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Dominant Role of Arbor Forests in Carbon Sink Enhancement: Dynamics and Drivers of Vegetation Carbon Storage in Pingxiang, China

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Abstract: Forests, as the dominant component of terrestrial ecosystems, have attracted significant attention for their carbon storage and sink capacity. This study investigated spatio-temporal dynamics and underlying mechanisms of forest vegetation carbon storage in Pingxiang City, Jiangxi Province, China. Utilizing forest resource inventory data from 2003, 2013, and 2019, carbon storage were calculated using volume-biomass conversion and average biomass methods, encompassing diverse vegetation types (arbor forest, economic forest, bamboo forest, open forest, shrubland). Comparative analysis specifically elucidated carbon storage trends across arbor forest types, age classes, and origins (natural vs. plantation). Results reveal a substantial increase in total forest carbon storage from 28.19×10^5 tC (tons of carbon) in 2003 to 58.63×10^5 tC in 2019. This corresponded to an average annual carbon sink of 1.90×10^5 tC, growing at 6.71%. arbor forests, identified as the primary carbon sink driver, increased their proportion of total carbon storage from 42.40% to 57.64%, with carbon density rising from 8.88 tC/hm² to 21.04 tC/hm². Young-growth and middle-aged stands dominated carbon storage of arbor forest and significantly contributed to the overall increase. Plantations played a pivotal role (> 57% of carbon storage in arbor forest), although both natural forests and plantations exhibited improving sequestration capacity. Afforestation and intensified plantation management represent key strategies for enhancing the carbon sequestration capacity, thereby supporting regional carbon neutrality goals.

Keywords: Pingxiang; Forest Vegetation; Arbor Forest; Carbon Storage; Carbon

Density

1. Introduction

As the main component of terrestrial ecosystems, forests possess irreplaceable ecological functions and play a crucial role in the global carbon cycle. Their carbon storage and carbon sink capabilities are of significant importance in mitigating global climate change(Le Noe et al. 2020; Friedlingstein et al. 2023). Forest vegetation absorbs CO₂ through photosynthesis, sequestering it in biomass to form a vast carbon pool, estimates indicate that global forest ecosystems store approximately 638 Gt of carbon, accounting for 45% of the total terrestrial carbon pool(Xiao et al. 2021). With the intensification of global climate change, enhancing forest carbon sinks is recognized as an effective strategy to curb the rise in atmospheric CO₂ concentration(Pugh et al. 2019; Peichl et al. 2022; Korkiakoski et al. 2023). In-depth studies on the dynamics of forest vegetation carbon storage advance our understanding of ecosystem carbon cycling mechanisms and provide a theoretical basis for developing forest management strategies(Assmuth et al. 2021; Jin et al. 2023).

Early in the 20th century, research on forest ecosystem carbon cycles was initiated in Europe and North America, yielding extensive datasets and methodological insights(Mitchard 2018). For instance, the United States has precisely estimated the carbon storage of forest vegetation and their dynamic changes through multiple national forest inventories, combined with advanced remote sensing and model simulations, Europe has implemented numerous forest carbon sink projects, conducting

comprehensive analyses of carbon storage characteristics across different forest types and stand age classes(Pan et al. 2011; Neumann et al. 2016). In recent years, amid escalating climate concerns, international research has expanded beyond quantifying carbon storage to investigate the response mechanisms of forest carbon sinks to climate change and the regulatory effects of management practices on carbon sequestration(Peichl et al. 2022). China possesses abundant forest resources and contributing significantly to global forest expansion, has conducted extensive carbon inventories since the late 20th century. These studies span regional to national scales and encompass diverse vegetation types, generating substantial scientific outputs(Qiu et al. 2020; Cheng et al. 2024). Regionally focused research includes dynamic monitoring of carbon storage in key forest areas such as Northeast and Southwest China(Sun and Liu 2019). Pingxiang City, a typical forest city in the subtropical region of China, has a forest coverage area that accounts for 66.87%(Zhang-quan et al. 2013). Its forest ecosystem holds unique geographical and ecological significance. However, in-depth studies on locally characteristic forest ecosystems like Pingxiang remain limited. A systematic investigation into the dynamics of forest carbon storage in this region would not only optimize local forest resource management and enhance carbon sequestration but also provide a reference case for carbon sink research in analogous subtropical areas. Such work carries significant scientific and practical value for advancing forest ecosystem conservation and sustainable development in Pingxiang and similar regions.

As the largest carbon pool in terrestrial ecosystems, forest carbon storage and sequestration are regulated by multiple ecological drivers, including vegetation type,

stand age, and forest origin(Thom and Keeton 2019; Adams et al. 2020). Research indicates pronounced differences in carbon allocation patterns among vegetation types. Broad-leaf forests typically exhibit higher carbon density due to greater biomass accumulation and wood density, though these traits are modulated by climate zones and species composition, resulting in significant spatial heterogeneity(Motlagh et al. 2020; Osei et al. 2022). The influence of stand age on carbon accumulation follows a nonlinear characteristic, with young-growth forests having high carbon sequestration rates; middle-aged forests entering a peak carbon accumulation; and mature forests tending towards carbon density saturation, with carbon sequestration rates gradually decreasing(Guan et al. 2019; Zhu and Xia 2020; Gregor et al. 2024). Regarding the impact of stand origin on carbon storage, academic consensus remains contentious, some studies suggest that plantations can achieve substantial short-term carbon sink enhancement through species selection and density management, while others argue that plantations may face issues such as soil organic carbon loss and reduced biodiversity, potentially overestimating their long-term carbon sequestration benefits. In contrast, natural forests, despite their slower carbon accumulation rates, possess greater resilience in carbon sequestration and enhanced capacity to adapt to climate change, attributed to their complex community structures, diverse species composition, and stable soil carbon pools(Seddon 2022; Alam et al. 2023). Current research predominantly focuses on isolated drivers, lacking systematic exploration of the combined effects of vegetation types, stand ages, and forest origins on carbon storage. This knowledge gap impedes

mechanistic understanding of forest carbon sink formation and constrains the development of precision management strategies.

