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Assessment of the ecological functions of primary greening tree species in arid and semi-arid urban areas of northern China: a field and UAV-based approach

Qilong Hao , Yange Wang*, Huiru Lv and Xinyao Li

School of Architecture, Inner Mongolia University of Technology, Hohhot, People's Republic of China

* Author to whom any correspondence should be addressed.

E-mail: 17839887025@163.com

Keywords: arid and semi-arid regions, landscape tree species, cooling function, species diversity maintenance function, carbon sequestration function

Abstract

In arid and semi-arid regions with limited water, evaluating the ecological functions of urban trees is essential to improve quality greening. This study evaluated the core ecological functions based on the physical traits of arbor species (cooling, species diversity maintenance, and carbon sequestration) of 261 trees from five species (*Salix matsudana*, *Styphnolobium japonicum*, *Populus alba*, *Pinus sylvestris* var. *mongholica*, and *Ulmus pumila*) across three arid and semi-arid urban areas: Hohhot, Baotou, and Yinchuan. (1) Among the evaluated morphological traits, crown width (Pearson $r = 0.77$, $P < 0.001$) was the significant driver of cooling. *Salix matsudana* (EMM: 12.43 °C) and *Styphnolobium japonicum* (EMM: 10.48 °C) exhibited the greatest cooling benefits. (2) Compared to morphological traits, tree species identity was identified by random forest (RF) analysis as an important factor influencing understory species diversity maintenance (%IncMSE = 27.84%). Baseline observations showed that *Pinus sylvestris* var. *mongholica* provided the highest understory species richness (EMM: 3.91), Shannon index (EMM: 1.02), and Simpson index (EMM: 0.56). (3) Fast-growing *Populus alba* exhibited the highest individual carbon sequestration (EMM: 130.86 ± 15.98 kg) and carbon sequestration efficiency (EMM: 3.95 ± 0.29 kg cm⁻¹). Furthermore, within the spatial context of Hohhot, Baotou, and Yinchuan, the functional divergence highlighted significant ecological trade-offs, indicating no single tree species simultaneously maximizes all targeted ecosystem services. Based on Entropy-weight TOPSIS evaluation, *Pinus sylvestris* var. *mongholica* (Overall Score: 0.607) and *Populus alba* (0.533) exhibited the optimal comprehensive performance regarding the three assessed ecological benefits among the selected arbor species in these study areas. These findings provide a scientific reference framework for goal-oriented construction of urban green spaces. When interpreting these conclusions, seasonal constraints of summer-only observations and methodological limitations of relying solely on above-ground biomass must be considered, as they may obscure comprehensive seasonal dynamics and conservatively underestimate the total carbon sink value.

1. Introduction

Arid and semi-arid regions experience sparse precipitation and intense evaporation, resulting in fragile ecosystems that are highly sensitive to climate change (Xu *et al* 2024). Urban greening plays a crucial role in regional hydrological, thermal and carbon cycles (Li *et al* 2024). Landscape greening systems, particularly the tree canopy layer, serve the dual functions of ecological regulation and aesthetic enhancement. These systems are essential for mitigating the urban heat island effect, improving air quality, and promoting carbon sequestration (Xu and Rui 2024, Ali *et al* 2025, Feng *et al* 2025). However, compared to humid regions, urban greening in arid and semi-arid zones faces severe water resource constraints and climatic stresses. Tree physiological activities and ecological effects in these areas are governed by

the dual influences of soil moisture availability and high-temperature drought stress (Zhao *et al* 2025), which results in highly nonlinear regulation of the urban microclimate, carbon storage and species diversity. The ecological benefits of these areas are jointly controlled by the characteristics of tree species, and management practices (Carmona-Yáñez *et al* 2023).

To systematically address these complex interactions, rebuilding community ecology from functional traits provides a more coherent and mechanistic reference framework (McGill *et al* 2006). As the global spectrum of plant form and function demonstrates, fundamental variations in physical size and leaf economics drive ecosystem processes worldwide (Díaz *et al* 2016). Transitioning this general theory to specific arid systems requires acknowledging the role of environmental stress. Recent empirical research on trait-environment relationships reveals that variations in the plasticity of functional traits indicate the differential impacts of abiotic and biotic factors on the structure and growth of plants in drought-stressed, fragmented ecosystems (Chaturvedi *et al* 2025). Integrating this disturbance-mediated, trait-based ecology framework is therefore essential for systematically understanding service trade-offs in urban environments. Under this framework, this study focuses on cooling, diversity maintenance, and carbon sequestration, deliberately excluding services like water use efficiency due to arid environmental constraints. Because extreme summer vapor pressure deficits (VPDs) induce stomatal closure and restrict physiological transpiration, physical canopy shading becomes the dominant mechanism for reducing surface temperatures and mitigating extreme heat (Meili *et al* 2020).

Viewed through this lens of functional traits, the cooling function of trees relies primarily on physiological transpiration and physical shading (Zhou *et al* 2022). The rates of transpiration and the capacity of canopies to conduct water vary among different urban tree species. Physiological transpiration cooling is controlled by environmental factors (Ballinas and Barradas 2016), with significant differences observed between species (Li *et al* 2017, Kang *et al* 2018, Feng *et al* 2023). However, as stomatal downregulation in water-limited arid regions restricts latent heat flux, physical shading mechanisms play a far more critical role (Fahmy *et al* 2010). Shading significantly reduces the average radiant temperature experienced by humans by blocking radiation (Fahmy *et al* 2010, Lee *et al* 2016, Ornelas *et al* 2023). The shading efficiency of different tree species depends on their morphological structure and is closely related to LAI, canopy closure (Tao *et al* 2024), three-dimensional green volume (Yang *et al* 2022) and crown width (Lin and Tsai 2017). Thus, shifting the focus to trait-driven functional ecology allows for the quantification of ‘morphological thresholds’: crown diameter exceeding 1.5 m (Lin and Tsai 2017), or optimal tree cover of 25%–30% (Zhang *et al* 2018), as well as cooling ‘saturation points’ for three-dimensional green volume density (Cao *et al* 2024). Current research is shifting toward utilizing technologies like unmanned aerial vehicles (UAVs) (Liu 2024, Sun *et al* 2024), enabling the transitioning from macro-level assessments to quantitative studies of individual plant morphology (Wang and Ma 2024).

Trees act as ‘habitat engineers’ that determine the diversity of understory species (Luo *et al* 2024). Similarly, the morphological traits that dictate canopy shading also drive the biodiversity maintenance function. Through ‘environmental filtering’ mechanisms (particularly light), trees alter understory microhabitats (Wu *et al* 2025), selecting plants with specific functional traits (Luo *et al* 2024), thereby influencing the species composition and ecological functions of understory communities (Srouf *et al* 2024). However, urban landscaping tree species diversity is severely constrained by the ‘selection funnel’ of nursery supply chains (Hilbert *et al* 2023) and is highly dependent on microhabitat integrity.

Urban greening is a crucial pathway to achieving carbon neutrality (Prabha *et al* 2013, Anjali *et al* 2020, Mo *et al* 2023, Pan *et al* 2023), but quantifying urban carbon sinks is limited (Anjali *et al* 2020). Relying on ‘single-point inventories’ and allometric growth equations (Jenerette *et al* 2024) may underestimate the tree growth rates in urban fringe areas (Trlica *et al* 2020). Furthermore, global data are biased toward temperate regions (Jenerette and Herrmann 2024), with a significant lack of data from arid and semi-arid zones (Steenberg *et al* 2023). Assessments also involve a trade-off between ‘stock’ and ‘rate’ (Trlica *et al* 2020). Through the evaluation of carbon storage (the cumulative ‘stock’) alongside carbon sequestration efficiency per unit diameter at breast height (DBH) (the active ‘rate’), a clear distinction is established between the absolute biomass accumulated over long-term growth and the dynamic carbon assimilation capacity relative to tree growth. This dual-dimensional assessment clearly reveals the fundamental differences in carbon performance among tree species with distinct life-history strategies (fast-growing vs. slow-growing). Additionally, the scale of the assessment is critical because above-ground carbon sequestration capacity varies depending on the scale (per unit leaf area, per individual tree, or per unit forest area) (Chen *et al* 2021, Zhao *et al* 2025). Three-dimensional green volume and complex structure are key to improving carbon sequestration benefits (Hou *et al* 2024).

Based on this integrated ecological functional trait theory and regional climatic constraints, proposed and tested three hypotheses: (1) because severe water deficits restrict physiological transpiration, physical

shading acts as the dominant cooling mechanism; thus, crown width is the primary predictor of cooling capacity in arid environments, with broad-canopied species (*Salix matsudana*) expected to perform best. (2) Tree species identity explains more variation in understory species diversity than physical morphological indicators like tree height or DBH. (3) Driven by differing life-history strategies, tree species assigned to fast-growing categories (*Populus alba*) will exhibit significantly higher carbon sequestration efficiency per unit of DBH than slow-growing species.

This study selected three representative cities in arid and semi-arid regions (Hohhot, Baotou, and Yinchuan) and targeted five major landscape tree species: *Salix matsudana*, *Styphnolobium japonicum*, *Populus alba*, *Pinus sylvestris* var. *mongholica*, and *Ulmus pumila*, aimed to address the following questions by integrating UAV infrared thermal imaging with ground-based measurements (Ornelas *et al* 2023, Sun *et al* 2024).

Quantitatively evaluate and compare the cooling function, species diversity maintenance function, and carbon sequestration function of the five tree species in arid and semi-arid urban environments, and analyze the differentiated driving mechanisms of tree morphological characteristics on these three ecological functions (Yang *et al* 2022). Based on multifunctional comprehensive performance, to select the optimal tree species to provide a scientific basis for the construction of 'ecological-type' urban green spaces in this region.

2. Materials and methods

2.1. Study area

The study areas of Hohhot, Baotou, and Yinchuan are all located within or adjacent to the Yellow River basin. This region is characterized by a temperate continental climate with annual precipitation ranging from 150 to 450 mm and a mean annual temperature ranging from approximately 3.0 °C–16.0 °C. During the field measurement period, the region experiences intense solar radiation and high thermal stress, with the average seasonal temperature averaging 29.55 °C.

Hohhot, located in the southern foothills of the Yin Mountains, belongs to a semi-arid grassland climate zone. It is a representative example of a grassland city in North China's arid and semi-arid regions. Baotou, located along the upper reaches of the Yellow River, is in a semi-arid climate zone. Its urban green spaces serve the dual functions of industrial ecological remediation and public recreation. Yinchuan, located on the Yellow River alluvial plain, belongs to an arid climate zone. Its urban green spaces primarily rely on water resources from the Yellow River for replenishment, making it a significant research subject for 'water-saving green space construction in arid regions'. Yinchuan is a typical example of an oasis city in the arid northwest.

