



Nature-based solutions: Assessing the carbon sink potential and influencing factors of urban park plant communities in the temperate monsoon climate zone

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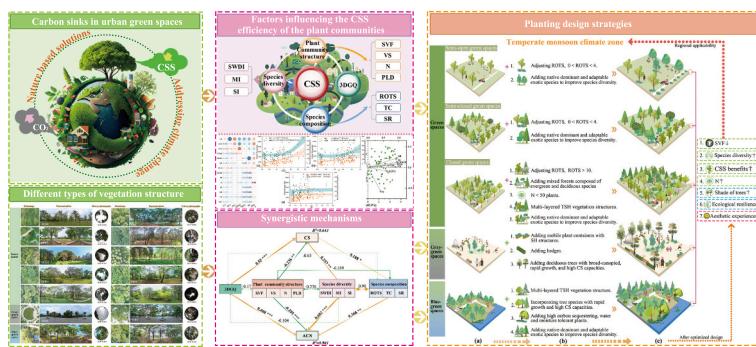
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HIGHLIGHTS

- Significant differences exist in CSS of plant communities in urban parks across different biotope types.
- We measured carbon sinks using multivariate heterogeneous data and mixed methods.
- Multiple driving factors synergistically influence the carbon sink efficiency of plant communities.
- Semi-closed green spaces could also exhibit high carbon sequestration efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

As nature-based solutions, urban park plant communities play a pivotal role in regulating urban carbon cycles, alleviating global climate change, and fostering sustainable urban development. However, the factors influencing the carbon sink efficiency of plant communities in urban parks within temperate monsoon climate zones have not been fully investigated. This study used multivariate heterogeneous data to evaluate plant communities' carbon storage (CS) and annual carbon sequestration (ACS) in 25 urban parks across different biotope types in Jinan, a

Abbreviations: ACS, annual carbon sequestration; CS, carbon storage; CSS, carbon storage and sequestration; BLF, broadleaf forest; CBS, closed broadleaf single-layer green space; CBM, closed broadleaf multi-layer green space; CDS, closed coniferous single-layer green space; CF, coniferous forest; CMM, closed mixed broadleaf-conifer multi-layer green space; CMS, closed mixed broadleaf-conifer single-layer green space; LULC, land use/land cover; MCBF, mixed coniferous and broadleaf forest; SOBS, open broadleaf single-layer green space; SCBM, semi-closed broadleaf multi-layer green space; SCBS, semi-closed broadleaf single-layer green space; SCMS, semi-closed mixed broadleaf-conifer single-layer green space; SCMM, semi-closed mixed broadleaf-conifer multi-layer green space; CD, crown diameter; DBH, diameter at breast height; LiDAR, light detection and ranging; MI, Margalef Richness Index; NTBC, National Tree Benefit Calculator; PCA, principal component analysis; ROTS, the ratio of trees to shrubs; SEM, structural equation modeling; SI, Simpson's diversity index; SVF, sky view factor; SWDI, Shannon-Wiener diversity index; SH, shrub-herb; TH, tree-herb; TSH, tree-shrub-herb; 3DGQ, three-dimensional green quantity; PLD, planting layout density; SR, species richness; VS, vertical structure.

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Biotype types
Carbon storage and sequestration
Sustainable carbon sink design

city located in China's temperate monsoon climate zone. The driving mechanisms affecting carbon sink efficacy were revealed using Spearman correlation, regression, principal component analyses, and structural equation modeling. Results demonstrated that: 1) Closed broadleaf multi-layer green space has significant carbon sink potential compared to other vegetation structures. 2) The carbon sink efficiency of the plant communities negatively correlated with the sky view factor and planting layout density. Three-dimensional green quantity (3DGQ), the ratio of trees and shrubs, species richness, and vertical structures positively correlated with plant communities' carbon storage and sequestration. 3) Whether increasing 3DGQ, the ratio of trees and shrubs, or the total number of individuals of all species, there is a certain threshold bottleneck in enhancing the carbon sink benefits of plant communities. 4) Plant community structure, species composition, and species diversity influenced carbon sink efficiency, collectively forming the first principal component. The 3DGQ affected carbon sink efficiency as the second principal component. Synergistic effects existed among these driving factors, jointly explained 64.3 % and 90.1 % of the CS and ACS of plant communities, respectively. Optimization design strategies for different plant communities in urban parks were proposed.

1. Introduction

Global climate change represents a severe challenge for human society in the 21st century, profoundly impacting the ecological environment and sustainable socioeconomic development (Karl and Trenberth, 2003). Cities, which are major carbon emissions sources, are expected to be key building blocks in decarbonization efforts (Holtz et al., 2018). The United Nations 2030 Agenda for Sustainable Development included urban green areas as a standalone goal within its global development strategy (Nations U, 2015). As nature-based solutions, urban green spaces are increasingly recognized globally for their role in addressing both the challenges and opportunities posed by climate change.

As a core component of urban green spaces, urban parks provide various ecosystem services to city residents and constitute significant near-natural ecological spaces within urban areas (Donahue et al., 2018). The plant communities in urban parks can effectively sequester atmospheric carbon dioxide (CO_2) through photosynthesis and help reduce the surrounding environmental CO_2 concentration (Singkran, 2022), thereby indirectly promoting carbon emission reduction and improving the local microclimate (Chen et al., 2023). Compared to forest carbon sinks, urban parks exhibit a high degree of heterogeneity in carbon sequestration (CS), with relatively more complex carbon sink mechanisms (Zhao et al., 2023). Furthermore, due to differences in greening area, plant design, landscape design, and spatial organization, different types of urban parks demonstrate varying carbon sink potentials (Othman et al., 2019). Studies have shown that the larger the greening area of urban parks, the higher their CS rate (Almeida et al., 2018; Othman et al., 2019). Additionally, the type and structure of vegetation significantly impact the assessment of urban parks' carbon sink potential (Wang et al., 2021b). Moreover, the CS capacity of urban park vegetation is influenced by geographical and climatic factors (e.g., climate zones and latitude) (Burman et al., 2021). For example, evergreen trees in tropical and subtropical climate zones have higher CO_2 assimilation potential than those in temperate zones (Baldocchi, 2008). Hence, in the context of escalating global climate change, research on the carbon sink efficiency of urban park plant communities based on climatic regions can aid in understanding and optimizing urban carbon cycles (Mitchell et al., 2018).

Urban vegetation, along with its carbon storage and sequestration (CSS), is one of nature's contributions to people, playing a crucial role in the terrestrial carbon cycle and global sustainable development goals (Zhuang et al., 2022). As essential components of green spaces, urban trees sequester CO_2 from the atmosphere, thus increasing urban resilience and reducing energy demands during the summer (Sharifi et al., 2020). Urban parks, as spaces where blue, green, and gray infrastructures converge (Potter et al., 2023), comprise biotope types constituting vegetation (green spaces) and other land cover (gray and blue spaces), fulfilling both wildlife habitat needs and the provision of recreational areas for people (Qiu et al., 2010). In particular, "biotope + plant community" is considered the fundamental component of natural ecosystems (Whittaker, 2013). Tree-planting design plays a vital role in

enhancing the carbon sink benefits of biotope types in urban parks (Wang et al., 2021b). Although current research on the carbon sink efficiency of urban green spaces focuses on regional ecosystems (Fan and Wei, 2022) and individual vegetation studies (Wang et al., 2021a), there remains a lack of systematic quantitative assessments of plant community CSS at the patch scale (Pataki et al., 2011). Due to their species diversity, structural complexity, and variety (LaPaix and Freedman, 2010), plant communities have posed challenges to the progression of carbon sink research. Existing studies have often focused only on estimating the aboveground carbon storage (CS) of urban tree species, overlooking the contributions of shrubs and herbaceous plants to CSS within urban ecosystems (Sun et al., 2019). Therefore, systematic research on the carbon sink benefits of plant communities in different biotope types within urban parks is required. Understanding the differences and shortcomings in CS and annual carbon sequestration (ACS) across various types of vegetated greenspace will aid in proposing optimal configurations and strategies for plant communities.

Currently, measuring CSS in urban green spaces has some limitations, mainly because of the lack of standardized methods and criteria for assessing the carbon sink efficiency of these spaces (Zhao et al., 2023). The i-Tree Eco model offers advantages in estimating and assessing CSS in urban green spaces (Raum et al., 2019). This software considers factors (e.g., tree height [H], diameter at breast height [DBH], and canopy width during calculations) that enhance the scientific validity and reasonableness of the simulation results (Jia et al., 2023). Additionally, the National Tree Benefit Calculator (NTBC), based on i-Tree software, can estimate the CS of individual plants in urban public green spaces (Mcpherson, 2010). NTBC software simplifies the user interface, technical routes, and data input and is an open-access resource (Company CTaDTE, 2018). These modeling methods require extensive field surveys to collect empirical data, which are transformed and used to calculate the CSS of the study area using formulas (Lin and Ge, 2019). Owing to the high cost and time-consuming nature of site surveys for collecting vegetation data, light detection and ranging (LiDAR)-based active remote sensing technology provides a faster and more convenient method for acquiring extensive forest vegetation data (Alonzo et al., 2016). LiDAR is renowned for its fully automated, high-precision 3D scanning capabilities, which work by emitting laser energy pulses and measuring the time required for these pulses to be reflected from the objects to the sensor (Gonzalez et al., 2010). This technology enables the rapid and direct acquisition of terrain surface models, making it suitable for capturing information about vegetation and other three-dimensional irregularly shaped features (Popescu, 2007; Meng et al., 2018), which is crucial for achieving high-precision mapping of urban green space CS. Analysis of the point cloud data obtained from LiDAR scans provides detailed information on forest stand structure and vegetation cover (Guo et al., 2017) and can supplement field survey data (Lee et al., 2016). Small unmanned aerial vehicles (UAVs) have become important research tools in environmental science (Qin et al., 2021). They produce low-cost, high-quality, and high-resolution images that complement other remote sensing data, making them suitable for observing local-

scale ecosystems and bridging the gap between ground-based surveys and satellite remote sensing (da Silva et al., 2022). To address the complex CSS mechanisms of plant communities in urban parks, various methods and tools for comprehensive measurement and assessment are available.

Harnessing the carbon sink potential of urban green spaces and optimizing their design and management are essential for mitigating climate change (Sun et al., 2019). Currently, the factors affecting the CSS of urban park plant communities remain unclear. Although some studies have focused on this subject (Wang et al., 2021b; Yang et al., 2024), research on the driving factors behind differences in carbon sink efficiency among various vegetation structure types remains limited. Investigations have typically examined CSS from the perspective of species selection (Nero et al., 2018; Park et al., 2021), with fewer studies exploring structural vegetation compositions. Compared with monoculture plant communities, complex-structured communities offer greater carbon sink benefits (Liu et al., 2018). Previous studies have not clearly defined the correlation between vegetation diversity and its carbon sequestration capacity (Sandifer et al., 2015). However, maintaining a high level of species diversity is crucial for the resilience of urban systems (Kremen, 2005). Notably, three-dimensional green quantity (3DGQ), as a potential metric for assessing urban green spaces, enables the accurate estimation of biomass and, thus, CS capacity (Liang et al., 2017). Additionally, the sky view factor (SVF) serves as a quantitative measure of vegetation cover (Li et al., 2018). Nevertheless, the potential contributions of 3DGQ, species diversity, plant community

structure, and species composition to plant communities' CSS are still not well defined. Therefore, the differences in carbon sink capabilities among different types of plant communities and their driving factors require further study, including the exploration of potential synergistic effects among these factors in the CSS process.

Jinan is the capital of eastern China's Shandong province and the central city within the national-level metropolitan area as well as the Yellow River Basin. Its low-carbon and green development is crucial (Wohlfart et al., 2016). Therefore, the city represents an ideal site for studying the CSS capabilities of urban park plant communities within the temperate monsoon climate zone. This study focuses on plant communities within various biotope types of urban parks in Jinan, analyzing the differences in CS and ACS, as well as the drivers behind their carbon sink efficiency. Specifically, this study aims to (a) quantify and evaluate the differences in CSS among different vegetation-structured green spaces; (b) identify the key drivers that influence the carbon sink efficiency of plant communities, and determine whether there are synergistic effects among these factors; and (c) devise diverse planting design strategies tailored to the functional requirements of different vegetation-structured green spaces. Thus, this study can provide scientific evidence and theoretical guidance for low-carbon and high-quality development, urban green space planning, and climate change adaptation in cities within the lower reaches of the Yellow River Basin and similar climatic backgrounds.

