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Assessing and optimizing the potential for climate change mitigation and carbon sequestration in urban residential green spaces: energizing sustainable cities

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Introduction: Urban green spaces play a crucial role in mitigating climate change by sequestering atmospheric carbon dioxide. This study aimed to evaluate the carbon sequestration potential of common plant species in urban residential areas and provide recommendations for optimizing green space design and management.

Methods: The research was conducted in four residential areas of Nanjing, China, where key growth parameters of 20 plant species, including evergreen trees, deciduous trees, evergreen shrubs, and deciduous shrubs, were measured. The assimilation method was employed to calculate carbon sequestration per unit canopy area and for entire plants.

Results: The results showed that the carbon sequestration capacities of different plant species and types exhibited significant differences, with p-values less than 0.05. In terms of daily carbon sequestration per unit canopy projection area, the ranking was as follows: evergreen trees > evergreen shrubs > deciduous trees > deciduous shrubs. For total plant carbon sequestration, the ranking was: evergreen trees > deciduous trees > evergreen shrubs > deciduous shrubs. Evergreen trees performed excellently in both carbon sequestration metrics, with the average daily carbon sequestration per unit canopy projection area and for the entire plant being 18.0024 g/(m^2·d) and 462.28 g/d, respectively. The study also observed seasonal variations, with carbon sequestration rates being higher in autumn and summer compared to spring and winter. During the summer, the average daily carbon sequestration per unit canopy projection area and for the entire plant were 11.975 g/(m^2·d) and 161.744 g/d, respectively, while in autumn, these values were 13.886 g/(m^2·d) and 98.458 g/d. Seasonal variations were also observed, with autumn and summer exhibiting higher carbon sequestration rates compared to spring and winter. Additionally, CO_2 concentrations were monitored across the four residential areas, providing insights into the spatial and temporal dynamics of carbon sequestration.

Discussion: Based on the findings, optimization strategies were proposed, such as prioritizing the selection and integration of high-performing evergreen tree species in urban green space design and incorporating diverse plant types to enhance year-round carbon sequestration. This study contributes to the development of sustainable urban planning and landscape management practices, promoting the role of green spaces in mitigating climate change and enhancing urban resilience.

KEYWORDS

greenhouse gases, green spaces in urban residential areas, assimilation method, carbon sequestration per unit projected canopy area, carbon sequestration of the whole plant

1 Introduction

The global climate change has emerged as the most pressing environmental challenge confronting human development, with anthropogenic activities resulting in greenhouse gas emissions recognized as the primary driver of global warming since the mid-20th century (Jiang et al., 2023; Tao et al., 2023; Zhang et al., 2023; Moody et al., 2021). Urban areas not only serve as focal points for fossil fuel consumption and greenhouse gas emissions but also experience significant impacts of climate change on human life. Amidst the persistent threat of climate change, reducing urban carbon dioxide emissions and enhancing carbon sequestration capabilities are identified as crucial strategies to combat climate change and alleviate its effects on cities (Yu et al., 2024a; Wang et al., 2013).

China, being one of the largest carbon dioxide emitters globally, announced in September 2020 its commitment to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, aiming to advance the adoption of sustainable development practices (Zhang et al., 2024). Urban green spaces, being the sole ecological spaces in cities closely linked to nature, assume a vital role in upholding carbon equilibrium, fostering human health, and offering ecosystem services (Leppänen et al., 2024; Yuan et al., 2023; Dong et al., 2023). Notably, green spaces within residential areas form the central element of urban green space networks. By augmenting the quantity and enhancing the quality of carbon sinks, it becomes possible not only to sustain the carbon-oxygen balance in cities, enhance the environment, and regulate urban microclimates but also to effectively alleviate carbon emission pressures and optimize ecological advantages (Wang et al., 2014; Lindén et al., 2020). Therefore, gaining a comprehensive understanding of current carbon sink measurement techniques, analyzing future development trajectories, and visualizing carbon management are key catalysts in attaining the “dual carbon” objectives.

The calculation methods for estimating carbon sequestration capacity in urban residential areas generally involve field-based data collection, statistical methods, remote sensing technology, GIS, and ecosystem modeling. Field-based data collection and statistical methods entail measuring vegetation biomass in green spaces like trees, shrubs, and grass, and estimating their carbon absorption rates. Common measurement indicators used include tree diameter at breast height, height, canopy width, etc., combined with plant growth models for estimating carbon sequestration. Tadesse et al. employed a systematic sampling design, establishing 30 sample plots along seven transects to assess woody plants, collect soil samples, and measure the biomass of dead branches and fallen leaves. The biomass carbon stock was subsequently estimated using an allometric growth equation (Tadesse and Tamiru, 2024). Bulusu et al. conducted a comprehensive literature review, summarizing research on above-ground carbon (AGC) and soil organic carbon (SOC) storage in Miombo woodlands from 1960 to 2018, with a focus on carbon storage variations across different forest types (Bulusu et al., 2021). Liu et al. utilized forest survey data and literature review to compile a biomass dataset for mature forests in China, analyzing the spatial distribution of carbon density and employing interpolation techniques to estimate the carbon carrying capacity of Chinese forests (Liu et al., 2014). Liu et al. taking Shenyang as a case study, evaluated the carbon storage and sequestration potential of urban forests through field surveys and high-resolution imagery, calculating their monetary value and exploring their contribution to offsetting carbon emissions. However, the statistical methods employed in field surveys are susceptible to human error and limited sampling scope, which may lead to deviations from actual conditions (Liu and Li, 2012). Additionally, these methods are unsuitable for large-scale regional assessments, as they cannot fully capture the spatial distribution of carbon sink capacity across a given area. Large-scale field surveys also require considerable human and financial resources and are often inefficient, posing challenges in meeting the demands of extensive carbon sink evaluations.

Remote sensing technology and geographic information systems (GIS) are instrumental in mapping urban green space distribution and vegetation cover through satellite imagery and GIS tools. By analyzing remote sensing data alongside vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), researchers can assess the health and growth of vegetation, providing an indirect estimate of the carbon sequestration capacity of green spaces (Huang et al., 2023; Yu et al., 2019). Pascual et al. integrated airborne laser scanning data with multi-source satellite imagery to estimate the above-ground carbon density and productivity of Hawaiian forests. This approach led to the creation of forest cover maps and the development of a carbon sequestration potential index, which identifies regions with the highest afforestation potential (Pascual et al., 2021). Torre-Tojal et al. (2022) leveraged forest resource survey data, allometric growth equations, and LiDAR data, employing a random forest model to estimate the biomass of radiata pine in the Basque Country. The model was optimized through hyperparameter tuning and cross-validation, resulting in an R^2 value greater than 0.7. Niu et al. introduced the CEVSA-ES model, which combines remote sensing leaf area index data to evaluate ecosystem services across China’s four major ecosystems (Niu et al., 2021). This model innovatively incorporates the effects of soil erosion on the carbon cycle and refines the carbon-water cycle algorithm. Despite the advancements in remote sensing and GIS technologies, model inversion techniques are influenced by input parameters, spectral resolution, and sensor accuracy, which can lead to substantial errors. These technologies face challenges in distinguishing complex vegetation structures and differentiating between various carbon pools, such as soil and dead organic matter. Even with improved resolution, accurately assessing the carbon sequestration potential of individual vegetation units in complex urban environments remains difficult. Additionally, the high costs associated with equipment and the acquisition of image data, particularly from commercial satellite sources, pose significant barriers to the widespread application of these technologies.

The ecosystem modeling approach employs various ecosystem process models, such as InVEST, i-Tree, and the assimilation method, to simulate the carbon cycle processes within urban green spaces. This approach integrates carbon inputs, such as photosynthesis, with carbon outputs, including respiration and decomposition, to comprehensively estimate the dynamic changes in carbon sequestration across these green spaces (Yu et al., 2024b; Alberdi et al., 2020; Sun and Liu, 2020). The InVEST model evaluates the carbon sequestration capacity of green spaces by simulating ecosystem processes and incorporating spatial data alongside ecological models. It further analyzes the impact of land use changes on carbon sequestration, thereby classifying it as an ecosystem modeling technique, and integrates GIS and remote sensing data. He et al. combined the LUSD (Land Use and Spatial Development) urban model with the InVEST model to assess the effects of urban expansion on regional carbon storage, simulating and forecasting urban growth patterns (He et al., 2016). Kaur et al. applied the InVEST model to carbon sequestration quantification for the years 2000 and 2020, aggregating biophysical data. i-Tree, a widely used model, assesses the ecosystem services provided by urban trees and forests, estimating carbon storage, air purification, and stormwater interception capabilities based on field data (Kaur et al., 2022). Ismaili Alaoui et al. integrated the i-Tree model with drone-based modeling and field surveys to estimate carbon storage in urban parks, reporting a carbon storage of 15.3 tons per hectare, with an average carbon storage of 8.6 tons per planted area (Ismaili Alaoui et al., 2023). Liu et al. introduced the SVGD-AE method, which combines Stein Variational Gradient Descent (SVGD) with Autoencoder (AE) neural networks in a geostatistical inversion framework to estimate geological carbon sequestration, thereby highlighting the application of advanced modeling techniques in quantifying carbon sequestration (Liu et al., 2024). The ecosystem modeling approach integrates remote sensing data with field observation data, enabling analyses across regional to global scales and effectively addressing data gaps. The model's grid resolution is flexible and adjustable, catering to the diverse needs of various research endeavors. Once the model is established, its operational costs are relatively low, making it especially suitable for long-term simulations and large-scale studies. The method employed in this study, known as the equivalence quantification method, is a type of ecosystem model that simulates carbon storage and sequestration capacity using field data and input variables such as climate and vegetation. It incorporates key processes such as photosynthesis, respiration, and soil carbon turnover, facilitating large-scale spatial analysis and trend forecasting, while maintaining both cost-effectiveness and applicability.