To address these limitations, this study utilizes forest inventory data of Pingxiang from 2003, 2013, and 2019 to investigate the characteristics of carbon storage in forest vegetation and its dynamic changes. Our primary objectives are to: (1) quantify carbon storage and density across major vegetation types—including arbor forests, economic forests, bamboo forests, open forests, and shrubland—using inventory-based biomass conversion methods; (2) specifically analyze variations of carbon storage in arbor forest by tree species composition, stand age classes, and forest origin (natural vs. plantation) to elucidate the mechanistic basis of their role as primary carbon sinks; and (3) identify key drivers of carbon storage increases to propose targeted forest management strategies that enhance carbon sequestration potential, thereby supporting regional carbon neutrality initiatives.

2 Materials and methods

2.1 Study Area Overview

Pingxiang City is located in western Jiangxi Province, China (26°57'–28°01' N, 113°35'–114°17' E). The region exhibits a typical subtropical humid monsoon climate by predominantly hilly topography. Climatic features include mild and humid conditions, with an annual mean temperature of approximately 17.3°C, distinct seasonal variations, and sufficient annual sunshine duration. Precipitation patterns yield a mean annual precipitation of 1,582.9 mm. The total area of the city is 3823.99 km², of which forest coverage accounts for 66.87% [34]. The vegetation community

structure demonstrates vertical zonation representative of subtropical ecosystems, comprising diverse ecological types such as evergreen broad-leaved forests, mixed evergreen-deciduous broad-leaved forests, deciduous broad-leaved forests, and alpine meadows. Species composition exhibits high complexity and biodiversity.

2.2 Data Sources

The forest resource inventory data used in this study were obtained from Pingxiang municipal forestry resources monitoring center. These datasets systematically document key forest stand parameters during the period from 2013 to 2019, including area and growing storage volume, for dominant tree species across different age classes. Given that the inventory data lack ecological component information (e.g., herbaceous layer, litter layer, understory layer, soil layer), the carbon storage estimates presented herein pertain exclusively to the living tree component of the forest ecosystem.

2.3 Methodology

2.3.1 Forest Type Determination

Forest classification followed the Chinese forest resource system, categorizing forest land into three types including arbor forests, economic forests, and bamboo forests. To comprehensively capture the dynamics of carbon storage and carbon density in forest vegetation, shrubland and open forests were also included within the scope of this study. Predominant arbor forest types encompass Masson pine (*Pinus massoniana*), exotic pine species, Chinese fir (*Cunninghamia lanceolata*), hardwood broad-leaved forests, softwood broad-leaved forests, and mixed forests.

2.3.2 Biomass Calculation for Forest Types

Calculation for arbor forest biomass: the volume-derived biomass method, which establishes relationships between biomass and stand volume, has been widely applied in research estimating carbon storage of forest vegetation (Yan and Haiqing 2005; ZhaoDi et al. 2013). This study estimated the biomass of major arbor tree species using species-specific biomass estimation equations, detailed in Table 1 (Fang et al. 1998; Zheng, W.S 2005; Liu, G.H., FU, B.J., & Fang 2012).

Calculation for economic forest biomass: the biomass of economic forests was calculated using the mean biomass method. Total biomass was estimated as the product of the economic forest area and the biomass per unit area. The mean biomass parameter for economic forests was set at 23.7 t/hm² (Fang et al. 1998). The specific calculation formula is given by equation (1):

$$W_{eco} = A_{eco} + S_{eco} \quad (1)$$

In the formula, W_{eco} denotes the biomass of the economic forest (t), A_{eco} signifies the biomass per unit area of the economic forest (t/hm²), and S_{eco} indicates the area of the economic forest (hm²).

Calculation for bamboo forest biomass: the biomass of bamboo forests was calculated using the mean biomass method. Total biomass was estimated as the product of the total number of bamboo culms and the mean biomass per culm. The mean biomass per culm parameter was set at 22.5 kg/culm [27]. Based on this, the bamboo forest biomass was estimated using equation (2):

$$W_{bam} = (A_{bam} \times N_{bam}) / 1000 \quad (2)$$

In the formula, W_{bam} represents the biomass of the bamboo forest (t), A_{bam} is the average biomass per bamboo plant (kg/plant), and N_{bam} is the number of bamboo plants.

Calculation for open forest and shrubland biomass: The mean biomass method was similarly employed for estimation. This involves calculating the total biomass as the product of the total coverage area and the biomass per unit area. The mean biomass per unit area for open forest and shrubland was set at 19.76 t/hm² (Li et al. 2023). Accordingly, the biomass estimation model for shrubland in Pingxiang City was constructed as equation (3):

$$W_{open/shrub} = A_{open/shrub} \times S_{open/shrub} \quad (3)$$

In the formula, $W_{open/shrub}$ represents the biomass of shrubland (t), $A_{open/shrub}$ is the biomass per unit area of shrubland (t/hm²), and $S_{open/shrub}$ is the area of shrubland (hm²).

2.3.3 Estimate of Carbon Storage and Carbon Density in Forest Vegetation

Carbon storage of forest vegetation typically includes contributions from the tree layer, understory shrub layer, herbaceous layer, and dead litter layer. In this study, the carbon storage of forest vegetation is restricted to the living biomass of trees (including arbor forests, bamboo forests, and economic forests), open forest, and shrubland. Understory, herbaceous, and litter carbon pools were excluded due to data limitations. The carbon storage of forest vegetation (tC) is calculated by multiplying the forest biomass (t) by its carbon content (gC/g). The carbon density of forest vegetation (tC/hm²) is obtained by dividing the forest carbon storage (tC) by the forest area (S).

