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Predicting people perceived plant diversity in urban green spaces using panoramic photos: a case study of Shanghai

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Introduction: Urban green spaces (UGSs) play a dual role in high-density cities: they are crucial for biodiversity conservation and serve as key venues for promoting residents' health. However, the benefits gained by people in these settings depend less on objectively measured biodiversity and more on their subjective perception of it. Visual cues, which account for over 80% of sensory input, significantly shape this perception.
Methods: This study explores the interrelationships among measured plant diversity, perceived plant diversity, and visual landscape characteristics in UGSs, so that to develop a predictive model for perceived diversity using the other two variables. Based on a case study of nine representative parks in Shanghai, the research compared measured plant diversity—using four indices (arbor, shrub, herbaceous, and community diversity)—with perceived plant diversity and evaluated the influence of visual landscape features.
Results: Results showed a significant mismatch between measured and perceived diversity. Furthermore, visual characteristics were more effective than measured biodiversity in predicting perceived plant diversity. These findings offer practical, short-term design strategies for enhancing perceived biodiversity in urban parks—complementing longer-term ecological measures aimed at increasing actual biodiversity.
Discussion: This study advances the understanding of how objective biodiversity, human perception, and visual environment interact, and supports the design of nature-based solutions that benefit both human well-being and biodiversity conservation.

KEYWORDS
human perception, plant diversity, prediction models, semantic segmentation, urban green spaces

Introduction

Biodiversity provides a critical foundation for ecosystem functions essential to human health and well-being, exerting its influence through several distinct pathways, including biological, psychological, social and physical activity, environmental buffering, and the moderation of urban heat island effects (Robinson et al., 2024). It is important to note that for the psychological, social, and physical pathways, the benefits are not a direct function of measured biodiversity but are instead shaped by an individual's perception of biodiversity (Rozario et al., 2024). Nevertheless, it is crucial to recognize that perceived biodiversity constitutes a subjective judgment, based on an individual's immediate interpretation and synthesis of an environmental scene, and is not directly synonymous with the measured biodiversity. A singular focus on elevating measured biodiversity is problematic, as it must be balanced against contextual environmental conditions and may not invariably lead to improved health outcomes. To date, few studies have adopted an integrated perspective that considers measured biodiversity, perceived biodiversity, and the environmental contexts shaping these perceptions. This study addresses this gap by examining plant diversity in urban green spaces (UGSs) and developing a predictive model for perceived biodiversity that incorporates key objective environmental factors. This approach will serve as a foundation for exploring multi-faceted strategies to optimize perceived plant diversity. Furthermore, it will enable the large-scale, efficient estimation of perceived biodiversity, thereby providing valuable insights for the planning and management of UGSs.

The role of perceived biodiversity in human–biodiversity relationship

The investigation into the human-biodiversity relationship is fundamentally grounded in the Biophilia Hypothesis (Kellert and Wilson, 1993). This hypothesis posits that humans possess an innate, instinctive affinity for nature and living organisms—a trait shaped by evolution, as humans developed over millennia within natural environments, becoming physiologically and psychologically adapted to such settings rather than to urban or built landscapes (Kaplan and Talbot, 1983; Wilson, 1984). As a result, individuals exhibit involuntary attention and positive affective responses toward natural elements and tend to preferentially seek out biodiverse environments, from which they derive measurable benefits (Kaplan and Kaplan, 1989; Hartig et al., 2014).

In assessing the effects of biodiversity on human physical and mental health, a conventional distinction is made between two conceptual approaches: measured biodiversity and perceived biodiversity. Measured biodiversity refers to the empirical quantification of species richness, structural diversity, and related attributes within a defined area, typically obtained through standardized ecological methods such as field surveys and computational metrics (Reinhard and Drossel, 2021). In contrast, perceived biodiversity denotes the richness of biological life as subjectively evaluated by individuals, generally captured via self-reported measures such as questionnaires or psychometric scales (Fuller et al., 2007). Although numerous studies have attempted to establish a clear link between biodiversity and human health (Marselle et al., 2019; Grilli and Sacchelli, 2020; Hedin et al., 2022), a consistent consensus has yet to emerge (Qiu et al., 2013; Sandifer et al., 2015; Methorst et al., 2021).

These inconsistencies have been attributed to several factors. One explanation points to the inherent limitations of objective biodiversity metrics; given that no single measure fully captures "true" biodiversity, all existing methods remain imperfect proxies (Rozario et al., 2025). Another perspective emphasizes that health outcomes—particularly psychological benefits—may be more strongly tied to perceived biodiversity than to objectively measured values (Wood et al., 2018). However, the relationship between the two constructs is itself unclear: while some studies report weak to moderate correlations (Ferraro et al., 2020; Rozario et al., 2024), others find no significant association (Dallimer et al., 2012; Phillips and Lindquist, 2021; Stobbe et al., 2022). In response to these contradictions, Shwartz et al. (2014) proposed the "human-biodiversity paradox," which highlights a key discrepancy: although people express a preference for biodiverse settings, they often fail to accurately assess actual species richness in their immediate environment (Fuller et al., 2007). This gap is regarded as a major constraint on the positive well-being effects of biodiversity.

Notably, perceived biodiversity is a direct and sometimes stronger predictor of well-being outcomes compared to measured biodiversity (Schebella et al., 2019; Cameron et al., 2020; Rozario et al., 2024). It represents an integrated product of environmental perception, reflecting the meaning and value individuals assign to an environment based on its variety of flora and fauna (Brown, 1984; Brown et al., 2004). As a cognitively mediated construct, perceived biodiversity is influenced by individual differences in knowledge, attitude, and experience (Gyllin and Grahn, 2015; Li et al., 2019; Marselle et al., 2016). This variability is evident across contexts: for example, individuals in Sweden were able to accurately discern biodiversity levels in temperate deciduous forests (Johansson et al., 2014), whereas users of urban parks in France consistently underestimated the actual number of plant species (Fuller et al., 2007; Dallimer et al., 2012; Muratet et al., 2015).