This study aims to assess the carbon sequestration capacity of different vegetation types in residential green spaces in Nanjing, along with the factors influencing this capacity, to provide scientific guidance for optimizing the ecological functions of urban green spaces. The research hypothesis posits that vegetation types—specifically evergreen trees, deciduous trees, evergreen shrubs, and deciduous shrubs—along with key growth parameters such as diameter at breast height, crown spread, and plant height, significantly affect carbon sequestration capacity. Additionally, seasonal variations are expected to play a critical role in modulating carbon sequestration.

2 Materials and methods

2.1 Experimental area

Nanjing is located in the central region of the Yangtze River Delta in eastern China, serving as a key gateway city in the Yangtze River Delta. Its geographical coordinates range from 31°14′ to 32°37′ north latitude and 118°22′ to 119°14′ east longitude. The total area is 6,587.04 km^2, with an urban built-up area of 868.28 km^2 as of 2020. Nanjing has a subtropical humid climate with distinct seasons and abundant rainfall. The forest coverage rate is 31.3%, and the urban greening coverage rate is 45.16%, ranking it among the top three in China. It is one of China's four major garden cities and is known as the "Green Capital."

To investigate the differences in carbon sequestration capacity across various plant types, this study selects four representative residential areas in Nanjing, highlighted with red pentagrams in Figure 1. These areas—Tanqiao Apartment, Luotuolula Town, Yinxiang Xinyu, and Yihe South Park—are all situated within the subtropical monsoon climate zone, characterized by warm, humid weather and distinct seasons. The regions experience abundant annual rainfall and ample sunlight, particularly in the spring and summer, providing favorable conditions for plant growth. The soil in these areas is diverse, fertile, and well-drained, promoting healthy root development. Due to the varying functions and designs of the residential communities, the plant species in each area differ notably. Specifically, Yihe South Park is predominantly planted with evergreen trees, Luotuolula Town features mainly deciduous trees, Tanqiao Apartment is primarily planted with evergreen shrubs, and Yinxiang Xinyu mostly contains deciduous shrubs.

The Yihe South Park (31°91′10″ N, 118°82′01″ E) site has a total area of 10,000 m^2, with a built-up area of 2,364 m^2 and a greening area of 5,619 m^2. The park's paved garden paths cover 2,017 m^2. The park is home to 105 households and 335 residents. The predominant plant species are evergreen trees, with representative species including *Magnolia grandiflora*, *Cinnamomum camphora*, *Osmanthus fragrans*, *Ilex crenata*, *Phoebe sheareri*, *Salix babylonica*, *Ginkgo biloba*, and *Prunus yedoensis*. The Luotuolula Town (31°90′92″ N, 118°85′65″ E) site also covers 10,000 m^2, with a built-up area of 1,630 m^2 and a greening area of 6,720 m^2. The paved garden paths within the site cover 1,539 m^2. Luotuolula Town has 104 households and 330 residents. The dominant plant species are deciduous trees, including *S. babylonica*, *G. biloba*, *P. yedoensis*, *Celtis sinensis*, and *Zelkova serrata*. The Tanqiao Apartment (31°92′44″ N, 118°84′64″ E) site spans 10,000 m^2, with a built-up area of 2,143 m^2 and a greening area of 5,169 m^2. The paved garden paths within the green area cover 2,688 m^2. Tanqiao Apartment has 110 households and 336 residents. The main plants are evergreen shrubs, including *Buxus sinica*, *Camellia japonica*, *Rhododendron sims*, *Photinia serrulata*, and *Aucuba japonica var.*

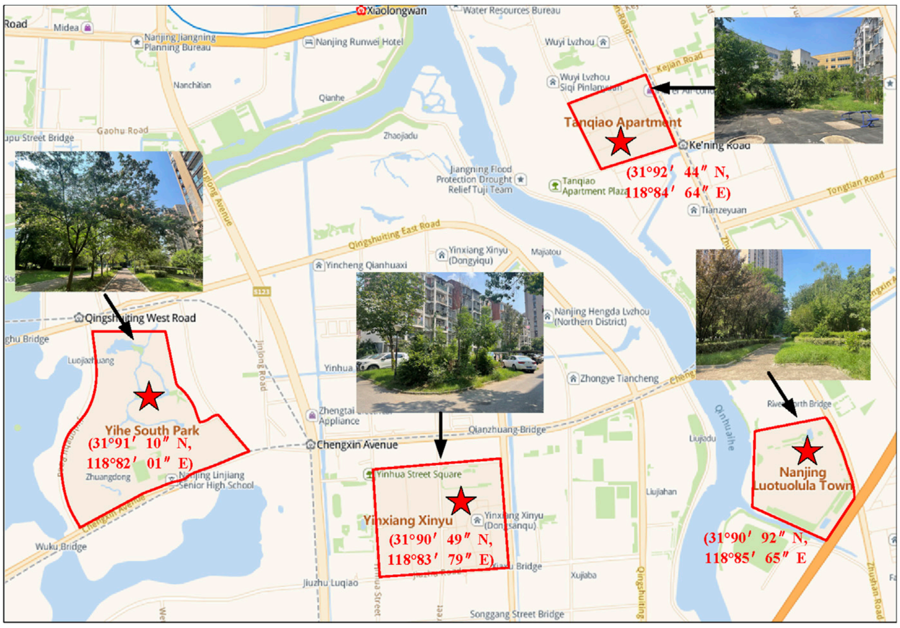

FIGURE 1
Distribution map of experimental area.

The Yinxiang Xinyu (31°90′49″ N, 118°83′79″ E) site also has a total area of 10,000 m^2, with a built-up area of 1,740 m^2 and a greening area of 6,831 m^2. The paved garden paths in the green area cover 1,540 m^2. Yinxiang Xinyu has 90 households and 290 residents. The main plants are deciduous shrubs, including *Chimonanthus praecox*, *Forsythia viridissima*, *Ligustrum quihou*, *Lagerstroemia indica cv*, and *Chaenomeles speciosa*.

2.2 Experimental method

This study is based on a comprehensive survey of plant types in the residential green spaces of four communities, systematically documenting the distribution of plant species within each sample plot. To investigate the carbon sequestration capacity of these plants, we selected the 20 most commonly planted species for detailed analysis (Rasoolzadeh et al., 2024). Growth parameters, including diameter at breast height, crown spread, and plant height, were measured using a tape measure, and these key growth characteristics were recorded for each species. Using these parameters, along with a plant taxonomy reference, the plants were classified into categories of evergreen trees, deciduous trees, evergreen shrubs, and deciduous shrubs, as summarized in the Table 1.

Based on the principles of plant photosynthesis, the daily carbon fixation of plants was calculated using the daily variation in the net photosynthetic rate, measured with a Li-6400XT portable photosynthesis system produced by Li-COR Biosciences. The seasonal divisions were based on the Spring Equinox, Summer Solstice, Autumn Equinox, and Winter Solstice. For each season, three clear, windless, and cloudless days were selected: March 24–30, 2023 (Spring), June 23–30, 2023 (Summer), September 22–30, 2023 (Autumn), and December 20–30, 2023 (Winter). During these days, measurements were taken under natural sunlight from 8:00 a.m. to 6:00 p.m., at 2-h intervals. The measurement sequence for the plants was kept consistent throughout the day. Three healthy, pest-free plants were selected, with five mature, sun-exposed leaves of similar size chosen from each plant. At each time point, five instantaneous net photosynthetic rate readings were recorded per leaf, and the average value was calculated. A total of 1,350 measurements were recorded for each tree in every season. The leaf area (LAI) was measured using optical instruments and image analysis. Canopy images were captured with a fisheye lens and digital camera, and processed with Hemiview canopy analysis software to calculate parameters such as solar radiation transmittance, canopy gap size, and gap fraction, ultimately determining the effective LAI (Bai and Ding, 2024; Jin et al., 2023; Nayak et al., 2022).

The Formula 1 for calculating the net assimilation rate of the current day is:

$$LAI = \frac{W \cdot SLA}{C} \tag{1}$$

In the formula, LAI represents the leaf area index of the plant; W is the total dry weight of the plant's leaves, kg; C is the plant's crown area, m^2; SLA stands for specific leaf area, cm^2/g.