The arithmetic mean of carbon content for various forest types in Pingxiang is presented in Table 2 (Wang, B., & Wei 2007; YANG Jie, HUANG Guo-xian, TIAN Li-xin 2023). For open forests, the carbon content fraction applied was that of shrubland.

3 Results

3.1 Impact of Different Forest Vegetation on Forest Carbon Storage - The Dominant Role of Arbor Forest Vegetation in Carbon Sink Growth

As depicted in Fig. 1, the total carbon storage of forest vegetation was 28.19×10^5 tC in 2003, increasing to 41.99×10^5 tC in 2013 and 58.63×10^5 tC in 2019. From 2003 to 2019, forest carbon storage increased by 30.44×10^5 tC, representing a growth rate of 107.98%. The average annual carbon sink was 1.90×10^5 tC, with an average annual growth rate in carbon storage of 6.71%. Forested areas across the three inventory periods were 26.99×10^4 hm², 29.07×10^4 hm², and 28.26×10^4 hm², respectively, yielding corresponding carbon densities of 10.45 tC/hm², 14.45 tC/hm², and 20.75 tC/hm². Comprehensive analysis indicated that both forest carbon storage and carbon density exhibited an increasing trend, signifying progressive enhancement of the forest carbon sink capacity.

As presented in Fig. 2, the area and carbon storage of shrubland, economic forests, and open forests have shown a declining trend up during the study period leading up to 2019, while the area and carbon storage of bamboo forest exhibited a consistent upward trend by 2019. Specifically, the shrubland area decreased by 31,500.04 hm² in 2019 compared to 2003. The proportion of carbon storage in shrubland to the total forest carbon storage decreased from 23.34% to 5.76%, with a reduction of 32.11×10^4 tC.

Carbon storage in shrublands decreased at an average annual rate of 2.01×10^4 tC/a, although its carbon density remained relatively stable. Economic forests accounted for 6.02-14.27% of the total forest carbon storage, both the area and carbon storage of economic forests initially increased but subsequently decreased, the 2019 area was reduced by 4,155.60 hm^2 compared to 2003, with a corresponding carbon storage decrease of 4.92×10^4 tC, averaging an annual decrease of 0.31×10^4 tC/a, while carbon density remained stable. Open forests constituted only 0.17-0.78% of the total forest carbon storage. Their area and carbon storage exhibited an initial decrease followed by an increase, resulting in a net area reduction of 471.2 hm^2 and a net carbon storage decrease of 0.52×10^3 tC. Carbon storage decreased at an average annual rate of 0.032×10^4 tC/a, while carbon density remained unchanged. Bamboo forests accounted for 19.18-30.29% of the total forest carbon storage. Their area, carbon density, and carbon storage demonstrated sustained growth over the study period. By 2019, bamboo forest area had increased by 22,794.43 hm^2 compared to 2003, with a corresponding carbon storage increase of 12.35×10^5 tC. Carbon storage increased at an average annual rate of 7.72×10^4 tC/a, and carbon density increased by 15.49 tC/ hm^2 .

As shown in Fig. 2, carbon storage of arbor forest ranged from 11.95 to 33.79×10^5 tC, with coverage areas of 13.46 to 16.06×10^4 hm^2 during the period from 2003 to 2019. Arbor forests exhibited a steady growth trend in their carbon sink capacity. The proportion of carbon storage in arbor forest to the total forest carbon storage was 42.40% in 2003, rising to 50.37% in 2013, and 57.64% in 2019. The net increase in carbon storage of arbor forest reached 21.80×10^5 tC, with an average annual carbon sink

increment of 1.37×10^5 tC and an average annual growth rate of 6.7%. Carbon density increased from 8.88 tC/hm² in 2003 to 21.04 tC/hm² in 2019. These results demonstrate that arbor forests play a critical role in forest carbon sequestration and serve as the primary contributor to maintaining the carbon sink capacity of forest ecosystems.

3.2 Impact of Different Types of Arbor Forest Vegetation on Carbon Storage

Table 3 presents the carbon storage, carbon density, and area of various arbor forest types across the study periods. Analysis indicates that broad-leaf forests (encompassing hardwood and softwood categories) and Chinese fir exhibit an initial increase in carbon storage followed by a decline. In contrast, Masson pine and slash pine demonstrate a continuous decrease. Conversely, mixed forests exhibit a significant upward trend in carbon storage. Comprehensive analysis identifies Chinese fir and mixed forests as the primary contributors to the forest carbon sink capacity within arbor forests. From 2003 to 2019, mixed forests recorded the largest increment in carbon storage, rising from 3.42×10^4 tC to 227.65×10^4 tC, corresponding to an average annual increase of 14.01×10^4 tC. Carbon density of mixed forests increased from 11.85 tC/hm² in 2003 to 26.74 tC/hm² in 2019, while their coverage area expanded from 2.89×10^3 hm² to 85.14×10^3 hm². Therefore, the concurrent increase in both carbon density and area is the main factor driving the carbon storage increase in mixed forests. Chinese fir accounted for the largest portion (65.92%) of total arbor forest carbon storage in 2003, decreasing to 58.26% by 2013. During this period (2003–2013), its carbon density increased from 7.85 tC/hm² to 11.67 tC/hm², and its coverage area expanded from 100.33 hm² to 105.60 hm². By 2019, although the carbon density of Chinese fir further increased to 14.35

tC/hm², its coverage area decreased to 59.95 hm². Concurrently, mixed forests increased to account for 67.34% of total arbor carbon storage, becoming the dominant component. The reduction in area of Chinese fir is the primary reason for its replacement by mixed forests as the main contributor to carbon storage of arbor forest.. Throughout the 2003-2019 period, *Pinus massoniana*, slash pine, and broad-leaf forests, remained non-dominant contributors to total arbor carbon storage due to their relatively limited coverage areas (ranging from 1.93-14.23 hm²).