Urban parks with diverse functional types, stable vegetation communities, and consistent management standards were selected as study sites across the three cities, covering comprehensive recreational, ecological leisure, and community service park types. These urban green spaces are subject to regular municipal maintenance regimes, including routine irrigation and pruning, which homogenize background soil moisture and habitat conditions. The selection of specific parks was strictly based on park typology to ensure broad applicability. Furthermore, the sampling strategy prioritized tree species based on the actual planting patterns within these highly managed systems; because the canopy layer in the sampled parks is heavily dominated by a few specific species, the five most abundant tree species were selected as the focal subjects to accurately represent the primary ecological functioning of the urban green spaces in this region.

Specific examples include Altay Amusement Park, Xilin Park, and Xinhua Park in Hohhot, Jinlin Park and Bayi Park in Baotou; Haibao Park in Yinchuan (figure 1).

2.2. Data collection

2.2.1. Tree species and ecological characteristics

The selection of the tree species adheres to the principles of strong adaptability, broad application, and consistent growth cycles. Priority was given to tree species commonly found in the green spaces in the three cities that can withstand arid and semi-arid climates. The planting years were controlled to be identical or similar, thereby eliminating the interference of age differences on growth indicators and ecological functions. The study included 261 specimens of the following species: *Salix matsudana*, *Styphnolobium japonicum*, *Populus alba*, *Pinus sylvestris* var. *mongholica*, and *Ulmus pumila*. Basic information is presented in table 1.

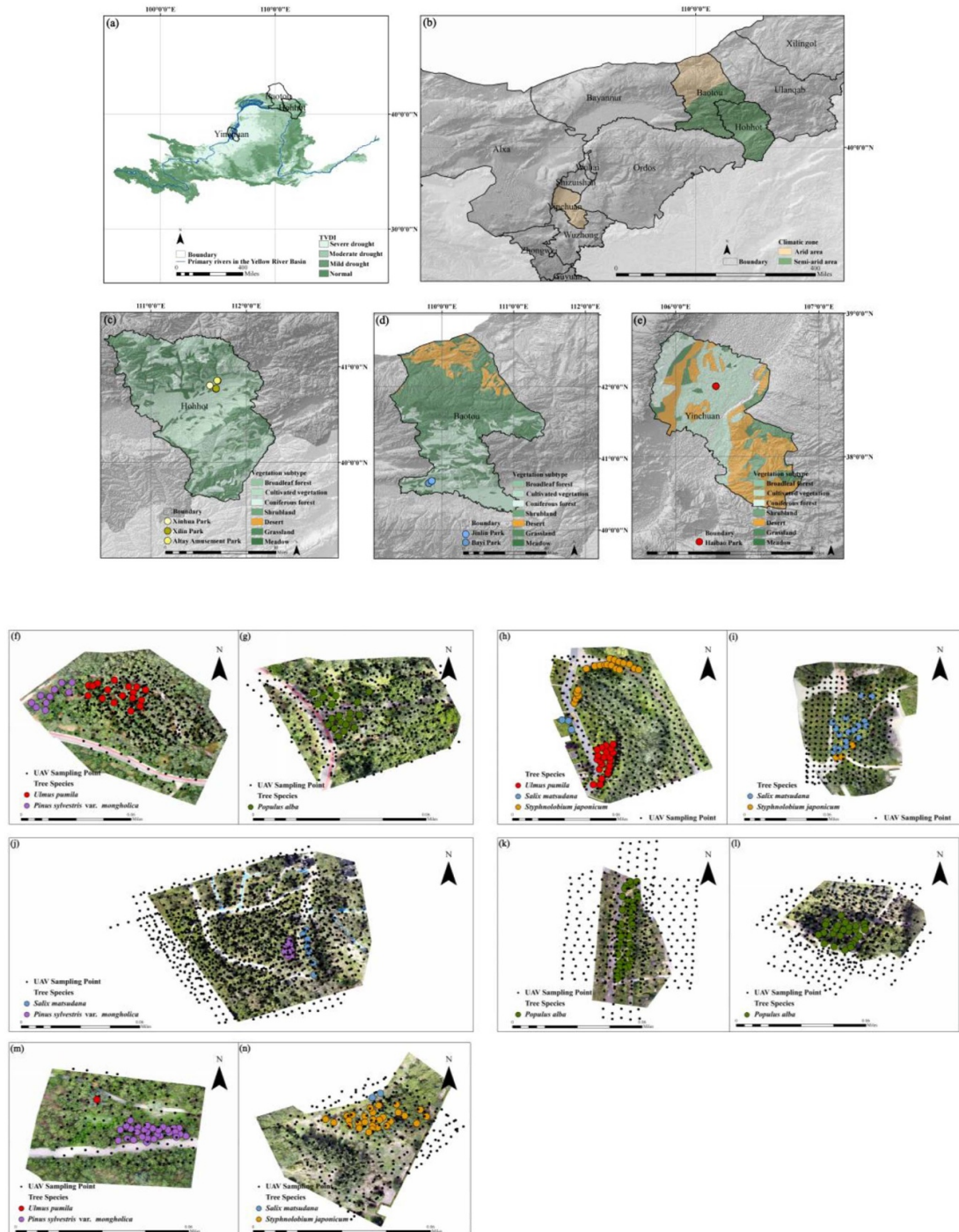


Figure 1. Study area overview map. (a) Location of the study cities within the Yellow River Basin; (b) climate zones of Hohhot, Baotou, and Yinchuan within the arid and semi-arid regions. Vegetation subtypes and study boundaries are shown for (c) Hohhot, (d) Baotou, and (e) Yinchuan. Sampling quadrats include: (f), (g) Altay Amusement Park, (h), (i) Xilin Park, (j) Xinhua Park, (k) Bayi Park, (l), (m) Jinlin Park, and (n) Haibao Park. Graphical distributions represent: (o) tree species, (p) tree height, (q) DBH, (r) crown width, (s) cooling effect intensity, and (t) understory species composition in wooded areas.

2.2.2. Infrared thermal imaging data collection

A MAVIC2-ENTERPRISE-A drone was employed for thermal imaging data collection in this study. Prior to formal data acquisition, on-site reflectance calibration was conducted by placing a calibration aluminum plate with an emissivity of 0.95 on the ground. Atmospheric transmittance was inverted using ground-measured temperatures, and time synchronization and thermal sensitivity adjustments were performed. Data collection occurred between 12:00 and 15:00 from July 1–1 September 2025. This ‘summer midday’ observation window was specifically chosen to evaluate the cooling capacity of trees under conditions of maximum thermal load and solar radiation. In arid and semi-arid environments, high VPD typically trigger midday stomatal closure, significantly restricting the physiological transpiration

Table 1. Tree species and their ecological characteristics.

Species	Leaf shape	Age (yr)	Phenology	Growth rate
<i>Populus alba</i> L.	Ovate or elliptic-ovate	15–20	Leaf expansion period in April; leaf abscission period in October–November	Fast-growing
<i>Pinus sylvestris</i> var. <i>mongholica</i> Litv.	Needles in bundles of 2, stiff and often twisted	15–20	Evergreen tree species without a distinct leaf abscission period	Slow-growing
<i>Salix matsudana</i> Koidz.	Lanceolate	15–20	Leaf expansion period in March–April; leaf abscission period in October–November	Fast-growing
<i>Styphnolobium japonicum</i> (L.) Schott	Pinnately compound	15–20	Leaf expansion period in April–May; leaf abscission period in October–November	Medium
<i>Ulmus pumila</i> L.	Elliptic-ovate, oblong-ovate, elliptic-lanceolate, or ovate-lanceolate	15–20	Leaf expansion period in March–April; leaf abscission period in October–November	Fast-growing

Table 2. Distribution of sampled trees across cities and parks.

City	Park name	<i>Populus alba</i> L.	<i>Pinus sylvestris</i> var. <i>mongholica</i> Litv.	<i>Salix matsudana</i> Koidz.	<i>Styphnolobium japonicum</i> (L.) Schott	<i>Ulmus pumila</i> L.
Hohhot	Altay Amusement Park	20	10	0	0	17
	Xilin Park	0	29	20	24	22
	Xinhua Park	0	10	9	0	0
Baotou	Bayi Park	44	0	0	0	0
	Jinlin Park	26	0	0	0	0
Yinchuan	Haibao Park	0	0	2	28	0
Total	261	90	49	31	52	39

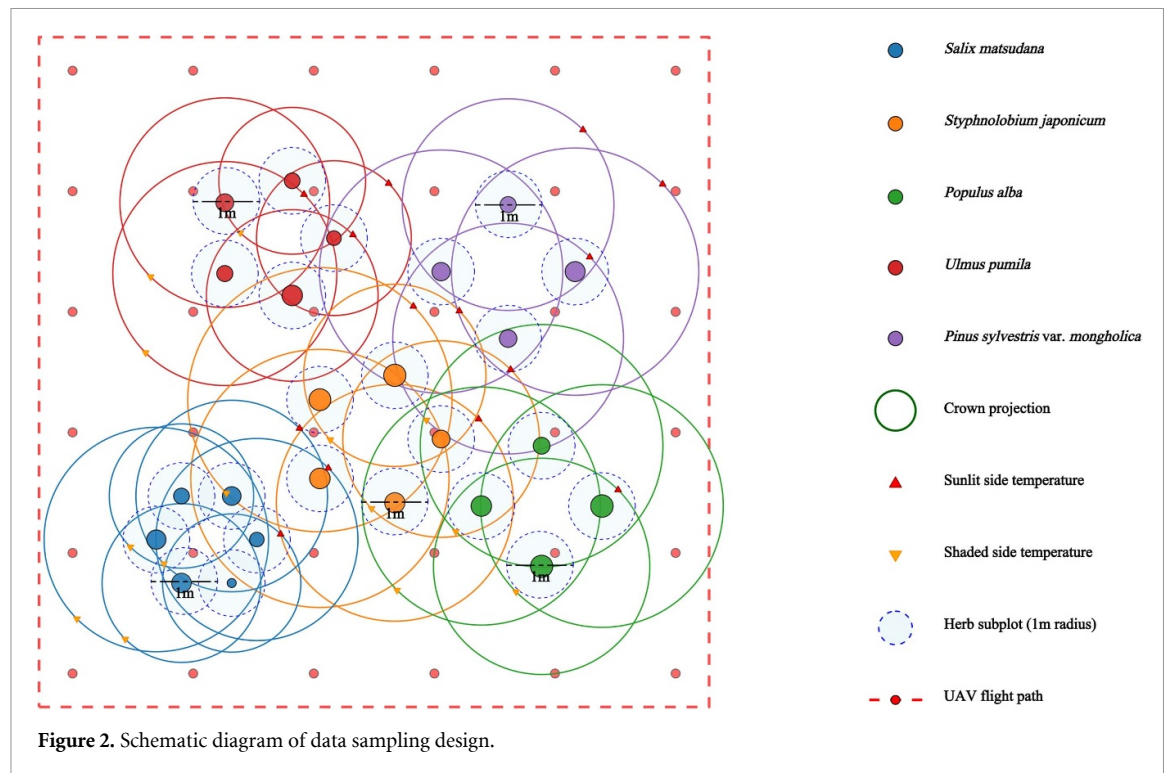
The drone acquired thermal infrared images every 15 min, and dynamic calibration was implemented via the ground thermometer to ensure data accuracy.