A growing body of evidence further indicates that perceived biodiversity plays a critical mediating role between measured biodiversity and key well-being outcomes, including recreational preference (Liang et al., 2023), health-promoting behaviors (Björk et al., 2008), attention restoration (Kaplan, 1995), and stress reduction (Ulrich et al., 1991). Consequently, it occupies a central position in the pathway linking biodiversity to human health. To date, research has largely focused either on establishing the direct health effects of perceived biodiversity (Rozario et al., 2024) or on examining the complex triadic relationship between measured biodiversity, perceived biodiversity, and health (Marselle et al., 2021). However, a significant limitation persists: the field remains reliant on predominantly subjective measurement tools, with environmental predictors and the potential for objective assessment of perceived biodiversity still underexplored. This methodological gap constrains both the generalizability of findings and the translation of research into planning and policy, highlighting a clear need for more integrative and predictive approaches.

Environmental indicators in relation to the perceived biodiversity

Perceived biodiversity is inherently a multisensory experience (Franco et al., 2017; Hedblom et al., 2019) and thus, an important part in landscape perception studies (Rozario et al., 2025). From an evolutionary standpoint, vision serves as the primary and dominant sense for acquiring environmental information, with over 80% of such information being processed visually (Hutmacher, 2019). During park visits, visual perception constitutes the foremost mode of interaction between individuals and their surroundings. People form rapid initial judgments of a scene within seconds—a process described as ecological momentary assessment (EMA; Shiffman et al., 2008). This includes an almost instantaneous evaluation of whether a place is rich in natural elements, a judgment that relies heavily, if not exclusively, on visual cues (Shao and Lyu, 2011). Accordingly, the majority of existing research has focused on how visually acquired environmental cues shape perceived biodiversity.

Studies have identified several visual drivers of perceived plant richness. For instance, Hoyle et al. (2018) found that color richness in flowering plants significantly predicts perceived plant diversity, with more colorful meadows being rated as more diverse. Similarly, grasslands characterized by greater vegetation height and uniformity also tend to receive higher perceived diversity ratings (Southon et al., 2018). Beyond natural features, human-designed elements in urban landscapes—such as park size (Jackson et al., 2001) and the composition of natural versus built components in public squares (Beninde et al., 2015)—can further influence these perceptions (Lindemann-Matthies and Bose, 2008). Moreover, many conventional biodiversity metrics—such as canopy structure (Maes et al., 2011), leaf area (Storch et al., 2018), the Shannon Diversity Index (Harper and Hawksworth, 1995), and animal abundance (Fairbairn et al., 2024)—are themselves derived from or dependent on visual information.

However, a notable limitation persists in current research on the environmental drivers of perceived plant diversity. Existing work predominantly focuses on variables that are not direct, objective visual descriptors. These include human-derived metrics (e.g., calculated indices of richness, evenness, or spatial configuration) and subjective perceptual attributes (e.g., perceived naturalness or canopy cover). This reliance on processed or subjectively reported measures inherently constrains the scalability and generalizability of findings, while also introducing biases related to individual differences. Furthermore, studies have often examined these pathways in isolation, analyzing how environmental factors influence either measured or perceived biodiversity separately, without sufficiently conceptualizing perceived diversity as an integrated outcome shaped by both objective environmental conditions and subjective perceptual processes (Pinto-Ledezma et al., 2025; Sun et al., 2022). This fragmented approach is partly attributable to the practical difficulty of collecting large-scale biodiversity perception data, which has traditionally relied on resource-intensive methods such as questionnaires (Strange et al., 2024). As UGSs continue to expand and diversify, there is a growing need for efficient, accurate approaches to optimize perceived plant diversity for public well-being. A critical step forward is to establish a more direct and explanatory link between perceived plant diversity and the objective visual characteristics of the environment—a link that must be grounded in a clear understanding of the tripartite relationship between measured biodiversity, perceptual processes, and human evaluation.

The aim of this study

Building on a holistic perspective, this study investigates the interrelationships among perceived plant diversity, measured plant diversity, and visual landscape characteristics in UGSs, as illustrated in Figure 1. Its primary objectives are twofold: first, to examine the correlations and discrepancies between measured and perceived plant diversity, along with the influence of visual landscape features on each; and second, to develop a predictive model for perceived plant diversity based on objectively measured diversity and visual characteristics. By doing so, the study aims to overcome the limitations inherent in individual-level perceptual research, which often relies on small-scale, subjective methods.

Using nine representative parks in Shanghai, China, as case studies, the research first analyzes the relationship between measured and perceived plant diversity and identifies key visual predictors. It then constructs a model to estimate perceived diversity using objective indicators. Ultimately, by clarifying the connections among these three factors, the study seeks to identify actionable environmental design cues that can enhance perceived plant diversity in UGSs, thereby supporting more effective landscape planning and management.

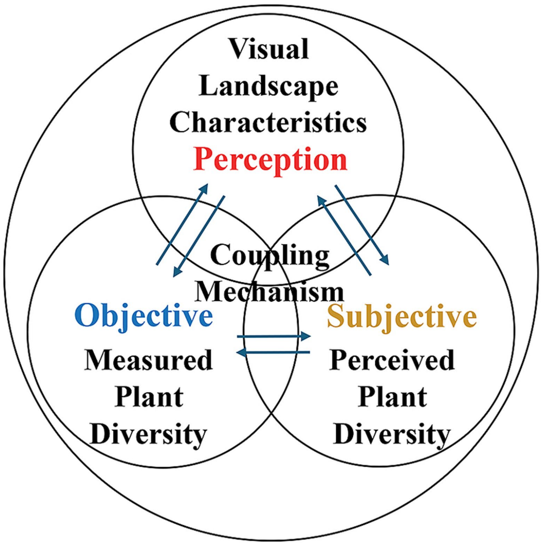


FIGURE 1
Potential influences on and between perceived and measured plant diversity within the visual landscape.