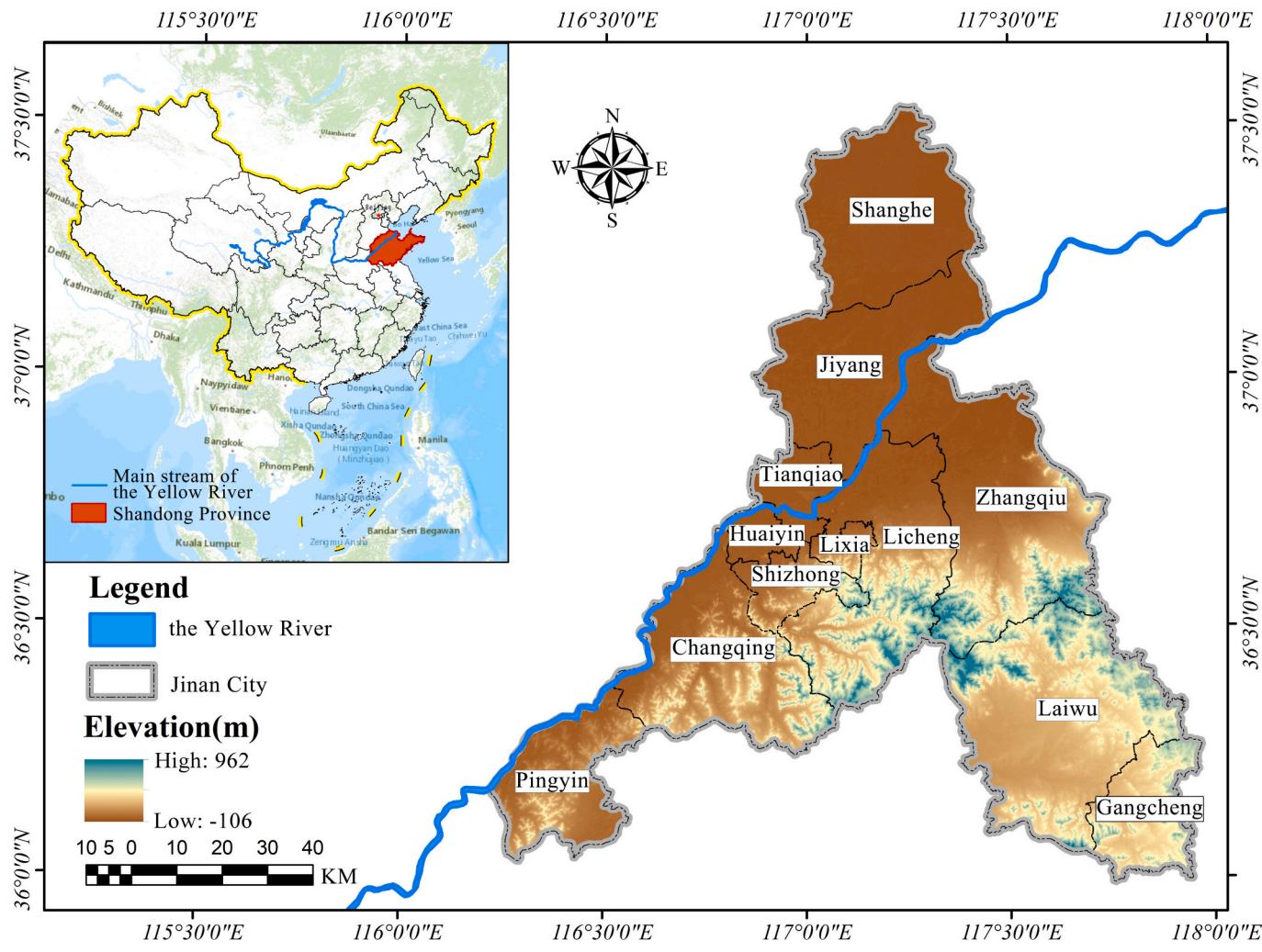


Fig. 1. Location of the study area.

2. Methods

2.1. Study area

Field trials were conducted in Jinan, the capital of Shandong Province, China ($36^{\circ}40'06''\text{N}$ and $117^{\circ}01'13''\text{E}$). The topography of Jinan is characterized by higher elevations in the south and lower elevations in the north, with small mountain ranges on the east and west sides, creating distinctive semi-basin geography (Fig. 1). Based on the Köppen climate classification, Jinan experiences a warm temperate, semi-humid monsoon climate with mild weather throughout the year, distinct seasons, hot and rainy summers, and cold, dry winters (Peel et al., 2007). As a major city in the lower Yellow River Basin, Jinan is undergoing rapid urbanization, population growth, and GDP growth. In 2023, Jinan's urban built-up area had a green space rate of 37 %, a green coverage rate of 42 %, and a per capita green space area of 13.7 m^2 (Government GOoJMPs, 2021).

2.2. Sample plot selection

This study categorized urban parks in Jinan according to the "Urban Green Space Classification Standard" (CJJ/T85-2002) and the "Jinan 47 Urban Park Green Space Sharing Pilot Project," aligned with municipal park management practices. The parks were classified into four types based on their primary functions: (1) comprehensive, (2) community, (3) specialized, and (4) mountain parks. Furthermore, they were divided into five size categories:

- (1) Category I (< 2 ha),
- (2) Category II (2 ha to 10 ha),
- (3) Category III (10 ha to 50 ha),
- (4) Category IV (50 ha to 100 ha), and
- (5) Category V (> 100 ha).

A systematic random sampling method was used to select 25 sample parks based on the type, location, and size of the parks (Fig. 2). The area of the sample parks ranged from 1.8 ha to 685 ha, including one with an area of <2 ha, seven parks and greenspaces with an area of 2 to 10 ha, nine parks and greenspaces with an area of 10–50 ha, three parks and greenspaces with an area of 50–100 ha and five parks and greenspaces with an area of >100 ha. Based on the name and latitude and longitude coordinates of the parks in the study area, the Baidu map API geocoding service combined with Python was used to locate each park and obtain the area of interest (AOI) of each park in the form of polygonal vector data. ArcGIS 10.6 combined with Google Earth satellite imagery was utilized to check the boundary accuracy of each park.

2.3. Data collection and process

2.3.1. Satellite image processing

We obtained cloud-free high-resolution GF-2 PMS satellite images of the study area from summer (September 12, 2022) and winter (December 5, 2023), with a panchromatic resolution of 1 m and a multispectral resolution of 4 m. After performing preprocessing steps (e.g., orthorectification, radiometric calibration, atmospheric correction, and image fusion) using ENVI 5.3 software, we employed the support

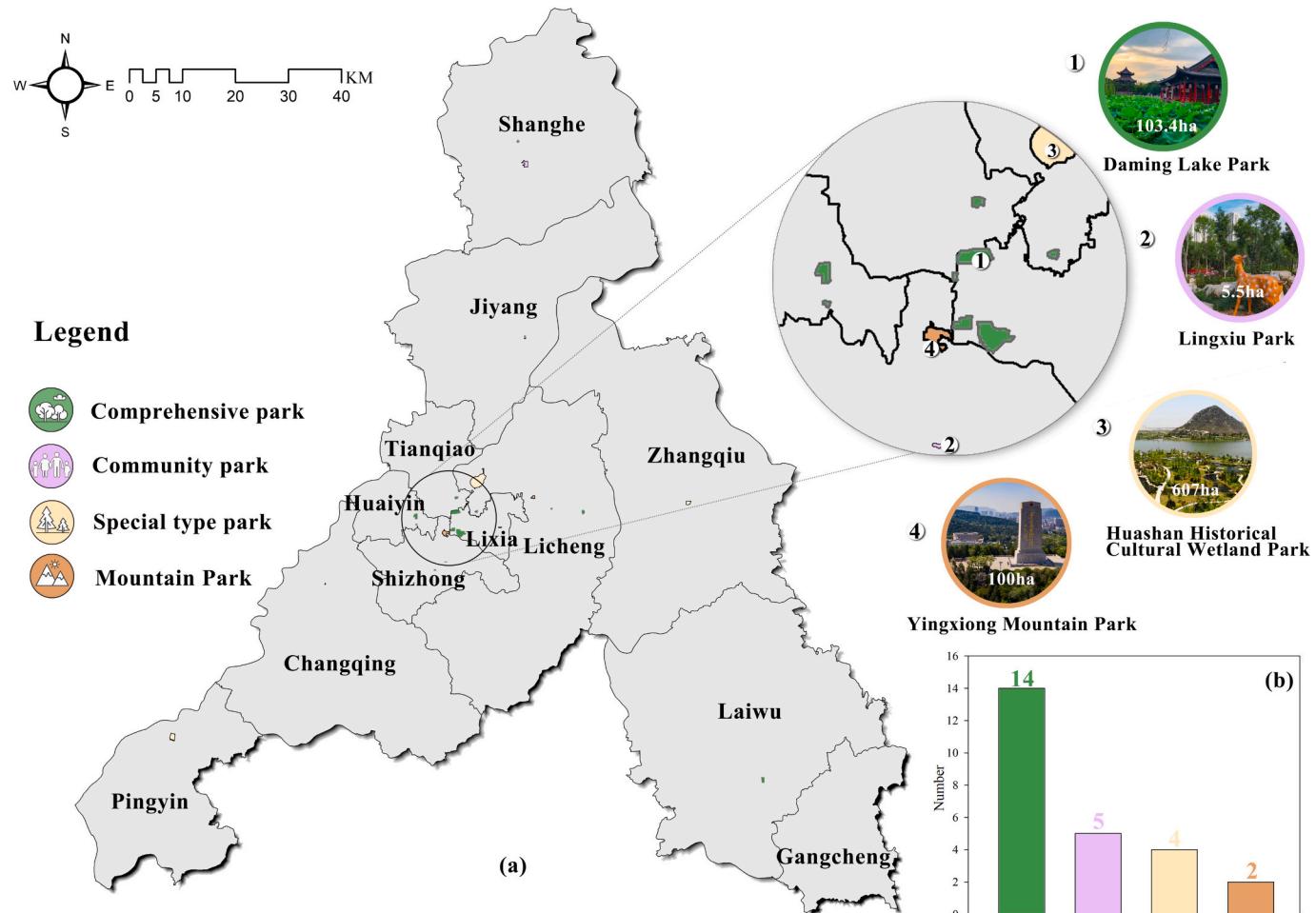


Fig. 2. (a) Spatial distribution of parks, (b) numbers of four types of parks.

vector machine classification method. Additionally, ortho imagery was captured at a 90° angle from an altitude of 100 m using a DJI Mavic2 drone to determine the land use/land cover (LULC) classification of each park.

2.3.2. Biotope-type division in the urban parks

Through field surveys and satellite images of the research area, and based on the biotope classification frameworks previously established by Qiu et al. (2010) and Jiang et al. (2022), we developed a biotope-type division system for the urban parks that incorporated vegetation structure factors (Table 1).

Initially, the system's first tier categorized the selected urban parks into green, gray-green, and blue-green spaces. Gray-green spaces contained natural ecological elements (e.g., vegetation and lawns), serving as recreational, social, and fitness areas (Zhang et al., 2022). Blue-green spaces were areas covered by both water bodies and vegetation, providing open waterside spaces suitable for outdoor recreation (Yuan et al., 2023). Vegetation is a major component of the biotype within a park, and vegetation structure affects the distribution and diversity of other species (Alberto Gallardo-Cruz et al., 2009). According to Gao et al. (2014), vegetation structure encompasses three levels: (1) horizontal structure, (2) vertical structure, and (3) species composition of plant communities. Therefore, the second, third, and fourth tiers of the classification in the current study were based on vegetation characteristics. In the second tier, the horizontal vegetation structure was further quantified into three categories based on trees and shrubs coverage: (1) Semi-open space (10 % to 40 % canopy cover), (2) semi-closed space (40 % to 70 % canopy cover), and (3) closed space (> 70 % canopy cover).

The third tier categorized semi-closed and closed green spaces based on their vertical structure into single-layer and multi-layer structures, excluding herb and ground cover layers from the multi-layer classification system. The fourth tier, based on tree species composition and field surveys, was divided into broadleaf, coniferous, and mixed broadleaf-conifer forests.

Based on this classification system, urban park biotope types were divided into 10 categories:

- (1) open broadleaf single-layer green space (SOBS),
- (2) semi-closed broadleaf single-layer green space (SCBS),
- (3) semi-closed mixed broadleaf-conifer single-layer green space (SCMS),
- (4) semi-closed broadleaf multi-layer green space (SCBM),
- (5) semi-closed mixed broadleaf-conifer multi-layer green space (SCMM),
- (6) closed broadleaf single-layer green space (CBS),
- (7) closed coniferous single-layer green space (CDS),
- (8) closed mixed broadleaf-conifer single-layer green space (CMS),
- (9) closed broadleaf multi-layer green space (CBM), and
- (10) closed mixed broadleaf-conifer multi-layer green space (CMM).

Table 1
Classification system for different biotope types in urban parks.