2.2.3. Field data collection

Using an ‘air-ground’ collaborative approach, data on the cooling function of all trees with a DBH of at least 5 cm within the sample plots was collected. Records included plant location, species, crown width, DBH, tree height, air temperature, temperature on the shaded side, and temperature on the sunlit side.

A hierarchical independent counting method was used to establish independent sample plots in each park and enumerate all tree species with a DBH ≥ 5 cm. The recorded data included species names, the number of individuals, DBH, tree height, crown width, canopy cover, and coordinate points. To avoid significant confounding noise introduced by overlapping canopies of adjacent trees, paved pathways, or uniform municipal turf management practices in highly managed urban parks, circular subplots with a radius of 1 m were established beneath tree species with a DBH ≥ 5 cm within each independent plot. Herbaceous species with a height of less than 30 cm were recorded and counted. The following data were documented: species name, number of individuals, cover, and average natural height. In total, 261 specimens were selected across the three cities to ensure geographical representation and species diversity. The detailed distribution of the five target tree species across the six study parks is summarized in table 2.

Data collection for carbon sequestration function targeted trees with a DBH of at least 5 cm within the sample plots. Each tree was recorded individually for species name, DBH, tree height, wood density, crown width, and coordinate points, as detailed in figure 2.



2.3. Data analysis

2.3.1. Processing of infrared thermal imaging data

DJI thermal analysis tool 3 was used to extract temperature data from infrared thermal imaging data captured by UAV, and the temperature measured by the thermometer was used to verify the temperature data to improve data reliability.

2.3.2. Statistical analysis

(1) Cooling function of tree species

The cooling effect (ΔT) was calculated as the difference between the temperature of the sunlit side and the temperature of the shaded side. Although this metric primarily captures localized shading contrast rather than the overall microclimatic regulation service provided by the entire tree to the surrounding environment, it serves as an appropriate proxy within the context of arid and semi-arid regions. In these water-limited areas, tree physiological transpiration is frequently suppressed due to stomatal downregulation, making physical shading the dominant mechanism for mitigating urban heat loads. By utilizing this ‘self-referencing’ measurement approach, this study effectively eliminates the environmental noise generated by highly heterogeneous ground surfaces in urban parks, thereby more accurately quantifying the contribution of species-specific morphological traits to the cooling function. Nevertheless, it is acknowledged that this metric has limitations, as it may not fully capture the heat exchange between the entire canopy and the ambient air or represent the comprehensive whole-tree cooling performance. To effectively decouple the intrinsic ecological traits from spatial environmental heterogeneity and account for unbalanced sampling, linear mixed-effects models (LMMs) were employed to evaluate the interspecific differences in the cooling function. In the LMM, tree species was set as a fixed effect, while city and park were included as random effects. The functional performance was quantified using estimated marginal means (EMMs) (Lenth 2016). Subsequently, Tukey’s honest significant difference (HSD) test was used for post-hoc multiple comparisons ($P < 0.05$) to identify specific statistical differences in cooling capabilities among the species.

Pearson correlation analysis was performed based on the data from the 261 sampled trees (including *Salix matsudana*, *Styphnolobium japonicum*, *Populus alba*, *Pinus sylvestris* var. *mongholica*, and *Ulmus pumila*) to examine the relationships between tree morphological traits (crown width, DBH, and tree

height) and the cooling effect (ΔT). Linear regression analysis was then applied to quantify the relationships between these morphological indices and the cooling function.

(2) Species diversity maintenance function

Based on the survey data of understory herbaceous communities, three species diversity indices were calculated: species richness, the Shannon–Wiener index, and the Simpson index.

Species richness refers to the total number of species within a community. The calculation formula is:

$$R = S \quad (1)$$

where R is the species richness and S is the total number of species recorded in the quadrat.

The Shannon–Wiener index reflects both species richness and the evenness of individual distribution. Based on the principle of information entropy (Shannon 1948), it is calculated as:

$$H' = - \sum_{i=1}^S (p_i \cdot \ln p_i) \quad (2)$$

where H' is the Shannon–Wiener index; S is the total number of species; p_i is the proportion of individuals of the i species to the total number of individuals in the community. By definition, $p_i \cdot \ln p_i = 0$ when $p_i = 0$.

The Simpson index focuses on the concentration of dominant species and represents the probability that two randomly selected individuals belong to different species (Simpson 1949). The formula is:

$$D = 1 - \sum_{i=1}^S p_i^2 \quad (3)$$

where D is the Simpson index, with variables defined as above. A higher value indicates a more even distribution of species within the community and a lower degree of dominance by a single species.

Statistical analysis strategy: an LMM was used to analyze interspecific differences in Species richness, Shannon–Wiener index, and Simpson index among different tree species, treating species as a fixed effect and spatial locations as random effects. EMMs were extracted, and Tukey's HSD test was performed for post-hoc multiple comparisons.

Additionally, Pearson's correlation analysis was performed to quantify the linear relationships between tree morphological traits (tree height, DBH, and crown width) and the three species diversity indices.

Importance assessment strategy: a RF model, configured with 1000 decision trees ($n_{\text{tree}} = 1000$), was used to determine the relative sensitivity of tree species, crown width, DBH, and tree height on the three species diversity indices. %IncMSE (increase in mean squared error) was used as the evaluation metric. Each variable was ranked based on its mean IncMSE value. IncMSE measures the importance of a variable by calculating the decrease in model prediction accuracy after randomly permuting its values in the out-of-bag (OOB) samples (Breiman 2001). The calculation formula is:

$$\text{IncMSE}_j = \frac{1}{B} \sum_{b=1}^B \left(\text{MSE}_{b=1}^{\text{perm}(j)} - \text{MSE}_b \right) \quad (4)$$

where IncMSE_j represents the importance of the j variable; B is the number of decision trees; and MSE_b is the mean squared error of the b tree on the OOB data. A higher value of IncMSE_j indicates a greater contribution of the variable to the model prediction.

Partial dependence plots (PDP) were used to visualize the marginal effects of key driving variables on species diversity indices (Friedman 2001). This method effectively reveals the nonlinear characteristics and directional effects of ecological driving mechanisms by calculating and quantifying the positive and negative effects of tree height, crown width, DBH, and tree species on the three species diversity indices. PDP demonstrates the marginal relationship between the independent variable x_j and the dependent variable y . The calculation formula is:

$$\hat{f}_{\text{PDP}}(x_j) = \frac{1}{n} \sum_{i=1}^n \hat{f}(x_j, x_{-j}^{(i)}) \quad (5)$$

where $\hat{f}_{\text{PDP}}(x_j)$ represents the partial dependence value of variable x_j ; $\hat{f}$ is the prediction function of the RF model; $x_{-j}^{(i)}$ represents the values of all other variables excluding x_j for the i sample; and n is the sample size. By calculating $\hat{f}_{\text{PDP}}(x_j)$ across different values of x_j , curves are plotted to reflect the positive or negative influence of x_j on species diversity indices.

(3) Carbon sequestration function

Individual biomass and carbon storage were calculated using allometric equations and the biomass conversion factor method based on measured DBH, tree height (H), and species-specific parameters. To improve the accuracy of assessment, differentiated form factors and wood density parameters were applied for different plant functional types. The specific calculation steps are as follows:

Stem volume calculation:

$$V = G \times H \times f \quad (6)$$

where V is the individual tree volume (m^3); G is the basal area (m^2); H is the tree height (m); and f is the form factor. These are based on the trunk form characteristics of major afforestation species in northern China:

For *Pinus sylvestris* var. *mongholica*, the form factor was set to 0.42. (Note: The empirical range for conifers is 0.40–0.44. Since northern conifers typically have straight trunks but significant tapering, the median value of 0.42 was selected.)

For *Salix matsudana*, *Styphnolobium japonicum*, *Populus alba*, and *Ulmus pumila*, the form factor was set uniformly to 0.47. Note: Northern broad-leaved trees tend to branch early and have less straight trunks than southern species. Therefore, a lower-median value of 0.47 was chosen from the empirical range of 0.45–0.50 to align with their morphological characteristics (Meng 2006).

Basal area calculation:

$$G = \frac{\pi}{4} \times (\text{DBH})^2 \quad (7)$$

where DBH is the diameter at breast height (cm), measured at 1.3 m above ground.

Biomass calculation:

$$\text{AGB} = V \times \rho \quad (8)$$

where ρ is the wood density. The mean air-dry density parameters were set as follows: *Populus alba* 410 kg m^{-3} (Wood Industry Research Institute 1982), *Pinus sylvestris* var. *mongholica* 470 kg m^{-3} , *Salix matsudana* 560 kg m^{-3} , *Ulmus pumila* 640 kg m^{-3} , and *Styphnolobium japonicum* 740 kg m^{-3} (Cheng *et al* 1992).

Carbon Storage Calculation:

$$C_{\text{stock}} = \text{AGB} \times \text{CF} \quad (9)$$

where C_{stock} is the individual carbon storage (Kg) and CF is the Carbon Fraction. A standard international coefficient of 0.47 was adopted based on IPCC guidelines and relevant studies (IPCC 2006).

Carbon sequestration efficiency per unit DBH:

$$E_{\text{carbon}} = \frac{C_{\text{stock}}}{\text{DBH}} \quad (10)$$

Additionally, it must be noted that this methodology relies solely on above-ground biomass, and the absence of below ground biomass quantification represents a methodological limitation in the total carbon stock assessment. Carbon sequestration differences among species were evaluated using generalized linear mixed models (GLMMs) (Bolker *et al* 2009). To prevent impossible negative predictions and accommodate right-skewed growth metrics, ‘Tree Species’ served as the fixed effect, while ‘Park’ nested within ‘City’ was treated as a random intercept to account for spatial heterogeneity. Calculated back-transformed EMMs on the original response scale and conducted pairwise comparisons using Tukey’s HSD test ($P < 0.05$).

(4) Comprehensive Ecological Assessment based on Entropy-TOPSIS

To quantify the overall ecological multifunctionality of each tree species without subjective bias, the Entropy-weighted TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method (Wang *et al* 2018) was employed. The calculation steps are as follows:

Data normalization: the EMMs were normalized to eliminate dimensional impacts:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (11)$$

where x'_{ij} is the normalized value and x_{ij} is the original EMM value of the j th indicator for the i th tree species.

Indicator proportion calculation:

$$p_{ij} = \frac{x'_{ij} + \varepsilon}{\sum_{i=1}^n (x'_{ij} + \varepsilon)} \quad (12)$$

where p_{ij} is the proportion of the i th species under the j th indicator, n is the total number of tree species, and ε is a negligible constant added to avoid the mathematical error of zero logarithms.

Information entropy calculation:

$$e_j = -k \sum_{i=1}^n p_{ij} \ln(p_{ij}) \quad (13)$$

where e_j is the information entropy of the j th indicator, and the constant $k = 1/\ln(n)$.