Select five representative healthy plants for measurement and compute the average value. Capture photographs of the plants under overcast conditions to avoid direct sunlight. The Formula 2 for calculating the net assimilation rate P on the measurement day is (Liu et al., 2013; Smith and Ramsay, 2018; Author Anonymous, 2002):

$$P = \sum_{i=1}^{j} \left[\left(p_{i+1} + p_i \right) \div 2^* \left(t_{i+1} - t_i \right)^* 3600 \div 1000 \right] \tag{2}$$

In the equation, P represents the net assimilation total of the day, $mmol \cdot m^{-2} \cdot d^{-1}$; p_i represents the instantaneous photosynthetic rate at the initial measuring point, $\mu mol \cdot m^{-2} \cdot d^{-1}$; p_{i+1} represents the instantaneous photosynthetic rate at the next measuring point, $\mu\mathrm{mol}\cdot\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$; t_i represents the instant time at the initial measuring point, h; t_{i+1} represents the instant time at the initial measuring point, h; j represents the number of tests.

This study assumes that the carbon dioxide released by plants during nocturnal dark respiration constitutes 20% of the daytime assimilation rate, treating this proportion as a fixed value without adjustments based on empirical data. Additionally, it is assumed that plants exclusively undergo dark respiration at night, with no photosynthetic activity occurring during this period. Consequently, the calculation of daytime net photosynthesis excludes respiratory processes (Kohonen et al., 2022). Measurements were taken at the seasonal nodes of the vernal equinox, summer solstice, autumnal equinox, and winter solstice, under the assumption that environmental conditions within each season remain relatively stable, and that nocturnal respiration rates are not subject to significant fluctuations. Furthermore, the plants selected for this study were healthy, pest-free individuals, with the assumption that their respiratory metabolism was not notably influenced by disease or external stress factors. The proportion of dark respiration is treated as an empirical constant, with no further differentiation made for plant type, age, or seasonal variations in respiration intensity. The total daily assimilation rate is converted into a fixed carbon dioxide mass for each measurement day, as described in the following Formula 3 (Dou et al., 2023):

$$w_{CO_2} = P(1-0.2)\times\frac{44}{1000} \tag{3}$$

In the equation, w_{CO_2} represents the mass of carbon dioxide fixed per unit area of leaf; 44 represents the molar mass of carbon dioxide.

Using a fixed percentage (20%) to estimate carbon dioxide release during nighttime respiration offers a simplified approach to modeling but is not without limitations. Respiration rates are highly variable and influenced by factors such as plant species, age, environmental conditions, and seasonal dynamics. As a result, the fixed-percentage method often fails to accurately capture the complexity of actual respiration processes. Furthermore, plant respiration patterns exhibit significant fluctuations over the course of their growth cycles. To improve the accuracy of such estimations, direct measurements—such as those obtained using the Li-6400XT photosynthesis system—can provide more precise and reliable data, thereby minimizing errors associated with the fixed-percentage assumption. In addition, regression models derived from empirical data can establish relationships between respiration rates and environmental variables, further refining carbon sequestration estimates. While the fixed-percentage approach offers simplicity, the integration of dynamic, data-driven methods yields more accurate and scientifically robust results.

The carbon sequestration per unit of canopy projection area is a critical parameter for quantifying urban carbon sequestration. As a standardized metric, it enables the evaluation of carbon uptake efficiency across different tree species, reduces uncertainties arising from the structural complexity of vegetation, and supports both dynamic monitoring and regional-scale assessments of carbon sequestration capacity. This metric provides a scientific basis for advancing urban carbon neutrality strategies. Moreover, it facilitates the comparison and optimization of green space distribution, enhances the efficiency of urban carbon sinks, and can be updated to account for plant growth, thereby meeting the requirements for long-term monitoring and predictive modeling. Overall, this approach is of considerable value for the management and optimization of urban ecosystems. The Formula 4 for calculating the daily carbon fixation per unit canopy projection area for individual plants is as follows:

$$W_{CO_2} = w_{CO_2}\times LAI \tag{4}$$

The total carbon sequestration by the entire plant is:

$$S_{CO_2} = w_{CO_2}\times C \tag{5}$$

In the Formula 5, C represents the crown width area, in square meters, m^2.

2.3 Statistical analysis

In this study, Principal Component Analysis (PCA) was first employed for dimensionality reduction and feature selection. By transforming the original variables into a set of uncorrelated principal components, PCA identifies the directions of maximum variance in the data. This approach effectively reduces dimensionality while retaining the most critical information that explains the majority of the variance. The process simplifies the data structure, eliminates redundancy among variables, and generates a robust feature set for subsequent analyses (Marteau et al., 2023).

Following PCA, Spearman's rank correlation analysis was conducted to explore the relationships between tree species, seasonal variations, and plant carbon sequestration capacity. The Spearman correlation coefficient, ranging from −1 to +1, was calculated to measure the strength and direction of these relationships. A coefficient of 0 indicates no correlation, +1 represents a perfect positive correlation, and −1 signifies a perfect negative correlation. This analysis provides insights into how tree species and seasonal dynamics influence carbon sequestration, offering valuable information for ecological management and urban planning.

Finally, one-way Analysis of Variance (ANOVA) was applied to evaluate the statistical significance of differences in daily carbon sequestration per unit canopy projection area and total plant carbon sequestration. ANOVA determines whether the mean values of a dependent variable differ significantly across multiple groups. To further investigate pairwise group differences, *post hoc* analysis was conducted using the Games-Howell test, which is particularly suitable for datasets with unequal sample sizes or heterogeneous variances. The Games-Howell test also controls for multiple comparisons, enhancing the reliability of the results. A p-value less than 0.05 was considered statistically significant, indicating meaningful differences between groups. This method demonstrates strong robustness under complex data conditions, ensuring the accuracy, reliability, and scientific rigor of the findings.

3 Results

3.1 Plant carbon sequestration capacity

As summarized in the Table 2, the growth parameters of trees exhibit considerable variation. The diameter at breast height (DBH)

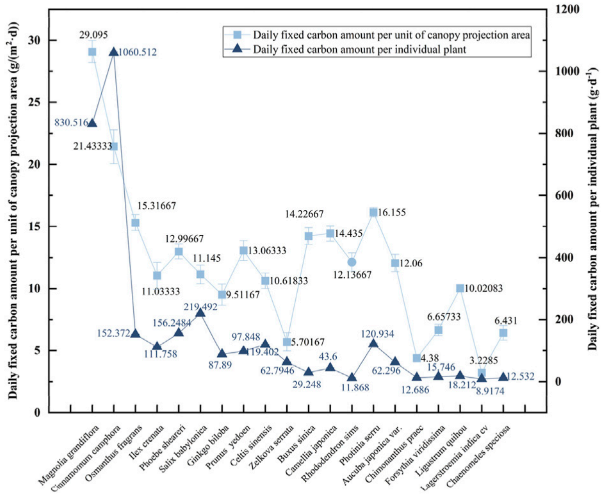

FIGURE 2
Comparison of carbon sequestration between plant unit canopy area and whole plant.

ranges from 13.7 to 66.3 cm, canopy spread spans 2.8–6.7 m, individual tree height varies between 3.3 and 18.2 m, and the height of the lowest branches ranges from 0.88 to 5.6 m. In contrast, shrubs demonstrate significantly smaller growth dimensions. For shrubs, DBH ranges from 0.3 to 2.4 cm, canopy spread varies between 0.7 and 1.8 m, individual height spans 0.7–3.6 m, and the height of the lowest branches ranges from 0.1 to 0.5 m.

Figure 2 illustrates the carbon sequestration performance of the tested plant species, including two key metrics: carbon sequestration per unit canopy projection area and total carbon sequestration at the whole-plant level. Carbon sequestration per unit canopy projection area represents the amount of CO_2 fixed through photosynthesis within the area covered by the plant's canopy projection. In contrast, total carbon sequestration measures the overall CO_2 absorption and fixation by the entire plant. These parameters are critical for evaluating the carbon sequestration capacity of plants and their role as carbon sinks within ecosystems.

The carbon sequestration per unit canopy projection area among the tested plants ranges from 3.2285 to 29.095 g/(m^2·d). *Magnolia grandiflora* demonstrates the highest rate at 29.095 g/(m^2·d), while *L. indica cv.* exhibits the lowest rate at 3.2285 g/(m^2·d). Among the tested species, *M. grandiflora*, *C. camphora*, and *O. fragrans* rank among the top three in carbon sequestration efficiency, while *Z. serrata*, *C. praecox*, and *L. indica cv.* show the weakest performance. Total daily carbon sequestration values range from 11.868 to 1060.512 g/d. *Cinnamomum camphora* achieves the highest total sequestration rate at 1060.512 g/d, followed by *M. grandiflora* (830.516 g/d), *S. babylonica* (219.429 g/d), and *P. serrulata* (120.934 g/d). By contrast, *L. indica cv.* exhibits the lowest total carbon sequestration at just 8.92 g/d. Shrubs such as *Rhododendron simsii*, *C. praecox*, and *C. speciosa* display significantly lower carbon sequestration capacities compared to larger tree species such as *C. camphora*. Overall, trees consistently outperform shrubs in terms of carbon sequestration, with shrubs exhibiting values well below the average.