LULC	Horizontal structure	Vertical structure	Species composition	Biotope types
Green spaces	Semi-open space	Single -layer	BLF	SOBS
		Single -layer	BLF	SCBS
		Multi-layer	MCFB	SCMS
	Semi-closed space	Single -layer	BLF	SCBM
		Single -layer	MCFB	SCMM
		Multi-layer	BLF	CBS
Gray-green spaces	Closed space	Single -layer	CF	CDS
		Single -layer	MCFB	CMS
	Closed space	Multi-layer	BLF	CBM
		Multi-layer	MCFB	CMM

2.3.3. Screening plant communities of different biotope types

Based on the developed biotope type classification system, community plots measuring 20 m × 20 m were selected within each biotope type to further assess the carbon sink potential of plant communities within the different biotope types (Fig. 3).

Where the shape or size of the space did not permit a 20 m × 20 m plot, the length of the plot was adjusted according to the width of the green space, but the area of the plot was always maintained at 400 m². Additionally, the plants within these plots were free of pests and diseases, uniformly managed, and exhibited good vigor. The number of plant community plots surveyed in different parks was determined by the size of the park, with 120 plots investigated across 25 parks.

2.3.4. Identification of potential influencing and driving factors

Previous studies have shown that the carbon sink efficiency of urban park plant communities is closely related to their internal community characteristics (Liu et al., 2018; Chen et al., 2024). However, the specific indicator characteristics that affect their carbon sink efficiency remain unclear. To further elucidate the driving mechanisms behind plant community carbon sink efficiency, we collected 12 factors related to plant community characteristics and identified them as potential influencing factors. Subsequently, these 12 potential factors were categorized into four primary driving factors: plant community structure, species diversity, species composition, and 3DGQ (Table 2). These drivers include plant community structure (SVF, VS, N, and PLD), species diversity (SWDI, SI, MI, and PI), species composition (TSC, ROTS, and SR), and 3DGQ.

2.4. Field survey

2.4.1. LiDAR combined with field surveys

We obtained basic data on trees within plant community plots using a combination of LiDAR and field surveys. Field surveys were conducted between August and September 2023, utilizing "Two Steps Road Outdoor Assistant" software to mark the centers and locations of sample plots within different biotope types in the parks, along with photographic documentation. We meticulously recorded the species and quantity of all trees within each plot.

We utilized a handheld 3D LiDAR scanner (GeoSLAM, ZEB-HORIZON) to measure H, crown diameter (CD), crown height, DBH, and health status of the avascular plants within the plots. The point cloud data obtained from the LiDAR were first processed using GeoSLAM Hub software to perform noise reduction and normalization, followed by cropping, ground point filtering, and individual tree segmentation using LiDAR360 software (Beijing Digital Green Earth Technology Co., Ltd., Beijing, China) (Fig. 4). For the shrub layer, we employed a laser tree height meter (Rxiry, XR-850) and a tape measure to assess plant characteristics (e.g., height, crown width, and basal diameter). We recorded the species names, cover, average height, and abundance in the herbaceous layer.

2.4.2. Panoramic photographs of the plant communities

As humans typically perceive a wider angle of view than that shown in standard photographs, panoramic images have been considered an effective method for assessing landscape diversity (Palmer and Hoffman, 2001). A panoramic camera (Insta360, ONE X2) was used to capture 360° panoramic images. The camera height was set to 1.5 m (average adult eye level) and positioned at the center of the plant communities to ensure that the panoramic photos adequately displayed the morphological features of the spatial units (Chen et al., 2022). Photographs were taken on clear days between 09:00 to 11:30 and 14:30 to 16:30.

2.4.3. SVF

Fisheye photographs of the sample plots were taken using the fisheye lens of the panoramic camera, and RayMan Pro software was used to process the images and calculate the SVF at each measurement point.

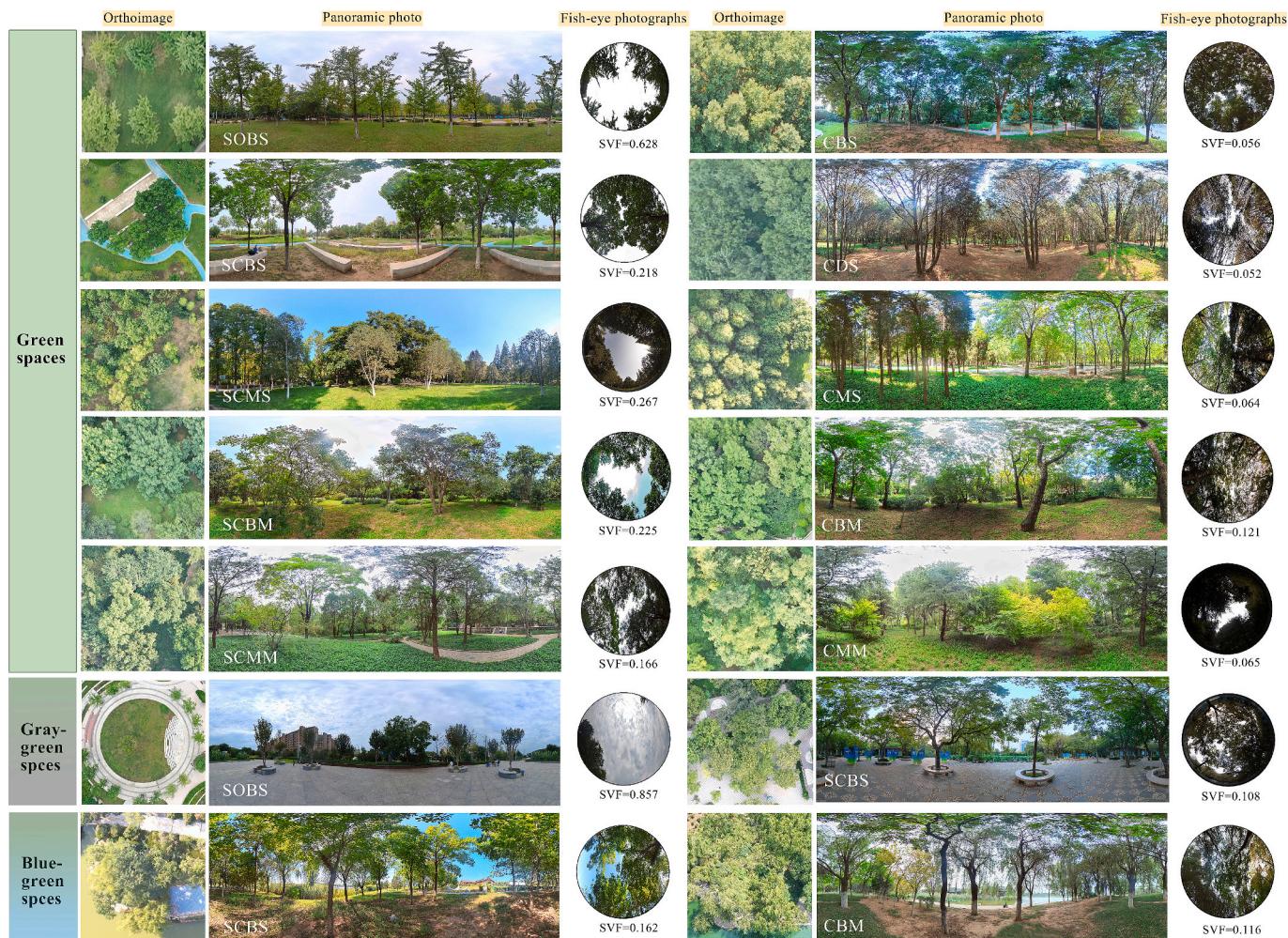


Fig. 3. Different types of vegetation structure.

SVF values range from 0 to 1, where a higher value indicates a more open space at the measurement point and a lower value indicates a more enclosed space (Li et al., 2018).

2.5. Calculation

2.5.1. Biomass

Using published allometric growth equations relevant to northern China, we estimated the dry-weight biomass of all vegetation in the plant community, as shown in Table S1. The aboveground biomass of individual trees was calculated using a combination of DBH and H. When a specific species equation was unavailable, a unified model from the same genus or family was used (Nowak et al., 2013). If no such model was found, the generalized equations from Jo and McPherson (1995) and Jo (2002) were applied. The above-ground biomass of the herbaceous layer was determined using the sample-harvest method. In each plot containing herbaceous plants, three 1 m × 1 m subplots were selected, and the collected plants were dried at 65 °C in the laboratory and weighed to obtain the biomass data per unit area (Fu et al., 2019).

Owing to pruning and maintenance, the biomass of urban trees was often overestimated when allometric growth equations from natural ecosystems were used. Based on the management of urban trees, the calculated biomass values were multiplied by 0.8 (Nowak et al., 1994).

2.5.2. Estimation of CSS

The CS of vegetation was calculated by multiplying the biomass of vegetation by the carbon content coefficient using the IPCC default

value of 0.5 (IPCC, 2007; McPherson et al., 2013). The CS for each plant community was determined by summing the products of the aboveground biomass and carbon content rate for all vegetation layers, including tree, shrub, and herbaceous layers.

The ACS of trees in the arboreal layer of the plant community was estimated using i-Tree Eco software, which required detailed local environmental parameters, as the software's default data were primarily suited for American and European conditions. Therefore, numerous parameters, including tree species, meteorology, air quality, precipitation, climatic zones, study area, and benefit pricing, were uploaded before using them to allow the model to match and use as many original parameters as possible. Further, the i-Tree Eco model divided the USA into 16 climate zones. To align with the climate zones of the model, the lower Midwest climate zone of the USA was selected as the background climate for modeling in this study.

The ACS of shrub layer plants was calculated using NTBC software. This software accurately estimates the carbon sequestration based on the plant species and environmental parameters. For herbaceous plants, carbon sequestration was calculated using the biomass method, which is based on the dark reactions of photosynthesis in which plants fix CO₂ and convert it into organic matter that accumulates as plant biomass. The ACS calculation for herbaceous layer plants was as follows:

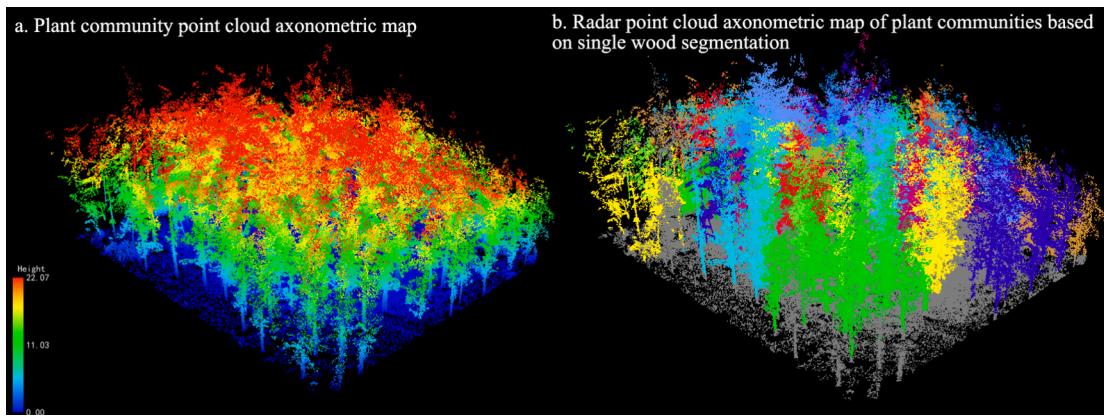
$$\text{CO}_2 + \text{H}_2\text{O} \rightarrow (\text{CH}_2\text{O}) + \text{O}_2 \quad (1)$$

$$M(C) = 12 \text{ g mol}^{-1} \quad (2)$$

Table 2

Potential influencing and driving factors on the carbon sink efficiency of urban park plant communities.

Categories of driving factors	Influencing factors (abbreviation)	Description
Plant community structure	Sky view factor (SVF)	SVF represents each sample site's spatial pattern, shade condition, and openness (Miao et al., 2020).
	Vertical structure (VS)	The vertical structure of plant communities.
	The total number of individuals of all species (N)	The total number of individuals of all species in a plant community.
	Planting layout density (PLD)	The space occupied by each plant ($m^2/plant$) reflects the overall spatial distribution and planting density of vegetation within the plot.
Species diversity	Shannon-Wiener diversity index (SWDI)	To characterize the α diversity index of plant communities in different plots, emphasizing the number of species within the biotypes (Whittaker, 1960).
	Simpson's diversity index (SI)	
	Margalef Richness Index (MI)	
Species Composition	Pielou's Evenness Index (PI)	
	Tree species composition (TSC)	The classification of tree species composition in plant communities includes broadleaf forests, coniferous forests, and mixed broadleaf-coniferous forests.
	The ratio of trees to shrubs (ROTS)	The ratio of trees to shrubs within plant communities.
3DGQ	Species richness (SR)	The number of species present in a plant community.
	Three-dimensional green quantity (3DGQ)	The three-dimensional volume is occupied by the stems and leaves of all growing plants within a plant community (Liang et al., 2017).