Objective entropy weight determination:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^m (1 - e_j)} \quad (14)$$

where w_j is the objective weight of the j th indicator based on its data dispersion, and m is the total number of evaluation indicators.

TOPSIS relative closeness (overall score): After applying the weights w_j to construct the weighted decision matrix, the Euclidean distances of each species from the positive ideal solution (D_i^+) and the negative ideal solution (D_i^-) were calculated. The final comprehensive score was determined as:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (15)$$

where C_i represents the relative closeness to the ideal solution. The value of C_i ranges from 0 to 1, with a higher value indicating a superior and more balanced multifunctional ecological performance.

3. Results and analysis

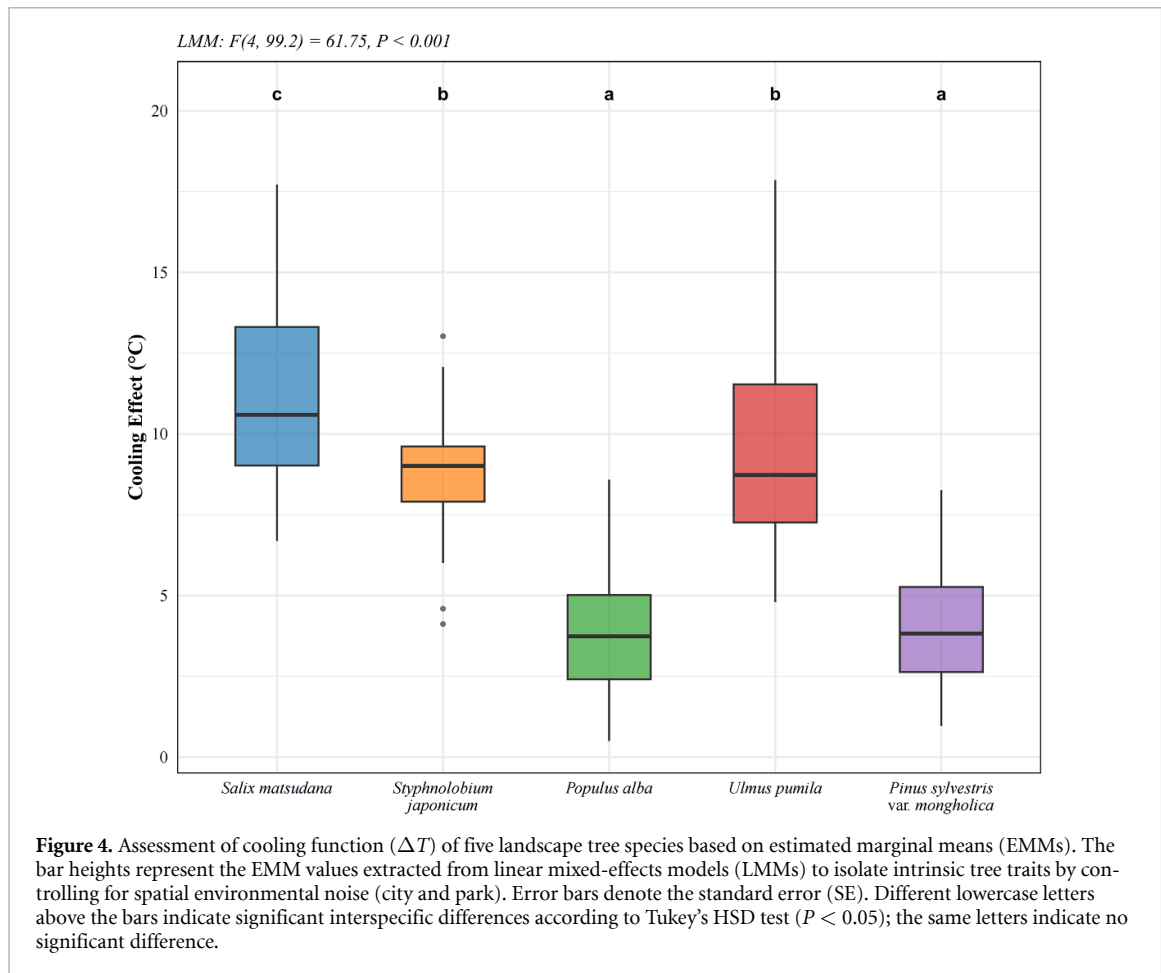
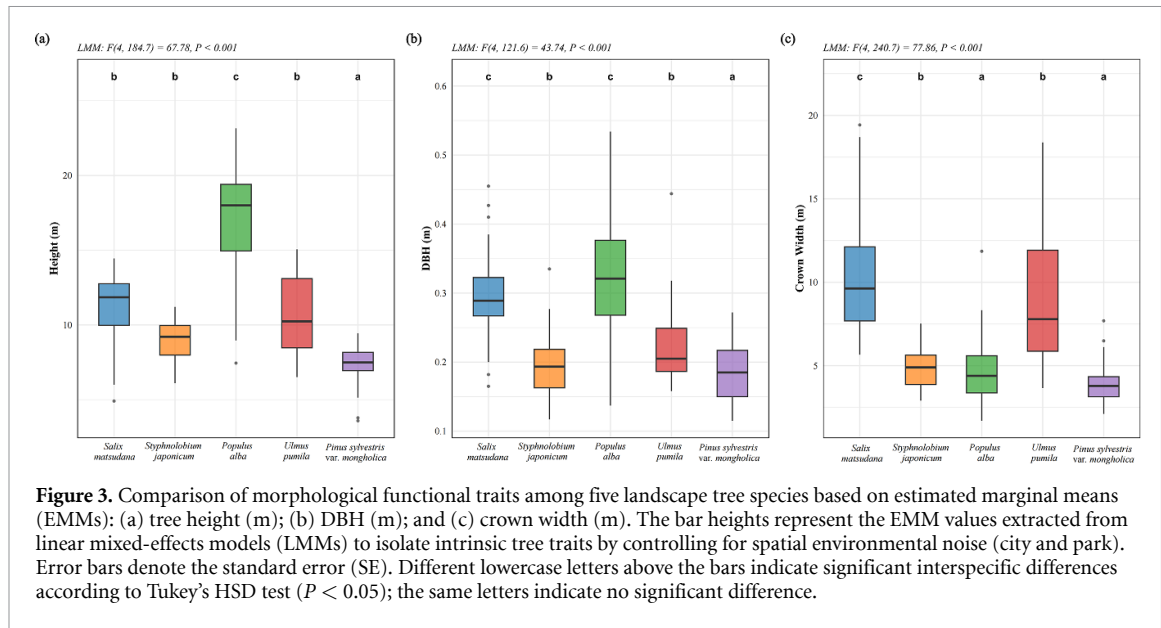
3.1. Comparison of functional traits among five landscape tree species

The study analyzed tree height, DBH, and crown width of five tree species using UAV thermal imaging and field data. Based on the LMMs, functional traits varied significantly among the species (figure 3). Tree height differed significantly ($P < 0.001$; figure 3(a)). According to the EMMs, *Populus alba* had the greatest mean height (17.08 m), while *Pinus sylvestris* var. *mongholica* was the shortest (5.96 m). DBH also varied significantly ($P < 0.001$; figure 3(b)). *Populus alba* (0.33 m) and *Salix matsudana* (0.30 m) exhibited larger values, whereas *Ulmus pumila* (0.21 m), *Styphnolobium japonicum* (0.21 m), and *Pinus sylvestris* var. *mongholica* (0.15 m) had significantly smaller values. Crown width showed significant interspecific variation ($P < 0.001$; figure 3(c)). *Salix matsudana* possessed the largest crown width (11.97 m), while *Populus alba* had the smallest width (2.74 m).

3.2. Assessment and analysis of tree cooling function

3.2.1. Assessment of tree cooling function

To effectively decouple intrinsic ecological traits from spatial environmental heterogeneity and account for unbalanced sampling, LMMs were employed to evaluate the interspecific differences in the cooling function (figure 4). The results demonstrated significant variations in the cooling effect among the five tree species ($P < 0.001$). Based on the extracted EMMs, *Salix matsudana* exhibited the most outstanding cooling benefit (12.43 °C). This was followed by *Styphnolobium japonicum* (10.48 °C) and *Ulmus pumila* (9.44 °C), which showed moderate cooling capacities. In contrast, *Pinus sylvestris* var. *mongholica* (3.66 °C) and *Populus alba* (2.76 °C) demonstrated significantly weaker cooling performances.



3.2.2. The factors influencing the cooling function of the trees

Pearson correlation analysis tested the relationships between tree height, DBH, crown width, and cooling values (figure 5). Crown width showed the strongest positive correlation overall ($r = 0.77$). All species showed positive correlations. *Ulmus pumila* ($r = 0.90$) and *Salix matsudana* ($r = 0.82$) had the strongest correlations. *Populus alba* had a high correlation ($r = 0.71$). *Pinus sylvestris* var. *mongholica* ($r = 0.46$) and *Styphnolobium japonicum* had moderate correlations ($r = 0.46$). DBH showed almost no correlation overall ($r = 0.004$). Species patterns varied. *Ulmus pumila*, *Salix matsudana*, and *Populus*

