Research Progress of Carbon Storage and Carbon Balance in Agroforestry Systems

Meng WAN*

Henan Forestry Resources Monitoring Institute, Zhengzhou 450045, China

Abstract Agroforestry systems, as composite ecosystems, possess dual characteristics of both forest and agricultural ecosystems. They have been widely recognized as an important land-use approach in agriculture and play a significant role in changing the climate. However, they also face limitations, including uncertainties related to future global climate change, land use, and land cover. This paper summarized the important role of agroforestry systems in the global carbon cycle and carbon balance from the methods and means used in the research on carbon storage and carbon balance and the research status of carbon storage and carbon balance in agroforestry ecosystems at home and abroad, and pointed out the problems that need to be paid attention to in future research.

Key words Agroforestry system; Forest; Global warming; Greenhouse gas; Carbon storage; Carbon balance; Carbon cycle

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Over the past century, atmospheric CO_2 concentration and other greenhouse gas levels have been rising continuously, and the growth trend will continue in the future. Carbon accumulates in the atmosphere at a rate of 3.5 Pg annually, primarily due to fossil fuel combustion and the conversion of tropical forests to agricultural land[1]. The ongoing decline in forest resources and increasing atmospheric CO_2 level have contributed significantly to global climate change[2–3]. Although studies indicate that elevated CO_2 concentration can enhance plant biomass accumulation[4–5], its adverse effects are more pronounced, including triggering climate anomalies such as rising temperature, extreme drought, and flood[6]. At the Third Conference of the United Nations Framework Convention on Climate Change in 1997, countries signed agreements to reduce atmospheric greenhouse gas concentrations. The emission reduction paths include reducing anthropogenic CO_2 emission and enhancing the carbon sequestration capacity of the biosphere.

The global terrestrial ecosystem (vegetation and soil) carbon storage is estimated at (2 000 ± 500) Pg, accounting for approximately 25% of the global carbon storage[7]. Through scientific management of various biological communities worldwide, the potential of terrestrial carbon sinks can be significantly enhanced. It is predicted that over the next 50 to 100 years, agricultural land could sequester 42 – 90 Pg of carbon from the atmosphere.

Agroforestry ecosystems, as a unique type between forest and agricultural ecosystems, combine the characteristics of both. Their role in addressing land-use change and global warming is increasingly attracting attention. Studies have confirmed that such systems significantly contribute to promoting sustainable agricultural development and mitigating soil degradation and desertification, and their carbon sequestration function is gradually being recognized. However, quantitative research in this field remains limited. This paper aimed to review the carbon storage potential of agroforestry ecosystems. It will provide supplementary perspectives for research on forest ecosystem carbon cycles through analysis on the carbon storage capacity and carbon balance mechanism of agroforestry ecosystems.

Estimation of Carbon Storage in Agroforestry Ecosystems

Carbon is one of the primary elements in living matter and a key component of organic material. Compared with other terrestrial ecosystems, forest ecosystems exhibit higher productivity, fixing approximately two-thirds of the total carbon sequestered by terrestrial ecosystems annually[8], making them the largest contributor to primary productivity in the biosphere. The carbon storage capacity of forest ecosystems serves as a fundamental parameter for studying carbon exchange between forest ecosystems and the atmosphere[9], as well as a critical factor in estimating the absorption and emission of carbon-containing gases between forest ecosystems and the atmosphere. Agroforestry ecosystems integrate the characteristics of both forest and agricultural ecosystems, so the study of their carbon storage should comprehensively consider the carbon stocks of both systems. The carbon storage in agroforestry ecosystems mainly includes vegetation carbon storage (forest vegetation carbon storage and crop carbon storage) and soil carbon storage. Since plant litter also contains a portion of carbon, it is treated as an independent carbon pool[10]. Forest vegetation carbon storage refers to the carbon fixed in both aboveground and underground living plant organisms, primarily including forests, crops, and certain economic trees. The carbon in soil carbon storage mainly exists in the form of organic carbon[11], encompassing carbon contained in soil fauna, microorganisms, and organic matter[12].