**Fig. 4.** (a) LiDAR point cloud map of sample plot plant community, (b) LiDAR individual tree segmentation map.

$$T = 0.5 \times 3.67 \times \sum_{i=1}^n D \bullet B \quad (3)$$

where T represents the ACS of herbaceous plants, measured in kilograms (kg); B is the biomass per unit area of the plants, in kilograms per square meter (kg/m^2); D is the area of the plot covered by the plants, in square meters (m^2); 0.5 is the conversion coefficient from biomass to carbon content; and 3.67 is the conversion factor from carbon to CO_2 for measuring the carbon sequestration in terms of CO_2 equivalent.

2.5.3. 3DGQ

The 3DGQ for tree species in the arboreal layer was calculated using a “planar simulation of volumetric mass” based on the morphology of

tree crowns and the correlation equations between CD and crown height (Liang et al., 2017), as shown in Table 3. For the shrub and herbaceous layers, 3DGQ was calculated as the product of their projected area and height. As herbaceous plants were frequently trimmed, their height was maintained at approximately 5 cm, which was used as the calculated height. The green volumes of the arboreal, shrub, and herbaceous layers were summed to obtain a total 3DGQ.

2.5.4. Plant community diversity

The species diversity indices of the plant community were assessed using Simpson's diversity index (Simpson, 1949), the Margalef richness index (Margalef, 1958), the Shannon-Wiener diversity index (Shannon, 1948), and Pielou's evenness index (Pielou, 1975). The following indices

Table 3

Calculation formula for 3DGQ of trees in the arboreal layer.

Crown shape	Formula
Ovoid OV, Spherical SP, Hemispherical SS	$\frac{\pi x^2 y}{6}$
Conical CO	$\frac{\pi x^2 y}{12}$
Spherical Sector SF	$\frac{\pi(2y^3 - y^2 \sqrt{4y^2 - x^2})}{3}$
Spherical notched AS	$\frac{\pi(3x^2 y - 2y^3)}{6}$
Cylindrical BC	$\frac{\pi x^2 y}{4}$

Note: x represents CD, and y represents crown height.

were expressed as follows:

(1) Simpson's diversity index (SI)

$$C = 1 - \sum_{i=1}^S (P_i)^2$$

(2) Margalef richness index (MI)

$$D = \frac{S - 1}{\ln N}$$

(3) Shannon-Wiener diversity index (SWDI)

The SWDI considers species richness and evenness and is widely used to measure species diversity (Li et al., 2019).

$$H = - \sum_{i=1}^S (P_i \ln P_i)$$

where S represents the number of species, and P_i represents the simplified dominance ratio for species i .

(4) Pielou's evenness index (PI)

$$E = 1 - \sum_{i=1}^S (N_i/N)^2 \left(1 - \frac{1}{S} \right)$$

where S , N_i , and N represent the number of species, total number of individuals of species i , and total number of individuals of all species, respectively.

2.6. Statistical analysis

Plant community diversity was calculated using the 'vegan' and 'biodiversityR' packages on the R studio platform, and all data were analyzed using SPSS 22.0 software (IBM® SPSS® Statistics, Armonk, NY, USA). One-way ANOVA was used to compare the CSS capabilities of different vegetation structures, followed by post-hoc Duncan's tests. Spearman correlation analysis was conducted to explore the factors influencing the differences in CS and ACS among different plant communities, and regression equations were established to relate these factors to the carbon sink efficiency of the plant communities.

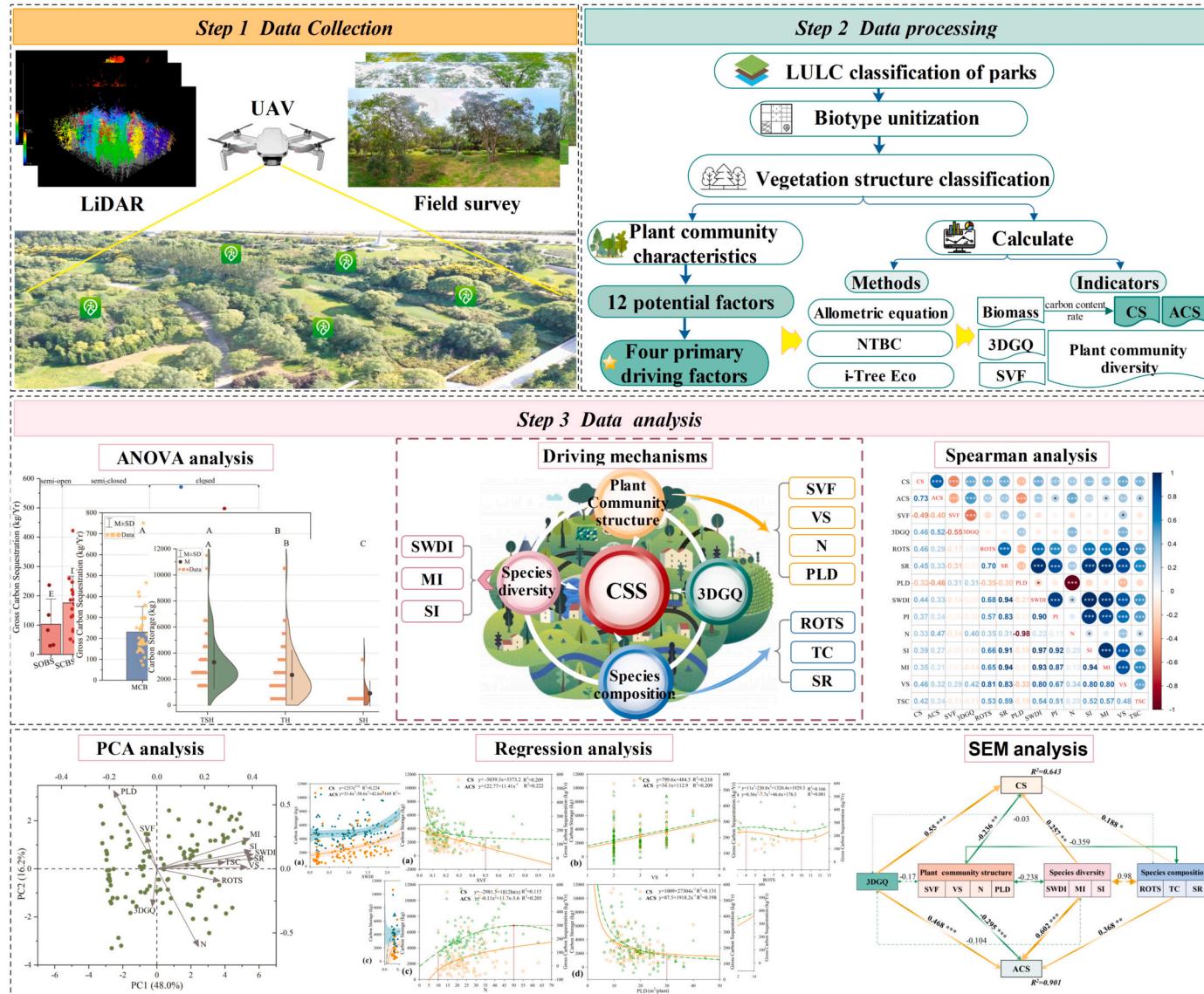


Fig. 5. Research workflow.

Moreover, Principal Component Analysis (PCA) was utilized to identify key parameters affecting the carbon sink efficiency of plant communities. We first excluded variables with a Variance Inflation Factor (VIF) exceeding 10 due to multicollinearity and redundancy among species diversity factors. Subsequently, a stepwise regression method was used to determine and correct the influence of species diversity factors on plant communities' CSS without affecting the research outcomes. The SWDI, MI, and SI factors were included as part of the species diversity factors.

Furthermore, to explore the extent to which key drivers explained the carbon sink efficiency of the plant communities, structural equation modeling (SEM) was constructed using Amos 24.0 software (IBM, Armonk, NY, USA). For all statistical comparisons, $p < 0.05$ was considered statistically significant. All diagrams were drawn using SigmaPlot 14.0 (Systat Software, Inc., San Jose, CA, USA), Origin 2021 (Origin Lab Corp., USA), and R software (Version 4.2.0).

2.7. Research workflow

The research framework of this study can be seen in Fig. 5.

3. Results

3.1. Differences in CS and ACS among different vegetation structures

CS and ACS differed significantly among the different vegetation structures (Fig. 6). Notably, there was a significant difference in CS and ACS between closed vegetation structures ($p < 0.05$). CBM had the highest CS and ACS values, whereas SOBS had the lowest. Closed vegetation structures exhibited the highest CS and ACS values, followed by semi-closed structures. Semi-open structures had the lowest CS and ACS values. Although there were clear differences in CS among the different semi-closed vegetation structures ($p < 0.05$), the differences in ACS were not significant ($p > 0.05$). There was no significant difference in ACS between the SCMM and CDS groups ($p > 0.05$).

3.2. Differences in CS and ACS among the different plant communities

3.2.1. Vertical structures

Fig. 7 reveals significant CS differences among the three vertical structures ($p < 0.05$). The tree-shrub-herb structure (TSH) had the highest CS value, followed by the tree-herb structure (TH), with the shrub-herb structure (SH) having the lowest. Regarding ACS, TSH levels were the highest at 238.88 kg/Yr. There was no significant difference

between TSH and TH ($p > 0.05$); however, both TSH and TH levels were different from those in SH ($p < 0.05$). Thus, the carbon sink efficiency of the plant communities was influenced by their vertical structure.

3.2.2. Tree species composition

As illustrated in Fig. 8, there were no significant differences in the CS of plant communities composed of the three different types of tree species ($p > 0.05$). However, communities with a mixed coniferous and broadleaf forest (MCBF) composition have the highest average CS, followed by broadleaf forest (BLF), with coniferous forest (CF) composition had the highest average CS. BLFs had the highest ACS, which was not significantly different from that of MCBFs ($p > 0.05$), but was significantly different from that of CFs ($p < 0.05$). This indicates that the configuration of different tree species affected the ACS of plant communities.

3.3. Factors influencing the carbon sink efficiency of the plant communities

3.3.1. Spearman correlation analysis of influencing factors

A Spearman correlation analysis was conducted on factors influencing the carbon sink efficiency of plant communities (Fig. 9). The results showed that 3DGQ, the ratio of trees to shrubs (ROTS), species richness (SR), and vertical structure (VS) all had a significant positive correlation with the CS ($p < 0.001$) and ACS ($p < 0.01$) of plant communities. Regarding species diversity, the CS of the plant communities showed significant positive correlations with SWDI, PI, MI, and SI ($p < 0.001$). While there was a significant positive correlation between ACS and SWDI ($p < 0.001$), the correlations between PI, MI, SI, and ACS were moderately positive ($p < 0.05$). However, the carbon sink efficiency of plant communities negatively correlated with SVF and planting layout density (PLD) ($p < 0.01$), indicating that enhancements in carbon sink efficiency were linked to scientifically- and rationally-configured community structures.

3.3.2. PCA of influencing factors

Furthermore, to determine the contribution of each factor to plant communities' CSS, PCA was performed on these factors (Fig. 10), where the length of the arrows represented the contribution of the data to the principal components. The results indicated that the first principal component (PC1) and second principal component (PC2) contributed 48 % and 16.2 %, respectively. Factors such as SR, SWDI, SI, MI, VS, TSC, ROTS, and N had significant contributions and high positive correlations with PC1, demonstrating that plant community structure,

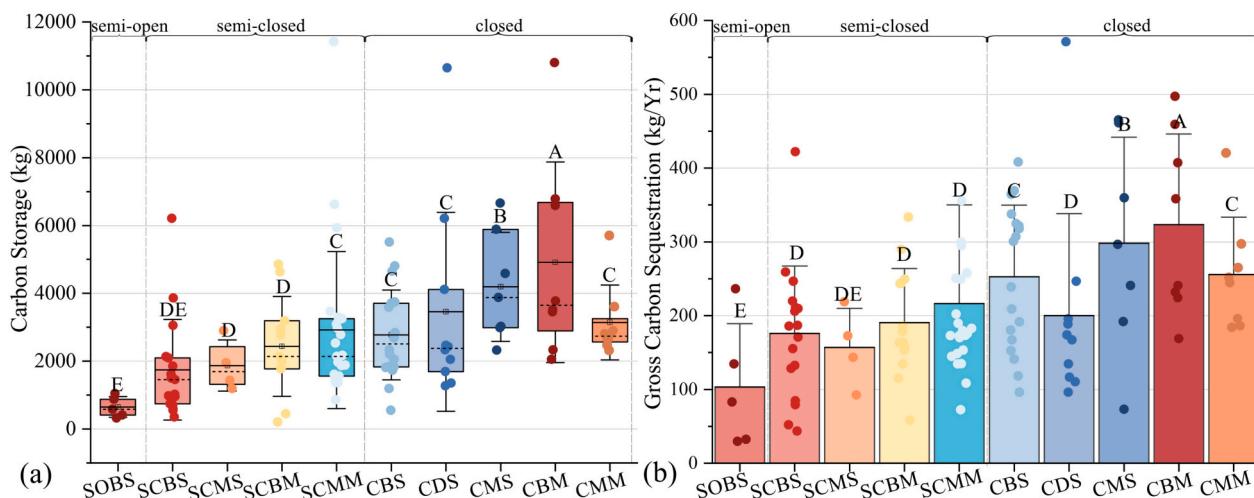


Fig. 6. Differences in CS and ACS among different vegetation structures: (a) CS, (b) ACS; Different capital letters indicate significant differences between different vegetation structures ($p < 0.05$).