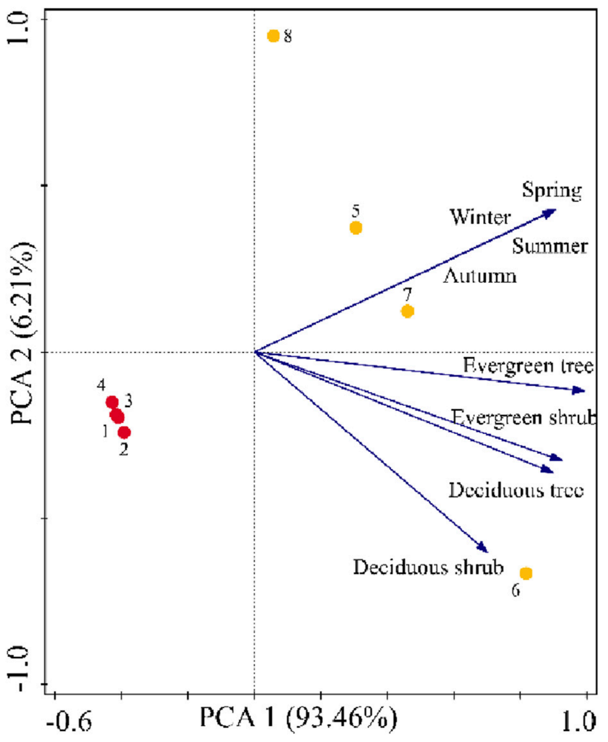

FIGURE 3
Principal component analysis (PCA) of seasonal and species effects on daily carbon sequestration.

Among evergreen trees, carbon sequestration per unit canopy projection area ranges from 11.033 to 29.095 g/(m^2·d). *Magnolia grandiflora* exhibits the highest rate, followed by *C. camphora* and *O. fragrans*, while *I. crenata* shows the lowest. In deciduous trees, species such as *S. babylonica, Prunus × yedoensis*, and *C. sinensis* demonstrate relatively high sequestration rates, with *Z. serrata* having the lowest rate at just 5.7 g/(m^2·d). Among evergreen shrubs, *P. serrulata* has the highest carbon sequestration per unit canopy projection area at 16.155 g/(m^2·d). Other evergreen shrub species exhibit similar values, all exceeding 12 g/(m^2·d). In deciduous shrubs, sequestration rates range from 3.2285 to 10.02 g/(m^2·d), with *Ligustrum quihoui* achieving the highest rate at 10.02 g/(m^2·d) and *L. indica cv.* the lowest at 3.23 g/(m^2·d).

For total plant carbon sequestration, evergreen trees demonstrate a wide range of values, from 111.758 to 1060.512 g/d. *Cinnamomum camphora* exhibits the highest total carbon sequestration capacity, followed by *M. grandiflora* and *O. fragrans*, while *I. crenata* shows the weakest performance. Among deciduous trees, *S. babylonica*, *G. biloba*, and *C. sinensis* demonstrate stronger carbon sequestration capacities, with *S. babylonica* reaching 219.492 g/d—nearly four times that of *Z. serrata*. In evergreen shrubs, *C. japonica* and *P. serrulata* exhibit the highest total carbon sequestration rates, at 43.6 g/d and 120.934 g/d, respectively, significantly outperforming other evergreen shrub species. Among deciduous shrubs, *L. quihoui* exhibits the highest total carbon sequestration rate at 18.212 g/d, while *L. indica cv.* shows the lowest rate at 8.917 g/d.

TABLE 1 Plant types, families, features, and uses: A detailed overview.

Label	Plants	Plant type	Family	Characteristics	Use
1	*Magnolia grandiflora*	Evergreen trees	Magnoliaceae	Flower large and fragrant, ideal for ornamental purposes	Ornamental tree with fragrant flowers, used in parks and gardens
2	*Cinnamomum camphora*	Evergreen trees	Lauraceae	Leaves with a fragrant scent, bark has a camphor-like aroma	Fragrant leaves and bark, used in spices and medicine; found in green spaces
3	*Osmanthus fragrans*	Evergreen trees	Oleaceae	Small fragrant flowers that bloom in autumn	Fragrant flowers, used in landscaping and flower beds
4	*Ilex crenata*	Evergreen trees	Aquifoliaceae	Red to black fruits, tolerant of shade	Used for hedges and ornamental shrubs, tolerant of shade
5	*Phoebe sheareri*	Evergreen trees	Lauraceae	Yellow flowers, commonly used for timber production	Timber used in construction, aromatic flowers, used in landscaping
6	*Salix babylonica*	Deciduous trees	Salicaceae	Weeping branches, well-suited for moist environments	Used in wetland areas and urban green spaces near water for stabilization
7	*Ginkgo biloba*	Deciduous trees	Ginkgoaceae	Fan-shaped leaves, fruit with a foul smell, highly resistant to pollution	Ornamental tree, tolerant of pollution, used in street plantings
8	*Prunus × yedoensis*	Deciduous trees	Rosaceae	Pink to white flowers in spring, short blooming period	Spring-flowering ornamental, used in parks and streetscapes
9	*Celtis sinensis*	Deciduous trees	Ulmaceae	Rough bark, small berry-like fruit, commonly used for landscaping	Street tree, pollution-tolerant, provides shade in urban areas
10	*Zelkova serrata*	Deciduous trees	Ulmaceae	Gray bark, leaves change color in autumn, perfect for garden settings	Used in street plantings and parks, tolerant of pruning
11	*Buxus sinica*	Evergreen Shrubs	Buxaceae	Small opposite leaves, ideal for hedging and pruning	Used for hedges and flower beds, easy to trim
12	*Camellia japonica*	Evergreen Shrubs	Theaceae	Large, vibrant flowers, thrives in shady conditions	Ornamental shrub with vibrant flowers, used in gardens and parks
13	*Rhododendron sims*	Evergreen Shrubs	Ericaceae	Large, brilliant flowers, commonly found in warm, humid environments	Ornamental plant for warm, humid areas, used in flower beds and parks
14	*Photinia serrulata*	Evergreen Shrubs	Rosaceae	Smooth leaves, red fruits, frequently used for hedges	Ornamental plant and hedge, adds color to landscapes
15	*Aucuba japonica* var.	Evergreen Shrubs	Cornaceae	Spotted leaves, tolerant of shade, often used in indoor landscaping	Shade-tolerant ornamental plant, used indoors or in shaded gardens
16	*Chimonanthus praec*	Deciduous Shrubs	Calycanthaceae	Yellow fragrant flowers, blooms typically in winter	Winter-flowering plant with strong fragrance, used in winter landscaping
17	*Forsythia viridissima*	Deciduous Shrubs	Oleaceae	Yellow flowers in spring, abundant blossoms, great for garden landscaping	Spring-flowering plant, adds color to gardens and parks
18	*Ligustrum quihou*	Deciduous Shrubs	Oleaceae	Small leaves, white flowers, commonly used for hedging	Used in hedges and parks, easy to maintain
19	*Lagerstroemia indica cv*	Deciduous Shrubs	Lythraceae	Flowers bloom in summer, long-lasting bloom period, ideal for garden settings	Ornamental tree with long flowering period, used in streets and parks
20	*Chaenomeles speciosa*	Deciduous Shrubs	Rosaceae	Red to pink flowers in spring, small fruits, perfect for floral borders	Ornamental plant with colorful flowers, used in garden borders

3.2 Seasonal and plant type variations in carbon sequestration

Figure 3 presents the results of a Principal Component Analysis (PCA) performed on the experimental data, effectively underscoring the primary research focus. The data exhibit a predominantly bimodal distribution along the Y-axis, with the left-hand cluster (red points) corresponding to carbon sequestration per unit canopy projection area and the right-hand cluster (orange points) representing total plant carbon sequestration. This study aims to elucidate the effects of seasonal variation and plant species on both carbon sequestration metrics, specifically unit canopy projection area carbon sequestration and total plant carbon sequestration.

Table 3 presents the Spearman correlation coefficients for carbon sequestration per unit canopy projection area across different seasons and plant types. A seasonal correlation analysis reveals a significant positive correlation between spring and all other seasons (summer, autumn, and winter), with coefficients of 0.727, 0.646, and 0.450 ($p < 0.01$), respectively. This suggests a strong consistency in carbon sequestration dynamics between spring and

TABLE 2 Morphological measurements of selected plant species: DBH, crown width, and height.