According to research data, it is predicted that in the future, the area of regions adopting agroforestry compound management

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Meng WAN (1979 –), male, P. R. China, PhD, senior engineer, devoted to research about forest resources monitoring and forest ecology and management.
* Corresponding author.

modes worldwide will show a significant growth trend. Consequently, such a condition will substantially influence flux inputs and long-term carbon storage in the terrestrial biosphere[13]. Agricultural ecosystems play a crucial role in the global carbon cycle, containing approximately 12% of the world's terrestrial carbon[9,13]. Soil degradation, as a direct consequence of land-use change, not only serves as a key driver of significant carbon loss from the soil carbon pool, but also acts as a major contributor to the continuous accumulation of atmospheric CO_2 concentration. Greenhouse gas emission associated with agroforestry ecosystems primarily includes shifting cultivation, overgrazing, paddy field farming, nitrogen fertilization, and livestock production[13-14]. Consequently, when carbon sequestration opportunities arise, trees in agricultural ecosystems often enhance the system's productivity[13,15-16].

Table 1 Carbon storage potential of agroforestry ecosystems in different ecological regions of the world[15-17]

Ecoregion		System	Carbon storage//Mg C/hm^2
Asia	Tropical high-temperature humid area	Agroforestry composite system	29 – 53
South America	Tropical low-temperature humid area	Agroforestry composite system	39 – 102[a]
	Arid low-lying land	Agroforestry composite system	39 – 195
North America	Tropical high-temperature humid area	Silvopastoral composite system	133 – 154
	Tropical low-temperature humid area	Silvopastoral composite system	104 – 198
	Arid low-lying area	Silvopastoral composite system	90 – 175
Northern Asia	Tropical low-temperature humid area	Silvopastoral composite system	15 – 18

"a" represents the carbon storage value based on a 50-year turnover standard.

The carbon sink assessment of agroforestry systems is primarily constrained by the spatial heterogeneity of their geographical locations, as well as the coupling representation of system structure and function with environmental and socio-economic factors at large scales. Key influencing factors also include tree species composition and configuration patterns and management intensity gradients. Table 1 reveals the spatial variation patterns of carbon storage in such systems through a comparative analysis of multiple regions.

Agroforestry ecosystems

Asia is one of the primary origins of agroforestry composite management. Subsequently, this integrated ecosystem model combining trees and crops has become widespread in Latin America, Southeast Asia, and equatorial Africa. In tropical regions, agroforestry composite ecosystems represent sustainable cropping systems[18-20]. China is a world-renowned ancient agricultural country with nearly 10 000 years of agricultural development history. During this time, it has created a rich variety of traditional agroforestry composite patterns, such as "four-side planting", intercropping of trees and crops, integrated forestry and livestock systems, and mulberry-dyke fish ponds. After the founding of the People's Republic of China, agroforestry developed rapidly. Over the past 50 years, organized and large-scale agroforestry practices and research have generated enormous ecological, economic, and social benefits, making significant contributions to the global development of agroforestry.

Carbon in plant biomass

The biomass accumulation of agroforestry systems depends on the combined effects of site conditions, soil type, land degradation status, and system developmental stage. Lasco *et al.*[21] conducted a six-year study on the productivity and carbon sequestration potential of the Naalad agroforestry ecosystem in the Philippines. Aboveground biomass increased from 4 Mg/hm^2 in the first year to 64 Mg/hm^2 in the sixth year. The estimated carbon in understory vegetation, soil, and woody debris accounted for about 25% of the aboveground carbon storage. The average carbon storage over the six-year period was 16 Mg/hm^2. A study on improved agroforestry ecosystems in western Kenya showed that while biomass production is influenced by plant species, local environment, and soil characteristics, the duration of agroforestry management is the primary factor causing biomass variation. Aboveground biomass ranged from 7 to 43.4 Mg/hm^2, and the carbon storage ranged from 4 to 22 Mg/hm^2. In agroforestry systems managed for 12 – 22 months, soil carbon storage ranged between 1.35 and 16.5 Mg/hm^2.