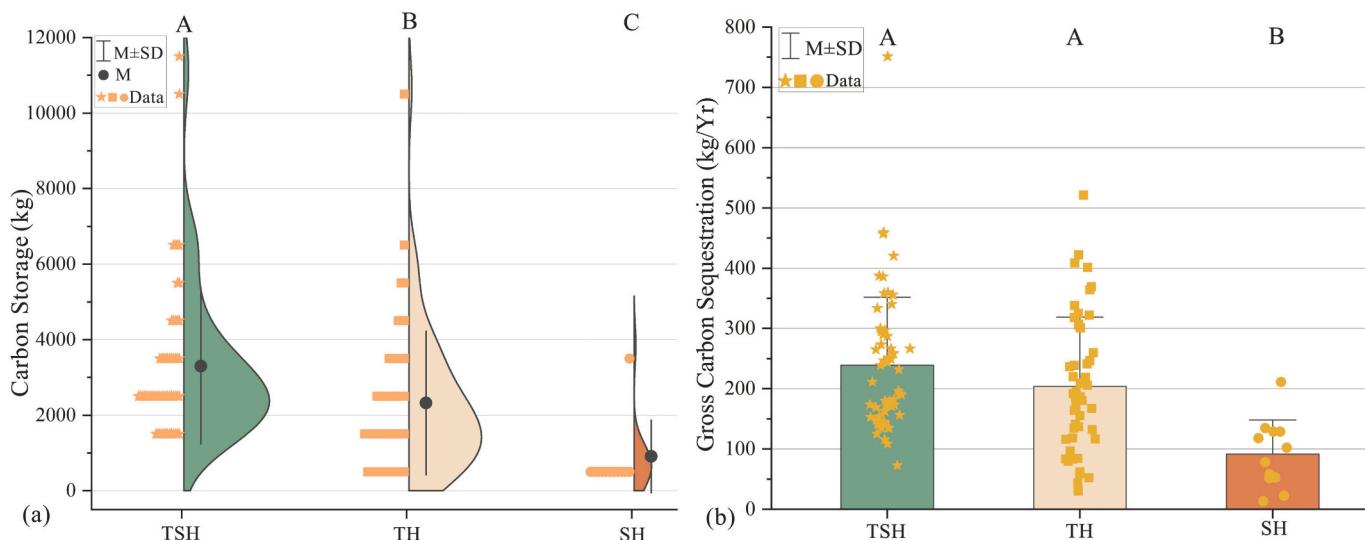


Fig. 7. Differences in CSS among different vertical structures of plant communities: (a) CS, (b) ACS; Different capital letters indicate significant differences between the vertical structures ($p < 0.05$).

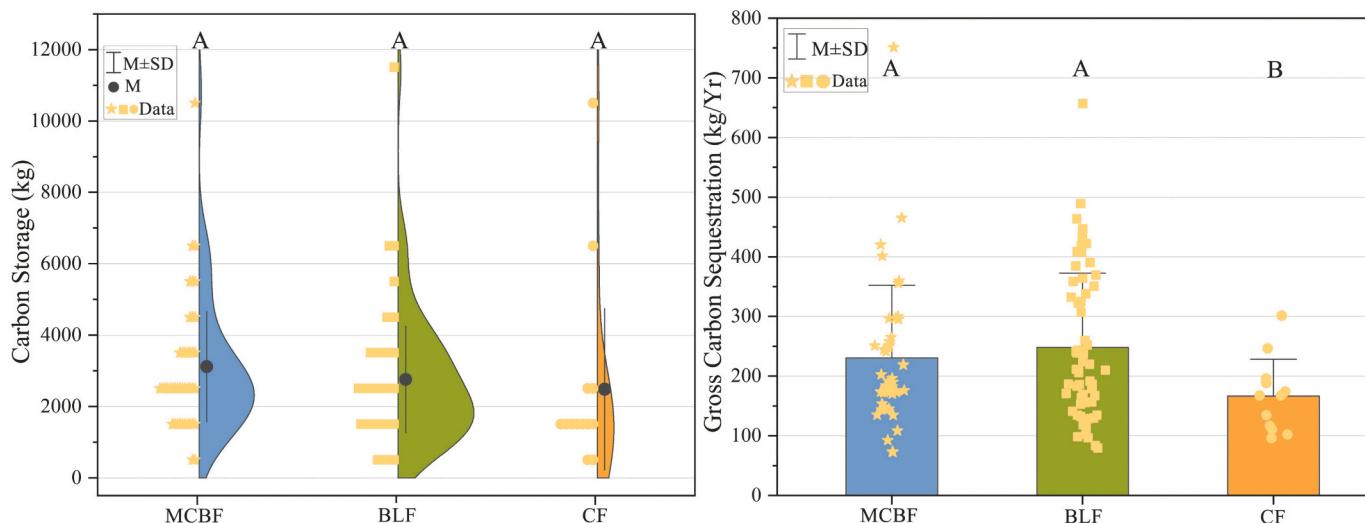


Fig. 8. Differences in CSS among plant communities among different types of tree species composition: (a) CS, (b) ACS; Different capital letters indicate significant differences between types ($p < 0.05$).

species composition, and species diversity played significant roles in the CSS efficiency of plant communities. The main components influencing PC2 were PLD, SVF, and 3DGQ. These factors showed high correlations with PC2, and by increasing the photosynthetic area and biomass of plant communities, 3DGQ optimized the carbon fixation process, enhancing the efficiency of CSS. This illustrates the importance of optimizing the structure and composition of urban park plant communities to increase their carbon sink efficiency.

3.4. Regression analysis of plant community CSS and driving factors

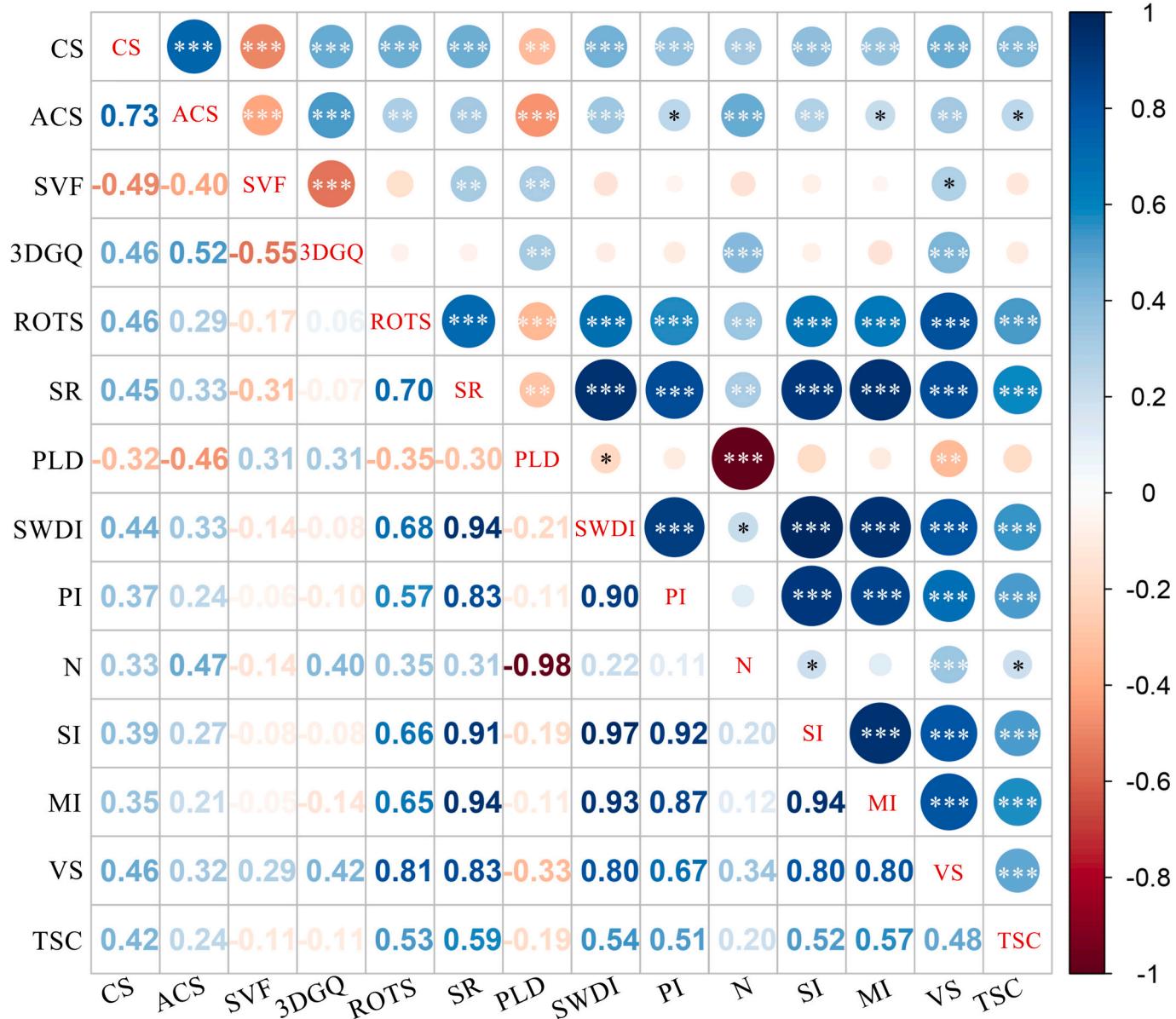
3.4.1. Impact of plant community structure factors on plant community CSS

Curve fitting was conducted on four plant community structure indicators (i.e., SVF, VS, N, and PLD) and their relationship with plant community CSS (Fig. 11). The relationship between plant community CSS and VS is linear (Fig. 11b, $p < 0.001$), whereas the relationships with SVF, N, and PLD were nonlinear (Fig. 11a, c-d, $p < 0.001$). Plant community CSS showed an increasing trend with the complexity of the

vertical structure, indicated by VS ($R^2_{cs} = 0.218$, $R^2_{acs} = 0.209$), demonstrating that more complex vertical structures enhance carbon sink efficiency. The CSS of plant communities decreases with increases in SVF and PLD. When SVF > 0.5 or PLD $> 30 \text{ m}^2/\text{plant}$, the ACS of the community reaches a minimum threshold after which the changes tend to stabilize. This finding highlights that the openness and layout density of planting significantly impacts the carbon sink capability of plant communities. The CSS shows a rapid growth trend when the N is between 10 and 50. However, even though CS continues to increase when N exceeds 50 plants, the ACS had a downward trend. Therefore, merely increasing the number of tree species does not necessarily enhance the overall ACS capacity of the plant community.

3.4.2. Impact of species diversity on plant community CSS

The CSS of plant communities formed nonlinear regression models with three species diversity indices: SWDI, SI, and MI (Fig. 12). The CSS of plant communities generally increases with the values of SWDI, SI, and MI, indicating that species diversity is a key driving parameter for assessing the carbon sink efficiency of plant communities. Additionally,

**Fig. 9.** Factors influencing carbon sink efficiency of plant communities.

Note: *, **, and *** denote significance levels at 0.05, 0.01, and 0.001 respectively.

SWDI had greater explanatory power for ACS than for CS, with CSS showing a rapid increase trend when SWDI exceeded 1.5 (Fig. 12a and b). Both SI and MI had less explanatory power for ACS than for CS (Fig. 12c and d), and carbon sink efficiency tended to stabilize when MI exceeded 0.5.

3.4.3. Impact of species composition factors on plant community CSS

As depicted in Fig. 13, the CSS of plant communities formed nonlinear regression models with species composition factors (TSC, ROTS, and SR). The CSS of plant communities increases with the complexity of TSC and SR, indicating that more complex tree compositions enhance carbon sink efficiency (Fig. 13a and c). The relationship between plant community CSS and ROTS was modeled by a cubic function. When ROTS was <4 or >10, the CSS of plant communities increased with ROTS. However, when ROTS was between 4 and 10, CSS decreased as ROTS increased, showing a downward trend (Fig. 13b). This suggests that an optimal ROTS range is crucial for enhancing the carbon sink efficiency of plant communities.