Method

Research site

Shanghai, as one of China's exemplary garden city models, has long prioritized the enhancement of park quality across its entire urban area. It regards demonstrating ecological value and fulfilling residents' needs as the primary objectives in developing its parks and green spaces. This study selects Shanghai as the case city. To ensure the systematic capture of variations in ecological and visual characteristics, and in line with the biodiversity focus of this study, research sites were selected based on several criteria. They needed to be comprehensive urban parks (thus excluding specialized types such as historical memorials, which may have low plant diversity, or botanical gardens, which, while diverse, are not representative of general UGSs), located within central urban areas, frequented by a sufficient number of visitors to ensure robust sampling, and representative of a range of size classes. Accordingly, a total of nine urban parks meeting these criteria were included in the study: three small parks (<10 ha), three medium-sized parks (10–50 ha), and three large parks (>50 ha). Each selected park maintains a greenery coverage exceeding 70% and is actively used by residents, ensuring that the findings are grounded in real-world usage patterns and hold practical relevance for landscape management. An overview of the selected sites is provided in Figure 2 and Table 1.

To account for internal heterogeneity and support the broader applicability of findings, uniformly sized quadrats were established within each park. Drawing on nested sampling principles (Agosti et al., 2000), an initial layout was designed to align with the spatial distribution patterns of trees, shrubs, and herbaceous plants, thereby capturing vertical structure and community diversity in an

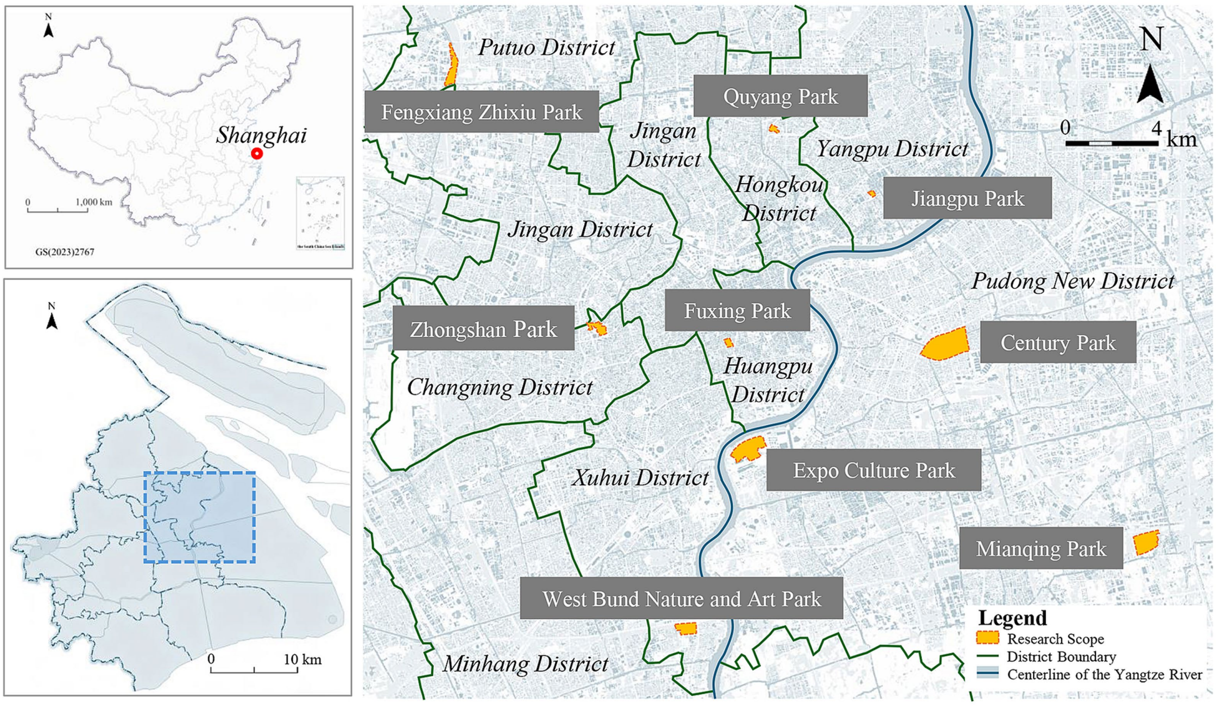


FIGURE 2
The selected case study sites in Shanghai.

ecologically meaningful way. This preliminary design was then refined according to each park's internal organization—considering functional zones, landscape features, and accessibility—to ensure representative sampling across recreational and vegetated areas. In accordance with the *Specifications for Vegetation Quadrat Survey Data* issued by the Plant Science Data Center of the Chinese Academy of Sciences, each quadrat was strictly delineated as a 20 m × 20 m plot, positioned to avoid major roads or water bodies. The final sampling scheme included 7–8 quadrats in each small park, 11–22 in each medium-sized park, and 20–24 in each large park, resulting in a total of 143 quadrats across all nine parks. All subsequent measurements of plant diversity (both measured and perceived) and environmental landscape characteristics were conducted at the quadrat level, as summarized in Table 1.

Data collection

The research team was partitioned into three groups, each assigned to a distinct data collection method (quadrat surveys, questionnaire surveys, and panoramic photo collection) to control for potential individual differences. To ensure consistency, all groups completed rigorous, standardized training on their assigned procedures prior to the commencement of formal data collection.

The measured plant diversity measured with quadrat survey

Building upon preliminary collation of data such as seedling inventories provided by the Shanghai Landscaping and City Appearance Administrative Bureau and its district-level counterparts, the survey team conducted field investigations within the quadrats. The measured species present on-site were verified, identified, and supplemented using the Flower Companion species identification tool, a software application recommended by the Plant Science Data Center.

Within each designated quadrat across the study sites, surveys were conducted, and records were made stratified by vegetation layer: the arbor layer, shrub layer, and herbaceous layer. Specifically, this included: (1) Species information for the overall tree entire within the entire quadrat; (2) Species information for the shrub entire within a 5 m × 5 m subplot centered within the quadrat; (3) Species information for the herbaceous entire surveyed within five 1 m × 1 m subplots distributed inside the quadrat. Species names and individual counts were recorded for each layer (Figure 3).

In the example table, the value listed for herbaceous plants represents the number of individual plants within the quadrat, while the figure in parentheses indicates the planting density used to calculate this number. The planting density data were obtained from the seedling construction drawings provided by the management units of the respective parks.