Label	Plants	Diameter at breast height/cm	Crown width/m	Plant height/m	Clear stem height/m
1	*Magnolia grandiflora*	66.3	4.4	18.2	3.3
2	*Cinnamomum camphora*	55.2	6.7	15.7	3.7
3	*Osmanthus fragrans*	27.3	3.2	3.8	0.88
4	*Ilex crenata*	29.7	3.3	8.7	2.91
5	*Phoebe sheareri*	31.7	3.4	8.8	2.9
6	*Salix babylonica*	20.7	4.1	7.2	5.6
7	*Ginkgo biloba*	33.7	2.9	13.5	2.8
8	*Prunus × yedoensis*	13.7	2.8	3.3	1.1
9	*Celtis sinensis*	23.2	3.3	6.7	1.8
10	*Zelkova serrata*	24.1	3.1	9.3	3.2
11	*Buxus sinica*	0.7	1.4	3.6	0.2
12	*Camellia japonica*	1.1	1.8	1.7	0.3
13	*Rhododendron sims*	1.7	1.0	0.8	0.2
14	*Photinia serrulata*	2.4	1.3	2.7	0.1
15	*Aucuba japonica* var.	0.3	0.7	0.7	0.2
16	*Chimonanthus praec*	2.2	1.8	1.9	0.5
17	*Forsythia viridissima*	1	1.7	1.6	0.1
18	*Ligustrum quihou*	0.9	1.6	1.8	0.2
19	*Lagerstroemia indica cv*	1.2	1.7	1	0.2
20	*Chaenomeles speciosa*	0.7	1.4	1.4	0.2

TABLE 3 Statistical correlations between seasonal changes and plant functional groups.

	Spring	Summer	Autumn	Winter	Evergreen trees	Deciduous trees	Evergreen shrubs	Deciduous shrubs
Spring	1							
Summer	0.727**	1						
Autumn	0.646**	0.889**	1					
Winter	0.450**	0.814**	0.887**	1				
Evergreen Trees	0.643**	0.37	0.144	0.275	1			
Deciduous Trees	0.445*	0.386	0.124	0.072	0.189	1		
Evergreen Shrubs	−0.103	−0.053	0.123	0.053	−0.093	0.085	1	
Deciduous Shrubs	0.355	0.302	0.064	0.152	0.213	0.171	−0.692**	1

** indicates $P < 0.01$, * indicates $P < 0.05$.

the other seasons, likely driven by the favorable temperatures and sunlight conditions in spring, which enhance photosynthetic activity and increase carbon fixation capacity. Notably, the correlation between summer and autumn is particularly strong, reaching 0.889, indicating a high degree of similarity in carbon sequestration patterns between these two seasons. In contrast, winter exhibits weaker correlations with other seasons, particularly with spring, where the coefficient is only 0.450. This

TABLE 4 Correlation analysis between seasonal changes and plant types.

	Spring	Summer	Autumn	Winter	Evergreen trees	Deciduous trees	Evergreen shrubs	Deciduous shrubs
Spring	1							
Summer	0.98**	1						
Autumn	0.976**	0.984**	1					
Winter	0.543**	0.588**	0.668**	1				
Evergreen Trees	0.448*	0.464*	0.402*	0.366	1			
Deciduous Trees	0.266	0.221	0.074	−0.052	−0.193	1		
Evergreen Shrubs	−0.335	−0.265	−0.236	−0.196	−0.294	−0.201	1	
Deciduous Shrubs	0.178	0.123	0.193	0.271	0.349	−0.274	−0.759**	1

** indicates P < 0.01, * indicates P < 0.05.

can be attributed to the reduced temperatures and daylight hours in winter, which decrease photosynthetic rates and, consequently, carbon sequestration.

When examining correlations across plant types, we find that evergreen trees exhibit relatively stable carbon sequestration across seasons, with a correlation coefficient of 0.643 ($p < 0.01$) with spring, indicating minimal seasonal variation in their carbon fixation. In contrast, deciduous trees display weaker seasonal correlations, particularly in autumn and winter, with coefficients of 0.124 and 0.072 ($p < 0.05$), respectively. This suggests that deciduous trees are more sensitive to seasonal fluctuations, especially in autumn and winter, when leaf loss and reduced photosynthetic activity lead to a significant decrease in carbon sequestration. Evergreen shrubs generally exhibit low correlations with seasonal variations, with coefficients of −0.103 and −0.053 for spring and summer ($p > 0.05$), indicating that their carbon sequestration fluctuates less across seasons. This could be due to their evergreen nature and relatively low photosynthetic efficiency. In contrast, deciduous shrubs display a more complex seasonal pattern: while correlations with other seasons are generally low, the intra-group correlation is negative (−0.692, $p < 0.01$), suggesting that their carbon sequestration is highly sensitive to seasonal changes, with pronounced fluctuations in carbon fixation across different seasons.

Table 4 presents the Spearman correlation coefficients for carbon fixation in whole plants across different seasons and plant types. Notably, the spring season exhibits significant positive correlations with the other seasons (summer, autumn, and winter), with coefficients of 0.98, 0.976, and 0.543 ($p < 0.01$), respectively. This suggests a high degree of consistency in carbon fixation between spring and the other seasons, likely attributed to the optimal growth conditions in spring, including sufficient sunlight and favorable temperatures, which enhance photosynthesis and carbon fixation capacity. A strong correlation is observed between summer and autumn, with a coefficient of 0.984, indicating near-perfect synchrony in carbon fixation between these two seasons. In contrast, the correlation in winter is weaker, particularly with spring and summer, with coefficients of 0.543 and 0.588, respectively. This is likely due to the limiting effects of low temperatures and short daylight hours on photosynthesis and carbon fixation during winter.

Among the different plant types, evergreen trees exhibit relatively strong seasonal correlations, particularly in spring, summer, and autumn, with coefficients of 0.448, 0.464, and 0.402 ($p < 0.05$), respectively. This suggests that evergreen trees maintain relatively stable carbon fixation across seasons, characterized by consistent photosynthetic activity. In contrast, deciduous trees display weaker seasonal correlations, especially in autumn and winter, with coefficients of 0.074 and −0.052, indicating that their carbon fixation capacity is highly influenced by seasonal changes, particularly during autumn and winter when leaf loss reduces photosynthesis and carbon fixation. Evergreen shrubs also exhibit low seasonal correlations, with coefficients of −0.335 and −0.265 in spring and summer ($p > 0.05$), which may be attributed to their lower photosynthetic efficiency and less pronounced changes in carbon fixation during seasonal transitions. The seasonal correlation of deciduous shrubs is more complex, with an overall weak correlation. However, in spring and winter, the correlation coefficients are 0.178 and 0.271, respectively, suggesting that deciduous shrubs maintain some photosynthetic activity during these seasons. Furthermore, the correlation between deciduous shrubs and other plant types (such as evergreen trees, deciduous trees, and evergreen shrubs) is relatively low, but the within-group correlation is stronger (e.g., with evergreen shrubs at −0.759, $p < 0.01$), indicating that the carbon fixation of deciduous shrubs is strongly influenced by seasonal changes, with more significant fluctuations in carbon fixation across different seasons.

3.3 Carbon sequestration potential of different plant types

To further elucidate the carbon sequestration potential of diverse plant species, we categorized the plant samples into four distinct groups: Evergreen Trees, Deciduous Trees, Evergreen Shrubs, and Deciduous Shrubs. The comparative analysis of daily carbon sequestration rates for these plant types is presented in the

TABLE 5 Mean comparison and significance testing of different plant categories.

Plant type	Mean (A)/ g/(m^2·d)	Mean difference (A)	Standard error (A)	Significance (A)	Mean (B)/g/d	Mean difference (B)	Standard error (B)	Significance (B)
Evergreen trees	18.002				462.281			
Deciduous trees	9.980				117.485			
Evergreen Shrubs	13.774				53.589			
Evergreen trees	6.147				13.619			
Evergreen trees		8.023	1.428	0.001		344.796	82.700	0.002
		4.228	1.371	0.023		408.692	82.316	0.001
		11.855	1.412	0.001		448.663	81.961	0.001
Deciduous trees		−8.023	1.428	0.001		−344.796	82.700	0.002
		−3.794	0.620	0.001		63.896	13.453	0.001
		3.832	0.705	0.001		103.867	11.075	0.001
Evergreen Shrubs		−4.228	1.371	0.023		−408.692	82.316	0.001
		3.794	0.620	0.001		−63.896	13.453	0.001
		7.627	0.581	0.001		39.971	7.694	0.001
Deciduous Shrubs		−11.855	1.412	0.001		−448.663	81.961	0.001
		−3.832	0.705	0.001		−103.867	11.075	0.001
		−7.627	0.581	0.001		−39.971	7.694	0.001

table below, along with the results of the corresponding statistical significance tests. Specifically, the table displays the mean values, mean differences, standard errors, and p-values for both daily carbon sequestration per unit canopy projection area (denoted as A) and total daily carbon sequestration (denoted as B).

Table 5 presents a comprehensive comparison of the average daily carbon sequestration rates per unit canopy projection area across various plant categories. Evergreen trees exhibit the highest sequestration rate, at 18.0024 g/(m^2·d), significantly outperforming all other plant types. In contrast, deciduous shrubs display the lowest rate, at 6.1474 g/(m^2·d). Notably, both evergreen trees and shrubs demonstrate higher carbon sequestration rates compared to their deciduous counterparts. The superior performance of evergreen trees can be attributed to specific biological traits, including leaf morphology, leaf area index, photosynthetic rate, and respiration rate, which directly enhance their carbon fixation capacity. To further elucidate these differences, we conducted additional analyses using SPSS software and the Games-Howell *post hoc* test. These results indicate that the carbon sequestration rate of evergreen trees is 8.0228 g/(m^2·d) higher than that of deciduous trees, 4.2284 g/(m^2·d) higher than evergreen shrubs, and 11.8550 g/(m^2·d) higher than deciduous shrubs, with all differences achieving statistical significance. Furthermore, we observed significant differences in carbon sequestration between deciduous trees and evergreen shrubs [3.794 g/(m^2·d)], deciduous trees and deciduous shrubs [3.833 g/(m^2·d)], and evergreen shrubs and deciduous shrubs [7.622 g/(m^2·d)]. These findings underscore the substantial variability in carbon sequestration potential among different plant types.