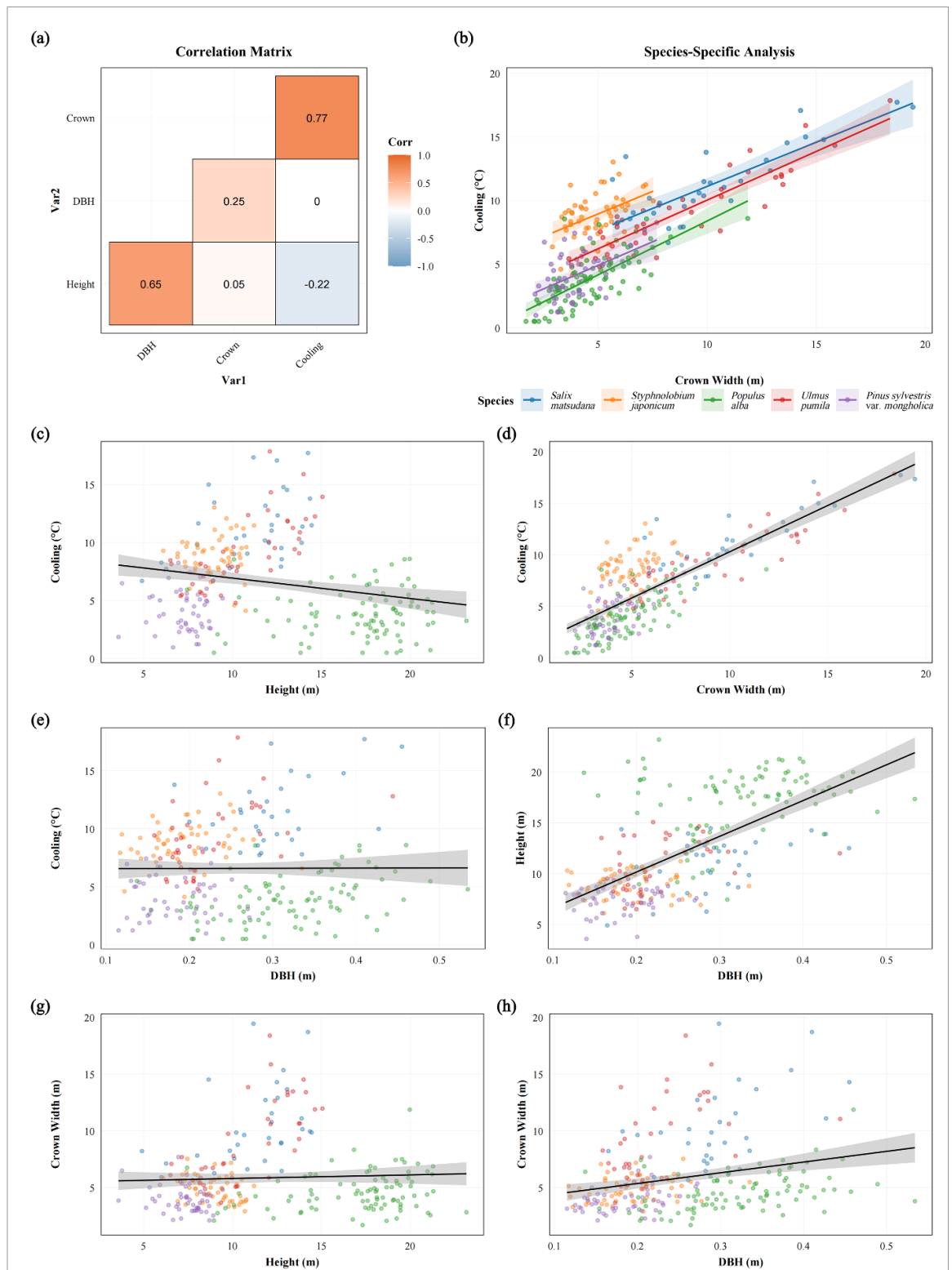
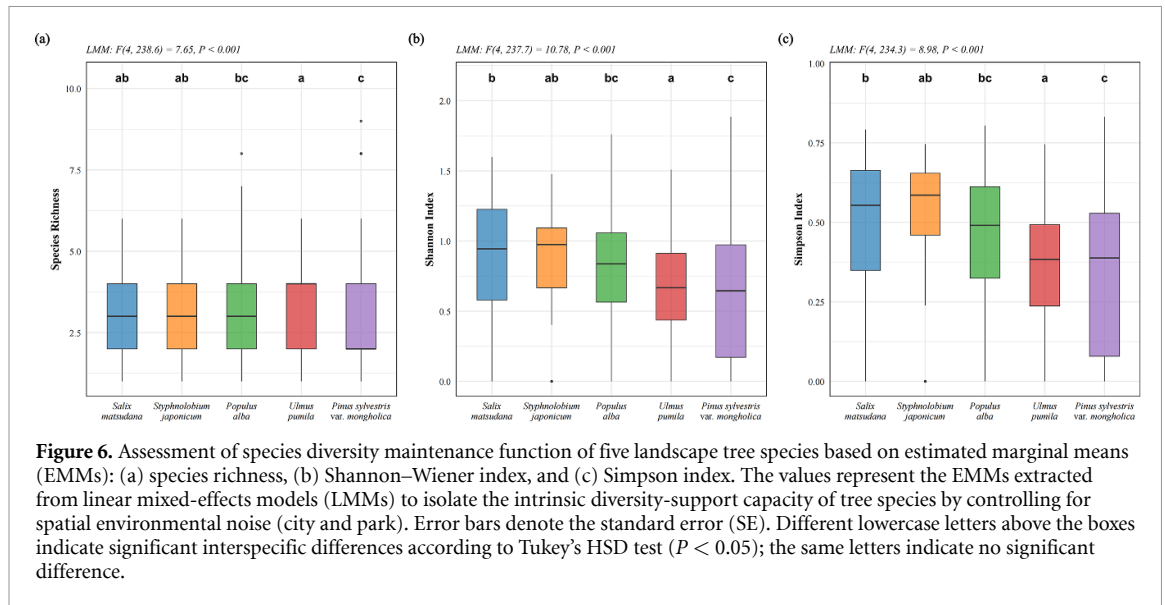


Figure 5. Analysis of factors influencing the cooling function of five landscape tree species. (a) Heatmap of Pearson correlation coefficients (r) among tree height, DBH, crown width, and cooling values ($^{\circ}\text{C}$). (b) Linear regression between cooling values and crown width for individual tree species. Scatter plots with linear regression lines show the relationships between: (c) cooling and height; (d) cooling and crown width; (e) cooling and DBH; (f) height and DBH; (g) crown width and height; and (h) crown width and DBH. Shaded areas around regression lines represent the 95% confidence intervals. Colored dots and lines in (b) and throughout the scatter plots correspond to *Salix matsudana*, *Styphnolobium japonicum*, *Populus alba*, *Ulmus pumila*, and *Pinus sylvestris var. mongholica*.



alba showed positive correlations ($r = 0.40$ – 0.48). Tree height showed a weak negative correlation overall ($r = -0.22$). *Ulmus pumila* ($r = 0.71$) and *Salix matsudana* ($r = 0.42$) showed positive correlations.

In arid and semi-arid regions, transpiration is often restricted by high VPDs under extreme heat (Meili et al 2020), making physical shading the dominant mechanism for mitigating microclimatic fluctuations. The correlation between crown width and cooling effect was significantly higher than that of other morphological indicators. This mechanism explains why *Salix matsudana*, which possesses the widest average crown width among the studied species, exhibited the optimal cooling performance. Although no significant correlations between cooling effect and tree height or DBH were observed overall, some individual species, such as *Ulmus pumila* and *Salix matsudana*, showed moderate positive correlations, indicating that species-specific patterns exist in the relationship between morphological traits (tree height or DBH) and cooling performance. It should be noted that the cooling assessment in this study was primarily based on observations during midday summer peaks and measured localized shading contrast; thus, it may not fully capture the seasonal dynamics or the comprehensive heat exchange process between the entire canopy and the ambient air.

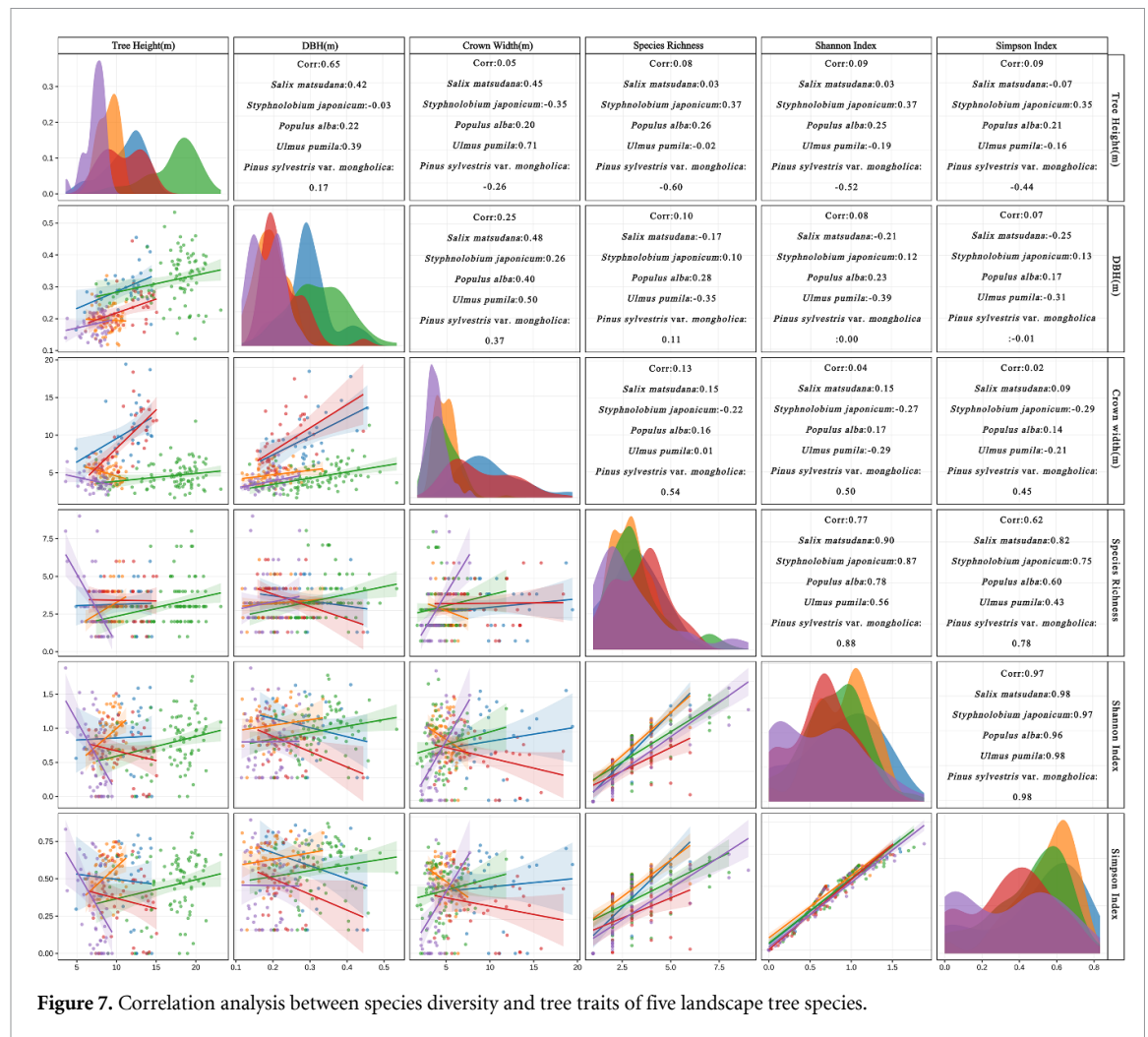
3.3. Assessment and analysis of the species diversity maintenance function of trees

3.3.1. Assessment of the species diversity maintenance function

The study analyzed understory species richness, Shannon–Wiener index, and Simpson index using LMMs to control for spatial environmental heterogeneity (figure 6). The results revealed significant interspecific variations across all diversity indices ($P < 0.001$). For species richness (figure 6(a)), *Pinus sylvestris* var. *mongholica* provided the highest baseline support with an EMM of 3.91, which was significantly higher than those of *Populus alba* (3.21), *Salix matsudana* (2.56), *Styphnolobium japonicum* (2.11), and *Ulmus pumila* (2.09). Significant differences were also observed for the Shannon–Wiener index (figure 6(b)) and Simpson index (figure 6(c)) ($P < 0.001$). *Pinus sylvestris* var. *mongholica* recorded the highest values (1.02 and 0.56), followed by *Populus alba* (0.79 and 0.44) and *Salix matsudana* (0.65 and 0.39). Conversely, *Ulmus pumila* exhibited the lowest capacity for diversity maintenance, with EMMs of 0.36 for the Shannon index and 0.24 for the Simpson index.