The perceived plant diversity measured with questionnaire

The perceived plant diversity evaluation was conducted using questionnaire surveys to gather relevant data. On-site questionnaires were administered on weekdays during October 2024, under conditions of clear weather and comfortable temperatures (15–23 °C), excellent air quality, and wind speeds below 5 m/s. Participants were recruited on-site by researchers within the quadrat areas. Eligible participants were required to have good visual acuity, with no conditions such as color vision deficiency. Given that the perception of plant diversity is contingent upon an individual's environmental knowledge and familiarity (Lindemann-Matthies et al., 2010), the participant

TABLE 1 Descriptive analysis of demographics, dialysis data and medical details.

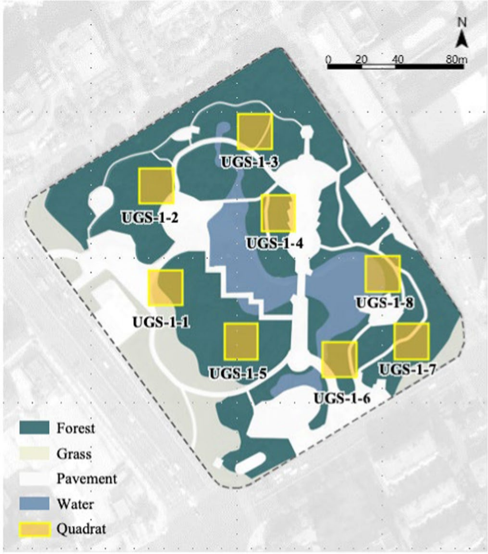
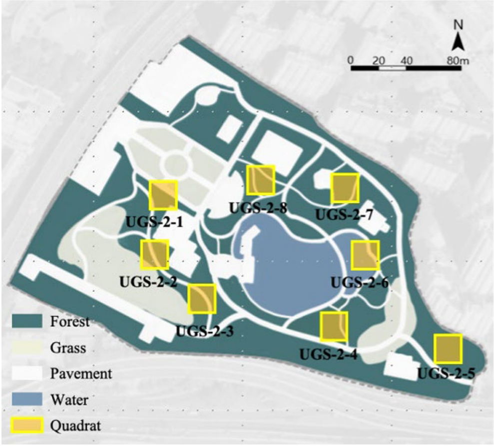
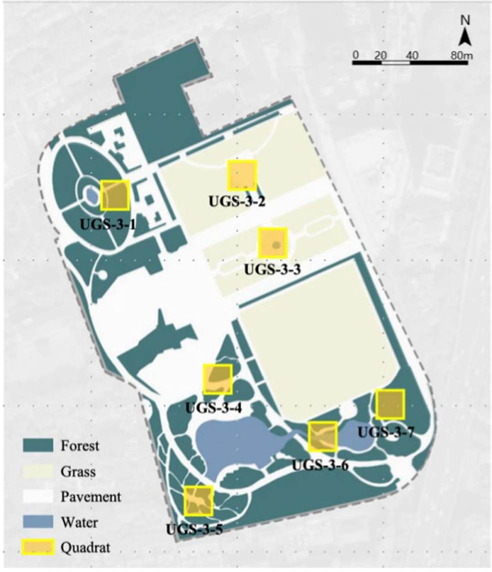
Scale level	Research sites	Size (ha)	Number of quadrats	Selected quadrats in sites
Small-scale (≤10 ha)	Jiangpu Park (UGS-1)	3.08	8	
	Quyang Park (UGS-2)	6.47	8	
	Fuxing Park (UGS-3)	7.68	7	

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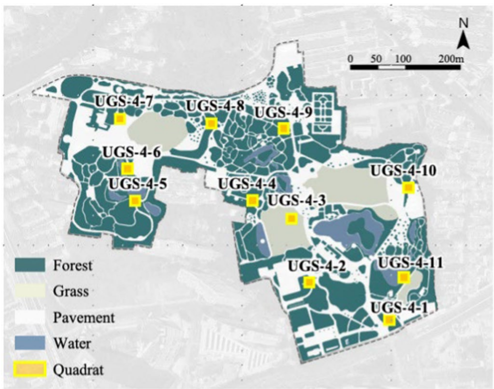
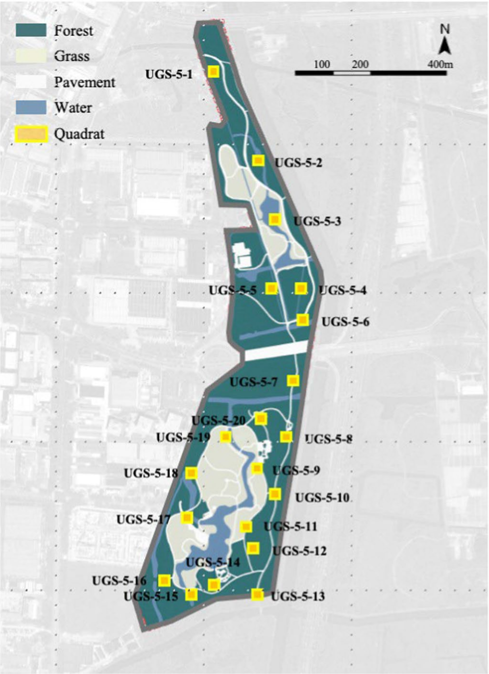
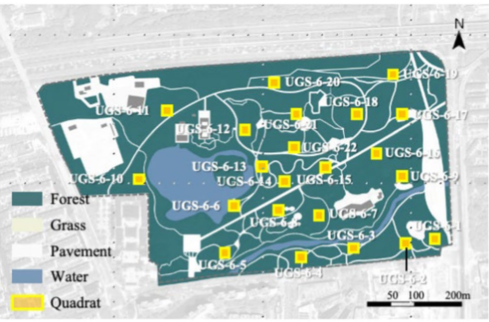
TABLE 1 (Continued)