3.3 Impact of Different Stand Ages on Carbon Storage in Arbor Forest Vegetation

As shown in Fig. 3, across the three forest inventories, arbor forests maintained a consistent ranking of carbon storage by age group: middle-aged forests > young-growth forests > near-mature forests > mature forests > over-mature forests. Except for the near-mature forest, exhibited an initial increase followed by a decrease in carbon storage, all other age groups showed increasing carbon storage trends. Young-growth and middle-aged forests consistently contained the largest carbon storage and areas during the inventory periods. Young-growth forests demonstrated increasing trends in area, carbon storage, and carbon density. Their area accounted for 30.19-35.47% of total arbor forest area, while their carbon storage represented 18.80-29.68% of the total. By 2019, young-growth forest area had increased by 13,795.83 hm² relative to 2003, with a corresponding carbon sink increase of 69.96×10^4 tC. Middle-aged forests exhibited increasing carbon storage and carbon density despite decreasing area. Their area represented 38.49-55.19% of total arbor forest area, while carbon storage accounted for 43.82-56.02% of the total. The proportional area of middle-aged forests displayed

decreasing trends. In 2019, middle-aged forest area decreased by 12,439.1 hm² compared to 2003, while carbon storage increased by 69.96×10^4 tC. This indicates that the carbon sink increase in middle-aged forests resulted primarily from rising carbon density. Carbon density increased across all age groups except over-mature forests, which showed an initial increase followed by a decrease. These trends demonstrate that afforestation and forest restoration initiatives in Pingxiang City have been effectively executed over the past decade, yielding measurable ecological improvements. Young-growth forest area has expanded rapidly, while mature and over-mature forest areas have increased rather than decreased. These changes reflect significant improvements in stand quality and substantial increases in growing stock per unit area.

3.4 Impact of Stand Origin on Carbon Storage in Arbor Forests

As depicted in Fig. 4, both natural forests and plantations exhibited continuous increases in carbon storage and carbon density across the three forest inventory periods. From 2003 to 2019, the net carbon storage increase for natural forests was 102.98×10^4 tC, while plantations showed an increase of 118.51×10^4 tC. These increments accounted for 47.24% and 54.37%, respectively, of the total net increase carbon storage (217.98×10^4 tC) in arbor forest vegetation, corresponding to annual net increases of 6.43×10^4 tC/a and 7.41×10^4 tC/a. Carbon density increased by 56.89 tC/hm² in natural forests and 45.84 tC/hm² in plantations, indicating progressive enhancement of carbon sink capacity in both forest types. The proportional area of plantations during the three inventory periods was 61.18%, 78.44%, and 62.39%, respectively. Correspondingly,

carbon storage of plantation accounted for 65.50%, 75.82%, and 57.28% of total arbor forest during these periods, underscoring their significant contribution to carbon sequestration in arbor forests.

Data presented in Fig. 5 indicate that across all three forest inventories, carbon storage in both natural forests and plantations was primarily contributed by young-growth forests, middle-aged forests, and near-mature forests. In plantations, over-mature forests exhibited the highest carbon density (ranging from 13.48-22.87 tC/hm²), followed by mature forests, while near-mature and middle-aged forests showed intermediate values (9.10-21.94 tC/hm²). Young forests displayed the lowest values (7.26-16.41 tC/hm²). For natural forests, over-mature forests also exhibit the highest carbon density (19.78-46.95 tC/hm²), succeeded by mature forests. Middle-aged and young-growth forests ranged from 6.67-29.35 tC/hm², whereas near-mature forests exhibited the lowest carbon density (4.99-14.81 tC/hm²). Notably, in both natural forests and plantations, the area of young-growth and middle-aged forests is much higher than that of other age classes, explaining their dominant contribution to vegetation carbon storage in natural and plantation forests.

4. Discussion

4.1 Policy and Ecological Drivers of Forest Carbon Storage Changes

Over the past 16 years, forest carbon storage in Pingxiang City increased by 107.98%. This growth primarily stemmed from the synergistic effects of forest conservation policies and tree species improvement initiatives. Since the

implementation of the Pingxiang Forest Conservation Management Regulations in 2009, human activities in critical areas such as water source protection zones and major transportation corridors have been restricted, which has promoted the natural succession from shrubland to arbor forests(Fang et al. 2001; Pregitzer and Euskirchen 2004; Liang et al. 2022). The results indicate a reduction in shrubland area and a decline in its proportional carbon storage, directly reflecting policy-driven replacement of low-efficiency shrubland with higher-carbon-density arbor forests(Guo and Gifford 2002; Gruenzweig et al. 2007; Kodero et al. 2024). Concurrently, bamboo forest area expanded significantly by 22,794.43 hectares (a 227.5% increase), while carbon density increased by 15.49 tC/hm², demonstrating that the government has effectively optimized the vegetation structure by transforming low-yield forests (e.g., converting *Camellia oleifera* forests into bamboo plantations) (Yen and Lee 2011; Mao et al. 2017; Yuen et al. 2017). Regarding ecological mechanisms, carbon density of arbor forests increased by 122.8%. This enhanced growth stems from two key factors: the optimized vertical structure of the forest stand, where increased carbon density in middle-aged forests effectively offsets the reduction in their area, demonstrating that tending practices like strategic selective thinning actively promote tree growth; and distinct functional complementarity among tree species, evidenced by mixed forests now contributing a significant 67.34% to total carbon storage. This affirms that subtropical mixed forests substantially boost carbon sequestration efficiency through niche differentiation and greater litter diversity(Liu et al. 2018; Lin et al. 2024; Yan et al. 2024).