In addition to the average daily carbon sequestration rates presented in Table 5, the table also provides the total carbon sequestration values for the entire plant (denoted as B) for each plant type. Evergreen trees exhibit the highest total carbon sequestration, averaging 462.28 g/d, while deciduous shrubs sequester the least, at only 13.618 g/d. Notably, within each plant category, evergreen trees sequester significantly more carbon than deciduous trees, and evergreen shrubs outperform deciduous shrubs. The ranking of carbon sequestration by plant type is as follows: evergreen trees > deciduous trees > evergreen shrubs > deciduous shrubs. Overall, trees generally sequester more carbon than shrubs, with this difference being statistically significant. This is primarily due to the larger size of trees, their broader leaf area, and more developed root systems, all of which enable them to accumulate more biomass (such as wood, bark, branches, and leaves) and absorb more water and nutrients through their stronger root systems, thereby enhancing their carbon sequestration capacity. In contrast, shrubs, due to their smaller size and simpler biological structures, exhibit weaker carbon sequestration capabilities. Further analysis using SPSS and the Games-Howell method confirmed significant differences in the daily carbon sequestration rates between plant types. Specifically, evergreen trees sequester 344.80 g/d more carbon than deciduous trees, 408.692 g/d more than evergreen shrubs, and 448.66 g/d more than deciduous shrubs, with all differences being statistically significant. Additionally, the differences between deciduous trees and evergreen shrubs (63.896 g/d), deciduous trees and deciduous shrubs (103.867 g/d), and evergreen shrubs and deciduous shrubs (39.97 g/d) were also found to be statistically significant.

In conclusion, evergreen trees demonstrate a marked superiority in carbon sequestration capacity per unit canopy projection area and total daily carbon sequestration compared to other plant types, with significant differences observed. This is primarily attributed to the larger canopy size and greater biomass of evergreen trees, which provide a greater surface area and extended time for photosynthesis, thereby facilitating the maximization of carbon sequestration through their long-lasting green foliage. In contrast, deciduous shrubs exhibit a weaker carbon sequestration capacity due to their smaller size and limited canopy and biomass, resulting in lower per unit canopy projection area and total daily carbon sequestration values compared to other plant types. Statistical analysis conducted using SPSS software and the Games-Howell method revealed a significant difference in carbon sequestration per unit canopy projection area between evergreen trees and deciduous trees and shrubs, with p-values below 0.001 and 0.05, respectively. These findings suggest that the ecological characteristics of plant species, including leaf morphology and photosynthetic rate, have a significant impact on carbon sequestration efficiency. This statistical analysis highlights the substantial differences in carbon sequestration capacities among plant types, providing valuable scientific insights for plant selection in ecological planning and management. The results of this study underscore the importance of considering the ecological characteristics of plant species in efforts to mitigate climate change and promote sustainable ecosystem management.

3.4 Seasonal carbon sequestration

The seasonal influence on daily carbon sequestration rates per unit canopy projection area varies significantly across plant species and environmental factors. To elucidate the dynamics of plant carbon sequestration capacity across different seasons, this study conducted a comprehensive analysis of the daily carbon sequestration rates for 20 plant species spanning the four seasons, as summarized in Table 6. The results indicate that autumn is characterized by the highest average daily carbon sequestration rate, at 13.886 g/(m^2·d), whereas summer exhibits a lower average value, which may be attributed to the more favorable light conditions in autumn that enhance photosynthesis. Notably, despite the reduced daylight duration in autumn compared to summer, the absence of stomatal closure in autumn facilitates sustained photosynthesis. In contrast, spring and winter exhibit the lowest carbon sequestration rates, averaging 6.363 g/(m^2·d) and 1.621 g/(m^2·d), respectively. This disparity is likely due to the detrimental effects of low temperatures in winter, which compromise the efficiency of photosynthesis and, consequently, lower carbon sequestration. The results of this study underscore the importance of considering seasonal variations in plant carbon sequestration capacity when developing strategies to mitigate climate change. Further research is needed to elucidate the underlying mechanisms driving these seasonal patterns and to explore potential applications for optimizing carbon sequestration through plant management practices.

To investigate the impact of seasonal variations on carbon sequestration, we conducted a one-way analysis of variance (ANOVA) using SPSS software, followed by *post hoc* comparisons with the Games-Howell method. The results revealed significant differences in daily carbon sequestration rates per unit canopy projection area between autumn and winter [$p = 0.324$, with a difference of 12.265 g/(m^2·d)], as well as between summer and winter [$p < 0.001$, with a difference of 10.355 g/(m^2·d)]. Moreover, significant differences were observed between spring and summer ($p < 0.001$) and between spring and winter ($p < 0.001$). In contrast, the differences between spring and autumn [$p > 0.05$, with a difference of 7.523 g/(m^2·d)] and autumn and summer [$p > 0.05$, with a difference of 1.91 g/(m^2·d)] were not statistically significant.

Table 7 reveals significant seasonal fluctuations in total plant carbon sequestration. Summer exhibits the highest rate, averaging 161.745 g/d, driven primarily by the peak growth period, characterized by enhanced leaf physiological activity and optimal photosynthetic efficiency. In contrast, winter sees a sharp decline to 35.49 g/d, the lowest of the year, due to the suppression of photosynthesis by low temperatures. Summer's favorable conditions, with abundant foliage and optimal light intensity, facilitate high photosynthetic rates, while winter's reduced chlorophyll content and leaf drop limit photosynthetic efficiency. Spring and autumn carbon sequestration rates (81.295 g/d and 98.454 g/d, respectively) fall between the summer and winter values, reflecting moderate sunlight and temperatures conducive to photosynthesis. Spring sees a gradual intensification of photosynthetic activity as plants recover from dormancy, and daylight hours increase, while autumn's remaining light intensity and temperatures still support effective photosynthesis, despite shorter daylight hours.

To evaluate the impact of seasonal variation on plant carbon sequestration, a one-way analysis of variance (ANOVA) was conducted using SPSS software, followed by *post hoc* comparisons with the Games-Howell method. The results reveal a significant seasonal difference in total plant carbon sequestration between summer and winter ($p = 0.001$, difference = 126.251 g/d), indicating a highly significant seasonal variation. Although the difference between summer and spring is smaller ($p = 0.044$, difference = 80.455 g/d), it is still statistically significant. Notably, significant seasonal differences were also observed between spring and winter ($p < 0.05$, difference = 45.80 g/d), autumn and summer ($p < 0.05$, difference = 63.29 g/d), and autumn and winter ($p < 0.05$, difference = 62.97 g/d). In contrast, the difference between spring and autumn ($p = 0.877$, difference = 45.80 g/d) is not statistically significant, suggesting minimal seasonal variation. The seasonal comparison between autumn and winter is particularly pronounced, with a highly significant difference ($p = 0.011$) and a large difference in carbon sequestration (62.97 g/d).

This study did not directly investigate the impact of seasonal variations on carbon sequestration capacity. However, it indirectly explored the influence of seasonal changes by comparing the carbon sequestration abilities of different plant types (evergreen vs. deciduous). Evergreen trees, which continue to undergo

TABLE 6 Seasonal variation in mean values and statistical significance across seasons.

Season	Mean	Mean difference	Standard error	Significance
Spring	6.363 g/(m²·d)			
Summer	11.975 g/(m²·d)			
Autumn	13.886 g/(m²·d)			
Winter	1.62 g/(m²·d)			
Spring		−5.6126500	0.6165107	0.001
		−7.5230000	7.1758988	0.721
		4.7424000	0.2867402	0.001
Summer		5.6126500	0.6165107	0.001
		−1.9103500	7.1967347	0.993
		10.3550500	0.6178085	0.001
Autumn		7.5230000	7.1758988	0.721
		1.9103500	7.1967347	0.993
		12.2654000	7.1760104	0.324
Winter		−4.7424000	0.2867402	0.001
		−10.3550500	0.6178085	0.001
		−12.2654000	7.1760104	0.324

TABLE 7 Seasonal differences in mean values: statistical analysis of variations and significance.

Season	Mean	Mean difference	Standard error	Significance
Spring	81.295 g/d			
Summer	161.745 g/d			
Autumn	98.458 g/d			
Winter	35.493 g/d			
Spring		−80.45518	30.37166	0.044
		−17.16986	22.89016	0.877
		45.79557	15.76699	0.022
Summer		80.45518	30.37166	0.044
		63.28532	32.76685	0.219
		126.25075	28.25430	0.001
Autumn		17.16986	22.89016	0.877
		−63.28532	32.76685	0.219
		62.96543	19.99567	0.011
Winter		−45.79557	15.76699	0.022
		−126.25075	28.25430	0.001
		−62.96543	19.99567	0.011

photosynthesis year-round, exhibit higher carbon sequestration capacity, whereas deciduous plants show lower sequestration rates due to reduced photosynthetic activity during winter leaf drop. By analyzing the average and standard deviation of carbon sequestration per unit canopy projection area, the study provided further insight into the potential impact of seasonal variations on plant carbon sequestration efficiency, shedding light on the year-round carbon sink capacity of plants.