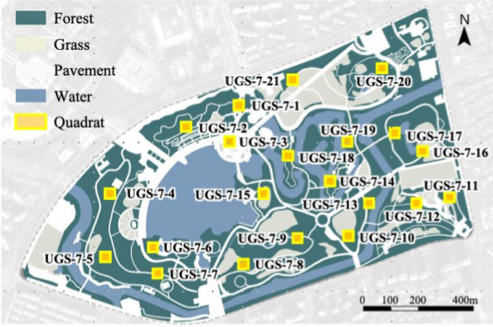
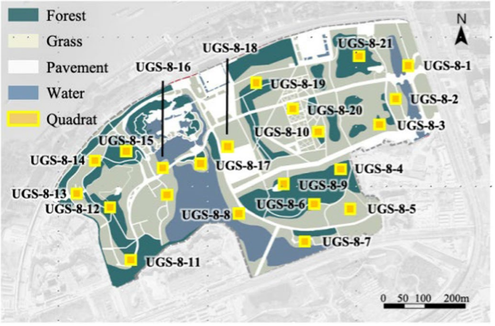
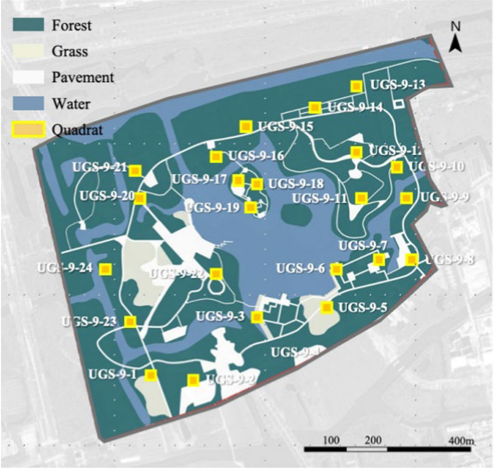
Scale level	Research sites	Size (ha)	Number of quadrats	Selected quadrats in sites
Medium-scale (10~50 ha)	Zhongshan Park (UGS-4)	20.00	11	
	Fengxiangzhixiu Park (UGS-5)	32.12	20	
	West Bund Nature and Art Park (UGS-6)	19.80	22	

(Continued)

selection criteria require that individuals are between the ages of 22 and 50 and are frequent visitors to the recruitment park, defined as visiting at least once per week.

The questionnaire comprised two parts: the first part collected participants' age, gender, and educational background and the second part employed a 5-point Likert scale to assess participants' perception of the richness of plant species within the quadrat area. The questionnaire for assessing perceived plant diversity was adapted from the method established by Fuller et al. (2007), which relies on subjective public reports to evaluate plant species richness in green spaces—a measure corresponding to perceived biodiversity. The original wording was refined to align with the specific context of the present study. Informed by existing literature, which suggests that respondents tend to comprehend and engage more readily with the term "richness" than "diversity" in such evaluations, the final instrument was designed accordingly. In addition to basic demographic items, the

TABLE 1 (Continued)

Scale level	Research sites	Size (ha)	Number of quadrats	Selected quadrats in sites
Large-scale (≥ 50 ha)	Century Park (UGS-7)	140.30	21	
	Expo Culture Park (UGS-8)	85.00	22	
	Mianqing Park (UGS-9)	60.40	24	

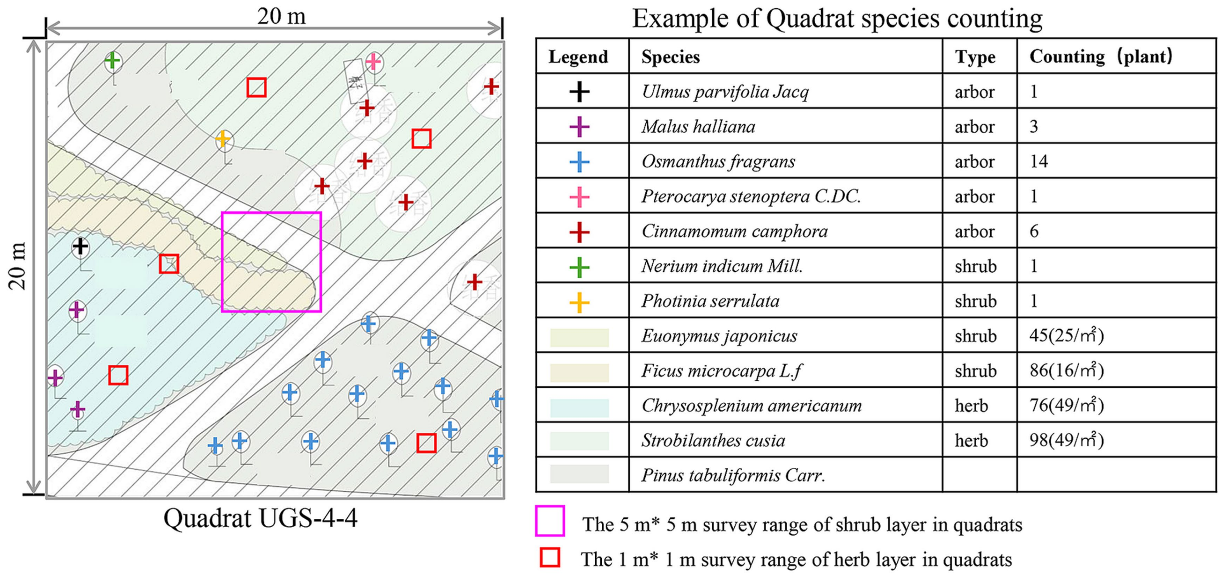
core question used for the assessment of perceived plant diversity was formulated as follows:

"Please rate the plant richness of the site around you (on a scale of 1–5, where 1 = very monotonous, 2 = monotonous, 3 = moderate, 4 = rich, 5 = very rich)."

At least 22 participants were surveyed within each quadrat area. To mitigate potential biases arising from participants' prior familiarity with the parks, all respondents were instructed to focus solely on the immediate visual scene within the quadrat during the three-minute observation period, rather than relying on prior memories or general impressions of the park. This standardized, momentary assessment approach (Shiffman et al., 2008) helps align perceptual judgments with the visual stimuli present at the time of data collection, thereby enhancing the internal validity of the perceived diversity measure. A total of 3,146 valid questionnaires were ultimately obtained. The male-to-female ratio was approximately 1:1, and the mean age of participants was approximately 39 years. This sample size meets the requirements for effect size in similar studies (Faul et al., 2007; Lindemann-Matthies et al., 2010).