As mentioned above, agroforestry systems exhibit the highest variability, with productivity depending on factors such as stand age, structure, and management practices. Beer *et al.*[18] studied two kinds of composite management models of 10-year-old cacao-laurel and cacao-pineapple in Costa Rica. They found an annual carbon storage rate of 11 Mg C/hm^2, including 6 Mg C/hm^2 stored in trees each year. In the 10 years, 11 Mg C/hm^2 of carbon was stored in the system every year, including 6 Mg C/hm^2 stored in trees every year. Even without taking belowground carbon into account, this storage rate was 7 – 25 Mg C/hm^2 higher than the estimates by Kürsten *et al.*[22] in similar systems. These findings align with the carbon storage estimates of Houghton *et al.*[23] for agroforestry ecosystems in the Americas and Asia.

Research by Chinese scholars has demonstrated distinct diurnal variations in CO_2 concentration over farmland, indicating that croplands act as a CO_2 sink during the day and a source at night during the growing season. Lin *et al.*[24] estimated the total carbon sequestration potential of intensively managed croplands in the United States to be 75 – 208 Mt per year. Liu[25] estimated that China's agricultural ecosystems absorbed 652.034 9 million t and 726.763 48 million t of carbon in 1990 and 2000, respectively. The study concluded that these systems functioned as a carbon sink rather than a source for atmospheric CO_2, with carbon absorption exceeding emissions. Chen *et al.*[26] also conducted separate estimations of China's CO_2 and CH_4 emissions.

Soil carbon

As the core component of terrestrial ecosystems, soil realizes material cycling by linking the atmosphere, hydrosphere, biosphere, and lithosphere. Its carbon pool dynamics are dually regulated: on one hand, by the input of plant litter and the decomposition of organic matter, and on the other hand, by the combined influence of vegetation type and climatic conditions. In agroforestry ecosystems, despite continuous biomass harvesting, the systematic return of plant residues (including litter, dead branches, and roots) not only effectively maintains soil productivity but also consistently improves the physicochemical properties of the soil. Beer *et al.* [18] found in agroforestry systems that soil organic matter in the 0 – 45 cm layer increased by 42 and 16 Mg C/hm^2 over 10 years in cacao-erythrina and cacao-laurel agroforestry ecosystems, respectively. The total carbon sequestration reached 21 and 8 Mg C/hm^2, respectively. Rao *et al.* [27] found in their study on shelterbelts in agroforestry systems that although litter production and root biomass per tree row were substantial, the relative contribution to soil carbon might not be significant due to the comparatively small proportion of land area covered by tree canopies. Carbon storage increased by 50% per 100 m of shelterbelt length, with a 10% increase per hectare converted. Shelterbelts improve soil conditions, indirectly enhancing crop productivity which consequently boosts soil carbon sequestration while reducing soil nutrient loss caused by soil erosion.

In tropical regions, the long-term accumulation of pruned branches and root turnover are major contributors to soil organic matter and nitrogen cycle[27–28]. Kang *et al.* [28] found in a 12-year-old agroforestry intercropping system in Nigeria that soil organic carbon increased by approximately 15% (2.38 Mg C/hm^2) compared with monocropped soil in the surface layer. A five-year observation of shrub hedge intercropping systems in a typical region of Peru revealed a 12% increase in soil organic carbon (0.23 Mg C/hm^2). The carbon storage of these systems ranged from 6 to 10 Mg C/hm^2[29]. Numerous studies have shown that planting trees on degraded lands leads to increased soil organic matter after just a few seasons, and the soil carbon gains range from 0.73 to 12.46 Mg/hm^2.

