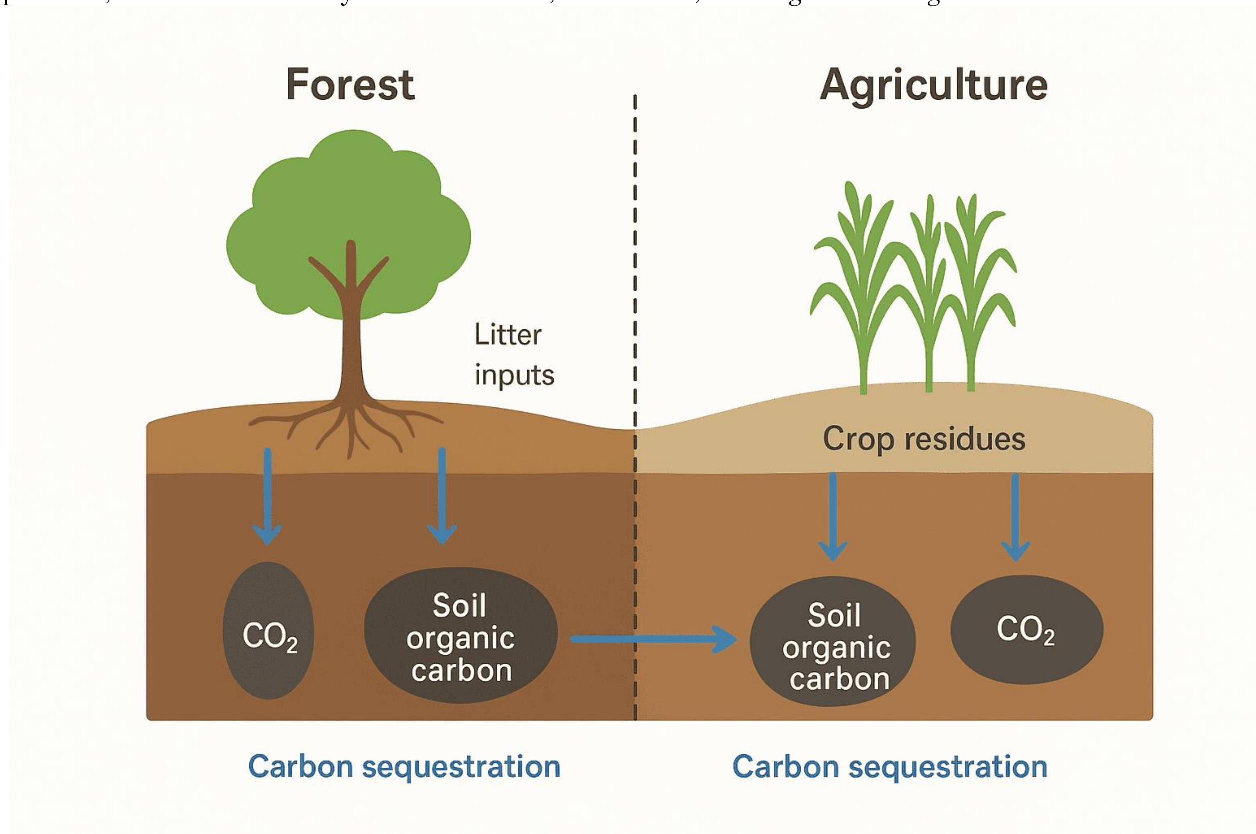

Figure 3. Carbon sequestration pathways in terrestrial ecosystems.

Soil texture and tree canopy litter interact, and this forms a complex relation. Different soil textures may contribute to SOC accumulation of litter in different ways (Angst et al., 2021). Yost and Hartemink (2019) contend that SOC in sandy soils can be lower than in loamy soils because sandy soils retain less water and have fewer nutrients, the main reasons being less retention of water and fewer nutrients available in sand. However, the trees can still offset these effects by enhancing the quality of the litter and the microbial assistance that is part of the decomposition succession (Giweta, 2020).