4.2 Ecological Mechanisms of Carbon Sink Advantages in Mixed Forests and Their Regional Applicability

The structure of arbor forests has undergone effective optimization, characterized by a reduction in the area of pure Chinese fir plantations and a substantial increase in both the area and carbon storage of mixed forests, the latter of which has become the main force driving the growth of carbon sinks(Li et al. 2016; Yang et al. 2019). This transition is not accidental but rather benefits from proactive local forestry policies. Since 2007-2008, certain forest farms in Pingxiang City began implementing "near-natural" silvicultural techniques. The core of this approach involves simulating natural forest succession processes through artificial interventions(Prach et al. 2001; Lambin and Meyfroidt 2010). For instance, selective logging creates canopy gaps within existing pure stands of Chinese fir or Masson pine forests, facilitating the introduction of adaptable native broad-leaved species (e.g., *Castanopsis* spp., *Michelia* trees), this practice aims to address the issues of structural simplicity and poor ecological stability inherent in pure stands(Wu et al. 2013). Enhanced species diversity promotes the development of structurally complex and functionally robust coniferous-broadleaved mixed forests(Wang et al. 2023). The mixed-species model improves forest microclimate, elevates soil fertility, and optimizes resource-use efficiency, thereby accelerating tree growth and carbon accumulation(Baker et al. 2014).

Concurrently, Pingxiang City vigorously promoted the transformation project targeting low-yield and inefficient forests. Statistics indicate that from 2003 to 2012, the city cumulatively transformed over 6,000 hectares of low-yield forests [63].

Although specific data detailing the area of transformed pure Chinese fir stands is unavailable, technical guidelines issued by Jiangxi Province for low-efficiency Chinese fir forests (e.g., "stunted forests" or poorly growing young and middle-aged stands) suggest that the transformation projects of Pingxiang likely included extensive conversion of declining pure Chinese fir plantations into mixed forests[64-65]. This shift is particularly relevant given the recurrent issues of soil degradation and nutrient depletion in successive rotations of Chinese fir monocultures, which drive productivity declines. Consequently, mixed arbor forests have emerged as the dominant carbon sink in Pingxiang City, with carbon storage reaching 227.65×10^4 tC, and an annual average increase of 14.01×10^4 tC, significantly higher than pure forests ((e.g., Chinese fir, Masson pine) (Gao et al. 2022).

The effects of mixed forests manifest in multiple aspects: firstly, light energy utilization is optimized, as mixed forests enhance photosynthetic rates and light capture efficiency through canopy stratification; secondly, soil carbon stability is strengthened, as the litter of coniferous and broad-leaf mixed forests promotes microbial activity, resulting in soil organic carbon reserves that are 30% higher than those of pure forests. Furthermore, system stability is improved, enhancing resistance to disturbances, as mixed forests reduce dependence on chemical control, thus maintaining long-term carbon sink capacity (Garcia-Franco et al. 2015; Huang et al. 2020).

4.3 Contradiction Between Age-Class Structure and Carbon Sink capacity in Plantation Forests

Strengthening management of existing forests, especially the young-growth and middle-aged stands, has significant potential for enhancing their carbon sink capacity. During the study period (2003-2019), Pingxiang City systematically implemented tending practices for young stands, including weeding, pruning, and fertilization, which directly improved the growth environment of the trees and increased the rate of biomass accumulation per unit area, thereby increasing carbon density(Schoenauer et al. 2021). Plantations contributed substantially to the regional carbon storage increment, accounting for 54.37%. Nevertheless, two key limitations persist: ecological efficiency and stand structure. Plantation carbon density (20 tC/hm^2) remains significantly lower than natural forests (42.72 tC/hm^2) and merely 60% of the national plantation average(Chen et al. 2005; Liao et al. 2010). Concerning stand structure, young-growth forests account for a high proportion of 35.47%, requiring a growth period of 20 to 30 years to reach the peak carbon sink, while the proportion of mature forest resources is less than 10%, restricting the current carbon sink efficiency [74-75]. This structural contradiction originates from the technical deviations in historical afforestation strategies, especially the large-scale broad-leaf tree seedling afforestation project implemented between 2003 and 2012, which rapidly expanded the afforestation area but ignored the scientific configuration of high-carbon density age class systems(Hublova and Frouz 2021). System dynamics modelling suggests rectifying age-class structure through target-tree whole-cycle cultivation, such as increasing near-mature forests to 20%, to temporally optimize carbon sequestration(Calle and Poulter 2021).

Therefore, the significant increase in forest carbon storage in Pingxiang City (2003–2019) represents a synergistic outcome driven by the interaction of proactive interventions and autonomous ecosystem development(Chen et al. 2021; Yu et al. 2022). Firstly, forward-looking forestry policies, such as "near-natural" forestry and the transformation of low-efficiency forests, have fundamentally improved the forest structure, transforming low-efficiency pure forests into efficient mixed forests, becoming the main source of carbon storage growth(Hurteau et al. 2016). Secondly, scientific forest management measures, including refined tending, sustainable harvesting, and effective fire prevention and control, ensure the quality and safety of forest assets and promote the stable accumulation of carbon sinks(Berthrong et al. 2009). Finally, the natural maturation process of the forest ecosystem also provides a continuous internal driving force for the increase in carbon storage. These three aspects promote each other and jointly drive the significant enhancement of the forest ecosystem service function in Pingxiang City, especially the carbon sink capacity(Liu et al. 2016; Zheng et al. 2023).

4.4 Advantages and Limitations

This study leverages multi-period forest inventory data (2003, 2013, 2019) to analyze arbor forests (the primary component of forest carbon sequestration) and systematically reveals the impacts of vegetation type, forest age, and stand origin on forest carbon storage. It fills the gap in existing research regarding the dynamic characteristics of urban forest carbon storage in subtropical areas and provides a scientific basis for forest management in the region and similar subtropical areas.