3.4.4. Impact of 3DGQ on the carbon sink efficiency of plant communities

Fig. 14 shows that the carbon sink efficiency of plant communities formed a nonlinear function model with 3DGQ. When $3DGQ < 10,000 m^3$, CS of the plant community increased with increasing 3DGQ. However, when $3DGQ > 10,000 m^3$, the CS of the plant community began to decrease. Additionally, the ACS of the plant community continued to increase with an increase in 3DGQ. However, the growth rate of ACS begins to level off once $3DGQ > 14,100 m^3$. Further increases in 3DGQ have limited effects on enhancing the ACS of the plant community. This indicated that 3DGQ was a vital parameter to consider when measuring the carbon sink efficiency of urban park plant communities.

3.5. Constructing the SEM for plant community carbon sink efficiency

Using the SEM, we clarified the complex driving relationships between community structure factors, species diversity, species composition factors, and 3DGQ on the CS and ACS of plant communities (Fig. 15). The results indicated that plant community structure, species diversity, species composition, and 3DGQ were crucial parameters for

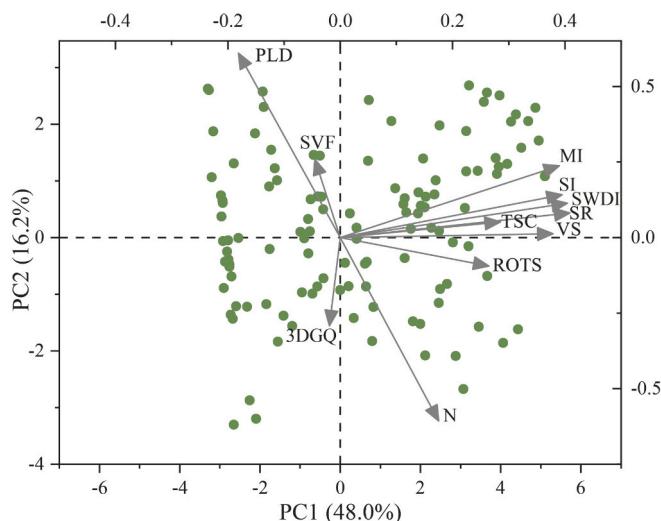


Fig. 10. PCA of factors influencing carbon sink efficiency in plant communities.

assessing the carbon sink efficiency of plant communities. Among these, 3DGQ showed no significant correlation with species diversity and species composition factors. Plant community structure factors were negatively correlated with other driving factors, whereas species diversity and species composition factors showed a significant positive correlation. Furthermore, only plant community structure factors showed a negative correlation with plant community CSS. 3DGQ explained 55 % of the variance in plant community CS and 46.8 % in ACS, whereas species diversity explained 60.2 % of the variance in ACS

and 25.7 % in CS. Species composition factors explained 36.8 % and 12 % of the variance in the CS and ACS plant communities, respectively. As shown in Fig. 15, there was a synergistic effect among the driving factors; plant community structure, species diversity, species composition, and 3DGQ together explain 64.3 % and 90.1 % of the variance in plant community CS and ACS, respectively. Thus, the carbon sink efficiency of plant communities was the result of synergistic interactions among multiple index parameters.

4. Discussion

4.1. Differences in carbon sink efficiency across different plant communities

The average ACS rate per unit area for the plant communities in this study was $0.53 \text{ kg Cm}^{-2} \text{ y}^{-1}$, which was very similar to the rate in Turkey at $0.575 \text{ kg Cm}^{-2} \text{ y}^{-1}$ (Grossi et al., 2023). However, this rate was nearly twice as high as the rate found by Nowak et al. (2013), which was $0.277 \text{ kg C m}^{-2} \text{ y}^{-1}$, and significantly lower than the rate reported by Wang et al. (2021b) for the suburban park plant communities in Beijing. The variations in results may be due to different climatic and soil conditions or due to the inclusion of shrubs and herbaceous plants in assessing the carbon sink capabilities of plant communities in this study, along with the use of diverse measurement methodologies.

In comparing the CSS capacities of different vegetation structures, the results indicate significant disparities. Notably, the CBM exhibited the highest CSS values, with an ACS capacity of 323.4 kg/Yr , which is 3.1 times that of SOBS. Additionally, the efficiency of CSS follows the order: closed > semi-closed > semi-open, a finding supported by Yang et al. (2024). This may be due to the high vegetation cover in closed

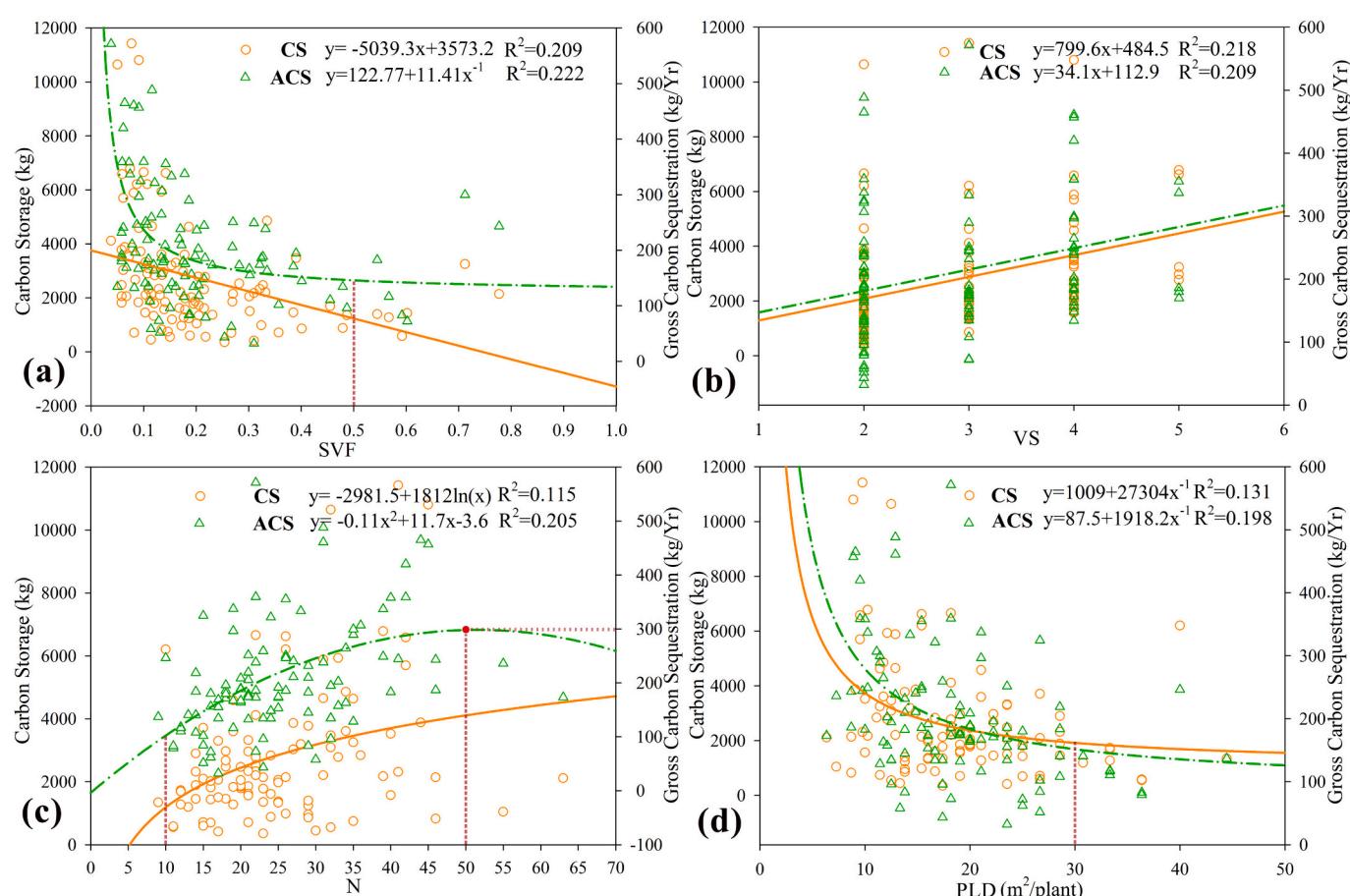


Fig. 11. Regression equation between plant community CSS and plant community structure factors: (a) SVF, (b) VS, (c) N, and (d) PLD.

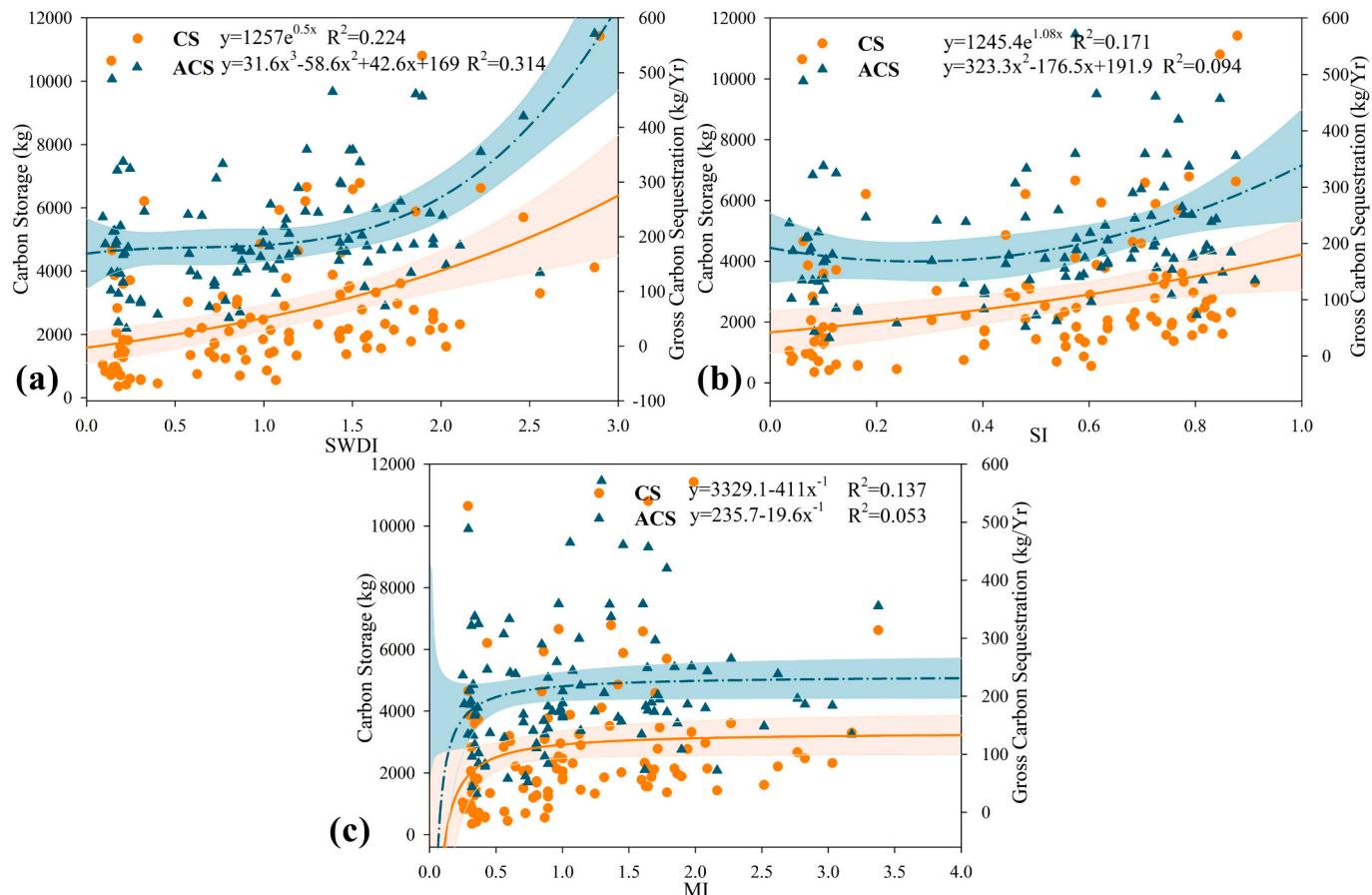


Fig. 12. Regression equations between plant community CSS and species diversity factors: (a) SWDI, (b) SI, and (c) MI.

structures significantly lowering ground surface albedo, which was negatively correlated with green space CS (Li et al., 2024). Surprisingly, we found that semi-closed green spaces could also exhibit high carbon sequestration efficiency, with negligible differences in CSS values between SCMM and CDS, a conclusion that aligned with the findings of Wang et al. (2021b). Semi-closed plant communities might have higher tree species diversity, allowing various species to efficiently photosynthesize under different environmental conditions, thereby compensating, to some extent, for lower coverage. Therefore, the complexity and diversity of vegetation structures should be considered when assessing and managing the carbon sink efficiency of plant communities.