3.3.2. Analysis of the factors influencing the maintenance function of species diversity

Pearson correlation analysis tested the relationships between dendrometric traits and species richness, Shannon–Wiener index, and Simpson index. Overall, no significant correlation occurred across all species. However, distinct patterns emerged for specific species (figure 7). *Salix matsudana* had almost no correlation with diversity indices ($|r| \leq 0.25$). *Styphnolobium japonicum* and *Populus alba* showed a weak positive correlation between tree height and diversity ($r = 0.21$ – 0.37). *Ulmus pumila* DBH



showed weak negative correlation with all three indices ($r = -0.31$ to -0.39). The strongest correlations appeared in *Pinus sylvestris var. mongholica*. Tree height showed a negative correlation with all three indices ($r = -0.44$ to -0.60). Crown width showed a positive correlation ($r = 0.45$ – 0.54).

A RF model (ntree = 1000) was employed to identify the relative importance of tree species identity and morphological traits (crown width, tree height, and DBH) in governing the species diversity maintenance function. Calculated based on the increase in mean squared error (%IncMSE), the mean importance value of tree species identity was 27.84%. The importance of the remaining morphological variables followed the order: crown width (21.58%), tree height (19.96%), and DBH (17.79%) (figure 8). This indicates that compared to other morphological indicators, the variable of tree species identity exhibits higher model sensitivity and is an important factor influencing understory vegetation species diversity. Furthermore, this finding also partially explains a phenomenon in previous studies regarding the relationship between tree morphology and diversity indices: significant differences exist in understory diversity indices among different tree species, but there is a lack of distinct linear correlation between diversity metrics and the overall morphological traits of trees. Error convergence plots (figures 8(f)–(h)) verified the robustness of this assessment. OOB error analysis indicated a sharp initial drop in mean squared error (MSE), with all three diversity index models stabilizing long before reaching the 1000-decision-tree limit.

The study utilized PDP visualizations to predict the complex, non-linear marginal effects of individual predictors on understory species diversity (figure 9). The results revealed a functional divergence among tree species in driving diversity metrics. *Pinus sylvestris var. mongholica* exerted the most significant positive marginal effect on species richness (figure 9(d)), identifying it as the primary

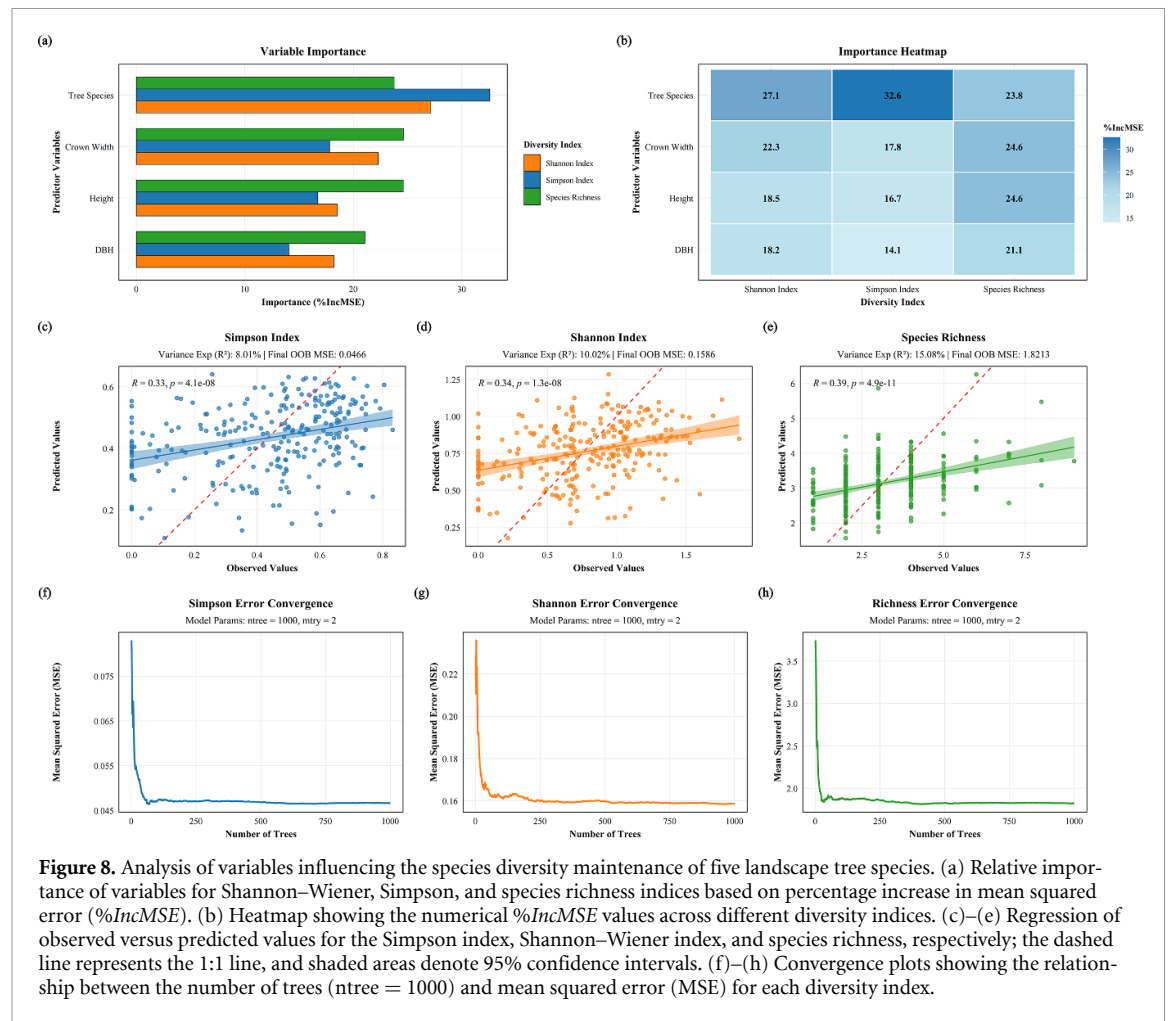


Figure 8. Analysis of variables influencing the species diversity maintenance of five landscape tree species. (a) Relative importance of variables for Shannon–Wiener, Simpson, and species richness indices based on percentage increase in mean squared error (%IncMSE). (b) Heatmap showing the numerical %IncMSE values across different diversity indices. (c)–(e) Regression of observed versus predicted values for the Simpson index, Shannon–Wiener index, and species richness, respectively; the dashed line represents the 1:1 line, and shaded areas denote 95% confidence intervals. (f)–(h) Convergence plots showing the relationship between the number of trees (ntree = 1000) and mean squared error (MSE) for each diversity index.

driver for maximizing the absolute number of understory species. *Styphnolobium japonicum* demonstrated the strongest marginal influence on the Shannon–Wiener (figure 9(h)) and Simpson indices (figure 9(l)).

Morphological traits exhibited distinct non-linear patterns. Tree height generally showed a negative marginal effect on all diversity indices, indicating that higher canopy strata might limit understory development through altered light competition or microclimatic shifts. Conversely, crown width displayed a consistent positive trend, where an expansion in canopy area facilitated a proportional increase in species diversity. The marginal effects of DBH were more nuanced, showing positive associations with species richness and the Shannon–Wiener index, while exhibiting a negative correlation with the Simpson index. These results underscore the complex, non-linear interactions between tree identity, architectural complexity, and the maintenance of understory biodiversity.

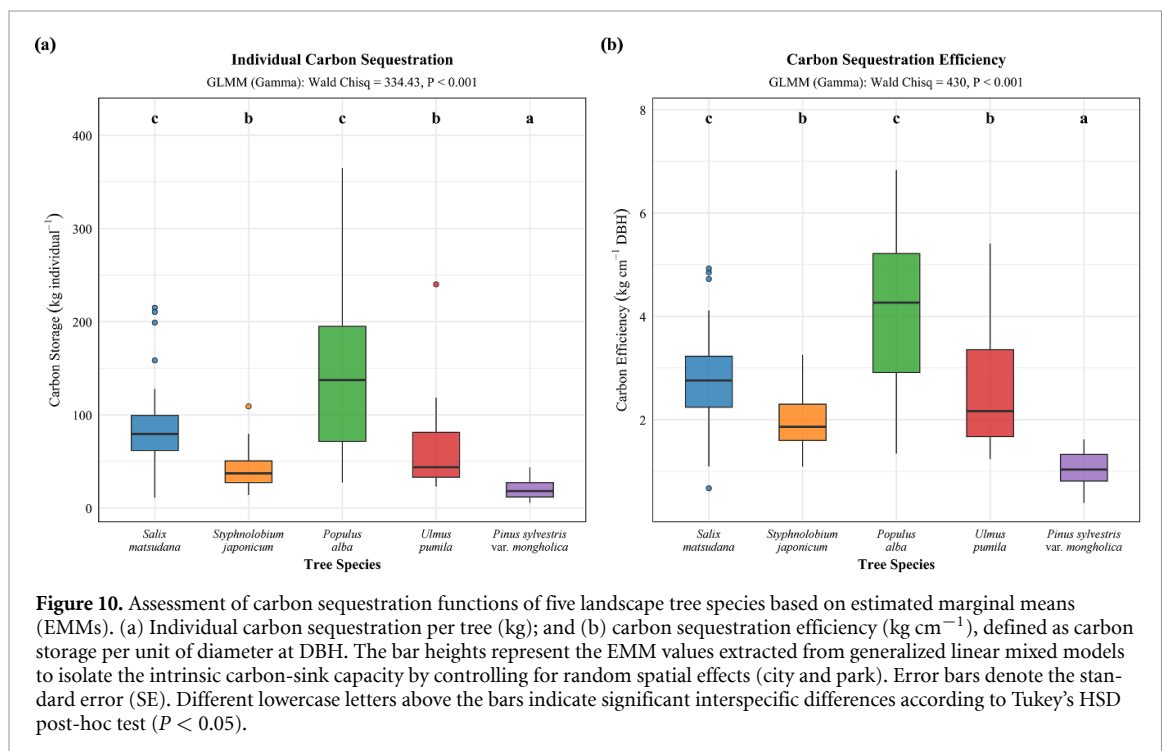
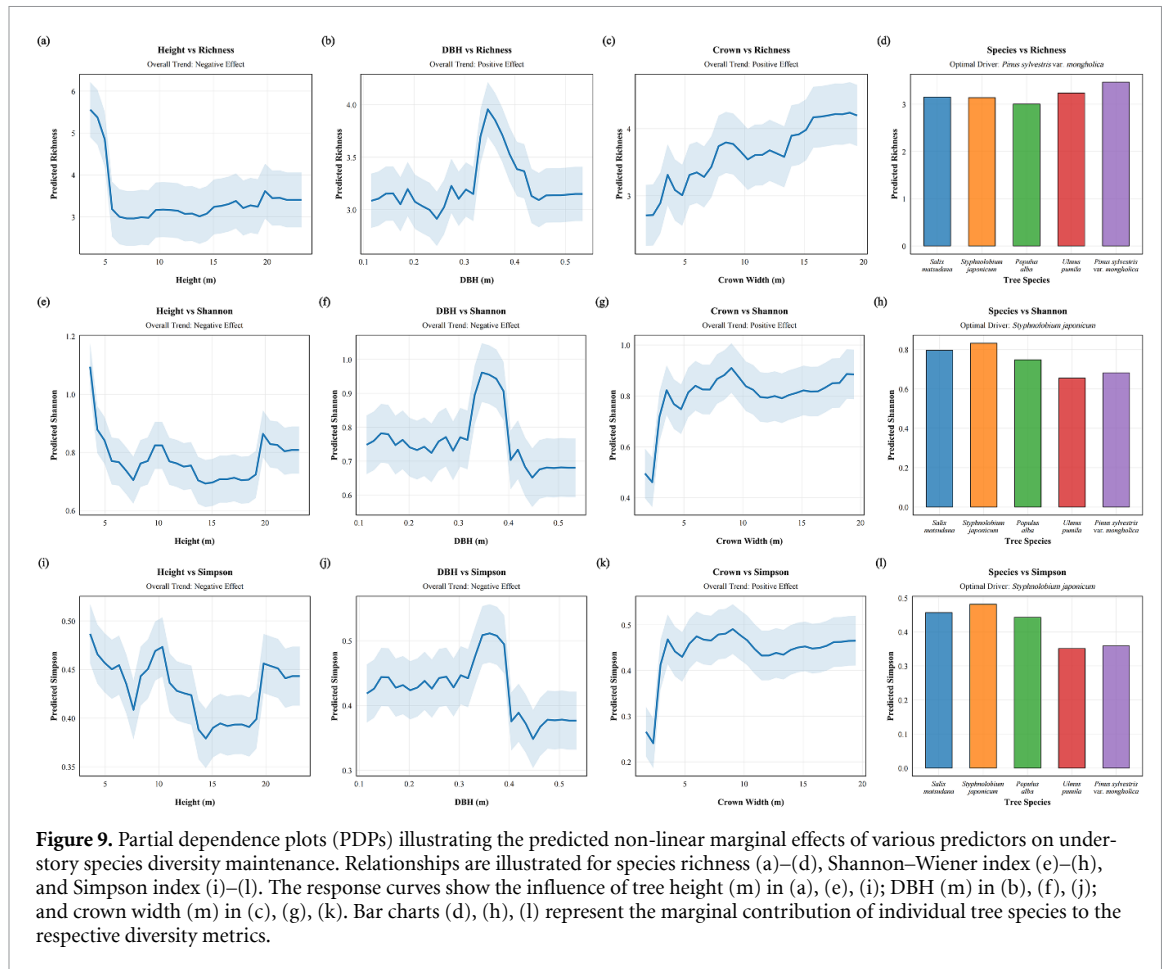
3.4. Assessment and analysis of carbon sequestration function