Carbon Sequestration Potential of Agroforestry

Research findings indicate that not all agroforestry ecosystems possess carbon sequestration potential. With the implementation of agroforestry management models, a small portion of atmospheric carbon can be stored in plant biomass and soil. Carbon sequestration in agroforestry ecosystems is a dynamic process. During the rapid growth and mature stages, significant amounts of carbon are stored in tree trunks, stems, roots, and soil. When trees are harvested at maturity or crops are collected, a portion of this carbon is released back into the atmosphere[13]. In reality, carbon storage in plant biomass persists over the long term in agroforestry ecosystems. Carbon sequestration in these systems does not cease with tree harvesting. If trunks, stems and branches remain in productive use, carbon storage can continue to accumulate sustainably[30].

Restoring degraded croplands and pastures is an effective way to enhance soil carbon storage. The current estimated carbon stock in cultivated areas is 222 Pg, which can be considered the upper limit for soil carbon sequestration[31]. Trees in agroforestry ecosystems also contribute additional carbon input to farmland. However, agroforestry systems alone cannot solve the current climate crisis. They can only play a partial role at a large scale.

Limitations and Uncertainties of Carbon Sequestration

When trees and shrubs extensively replace grasslands over the long term, carbon storage increases. However, studies show that actual sequestration efficiency is constrained by multiple ecological thresholds, leading to significant differences between theoretical models and practical outcomes. Soil carbon only increases in arid regions, while it decreases in humid areas. Therefore, the carbon balance is positive in arid regions but remains highly uncertain in humid areas. Current land-based methods have led to overestimations of carbon sinks in many regions worldwide[32]. Over the next 50 years, inaccuracy in carbon flux estimates will intensify due to global climate change. It is still unclear about the change of carbon flux level and direction[33]. Similarly, degraded soil and wasteland cover vast areas of the planet. It is widely believed that converting these areas into agroforestry systems could present a major global opportunity for atmospheric CO_2 absorption[13]. In regions with infertile or semi-arid soils, tree growth is typically sparse, and such environments are often well-suited for agroforestry ecosystems[34]. However, cultivating crops and trees in nutrient-poor soils poses significant challenges.

Other Greenhouse Gases

Current monitoring techniques for greenhouse gas fluxes such as N_2O and CH_4 in agroforestry systems still face technical bottlenecks. Leguminous plants significantly enhance nutrient cycling efficiency in degraded soils through biological nitrogen fixation, but their nitrogen transformation processes may increase N_2O emission, highlighting the importance of carbon-nitrogen synergistic regulation. Studies show that nitrogen inputs from agroforestry practices exceed those from subsequent agricultural management, with excess nitrogen being released into the atmosphere as N_2O[35]. N_2O is one of the most important trace gases, with a global warming potential 200 – 300 times greater than CO_2[36]. Similarly, livestock grazing and rice cultivation in agroforestry systems also generate significant CH_4 emission at a global scale[13]. Therefore, future research should place greater emphasis on quantifying trace gas emission from agroforestry ecosystems.

Future Research Priorities

Global carbon sink simulation studies indicate that widespread adoption of agroforestry systems over the next 50 years could achieve an annual carbon sequestration potential of 1.1 – 2.2 Pg C. The systems' carbon storage exhibits significant spatial heterogeneity, primarily regulated by three factors: hydrothermal conditions, soil texture, and regional economic development levels. The biomass pool and wood product pool form the core carbon sink components, while soil carbon sequestration is realized through root turnover and organic matter stabilization processes. However, significant uncertainties remain regarding carbon storage in agroforestry ecosystems and their role in global climate. Current research faces three major bottlenecks. First, the lack of monitoring techniques for belowground carbon pools (particularly deep soil below 1 m and coarse root carbon) leads to excessive estimation error. Second, climate-land use coupling model has not yet integrated the carbon-nitrogen-water synergistic mechanism of agroforestry systems. Third, the disturbance of pests and diseases and the N_2O/CH_4 emission flux lack dynamic quantification.

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