However, three methodological limitations warrant acknowledgment: (1) The spatial heterogeneity of vegetation type, forest age, and stand origin impacts on carbon storage remains unquantified, potentially obscuring localized driving factors. (2) Exclusion of non-arbor carbon pools (e.g., herbaceous understory, litterfall, and soil strata) restricts carbon estimation solely to living tree biomass. (3) The 16-year temporal scope spanning only three inventory periods precludes comprehensive quantification of long-term carbon storage trajectories. Future research should integrate multi-source remote sensing, soil carbon datasets, and spatio-temporal machine learning frameworks to holistically unravel carbon sink formation mechanisms across subtropical forest ecosystems

5 Conclusion

This study analyzed forest resource inventory data from 2003, 2013, and 2019 to elucidate trends and driving mechanisms of forest vegetation carbon storage in Pingxiang City, Jiangxi Province. Results indicated that the forest vegetation exhibited a strong carbon sink capacity during the study period, with a significant increase in forest carbon storage. Arbor forests, serving as the primary contributor to forest carbon sequestration, showed increasing trends in both carbon storage and carbon density. Variations in carbon storage changes were observed among different forest types, mixed forests account for 67.34% of total storage, becoming the dominant component. Young and middle-aged forests accounted for a substantial proportion of carbon storage in arbor forest, and the accelerated growth serving as a primary driver of overall carbon accumulation. Additionally, plantations held significant importance in carbon storage

of arbor forests, constituting over 57% of total storage. Both natural forests and plantations demonstrated progressively improving carbon sink capacity. Implementing measures such as afforestation and strengthening the management of plantations could further enhance the carbon sink capacity of its terrestrial ecosystems, providing vital support for achieving carbon neutrality goals. Future research should continue to monitor the dynamic changes in forest carbon storage, deeply explore the key factors and mechanisms affecting forest carbon storage, thereby contributing greater insights and efforts towards the scientific management of forest resources and the realization of carbon neutrality objectives.

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Table 1 Regression equations between biomass and volume for different arbor forest

types		
Arbor forest type	Biomass(B/t) - Volume (V/m ³)	References
regression equations		
<i>Pinus massoniana Lamb.</i>	$B = 0.52V$	Fang, J. Y et al
<i>Slash Pine Plantation</i>	$B = 0.5168V+33.2378$	Fang, J. Y et al ^[37]
<i>Chinese fir forest</i>	$B = 0.3999V+22.5410$	Fang, J. Y et al ^[27]
<i>Hard broadleaf</i>	$B = 0.7564V+8.3103$	Zeng, W. S et al ^[38]
<i>Soft broadleaf</i>	$B = 0.4754V+30.6034$	Zeng, W. S et al ^[38]
<i>Conifer-broadleaf mixed forest</i>	$B = 0.8019V+12.2799$	Liu, G.H et al ^[39]

Table 2 Arithmetic Mean Carbon Content of Existing Forest Vegetation in Pingxiang City

Tree species	Pinus massoniana	Foreign Pine Forest	Chinese fir	<i>Hard broadleaf</i>	<i>Soft broadleaf</i>	Mixedforest	Economic forest	Bamboo forest	Open forest	Shrubland
Carbon content (gC / g)	0.541	0.521	0.505	0.500	0.500	0.500	0.500	0.484	0.499	0.499
References	Wang, B. et,al ^[34]	Wang, B. et,al ^[34]	Wang, B. et,al ^[34]	Wang, B. et,al ^[34]	Wang, B. et,al ^[34]	Wang, B. et,al ^[34]	Yang.J. et,al ^[35]	Yang.J. et,al ^[35]	Wang, B. et,al ^[34]	Wang, B. et,al ^[34]

Table 3 Carbon storage, carbon density, and area of different forest types during
the study period

Forest types	2003 year		2013 year				2019 year		
	Area/ ($\times 10^3$ hm ²)	Carb on stora ge/($\times 10^4$ tC)	Carbo n densit y/(tC/ hm ²)	Area / ($\times 10^3$ hm ²)	Carbo n storag e/($\times 10^4$ tC)	Carbo n densit y/(tC/ hm ²)	Area/ ($\times 10^3$ hm ²)	Carbo n storag e/($\times 10^4$ tC)	Carbo n densit y/(tC/ hm ²)
Masson pine	9.78	8.88	9.08	3.26	6.73	20.63	1.14	2.40	21.00
Exotic pine	10.13	10.84	10.70	8.81	9.77	11.09	4.52	5.60	12.38
species									
Chinese fir	100.33	78.80	7.85	105.60	123.24	11.67	59.95	86.04	14.35
Hard broad-leaf	9.49	16.05	16.91	7.89	17.57	22.27	6.45	14.23	22.07
Soft broad-leaf	1.93	1.54	7.97	3.65	2.93	8.01	3.39	2.01	5.92

Mixed				29.4					
forest	2.89	3.42	11.85	9	51.31	17.40	85.14	227.65	26.74
Total	134.5	119.5		158.					
	5	4	64.38	71	211.55	91.07	160.59	337.92	102.46