3.4.1. Assessment of carbon sequestration function

Individual carbon sequestration capacity and efficiency per unit DBH exhibited significant inter-specific variation ($P < 0.001$). Based on the EMMs extracted from the GLMMs, the average individual carbon sequestration followed the order: *Populus alba* (130.86 ± 15.98 kg) > *Salix matsudana* (117.46 ± 16.33 kg) > *Styphnolobium japonicum* (59.79 ± 8.26 kg) > *Ulmus pumila* (56.86 ± 7.24 kg) > *Pinus sylvestris* var. *mongholica* (13.12 ± 1.72 kg).

The carbon sequestration efficiency per unit DBH followed an identical descending order: *Populus alba* (3.95 ± 0.29 kg cm⁻¹) > *Salix matsudana* (3.40 ± 0.28 kg cm⁻¹) > *Styphnolobium japonicum* (2.64 ± 0.22 kg cm⁻¹) > *Ulmus pumila* (2.48 ± 0.19 kg cm⁻¹) > *Pinus sylvestris* var. *mongholica* (0.78 ± 0.06 kg cm⁻¹) (figure 10).

As a typical fast-growing species, *Populus alba* ranked highest in both individual carbon sequestration and carbon sequestration efficiency, performing significantly better than the other species. This result



further confirms the significant advantages of fast-growing species (e.g. *Populus alba* and *Salix matsudana*) in reducing the carbon footprint of urban parks and rapidly achieving carbon neutrality goals (Lind *et al* 2023). However, this high unit DBH efficiency primarily reflects the rate of carbon gain during the active growth period. When evaluating long-term ecological services, it is essential to distinguish

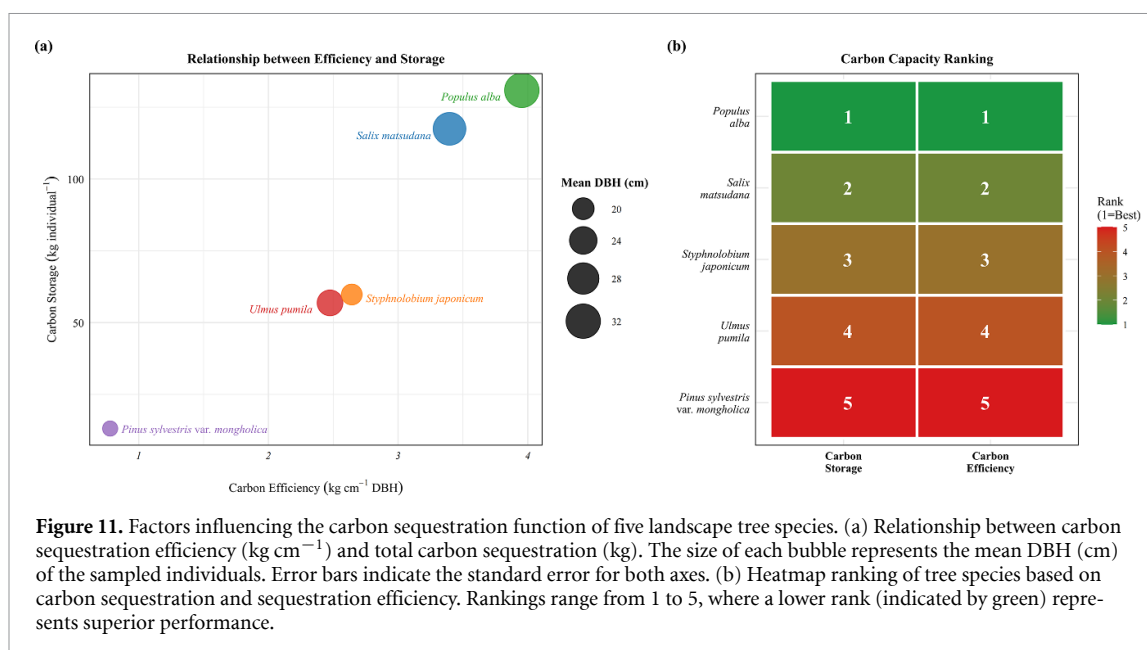


Figure 11. Factors influencing the carbon sequestration function of five landscape tree species. (a) Relationship between carbon sequestration efficiency (kg cm⁻¹) and total carbon sequestration (kg). The size of each bubble represents the mean DBH (cm) of the sampled individuals. Error bars indicate the standard error for both axes. (b) Heatmap ranking of tree species based on carbon sequestration and sequestration efficiency. Rankings range from 1 to 5, where a lower rank (indicated by green) represents superior performance.

this rapid short-term accumulation rate from the stable, long-term carbon stock preservation provided by mature, slow-growing species.

3.4.2. Analysis of factors influencing carbon sequestration function

As a typical fast-growing species, *Populus alba* ranked highest in both individual carbon sequestration and carbon sequestration efficiency, performing significantly better than the other species. Similarly, the fast-growing species *Salix matsudana* showed relatively high carbon sequestration function. In contrast, the slow-growing species *Pinus sylvestris* var. *mongholica* exhibited the lowest levels in both carbon sequestration amount and efficiency. The specific results are illustrated in figure 11.

3.5. Comprehensive comparison of ecological functions among five landscape tree species

A comprehensive assessment of the cooling effect, species diversity maintenance, and carbon sequestration functions across the five landscape tree species revealed significant ecological ‘trade-offs’. No single ‘all-around’ species was found to perform optimally across all functional dimensions. The entropy-weight TOPSIS evaluation showed that *Pinus sylvestris* var. *mongholica* had the best overall ecological performance score. Although it exhibited the lowest carbon sequestration capacity and limited cooling effects, it demonstrated a superiority in fostering understory biodiversity (recording the highest species richness, Shannon–Wiener, and Simpson indices).

Populus alba secured the second position, driven by its carbon-sink capacity and efficiency, despite exhibiting relatively weak cooling performance. *Salix matsudana* ranked third, offering a more balanced functional profile characterized by exceptional cooling effects and robust carbon sequestration, alongside moderate diversity maintenance. Conversely, *Styphnolobium japonicum* and *Ulmus pumila* exhibited lower overall scores, as their functional benefits were less pronounced across multiple dimensions. Based on the comprehensive ecological evaluation scores (figure 12), the final hierarchy of total ecological service value in these urban green spaces was: *Pinus sylvestris* var. *mongholica* > *Populus alba* > *Salix matsudana* > *Styphnolobium japonicum* > *Ulmus pumila*.

4. Discussion and limitations

4.1. Discussion

The study assessed the ecological functions of major landscape trees in arid and semi-arid regions. It revealed distinct driving mechanisms for each one, as well as significant trade-offs between different functions. Within the context of this study, an ecological trade-off is defined by the observation that no single tree species can simultaneously maximize its performance across the dimensions of cooling, diversity maintenance, and carbon sequestration; enhancing one targeted function frequently necessitates a compromise in another (Cueva et al 2022).