Landscape characteristics measured with panoramic photos and semantic segmentation

Existing research has shown that people's perception of plant diversity in UGSs is influenced by a combination of various environmental factors (Williams and Cary, 2002). The structural complexity of plant communities (i.e., the composition of trees, shrubs, and herbaceous plants) serves as one of the direct visual cues affecting this perception (Shi et al., 2022). In addition, the quantity, color, and form of flowering plants within the visual field are also key factors enhancing the perceived biodiversity (Hoyle et al., 2017). Elements such as the sky and water features can indirectly influence the perception of plant diversity by increasing the attractiveness of the environment and encouraging greater engagement with the surroundings (Sztuka et al.,



Legend	Species	Type	Counting（plant）
+	*Ulmus parvifolia Jacq*	arbor	1
+	*Malus halliana*	arbor	3
+	*Osmanthus fragrans*	arbor	14
+	*Pterocarya stenoptera C.DC.*	arbor	1
+	*Cinnamomum camphora*	arbor	6
+	*Nerium indicum Mill.*	shrub	1
+	*Photinia serrulata*	shrub	1
■	*Euonymus japonicus*	shrub	45(25/m^2)
■	*Ficus microcarpa L.f*	shrub	86(16/m^2)
■	*Chrysosplenium americanum*	herb	76(49/m^2)
■	*Strobilanthes cusia*	herb	98(49/m^2)
■	*Pinus tabuliformis Carr.*		

FIGURE 3
An illustration of species counting in each quadrat.

TABLE 2 Selected visual landscape indicators.

Visual landscape indicators	Operational definition	Semantic labels involved	Rationale and justification	Supporting references
Tree visibility ratio (TVR)	Percentage of tree pixels in panoramic image	Tree, palm, palm tree	Vegetation structure and layering drive perceived diversity ratings Southon et al. (2018). Shi et al. (2022) posit that plant community structural complexity functions as a direct visual cue, central not only to perception but also to the understanding of aesthetics.	Celikors and Wells (2022), Chen et al. (2022), Cinnamon and Jahiu (2023), and Ito et al. (2024)
Shrub visibility ratio (ShVR)	Percentage of shrub pixels in panoramic image	Plant, flora, plant life		
Herb visibility ratio (HVR)	Percentage of herb pixels in panoramic image	Grass, field		
Flower visibility ratio (FVR)	Percentage of flower pixels in panoramic image	Flower	Perceived plant richness is significantly predicted by the color richness of flowering plants Hoyle et al. (2018).	
Sky visibility ratio (SVR)	Percentage of sky pixels in panoramic image	Sky	The sky is a key component in the perception of nature, fundamentally shaping the overall visual setting Sztuka et al. (2022).	Cao et al. (2019) and Xia et al. (2021)
Water visibility ratio (WVR)	Percentage of water pixels in panoramic image	Water, river, lake, fountain	Water features exert an indirect influence on perception by enhancing the overall attractiveness of the environment Sztuka et al. (2022).	Luo J. et al. (2022) and Luo, S. et al. (2022)
Spatial enclosure (SPE)	Remaining proportion of sky pixels in fisheye view image	Sky	By governing light heterogeneity and visual range, it shapes the perceptual environment in terms of depth and spatial awareness Valladares et al. (2016) and Yang et al. (2009).	Xia et al. (2021) and Chen et al. (2023)

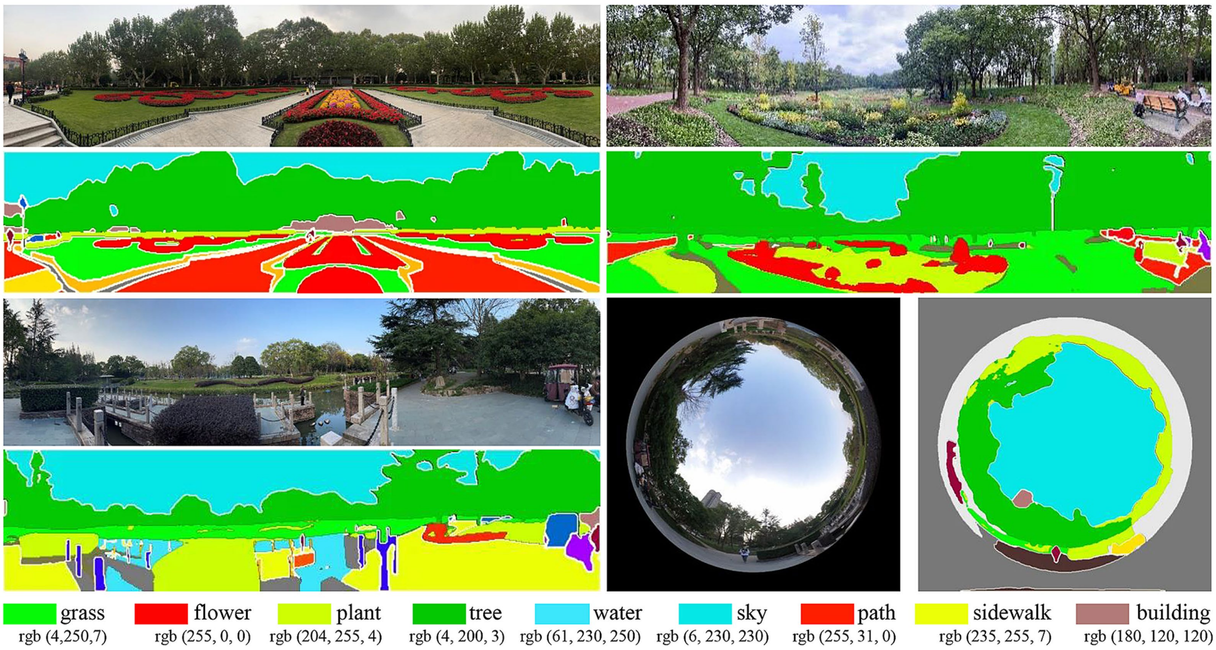


FIGURE 4
An illustration of panoramic image semantic segmentation.