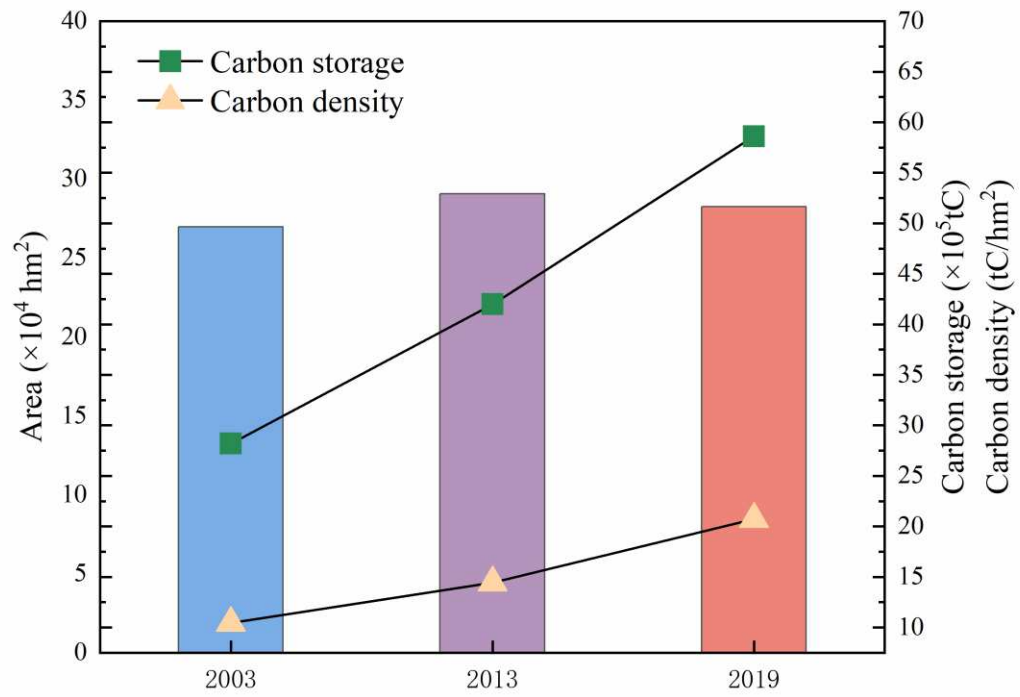


Fig.1. Carbon storage, carbon density, and area of forests during the study period

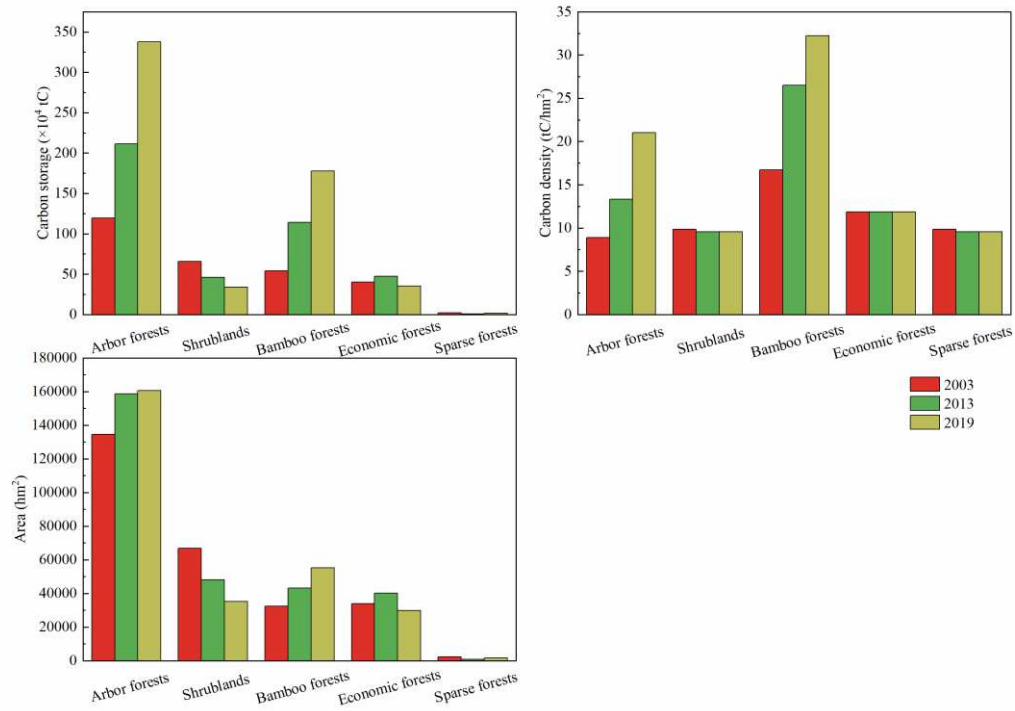


Fig. 2. Carbon storage, carbon density, and area of different forest vegetation types during the study period

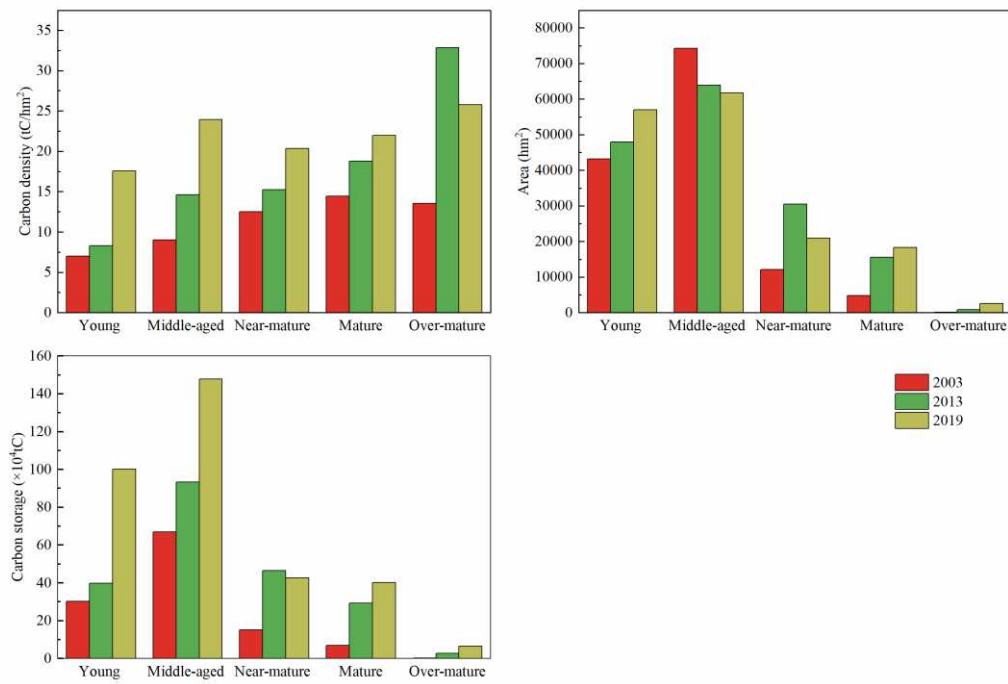


Fig.3. Carbon storage, carbon density, and area of arbor forest in different age classes across the study period