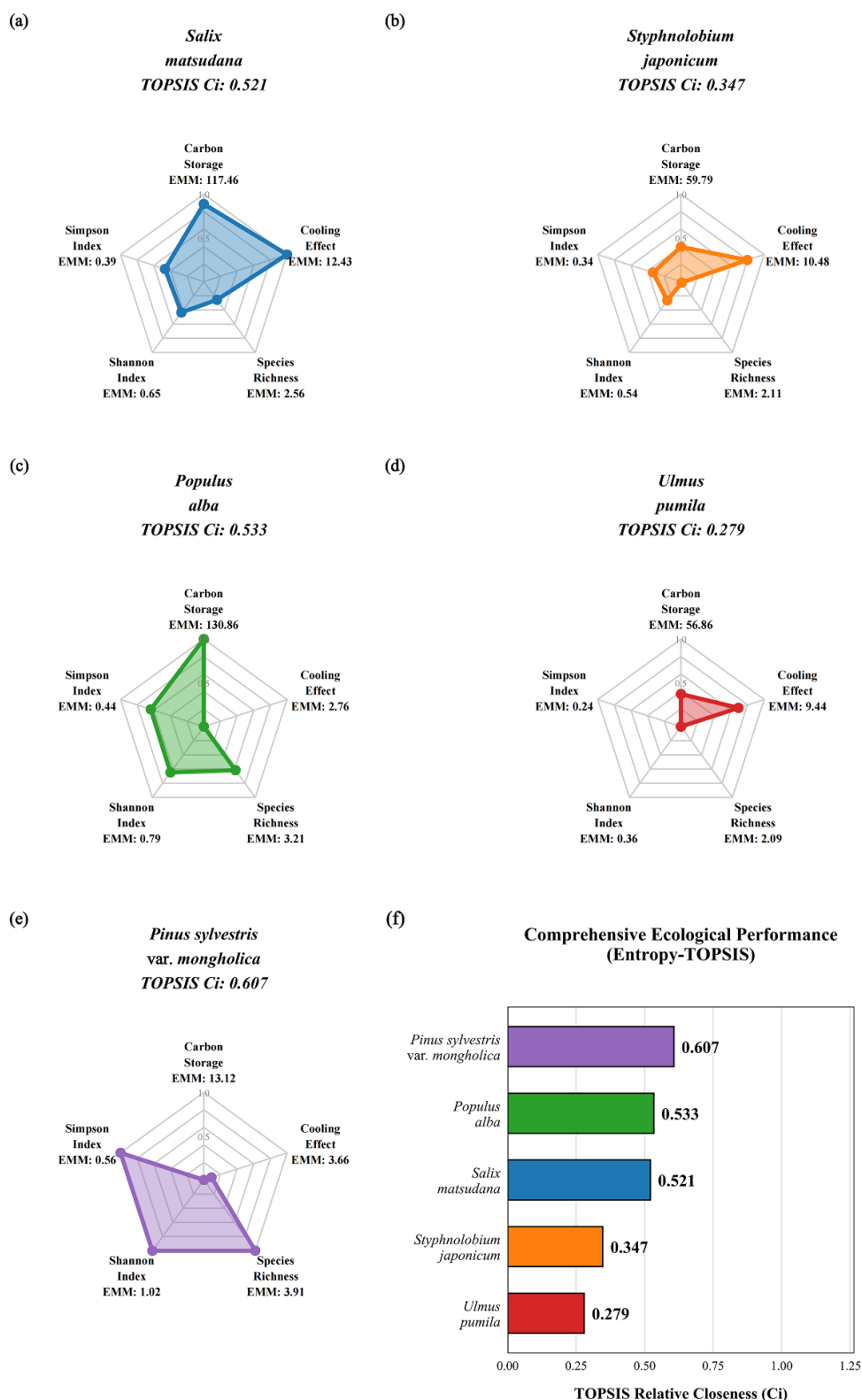


Figure 12. Comprehensive evaluation and functional trade-offs of five landscape tree species. (a)–(e) Radar charts illustrating the multi-dimensional functional trade-offs for *Pinus sylvestris* var. *mongholica*, *Populus alba*, *Salix matsudana*, *Styphnolobium japonicum*, and *Ulmus pumila*, respectively. Each axis represents a standardized score (ranging from 0 to 1) for specific ecological dimensions: carbon sequestration, cooling effect, and species diversity maintenance. (f) Bar chart illustrating the comprehensive ecological performance of the species calculated via the Entropy-weight TOPSIS model.

Compared to the morphological indices evaluated in this study, this cooling function was found to be primarily controlled by crown width, showing a highly significant positive correlation ($r = 0.77$). However, the overall correlations between the cooling function and DBH ($r = 0.00$) or tree height ($r = -0.22$) were extremely weak. Species with larger mean crown widths, such as *Salix matsudana*,

Styphnolobium japonicum, and *Ulmus pumila*, had superior cooling function. Conversely, *Populus alba* performed the weakest in cooling despite its greater tree height and DBH, due to its smaller crown width. Previous studies support this view, for instance, Fahmy *et al* (2010) pointed out that physical ‘shading’ is the dominant cooling mechanism in arid regions, which aligns with our findings. Furthermore, incorporating the perspective of trait plasticity is crucial when interpreting these morphological effects under urban environmental stress. As Chaturvedi *et al* (2024) pointed out, variations in the plasticity of functional traits indicate the differential impacts of abiotic and biotic factors on the structure and growth of trees in fragmented and stressed ecosystems. In our context, this implies that urban disturbances and drought stress may dynamically alter canopy architecture and leaf area distribution, thereby interacting with physical morphological metrics to jointly dictate the final cooling function.

Our study indicates that canopy ‘species identity’ is a highly sensitive factor influencing understory herbaceous plant diversity. RF model analysis shows that the species variable (%IncMSE = 27.84%) exhibits higher model sensitivity compared to overall morphological indicators. This analytical result indicates that among the five tree species in this study area, their species identity is more decisive than the physical morphological indicators of the trees themselves. Although baseline field observations indicate that the understory of *Pinus sylvestris* var. *mongholica* maintains the highest absolute values across all diversity indicators (species richness, Shannon index, and Simpson index), further PDP analysis reveals more complex rules of functional differentiation. By independently analyzing the pure marginal effects of species identity, the PDP shows that *Pinus sylvestris* var. *mongholica* is the only species that has a primary positive driving effect on enhancing species richness; in contrast, *Styphnolobium japonicum* is the most effective species for enhancing the Shannon index and Simpson index. Different tree species cannot equally enhance the species diversity of understory vegetation; instead, they each selectively promote different diversity dimensions. This differentiation may be closely related to their inherent crown architecture (rather than mere canopy width). For example, the relatively sparse needle-leaved structure of *Pinus sylvestris* var. *mongholica* and the dense broad-leaved crown of *Styphnolobium japonicum* may regulate the transmittance of understory light in different ways. The differences observed in these diversity indices are highly consistent with the ‘habitat filtering’ theory. This theory posits that the ‘species identity’ of trees is a fundamental structural filtering factor that influencing understory microhabitats and community assembly (Luo *et al* 2024).

This study found that the carbon sequestration function was predominantly driven by the physiological ‘growth rate’ of plants. Fast-growing species, such as *Populus alba* and *Salix matsudana*, performed well in terms of both individual carbon sequestration and carbon sequestration efficiency per unit DBH, with *Populus alba* ranking highest in both metrics. In contrast, the slow-growing species *Pinus sylvestris* var. *mongholica* performed the worst. These results suggest that tree life history strategies (growth forms) must be considered when evaluating carbon sequestration. Within the scope of urban green space construction, fast-growing species have an advantage in achieving rapid carbon accumulation, and carbon sequestration at the individual scale is primarily determined by total biomass. These findings support the idea that fast-growing species have high carbon sequestration rates (Trlica *et al* 2020). Furthermore, the species ranking in this study is strongly supported by regional physiological research. For example, Wu *et al* (2024) study in Baotou City similarly classified ranked *Pinus sylvestris* var. *mongholica* lower.

4.2. Limitations

The findings of this study are subject to a few methodological constraints. Field measurements were limited to a single summer season without continuous soil moisture monitoring. To mitigate this, we specifically selected the midday observation window during peak summer to evaluate structural cooling efficiency under maximum thermal load, thereby minimizing the confounding variability caused by plant physiological regulation. Despite this targeted approach, the data inherently reflects peak performance rather than comprehensive seasonal dynamics, and residual transpiration effects from localized park irrigation practices cannot be fully decoupled.

Uncertainties are inherently associated with UAV data acquisition and the assessment of microclimate variables. To account for spatial environmental heterogeneity and flight altitude variations, we adopted the temperature difference between the sunlit and shaded sides of a tree as a ‘self-referencing’ cooling proxy. While this method effectively eliminates ground surface noise, transient atmospheric conditions may still introduce calibration variance, and this localized metric may not fully capture the comprehensive heat exchange between the entire canopy and the ambient air.

Urban trees are subjected to intensive management practices, such as pruning, and our sampling strategy relied on the actual, unbalanced planting distributions across the parks. To address these challenges, we employed LMMs to control for spatial random effects and isolate intrinsic species traits.

Nevertheless, generalized allometric equations cannot perfectly capture altered urban growth allometry, and unbalanced sample sizes may still harbor underlying site-specific spatial biases.

Destructive root sampling is strictly restricted in urban areas, necessitating that the carbon sequestration assessment be deliberately confined to above-ground biomass. Consequently, the total carbon sink is conservatively underestimated. Future investigations utilizing non-destructive root modeling, strictly controlled balanced sampling designs, and cross-seasonal monitoring are needed to further refine these results.

5. Conclusion

This study evaluated the ecological functions of urban greenery trees in China's arid and semi-arid regions. Subject to the spatial boundaries of the studied cities and the specific conditions of midday summer observations, the study yielded the following key conclusions:

- (1) Crown Width Dictates Cooling: Among the evaluated morphological traits, crown width ($r = 0.77$) is the significant driver of the cooling effect, with its impact surpassing that of DBH and tree height.
- (2) Tree Species Identity Influences Understory Species Diversity: RF model analysis indicates that 'species identity' (%IncMSE = 27.84%) exhibits higher model sensitivity than physical morphological indicators and is an important factor influencing understory herbaceous diversity. Although baseline field data LMMs indicated that *Pinus sylvestris* var. *mongholica* maintained the highest absolute levels across all diversity metrics, PDPs revealed significant functional differentiation in marginal effects: *Pinus sylvestris* var. *mongholica* exerts the strongest positive drive on species richness, while *Styphnolobium japonicum* exhibits the optimal marginal effect in maximizing community evenness (Shannon and Simpson indices).
- (3) In terms of carbon sequestration, the fast-growing species *Populus alba* exhibited the highest urban carbon accumulation capacity and efficiency among the five tree species evaluated in the study area.

In arid and semi-arid regions, the pronounced functional trade-offs necessitate a shift toward a 'goal-oriented' urban forestry model. Within the spatial limits of the studied urban parks, we recommend that priority can be given to species with expansive crown widths in high-use public recreational areas to achieve cooling effects, while *Pinus sylvestris* var. *mongholica* can be incorporated into ecological buffer zones to enhance biodiversity resilience. *Styphnolobium japonicum* is recommended for constructing structurally stable understory communities, and *Populus alba* can be deployed in specific restorative or carbon-sink patches to rapidly achieve carbon neutrality. Ultimately, landscape configurations must strategically mix functionally complementary species to achieve optimal ecosystem synergy. For practical implementation, community configurations should adopt multi-layered mixed planting models, strategically pairing *Populus alba* with slow-growing evergreen species to balance rapid carbon accumulation with long-term habitat stability. Furthermore, these structural configurations must be supported by adaptive maintenance strategies, including targeted pruning to promote lateral canopy expansion for enhanced shading, and precision irrigation tailored to specific canopy types to sustain understory biodiversity under severe water constraints.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no conflict of interest.

ORCID iD

Qilong Hao  0009-0001-1689-4446

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