2022). Similarly, spatial enclosure exerts an indirect effect, as the density of tree canopies determines light heterogeneity within the area. Light conditions not only contribute to the habitat health of the plant community but also affect the observer's visual range and depth (Yang et al., 2009; Valladares et al., 2016). Based on existing empirical evidence and current image processing techniques, it is possible to compute and extract visual landscape indicators—including the visibility ratios of trees, herbs, shrubs, flowers, sky, and water, as well as spatial enclosure—and to assess their impact on the perception of plant diversity (Table 2).

The study employed panoramic imagery and semantic segmentation to measure landscape characteristics within the quadrats. Panoramic imagery offers a significant advantage by combining high-fidelity visual representation with the capacity for efficient generation of standardized experimental materials (Figure 4; Gao et al., 2022). This is a prerequisite for achieving the study's objective of large-scale predictive modelling of perceived plant diversity. Panoramic image acquisition for the quadrats was also conducted in October 2024, using an Insta360 ONE panoramic camera. During capture, the camera was mounted on a tripod at a height of 1.6 meters above ground level. This height ensured consistency with typical human eye level while minimizing errors introduced by handheld operation. A total of 206 panoramic images were captured, with an output resolution of 6,912 × 3,456 pixels. Following the discarding of images exhibiting duplicate captures, significant inconsistencies in lighting, or excessive irrelevant content, a total of 143 panoramic images capable of accurately representing the actual scene within each quadrat area were selected (1 image per plot). The OneFormer model was used to perform semantic segmentation on the collected images. OneFormer was trained on ADE20K dataset of over 25,000 images, each with detailed annotations covering 150 semantic categories, facilitating research in scene parsing, semantic segmentation, and object detection (Zhou et al., 2017; Jain et al., 2023). The labels used to compute the seven visual landscape characteristics are summarized (Table 2). The panoptic semantic segmentation model employed in this study was validated on the ADE20K dataset, achieving a Panoptic Quality (PQ) score of 51.5. This score indicates advanced performance in both segmentation quality (object recognition accuracy) and recognition quality (edge clarity of detected objects), positioning the model competitively among current state-of-the-art approaches, which typically attain PQ scores ranging from 45 to 52 (Jain et al., 2023).

Data analysis

The measured plant diversity, perceived plant diversity, and landscape characteristics within the quadrats will then be used to construct regression models. This will enable the efficient prediction of perceived plant diversity in areas outside the quadrats using easily accessible quantitative inputs.

The perceived plant diversity scores, collected via questionnaires, were first tested for normality to determine their suitability for inclusion in regression modelling. Subsequently, independent-samples *t*-tests were performed separately based on age, gender, and educational background. The presence or absence of individual perceptual differences identified through these tests determines whether subsequent analysis should be conducted as a group-based analysis.

The measured plant diversity was quantified using the Shannon-Wiener diversity index to calculate plant richness within the sample parks. The Shannon-Wiener index is a widely used metric in ecology that estimates species diversity based on Claude Shannon's entropy formula. This index integrates two key dimensions of species within a given habitat: abundance (the overall number of individuals) and evenness (the relative density or distribution of individuals across species; Scheiner, 2003). Utilizing the total number of species and the number of individuals per species recorded for the arbor, shrub, and herbaceous layers within each quadrat, the Shannon-Wiener diversity index was calculated separately for the herbaceous layer, shrub layer, arbor layer, and the entire plant community within each park, according to Equation 1:

$$H' = -\sum_{i=1}^{S} \left(P_i \times \ln P_i \right), P_i = N_i / N \tag{1}$$

Where,

S = total number of species recorded within the quadrats;

i = the probability that a randomly selected individual belongs to the i th species;

N_i = abundance (individual count) of the i th species within the quadrats;

N = aggregate abundance of all species within the respective vegetation layer or entire;

P_i = the proportional abundance of the i th species, calculated as $P_i = N_i/N$;

$\ln P_i$ = the natural logarithm (base $e \approx 2.718$) of P_i.

Among the seven landscape indicators, the TVR, ShVR, HVR, FVR, SVR and WVR can be directly calculated using Equation 2, while the other indicator, spatial enclosure (SPE), is defined as Equation 3 (Figure 4).

$$xVR = \frac{A_x}{A_{Total}} \tag{2}$$

Where,

xVR refers to the visibility ratio of landscape element category x within a 360° cylindrical panoramic image;

A_x denotes the area (in pixels) occupied by this landscape element in the image. The pixel area of arbors is denoted as A_t, that of shrubs as A_p, herbaceous vegetation as A_h, flowers as A_f, water features as A_w, and the sky as A_s;

A_{Total} denote the total pixel area of the 360° cylindrical panoramic image.

$$SPE = \frac{A_x^f}{A_{Total}^f} \tag{3}$$

Where,

SPE denote the visibility ratio of the sky in the 180° fisheye image;

A_x^f denotes the combined pixel area of all landscape elements in the image, excluding the sky;

A_{Total}^f refers to the total pixel area of the resulting 180° fisheye image after projection from the panoramic image.

Employing a quadrat-based geospatial framework, all data—including field-measured plant surveys, visitor questionnaire ratings, and hemispherical panoramic imagery—were integrated using unique identifiers to ensure precise spatial alignment. Plant diversity was quantified via the Shannon–Wiener index across vegetation layers, while visual landscape metrics were extracted from semantically segmented images based on standardized definitions. These variables were compiled into a unified dataset and standardized prior to analysis. The analytical procedure followed a sequential logic: it commenced with a descriptive overview of perceived diversity, measured diversity, and visual characteristics across the nine parks. This was followed by a comparative analysis to identify significant discrepancies between perceived and measured plant diversity, the patterns of which were then examined in relation to visual landscape features. Subsequently, an integrated correlation analysis explored the interrelationships among all three variable sets. Finally, key factors identified through these stages were used to construct and validate a multiple linear regression model, predicting perceived plant diversity based on measured ecological indices and visual metrics, thereby systematically investigating the drivers and predictability of public perception in UGSs.