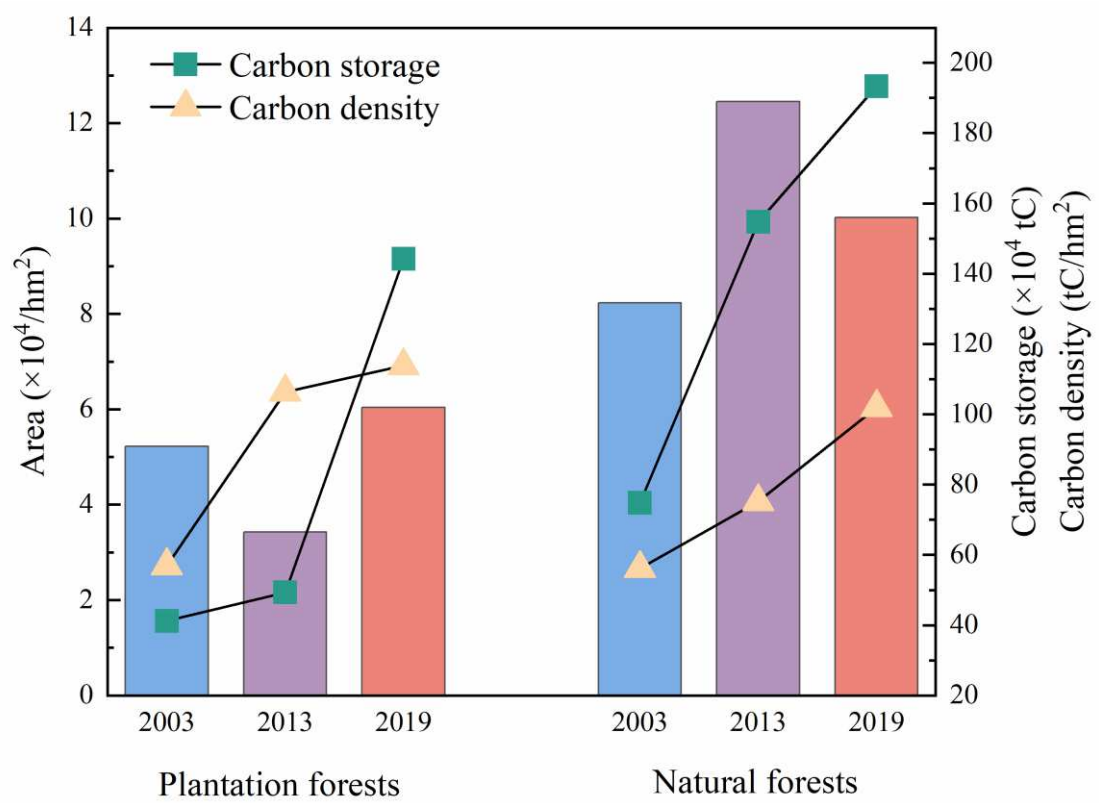


Fig.4. Carbon storage, carbon density, and area of plantation and natural forests
in the study period

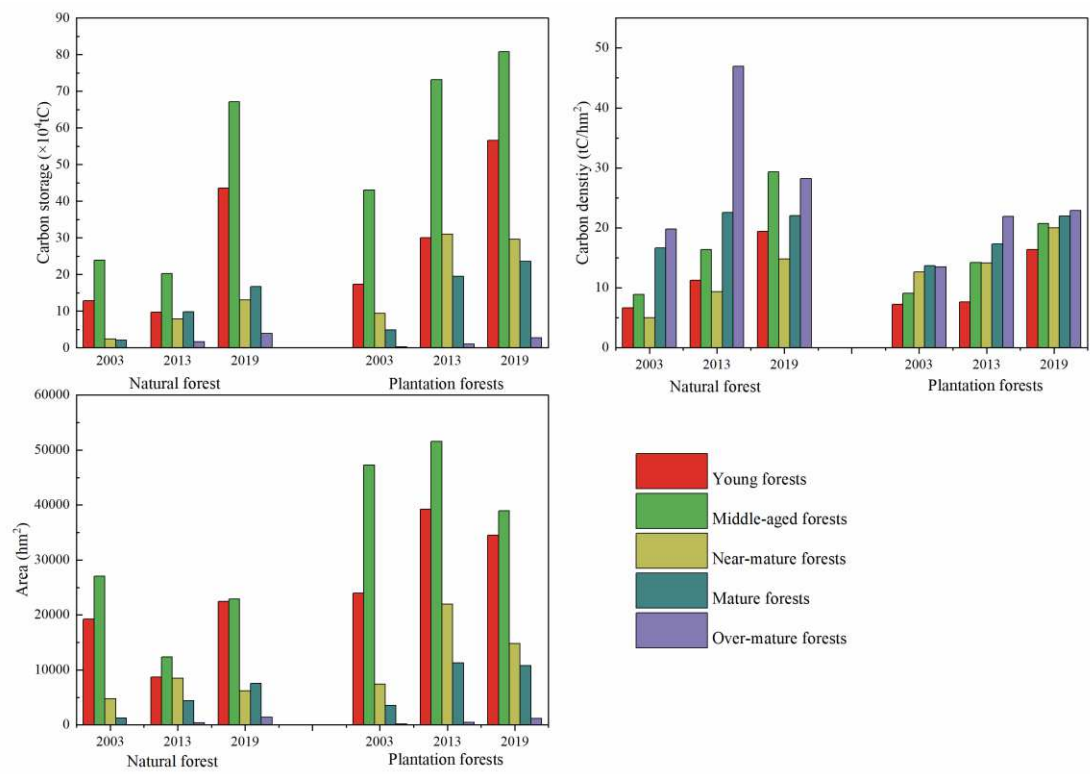


Fig.5. Carbon storage, carbon density, and area of vegetation in different age groups from various origins during the study period