Although there were no significant differences in ACS between TSH and TH structures, the average ACS of the TSH structure remained higher than that of the TH structure. This finding aligned with Carr et al. (2018), who suggested that plant communities composed of TSH structures had higher CS capabilities than other species compositions. Moreover, some studies (Velasco et al., 2016; Fu et al., 2019) have argued that, owing to the high maintenance intensity of herbaceous plants, their CS can be considered negligible. These studies highlighted that maintenance activities for herbaceous plants (e.g., frequent mowing and irrigation) can lead to carbon emissions, thus offsetting carbon fixation through photosynthesis. Conversely, Amoatey and Sulaiman (2020) stated that herbaceous plants act as significant carbon sinks within urban green spaces, noting their rapid growth rates, which allow for quick photosynthesis and carbon fixation. However, herbaceous plants typically have short lifecycles, often being annuals, meaning they can fix carbon in the short term but have a weak long-term CS capacity (Deng et al., 2022). Therefore, plant communities composed of trees, shrubs, and herbs can achieve the dual aims of rapid carbon fixation and stable long-term CS.

Moreover, plant communities composed of CFs had lower ACS than

those composed of BLFs. Su et al.'s (2021) findings support this observation, which may be attributed to the coniferous trees having a hard outer cuticle and relatively smaller leaf surface area, affecting their photosynthetic efficiency and potentially limiting their carbon fixation capabilities (Tsay et al., 2015). Although there were no significant differences in CS between MCBFs, BLFs, and CFs, understanding the CS potential of plant communities based on different types of tree compositions is essential. Studies have found that the average CS is MCBFs > BLFs > CFs, suggesting that mixed species composition may be more beneficial for carbon absorption and storage. Hence, in dealing with the complexity of carbon sink efficiency in urban park plant communities, a deep understanding of its driving factors is a crucial step toward achieving carbon neutrality goals.

4.2. Factors influencing carbon sink efficiency of plant communities

While there has been considerable research into the factors influencing carbon sink capabilities in urban green spaces, most studies have been limited to the impact of single factors (e.g., species selection) (Sharma et al., 2021; Shadman et al., 2022). The complex interplay of physiological and ecological mechanisms within plant communities made it essential to identify the drivers of carbon sink efficacy. Our study highlights the roles of plant community structure, species diversity, species composition, and 3DGQ as key drivers affecting carbon sinks in urban park plant communities.

Our findings reveal a correlation between the carbon sink capacity of plant communities and community structure factors. There was a linear regression equation between VS and CSS, indicating that multi-layered plant communities have stronger carbon sink capabilities, a view supported by Chen et al. (2024). The SVF, as an indicator factor measuring the density and distribution of vegetation structure, also highlights its

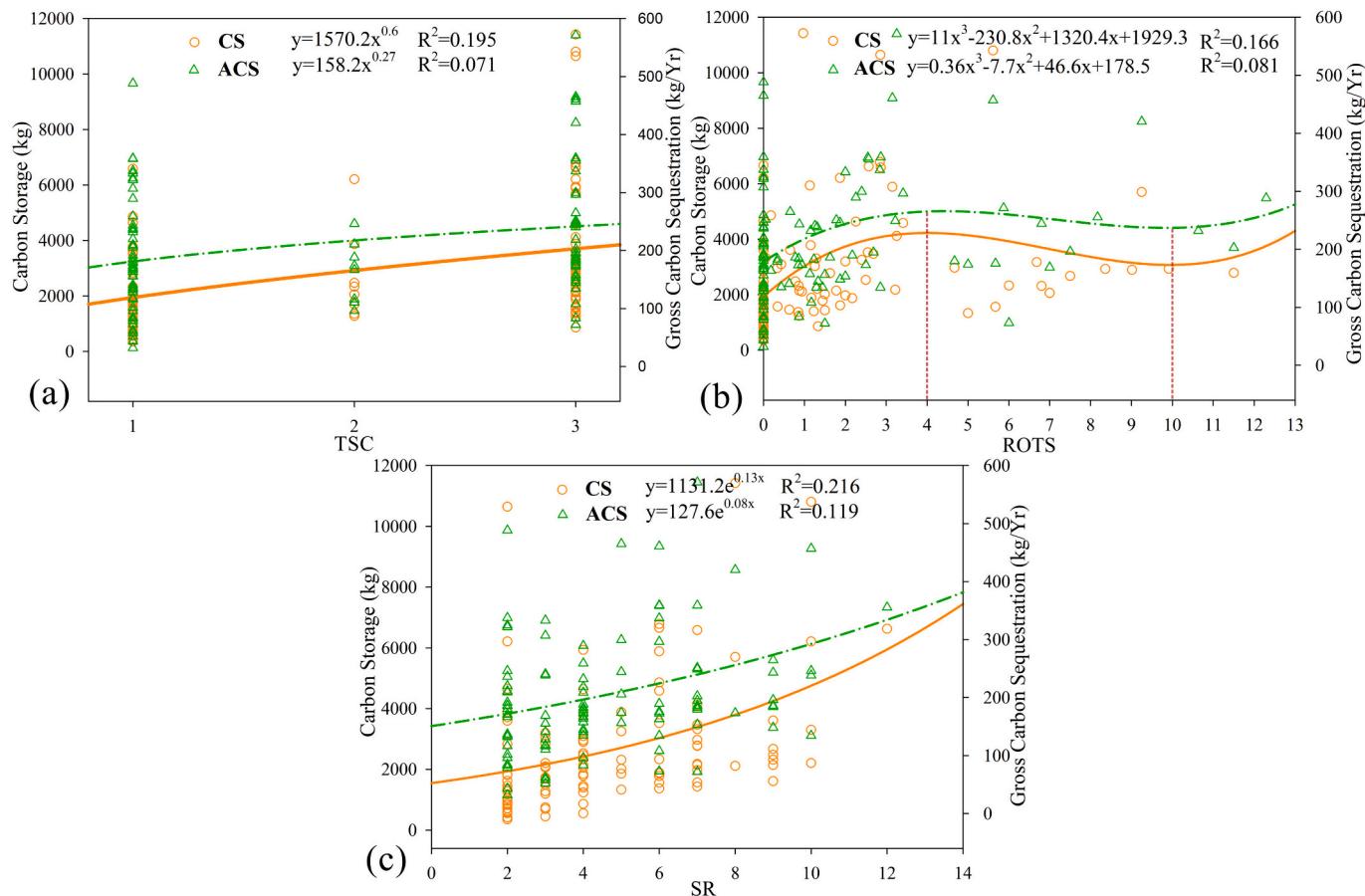


Fig. 13. Regression equation between plant community CSS and species composition factors: (a) TSC, (b) ROTS, and (c) SR.

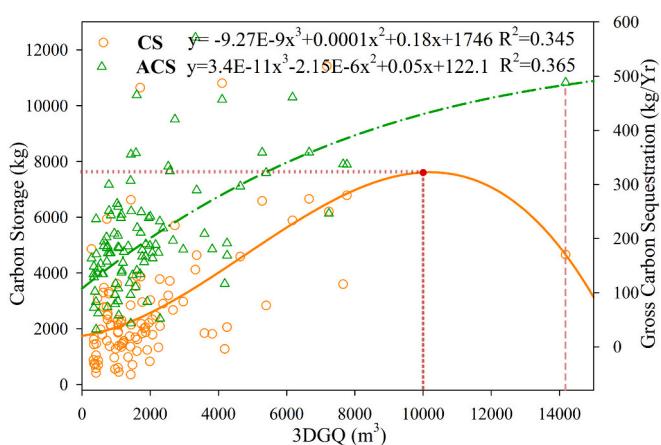


Fig. 14. Fitting function model between plant community CSS and 3DGQ.

importance in studies of plant community carbon sinks. According to Yin et al. (2019), SVF significantly affects the penetration of sunlight and the amount of light energy reaching the ground, thereby influencing the carbon sink efficiency of plant communities. Although previous studies have confirmed that densely planted forests can sequester carbon more effectively than other types of urban green spaces (De la Sota et al., 2019), our study indicated a negative correlation between plant community carbon sequestration efficiency and PLD and SVF. This discrepancy may be due to high planting densities, where vegetation competes for resources and space, reducing the sunlight, water, and nutrients necessary for individual growth (Phillips et al., 1994), which in

turn affects their growth and CS capacity (Nowak et al., 2002a). Furthermore, densely planted vegetation may increase the risk of air pollutants, thereby affecting respiratory health (Vos et al., 2013).

It is noteworthy that although increasing the N can, to some extent, enhance the CSS capacity of a plant community, once the N within a sample plot exceeds 50, the ACS of plant communities reaches a threshold. Beyond this, simply adding more trees did not yield additional ACS benefits and may even lead to increased carbon emissions due to frequent maintenance management (i.e., mowing, pruning, watering, fertilizing, etc.), thereby reducing the overall carbon sink effectiveness. This view is supported by Mexia et al. (2018), who suggested that in parks with reasonable planting densities, the carbon sink capacity is proportional to the number of trees planted. Furthermore, a novel finding from our study is that some low-density plant communities can also possess high carbon sink efficiencies, likely because these communities are composed of high CS rate tree species. Therefore, we recommend that efforts to enhance the carbon sink efficiency of urban green spaces should prioritize optimizing plant community structure rather than merely increasing the number of trees.

Different plant communities show variations in tree species composition, structure, and function, which lead to differences in species diversity, dominance index, evenness, and richness (Gao et al., 2014). This study demonstrated a significant correlation between plant community CS and SWDI ($p < 0.001$), while the correlation between ACS and SWDI was weaker. This finding is consistent with that of Chen et al. (2024), who observed the dual role of multi-layered planting structures in increasing CS and maintaining urban ecosystem diversity. Complex forest structures (e.g., upper-layer trees, mid-layer shrubs, and lower-layer herbaceous plants) often exhibit high species diversity (Vierling et al., 2008). Through complementary interactions among plants,

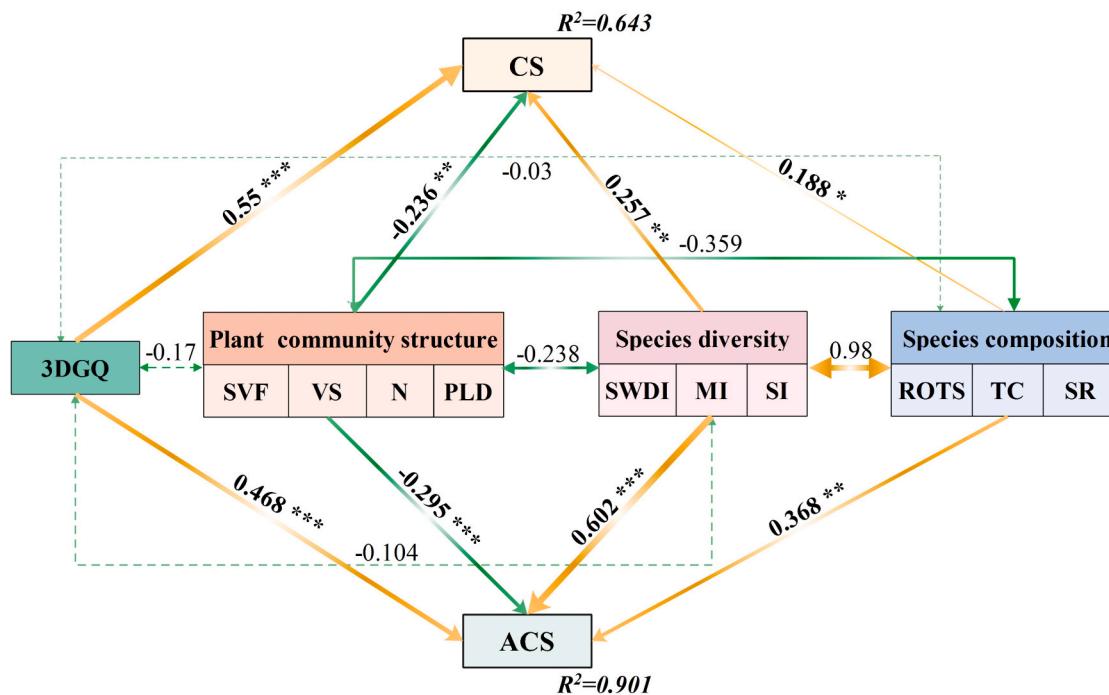


Fig. 15. SEM outlines the influence of each driver on the contribution of plant community CSS. The values of the arrows are path coefficients that indicate the degree of influence of the relationships between the variables. Solid yellow and green lines represent relationships with positive and negative effects on the model, respectively, and dashed lines indicate non-effective paths. Path coefficients are estimated using great likelihood, reflecting the effect size of the relationship. R^2 values indicate the proportion of variance explained. Significance levels: * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$.

maximal light utilization is achieved, thereby enhancing carbon sink efficiency. High richness and dominance indices indicate plant communities' high complexity and ecological stability (Poorter et al., 2015). Our study confirmed this viewpoint and showed that plant community CSS increased with SI and MI. However, the relationship between species diversity and carbon sink efficiency is still debated. Chen et al. (2020) suggested that plant diversity significantly affects ecosystem carbon sink efficiency. Despite these debates, increasing evidence supports the critical role of species diversity in sustaining and enhancing ecosystem carbon sink efficiency (Mori et al., 2021). Focusing solely on planting a few species with high carbon sequestration potential may increase CS, but sacrifice the long-term stability and resilience of the ecosystem (Jactel et al., 2018). Future research could further explore the relationship between species diversity and carbon sink efficiency under different climatic conditions and geographical locations.