Furthermore, the role of tree canopy litter is not just as a direct cause of SOC but also as an indirect contributor through the soil's physical and chemical properties in various ways (Augusto & Boča, 2022). Different tree species have different effects on soil profile concerning pH, cation exchange capacity (CEC), and nutrient availability. Solly et al. (2020) report that in the case of some species, litter can help nutrient cycling by making the macronutrients, particularly nitrogen and phosphorus, which are crucial for plant growth and overall ecosystem productivity, more available (Sayer et al., 2013). The role of forest ecosystems in the global carbon cycle cannot be overlooked. Through aboveground biomass accumulation, forests sequester carbon, and through belowground processes such as SOC storage, they are also significant carbon sinks (Houghton & Nassikas, 2018). Thus, the dynamics of tree canopy litter in models predicting forest carbon sequestration will lead to more accurate evaluations of the forest's health and its potential to mitigate climate change (Biral, Will, & Zou, 2019; Quijas et al., 2018).

1.8. Deep Soil Carbon Storage and Long-Term Stability: The Importance of Vertical Carbon Translocation

Carbon sequestration aimed at reducing climate impacts over the long term is certainly the one to start with soil carbon storage (SOC) in deep soil layers (mainly below 30 cm), where carbon is isolated from quick turnover and surface disturbances due to agricultural practices. In addition to their significant carbon storage through root decay and the downward movement of dissolved organic carbon by root-assisted vertical movement, tree-based systems have a lot more to offer than conventional farming practices in terms of carbon capture through their complex, deeper root systems. Tree-based systems are found to sequester more carbon in both upper and lower soil layers when compared with annual cropping systems (Cardinael et al., 2018). In the case of an 18-year silvopastoral (walnut–wheat) experiment, the agroforestry system had an additional 6.3 t C ha^{-1} at 1 m depth compared to the adjacent arable control. There was a concentration of this gain in the top 30 cm and tree rows (Cardinael et al., 2018). Hombegowda, van Straaten, Köhler, and Hölscher (2016) stated a significant rise in deep soil carbon under tree-based land uses. The issue of deep SOC withholding needs to be addressed through the scrutiny of microbial child effects and not through the traditional input accounting method of soils. Fontaine et al. (2007) reported that bringing in fresh labile carbon can cause the breakdown of older carbon in the subsoil, while modeling plus empirical data from long-term agroforestry sites show that priming and depth-dependent microbial activity are crucial for achieving the envisioned SOC distribution at various depths. Consequently, the long-term survival of deep SOC in agroforestry is determined by a trade-off: inputs from deep roots that promote stabilization (through aggregation and mineral association) but may also cause some turnover through priming as a result of the induced microbial activity. Studies of deep rhizosphere microbial communities will indeed be helpful in forecasting permanence. Global and regional syntheses indicate a wide range of total SOC stocks to 1 m (very rough reference ranges 30–300 Mg C ha^{-1} depending on system, climate, and soil), and considerable variability in sequestration rates based on system type, climate, prior land use, and management (Beillouin et al., 2023). In the sub-Saharan Africa region, a systematic review revealed soil stocks (0-1 m) of about 98.8 ± 12.2 Mg C ha^{-1} on average in agroforestry systems, with homegardens normally being among the highest SOC systems in the region (Muthuri et al., 2023). Kuyah et al. (2019) said that agroforestry's effect on SOC is often stronger in drier areas (more arid/semi-arid), thus strengthening the argument that agroforestry is an important practice for mitigation and adaptation. The actual carbon results are highly dependent on management (species selection, residue retention, tree density, rotation/chronosequence), climate (temperature/moisture regimes), and soil characteristics (texture, mineralogy) (Brill, 2020).

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1.9. Role of Agroforestry in Climate Change Mitigation