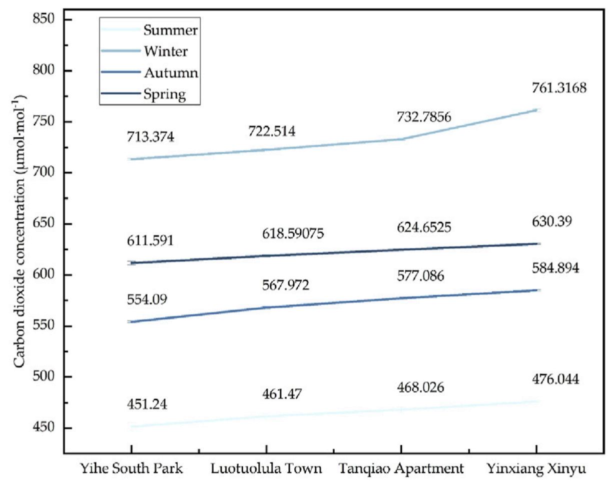

FIGURE 4
Seasonal variation in carbon dioxide concentration across four experimental areas.

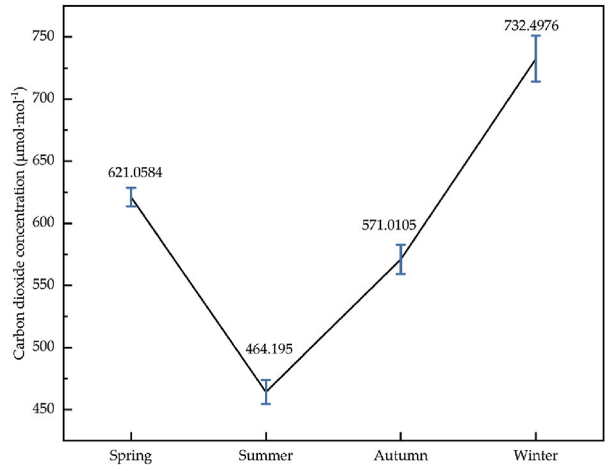

FIGURE 5
Seasonal changes in carbon dioxide concentration levels.

3.5 Seasonal CO_2 concentration variations

Figure 4 illustrates the variations in CO_2 concentration across four zones during different seasons. The data reveal that CO_2 concentrations are generally higher in winter, with average values exceeding 700 μmol mol^{-1}. In contrast, summer concentrations average about 460 μmol mol^{-1}, reflecting a significant seasonal difference of 250 μmol mol^{-1}. Additionally, CO_2 concentrations vary among the four zones. The Yihe South Park zone consistently exhibits the lowest CO_2 levels across all seasons, with a summer concentration of 451.24 μmol mol^{-1} and a winter peak of 713.37 μmol mol^{-1}. Conversely, the Yinxiang Xinyu zone maintains higher CO_2 concentrations year-round, reaching up to 761.32 μmol mol^{-1} in winter. Arranged from lowest to highest CO_2 concentration, the zones are: Yihe South Park, Luotuolula Town, Tanqiao Apartment, and Yinxiang Xinyu. These variations are primarily attributed to the different types of vegetation in each zone: Yihe South Park predominantly features Evergreen trees, Luotuolula Town is characterized by Deciduous trees, Tanqiao Apartment is primarily composed of Evergreen shrubs, and Yinxiang Xinyu contains mostly Deciduous shrubs. The differences in carbon sequestration capabilities among these plant types result in the observed CO_2 concentration variations, which are more pronounced in winter.

Figure 5 illustrates the seasonal variation in carbon dioxide concentration across four regions. The data reveal a clear pattern, with CO_2 levels lowest in summer (464.195 μmol mol^{-1}) and highest in winter (732.49 μmol mol^{-1}). Spring and autumn exhibit intermediate concentrations (621.058 μmol mol^{-1} and 571.01 μmol mol^{-1}, respectively). This seasonal variability is likely driven by the contrasting patterns of plant growth and photosynthesis. In summer, enhanced plant growth and photosynthesis lead to increased CO_2 absorption for carbon fixation, thereby reducing atmospheric CO_2 levels. In contrast, winter sees reduced plant activity and weaker photosynthesis, resulting in decreased carbon fixation and potentially increased CO_2 release from respiration and other biological processes. The CO_2 levels in spring and autumn are probably influenced by the varying intensities of plant growth and photosynthesis, falling between the extremes observed in summer and winter.

4 Discussion

This study uses a standardized quantification method to assess the climate change mitigation and carbon sequestration potential of urban residential green spaces. The findings show that evergreen trees and woody plants exhibit significantly higher carbon sequestration capacity compared to deciduous plants and shrubs. These results are consistent with existing literature, which highlights the strong correlation between plant types and their carbon sequestration capabilities. Evergreen plants, which maintain photosynthesis throughout the year, can absorb carbon dioxide continuously, whereas deciduous plants experience a significant reduction in carbon sequestration capacity during winter due to the decline in photosynthetic activity associated with leaf drop. A study on urban tree carbon storage and sequestration in the United States found that tree density and species type have a substantial impact on carbon storage, with variations in tree carbon storage density and annual sequestration rates across cities providing valuable insights into the role of plant types in carbon sequestration (Nowak et al., 2013).

This study provides a more comprehensive and quantitative evaluation of the carbon sequestration potential of urban residential green spaces through a standardized methodology. Unlike previous research, which often focuses on individual plant species or specific environmental factors, this study fills a gap by incorporating a multidimensional analysis. Research on the relationship between urban park ecosystem services and vegetation types highlights the trade-offs between vegetation diversity and ecosystem services, further underscoring the importance of different plant types in carbon sequestration (Mexia et al., 2018). Additionally, studies on county-level ecological space management and carbon sink capacity optimization have proposed strategies to enhance carbon sink capacity through improved ecological space management, offering practical insights for optimizing carbon sequestration in urban green spaces (Li et al., 2024).

However, most previous studies have focused on single factors, neglecting the integrated impact of plant species, green space layout, and management strategies. In contrast, this study examines the carbon sequestration potential of different plant species and their seasonal variations, while also investigating the role of green space design and management practices. This multidimensional approach bridges gaps in the current literature and offers new perspectives and practical pathways for enhancing the carbon sequestration efficiency of urban green spaces.

4.1 The limitations of the method

The fixed percentage method, which typically employs a 20% estimate of nighttime respiration carbon emissions, is a widely used approach for quantifying plant carbon losses. However, this method has several limitations that can lead to biased estimates of carbon sequestration. Firstly, it fails to account for the temperature effect on nighttime respiration rates, which can be up to 40%–50% higher in high-temperature environments, resulting in underestimation of carbon sequestration. For instance, if a plant's photosynthetic carbon uptake is 100 g/m^2/day, the fixed percentage method would estimate nighttime respiration at 20 g, but the actual rate could be as high as 30 g, leading to a 12.5% error in the carbon sequestration estimate. Secondly, water stress can significantly reduce respiration rates, particularly in arid regions, where the fixed percentage method may overestimate nighttime respiration, introducing errors as high as 40%. Under drought conditions, a plant with 100 g of photosynthetic carbon uptake might have an actual nighttime respiration of only 12 g, but the fixed percentage method would still estimate it at 20 g, causing a 40% error. Furthermore, the fixed percentage method does not account for species-specific differences in respiration rates, which can lead to significant errors in carbon sequestration estimates. For example, coniferous trees and herbaceous plants may exhibit significantly different respiration rates, even within the same environment, resulting in errors of 10%–20%. Finally, the method fails to consider changes in respiration rates across different growth stages, which can lead to underestimation of carbon sequestration during active growth periods and overestimation during dormancy, with errors potentially reaching 25%. To enhance the accuracy of carbon sequestration estimates, future research should incorporate more precise, real-time respiration measurement methods, such as automated gas exchange systems, to reduce the errors and uncertainties introduced by the fixed percentage assumption (Zhao et al., 2022).

Furthermore, neglecting the impact of tree age on carbon storage potential may lead to inaccurate estimates, as tree age is closely related to carbon storage capacity. Younger trees, with limited carbon storage potential, can be overestimated, while older trees, with higher carbon storage potential, can be underestimated. Shrubs, with their shorter life cycle, have limited carbon sequestration capacity. Failing to consider tree age can result in inaccurate assessments of carbon storage potential, affecting forest management decisions. To address this, future research should incorporate tree age as a factor, refine age categories, and utilize models relating tree age to biomass to ensure more accurate carbon storage estimates. It is also essential to distinguish and evaluate the carbon storage characteristics of trees and shrubs separately for their carbon sequestration potential. This distinction is crucial for developing effective strategies for mitigating urban warming.