Our findings are compatible with those obtained by Fu et al. (2019), who proved that plant communities' SR is positively correlated with carbon sink efficiency. Othman et al. (2019) explored this issue, studying the impact of species composition on the carbon sink efficiency of plant communities. They found that more complex species compositions correspond to higher CSS, conclusions we also reached. Additionally, ROTS affects the carbon sink efficiency of plant communities, particularly when ROTS was <4 or >10 , where carbon sink efficiency increased with ROTS. This further illustrates that a reasonable ROTS can maximize CSS effectiveness.

Our study revealed that, when the 3DGQ of a plant community reaches $10,000 \text{ m}^3$, its CS reaches a threshold, and increases beyond this value are not significant. This suggests that merely expanding the 3DGQ of plant communities is not an effective measure to enhance carbon sink efficiency. Instead, species diversity, species composition, and plant community structure must also be considered, which supports the idea that carbon sink efficiency in plant communities is the result of a combination of multiple indicator parameters. Therefore, future research and practice should take a more comprehensive approach to these factors to scientifically and reasonably optimize the design and

management of urban green spaces, thus maximizing their carbon sequestration function.

Additionally, our findings underscore that multiple driving factors synergistically influence the carbon sink efficiency of plant communities (Fig. 15). Jia et al. (2023) found that forest structure and species diversity together explain 64 % of the CSS variation, which differs from our results, possibly due to differences in the study locations. Their research area was a specialized exposition garden, wherein the plant community structure and level of species diversity are generally higher than those in typical urban parks. Hence, different types of parks also impact the carbon sink efficiency of plant communities. Moreover, our study found that the species diversity index explains ACS better than CS, this finding was also reported by Jia et al. (2023), indicating that the CSS function of plant communities in different types of green spaces is influenced by multiple factors, which should be comprehensively considered in practical applications.

4.3. Optimized planting strategies for plant communities in different biotope types

Mitigating urban climate change and enhancing the carbon sink capacity of urban park plant communities have become key focal points in carbon neutrality efforts (Mitchell et al., 2018). Urban parks not only provide climate regulation services but also carry multiple functions (e.g., aesthetic experiences and recreational opportunities), making significant contributions to human well-being (Krennberg et al., 2021). To design sustainable carbon sequestration for urban park plant communities, it is crucial to balance landscape aesthetic perceptions with ecological values. Based on these considerations, this study proposed optimized planting strategies for different biotope types (Fig. 16) to enhance the CSS of urban park plant communities in the temperate monsoon climate zone. The designated sample area for these plant communities measures 400 m^2 .

For gray-green spaces, it is imperative to ensure that they provide adequate activity areas while also maximizing the CSS benefits of plant

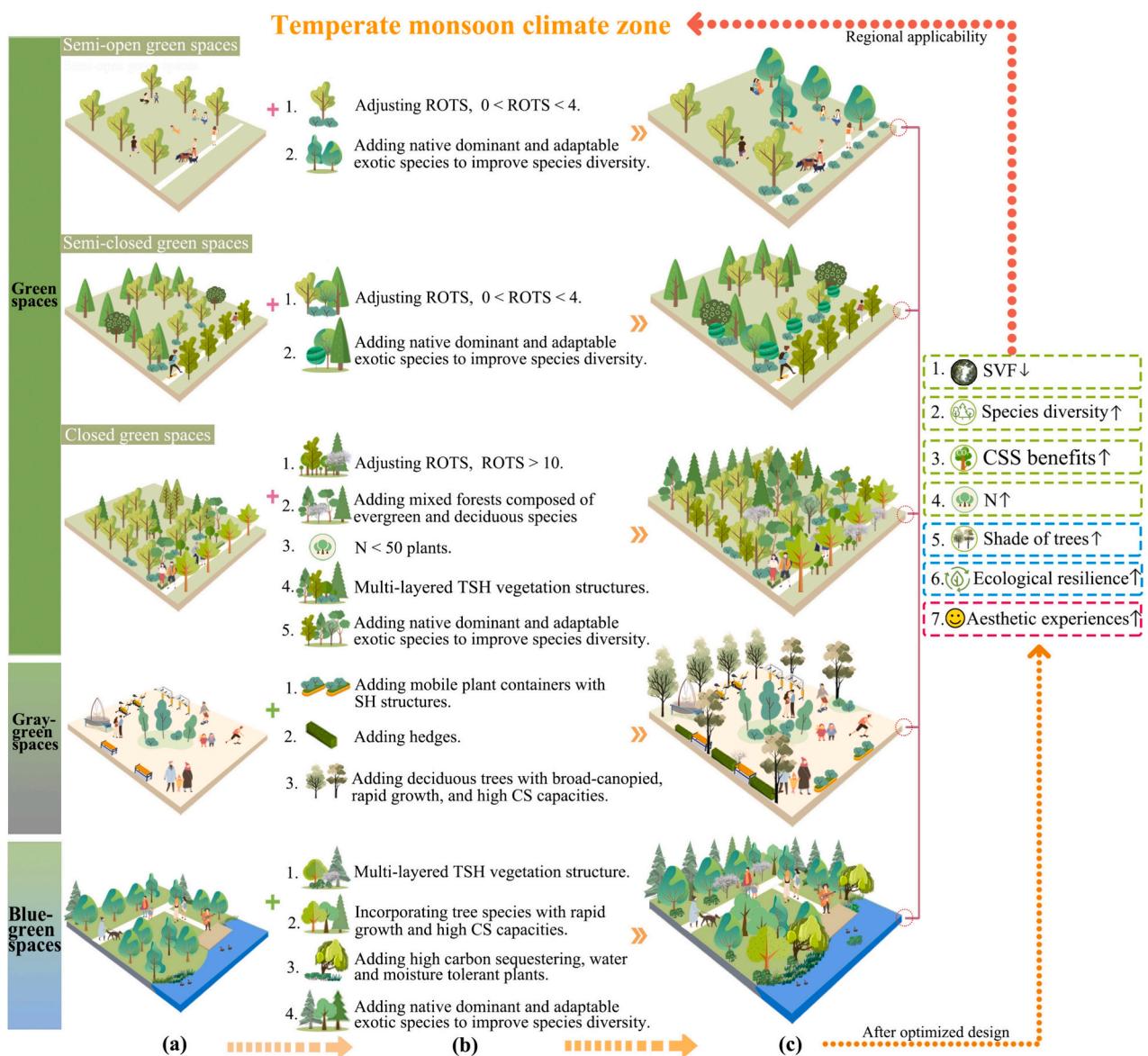


Fig. 16. Planting design strategies for plant communities in different biotope types (present situation (a), optimal planting design strategies (b), and optimized planting design diagrams (c)).

communities. Gray-green spaces can incorporate flexible planting strips or small green patches among hard pavement, featuring deciduous trees with broad-canopied, fast-growing, and aesthetic appeal. Alternatively, movable plant containers with SH structures can enhance these areas' carbon sink capacity.

For blue-green spaces, the design should incorporate multifunctional green spaces that take advantage of the waterfront characteristics. Research has indicated that the synergistic effects between water bodies and green spaces significantly impact carbon sink efficiency (Li et al., 2024). By creating multi-layered TSH vegetation structures that combine moisture-tolerant trees, shrubs, herbaceous plants, and aquatic plants, the species diversity of plant communities can be increased. Additionally, selecting native species with rapid growth and high CS capacities can further improve the carbon sink efficiency of blue-green spaces while enhancing the stability and resilience of the ecosystem.

To optimize green spaces with different vegetation structures, ensuring that they have efficient carbon sink capabilities while maintaining ecological balance and aesthetics, the following steps can be taken:

- (1) Control the SVF between 0.01 and 0.5 to increase canopy coverage and reduce ground-level heat radiation, thereby enhancing carbon sink capabilities.
- (2) Utilize high carbon-sequestering multi-layered TSH structures, ensuring $0 < \text{ROTS} < 4$ or $\text{ROTS} > 10$, to adjust planting density and distribution based on the size and shape of the plot. Lower ROTS values are suitable for semi-closed and semi-open vegetation structures, while higher values are appropriate for closed structure green spaces, such as shaded areas. In closed structures, ensure $N < 50$ plants and consider creating mixed forests with evergreen and deciduous species to enhance ecological resilience and biodiversity.
- (3) Increase the diversity of vegetation types by selecting native dominant species well-adapted to the local environment. Additionally, introduce adaptable exotic species appropriately to enhance the richness and biodiversity of plant communities. Furthermore, design seasonal plant landscapes that reflect the climatic variations of the region. This approach ensures that the plant community structure meets functional requirements while also achieving aesthetic and ecological diversity goals.

4.4. Limitations

Several limitations of this study should be acknowledged. First, this study did not consider soil carbon sequestration. Secondly, urban vegetation, as an integral part of urban ecosystems and carbon cycles, also provides aesthetic, economic, and ecological values to urban residents (Nowak et al., 2002b; Teo et al., 2021). In addition, the trade-offs and synergistic effects between different types of ecosystem services have not been thoroughly studied, especially in urban park green spaces. Future research should aim to enhance the aesthetic value of low-carbon landscapes, utilize high carbon-sequestering tree species combined with landscape visual effects and public perceptual preferences to arrange plant individuals, create plant communities with rich vegetation types, strong carbon sink capabilities, and align with the public aesthetic preferences, to achieve sustainable carbon sink design in urban green spaces.

5. Conclusion

Quantifying the carbon sink efficiency of plant communities within different biotope types in urban parks is crucial for achieving carbon neutrality goals. This study employed a mixture of methods including detailed field surveys, LiDAR point cloud data, i-Tree Eco, NTBC software, and satellite remote sensing imagery, to assess plant communities' CSS in various biotope types of urban parks. Our study was the first to clearly define the contributions of plant community structure, species diversity, species composition, and 3DGQ to the carbon sink efficiency of plant communities. The principal conclusions could be drawn as follows:

- (1) There were differences in the CSS among different vegetation structures. Closed structures have the highest average CSS values, followed by semi-closed and semi-open structures. Compared to closed single-layer coniferous green spaces, semi-closed multi-layer mixed structures can also demonstrate high carbon sink capabilities.
- (2) Carbon sink efficiency varied among the plant communities with different vertical structures and species compositions. However, there were no significant differences in CS among the three different species compositions. Regarding ACS, BCMF had the highest ACS, followed by BLF and CF.
- (3) The carbon sink efficiency of plant communities was influenced by plant community structure, species diversity, species composition, and 3DGQ. Among these, only SVF and PLD showed a significant negative correlation with the carbon sink efficiency of plant communities, while all other factors are positively correlated. Non-linear regression equations predominantly model the relationships between these factors and the CSS of plant communities.
- (4) The carbon sink efficiency of plant communities resulted from the synergistic effects of multiple parameters. There was a synergistic effect among driving factors, with SEM showing that plant community structure, species diversity, species composition, and 3DGQ collectively explain 64.3 % and 90.1 % of the variance in CS and ACS, respectively.

Our study sheds light on selecting appropriate vegetation planting strategies for different biotope types in urban parks in the temperate monsoon climate zone, to adapt to and mitigate the impacts of climate change. Although our research primarily focused on a city in the lower reaches of the Yellow River basin, planting strategies for plant communities are also applicable to other cities with similar climatic conditions. Finally, to achieve a win-win scenario for CSS and species diversity, we recommend adopting multi-layer vertical planting structures, controlling ROTS, N, and planting density, and increasing SR within the community while considering the functional attributes of

different biotype types. This study provides scientific methodological support and strategic guidance for enhancing CSS in urban park plant communities under carbon neutrality goals.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitenv.2024.175347>.

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CRediT authorship contribution statement

Dan Zhao: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jun Cai:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Shijia Shen:** Investigation, Data curation. **Qianchi Liu:** Investigation, Data curation. **Yujian Lan:** Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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