The main idea behind agroforestry complexity is the management of temporal and spatial resource use complementarity, which is at the same time the most effective climate change mitigation mechanism, mainly through the increase of ecosystem carbon (C) storage and the control of greenhouse gases (GHG) emissions. Among the characteristics of agroforestry as the best climate change adaptation and mitigation practice are the increase of above-ground biomass (the stems, branches, leaves) as well as below-ground biomass (roots and Soil Organic Carbon (SOC) pools) (Chauhan, Kengoo, Kishore, Haksinhbhai, & Rana, 2025; Nair, Kumar, & Nair, 2022). The entire process of climate-change mitigation promises to demonstrate environmental stability improvements that are significant, measurable, and long-lasting. A global study estimates that converting to agroforestry could result in carbon sequestration ranging from 12 to 19 petagrams (PgC). Additionally, it has been estimated that a mere 10% increase in global forest cover in agricultural areas could lead to over 18 PgC of carbon sequestration, highlighting the potential of this nature-based climate solution, particularly in regions such as South America, Southeast Asia, and North America (Zomer, Yang, Spano, & Trabucco, 2023). Long-term agroforestry practice has been compared with traditional systems of annual cropping in terms of the stability and increase of SOC pools (Dhyani, Ram, Newaj, Handa, & Dev, 2019). Continuous field studies confirm the significance of integrated woody features. Some authors like Cardinael et al. (2018) maintain that specific linear features, very common in temperate agroforestry systems, e.g., shelterbelts and hedgerow woodlands, were recognized to have C stocks equivalent to cropland from 2.09 to 3.03 times more C than previously thought. It thus becomes the need of the hour to conduct existing woodland features across agroecosystems and, at the same time, actively manage them, to gain the maximum local mitigation potential and increase the resilience of the entire farm scale. Cardinael et al. (2018) further confirm that processes like increased organic matter deposition and microbial activity in agroforestry can lead to trade-offs (such as the release of non-CO2 greenhouse gases like N2O and CH4), but the specialized research does indicate that the GHG flux balance with the atmosphere is still largely positive. The carbon uptake due to the increase in above and below-ground biomass is so high that it usually overshadows the overall balance, thereby affirming the crucial position of the AF systems being net atmospheric carbon sinks. The success of mitigation is also due to the capability of the system in maintaining soil health stability and using resources efficiently. Under the use of agroforestry systems, GHG intensity is decreased due to better nutrient cycling and resource use efficiency (Sileshi, Mafongoya, & Nath, 2020). Particularly, legumes among the tree species promote biological nitrogen fixation, thus making synthetic nitrogen fertilizers less dependent (Kebede, 2021; Zheng et al., 2016). The reduced application of synthetic nitrogen contributes to climate change mitigation indirectly by minimizing energy consumption for industrial fertilizer production and reducing the release of N2O (a potent GHG) associated with excess nitrogen in the soil. Besides, the diverse litter, organic matter, and root exudates from under the trees contribute to an increase in the soil microbial population (Prescott et al., 2013). The recovery of functional capacity, which is shown by the rise in microbial biomass carbon and nitrogen, often reaches levels similar to those of natural forests (Huajun, Phillips, Liang, Xu, & Liu, 2016). This high and diverse microbial activity helps to bind and stabilize the organic carbon in the soil in the long run, thus ensuring the permanence of the carbon sink. Microbial diversity in the soil is uniquely enriched by increased beta diversity, which is the spatial variation in microbial community composition between the tree-row and crop-row linked microbiomes and contributes to greater functional stability (Beule & Karlovsky, 2021; Vaupel et al., 2025). The systems indicate substantial carbon sequestration, thereby giving quantified, global-scale benefits and keeping a favorable net GHG balance (Sykes et al., 2020). The incorporation of woody perennials not only enhances the biological capacity of the soil to retain carbon permanently but also improves the efficiency of resource use, so agroforestry becomes the scientifically accepted and essential Natural Climate Solution for the transition to a low-carbon but resilient global agricultural sector.

2. CONCLUSION

The study identifies agroforestry as the most effective global strategy to mitigate the negative effects of climate change. This approach has catalyzed soil revitalization and the adoption of sustainable agricultural practices. It not only increases the levels of Soil Organic Carbon (SOC) but also efficiently locks carbon into deeper soil layers through various methods, enabling long-term carbon storage while enhancing short-term productivity. The success of these strategies is contingent upon the methods employed, which are intended to define optimal outcomes for both long-term SOC retention and immediate agricultural yield. For political institutions and governments, a low-cost strategy is suggested to help nations meet their Nationally Determined Contributions by participating in the carbon market. The report emphasizes the necessity for policy adjustments focusing on long-term carbon storage, which should prioritize training resource-poor farmers and integrating climate-resilient agricultural practices globally.

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