Additionally, this study's reliance on a limited sample size (1,350 samples over 3 days during each season) may not provide a comprehensive seasonal overview. To address this, future research should increase the sample size to explore more factors influencing plant carbon sequestration and ultimately develop more effective strategies for mitigating urban warming.

4.2 Optimizing urban carbon sequestration

4.2.1 Optimizing carbon estimation

To more accurately estimate the carbon sequestration potential of urban green spaces, a species-weighted average method should be adopted when calculating the carbon sequestration capacity of individual plants. This approach integrates the carbon sequestration abilities of various plant types and species, providing a more nuanced understanding of how plant diversity and environmental factors influence carbon sequestration outcomes. In addition, factors such as plant density, spatial configuration, and total area should be carefully considered during the assessment process. High-density planting can significantly increase above-ground biomass, thereby enhancing overall carbon sequestration. To further improve predictive accuracy, dynamic models should be employed, incorporating variables such as plant growth cycles, seasonal fluctuations, and climate conditions. This will enable more precise estimation of carbon sequestration potential. Root carbon storage should also be included in the evaluation framework, as roots play a critical role in carbon storage within green spaces. Implementing these optimization strategies will facilitate a more comprehensive and precise estimation of the carbon sequestration capacity of urban green spaces (Chen, 2015; Zaid et al., 2018).

4.2.2 Evergreen trees strategy

When planning urban green space systems, evergreen trees should be prioritized due to their high carbon sequestration capacity per unit of crown area and overall carbon storage potential. These plants offer a consistent rate of carbon fixation throughout the year, including during winter, providing long-term and stable ecological services to the ecosystem. In contrast, deciduous plants enter dormancy in winter and temporarily cease photosynthesis, reducing their carbon sequestration capacity. However, their efficient carbon fixation capacity during the growing season should not be overlooked. Deciduous trees, with their large size and broad leaf area, can absorb and store significant amounts of carbon dioxide during their growing period. While evergreen trees have slower growth rates, which may affect short-term carbon sink benefits in the early stages of green space development, deciduous species can provide a temporary boost to carbon sequestration capacity during the growing season. Therefore, it is essential to carefully weigh the advantages and disadvantages of evergreen versus deciduous species in the planning process (Jevon et al., 2024; Zhao et al., 2023).

To maximize the carbon sequestration potential of plants while promoting sustainable urban ecological development, a carefully designed plant configuration strategy is necessary. This strategy requires consideration of the ecological adaptability and growth requirements of different plant species to ensure the stability of the plant community and its efficient carbon sink function. A scientifically based approach is essential to determine the optimal planting ratio of evergreen shrubs, deciduous trees, and deciduous shrubs. This should be achieved by adjusting the planting ratio according to the carbon fixation capacity and ecological characteristics of each species. It is generally recommended to increase the planting area of evergreen shrubs and deciduous trees, while strategically incorporating deciduous shrubs. This approach not only enhances the landscape's spatial layers and seasonal diversity but also ensures a balanced carbon sequestration capacity while maintaining ecological services. By adopting this strategy, it is possible to promote a sustainable urban ecological environment that maximizes carbon sequestration potential while maintaining ecological stability.

4.2.3 Winter greening management

Seasonal climate variations, particularly changes in solar radiation, temperature, precipitation, and daylight duration, have a direct and significant impact on plant photosynthetic efficiency. In spring and summer, characterized by extended daylight and high solar radiation intensity, photosynthetic activity is markedly enhanced, leading to increased carbon fixation. Conversely, the shorter daylight hours and lower temperatures of autumn and winter substantially limit photosynthesis, resulting in a pronounced decline in carbon fixation capacity. Plants also exhibit adaptive physiological responses to these seasonal changes. For instance, deciduous species enter dormancy in autumn, shedding leaves and nearly halting photosynthetic activity, while evergreen species, though retaining their foliage, experience reduced photosynthetic efficiency during colder months. The harsh environmental conditions of winter, including low temperatures and dryness, pose substantial challenges to plant survival, necessitating effective winter greening management strategies. Scientifically guided maintenance practices, such as optimized watering and fertilization, can help sustain plant vitality and partially mitigate the seasonal reduction in carbon sequestration capacity. This is particularly important for enhancing urban carbon sequestration. Strategic watering practices, tailored to plant species, growth stages, and soil moisture levels, are critical to ensuring adequate hydration without the risks associated with overwatering or underwatering. Similarly, careful fertilization—encompassing appropriate nutrient selection, application methods, and regulation of quantity and frequency—minimizes the risk of damage from over-fertilization while supporting plant health during winter.

Winter pruning also plays a vital role in green infrastructure management. By removing dead leaves, damaged branches, and weak plants, pruning not only promotes photosynthetic efficiency and growth but also improves plant structure and aesthetic value. Collectively, these measures contribute to maintaining plant health and enhancing urban ecosystem carbon sequestration, even under the limiting conditions of winter (Shirley et al., 2022; Filipiak et al., 2023).

4.2.4 Scientific greening strategy

Scientific greening principles and technologies enable urban landscaping to harmonize with natural laws, maximizing carbon sequestration potential. A continuous monitoring and evaluation system ensures that greening projects progress steadily, allowing for timely identification and correction of deviations, and guaranteeing the sustainability and stability of carbon sequestration effects. Promoting scientific greening principles and enhancing monitoring and evaluation frameworks are crucial for building a healthy, stable ecosystem, improving urban ecological carrying capacity, and enhancing environmental resilience. To achieve these goals, public education and demonstration efforts are essential, increasing awareness and participation in greening initiatives and fostering a societal atmosphere that supports and values greening efforts (Dai et al., 2024). Effective greening projects can disseminate scientific greening principles and technologies through various activities, such as lectures, exhibitions, and workshops, while tailoring plans to the region's climate, soil, and water conditions to ensure scientific soundness and regional appropriateness. Advanced greening technologies, including water-saving irrigation, soil improvement, and pest control, should be actively introduced and promoted. Encouraging the development of plant varieties adapted to local climate and soil conditions can further enhance carbon sequestration capacity and environmental adaptability.

To ensure long-term effectiveness, a comprehensive monitoring system is critical. Monitoring stations should be established within greening areas, equipped with advanced tools, and detailed monitoring plans should be developed to collect key data, including species composition, leaf area index, soil moisture, and light intensity. The monitoring results should inform adjusting greening strategies and optimizing resource allocation, allowing for optimized carbon storage efficiency. For instance, using data on leaf area index and carbon sequestration potential can inform the optimal planting ratio of evergreen and deciduous trees. In cases where carbon sequestration is insufficient, solutions can include increasing vegetation density, adjusting irrigation and fertilization practices, or selecting plant varieties with higher carbon storage capacity. Regular assessments of greening project implementation will ensure that strategies are adjusted in a timely manner, enabling better long-term ecological and carbon sequestration benefits (Gao et al., 2023).

4.2.5 Advancing carbon sequestration estimation

To improve the accuracy of plant carbon sequestration estimates, advanced modeling techniques and diverse data sources, including machine learning, big data analysis, and remote sensing technologies, must be integrated. By combining remote sensing imagery, climate models, plant growth models, and soil carbon storage data, machine learning algorithms can accurately identify and classify various plant species, green space types, and environmental conditions, resulting in more precise carbon sequestration predictions. Furthermore, incorporating long-term monitoring data and historical climate records enables artificial intelligence to recognize patterns and analyze trends, providing insights into the impact of climate change on urban carbon sequestration potential and informing mitigation strategies. This integrated, data-driven approach not only enhances the accuracy of estimates but also enables real-time updates and adjustments, thereby increasing the reliability of future carbon sequestration projections. The resulting scientifically robust decision-making tools empower urban planners to design green space systems that align with sustainable development goals, effectively combat climate change, and support the achievement of carbon neutrality targets. By leveraging the power of data analytics and machine learning, urban planners can create greener, more resilient cities that mitigate the effects of climate change and promote a sustainable future.

5 Conclusion

This study highlights the pivotal role of urban green spaces in mitigating climate change, with a specific emphasis on their carbon sequestration potential in residential areas. By analyzing four representative residential areas in Nanjing, the research reveals how plant types and seasonal variations influence carbon sequestration. Evergreen trees demonstrated the highest sequestration potential, particularly in autumn, while total sequestration across all vegetation peaked during the summer. Key growth parameters, including tree diameter, canopy spread, and height, were strongly correlated with carbon sequestration capacity.

To enhance carbon sequestration efforts, future research should expand to include diverse urban green spaces, such as parks and riparian zones, and leverage advanced tools like remote sensing and ecosystem models to improve data accuracy. Additionally, the effects of human management practices, such as pruning, on carbon sequestration should be investigated to provide actionable insights for urban planning.

The study offers several policy recommendations: prioritize the planting of evergreen tree species, optimize vegetation composition to align with seasonal dynamics, and integrate carbon sequestration targets into urban planning frameworks. These strategies will not only support carbon neutrality goals but also enhance urban ecosystem services and resilience.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing–original draft. JZ: Project administration, Supervision, Writing–review and editing. ZW: Project administration, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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