Results

Analysis of the measured and perceived plant biodiversity characteristics

Descriptive analysis

The questionnaire data were analyzed using SPSS V26.0. The results of Levene's test indicated that all values for homogeneity of variance exceeded 0.05, confirming that the data were approximately normally distributed and met the assumption of equal variances. This satisfied the prerequisites for the subsequent parametric analyses. Independent-samples t-tests revealed no statistically significant differences ($p > 0.05$) among participant groups stratified by age, gender, or educational background. This suggests an absence of perception variations attributable to these demographic factors, confirming that they did not significantly influence the evaluation outcomes. Consequently, these variables were excluded from further analysis.

The fundamental characteristics of both measured and perceived plant diversity are summarized in Table 3. Overall, the ratings for perceived plant diversity were high across the nine parks, with mean scores ranging from 3.66 to 4.32 on a 5-point scale. This reflects a generally positive public perception of plant richness in Shanghai's UGSs. Among the parks, Zhongshan Park (UGS-4, $p = 4.32$) received the highest perceptual rating, whereas Fengxiang Zhixiu Park (UGS-5, $p = 3.66$) received the lowest.

In terms of objectively measured diversity, the overall plant community Shannon-Wiener index varied between 1.32 and 1.69. The highest values were recorded in Fuxing Park (UGS-3, $H' = 1.69$) and Expo Culture Park (UGS-8, $H' = 1.69$), while Jiangpu Park (UGS-1, $H' = 1.32$) showed the lowest. When examined by vegetation layer, the maximum arbor diversity (H_t') was observed in Quyang Park (1.95). For the shrub layer, the peak diversity ($H_s' = 1.71$) occurred in Expo Culture Park, and for the herb layer, the highest diversity ($H_h' = 1.99$) was found in Fuxing Park (Table 3).

Comparison between measured and perceived plant diversity

A discrepancy analysis was conducted between perceived and measured plant diversity. Given the substantial differences in value ranges among various indicators, data were normalized prior to analysis to mitigate the influence of differing units of measurement. The results of the paired-sample t-test on the normalized perceived and measured plant diversity are presented in the table below. The findings

TABLE 3 Descriptive analysis results of the measured and people perceived plant biodiversity.

Plant biodiversity	Statistical indicators	UGS-1	UGS-2	UGS-3	UGS-4	UGS-5	UGS-6	UGS-7	UGS-8	UGS-9
P	Mean	4.04	4.20	4.07	4.32	3.66	4.21	4.20	4.01	4.00
	Std. dev	0.21	0.14	0.16	0.15	0.34	0.13	0.16	0.15	0.15
H'	Mean	1.32	1.68	1.69	1.52	1.53	1.61	1.53	1.69	1.54
	Std. dev	0.38	0.38	0.57	0.69	0.44	0.44	0.47	0.52	0.36
H_t'	Mean	1.67	1.95	1.62	1.64	1.88	1.84	1.84	1.75	1.71
	Std. dev	0.59	0.57	0.56	0.74	0.66	0.84	0.64	0.78	0.71
H_s'	Mean	1.17	1.44	1.46	1.37	1.53	1.49	1.26	1.71	1.45
	Std. dev	0.63	0.70	0.77	0.92	0.76	0.69	0.83	0.86	0.62
H_h'	Mean	1.12	1.64	1.99	1.55	1.16	1.47	1.48	1.60	1.48
	Std. dev	0.80	0.56	1.00	0.15	0.75	0.69	0.78	0.75	0.92

TABLE 4 Paired sample t-test to verify differences.

Paired indicators	Mean ± Std		diff	t	Cohen's d value	p-value
	P	$H' \sim H_h'$				
P paired H'	0.60 ± 0.18	0.39 ± 0.19	0.21	9.773	0.817	0.000**
P paired H_t'	0.60 ± 0.18	0.45 ± 0.23	0.14	6.162	0.515	0.000**
P paired H_s'	0.60 ± 0.18	0.40 ± 0.23	0.20	8.060	0.674	0.000**
P paired H_h'	0.60 ± 0.18	0.42 ± 0.24	0.17	7.213	0.603	0.000**

** $p < 0.01$.

indicate significant discrepancies between all four indicators of perceived plant diversity and measured plant diversity. Among these, the difference between perceived plant diversity and the overall community plant diversity was the most pronounced (mean difference = 0.21, $t = 9.773$, $d = 0.817$), while the difference with the arbor layer plant diversity was relatively smallest (mean difference = 0.14, $t = 6.162$, $d = 0.515$). All Cohen's d values exceeded 0.5, indicating that these discrepancies are not only statistically significant but also practically meaningful (Table 4).

This observed discrepancy is further evidenced by the lack of alignment in their respective variation trends. As illustrated in Figure 5, no clear correspondence exists between the ranking of parks based on perceived diversity and their ranking according to any of the four measured diversity indices. For example, Fengxiang Zhixiu Park (UGS-5), which received the lowest perceived score, did not exhibit the lowest values for any of the measured indices among the nine parks. Conversely, Zhongshan Park (UGS-4), with the highest perceived rating, did not rank highest on any objective measure. This visual and statistical disconnect provides compelling support for the presence of a "human-biodiversity paradox" in this context, indicating that the public's subjective assessment of plant richness is not a reliable reflection of the objective ecological reality.

Analysis of visual landscape characteristics associated with plant diversity

Descriptive analysis

Within the visual composition of the sampled parks, vegetation emerges as the dominant element. At the user's eye level, plants account for a significantly high visibility rate of 59.77%. This finding is further supported by fisheye-image analysis, which indicates an upward spatial enclosure rate of 71.00%, reflecting a dense, multilayered vegetative environment.

Among the vegetative components, trees constitute the primary visual element, comprising 36.53% of the total landscape. The visibility rates of herbaceous plants (12.13%) and shrubs (10.93%) are relatively similar, while flowers exhibit the lowest visibility at merely 1.16%—substantially lower than the other three categories. Non-vegetative features also demonstrate limited prominence: water features account for only 2.06%, and the sky visibility rate measures 13.89%, a value closely aligned with those of herbs and shrubs (Table 5).

Regarding vegetation composition across the nine parks, Zhongshan Park (UGS-4) and Jiangpu Park (UGS-1) showed the highest proportion of trees, at 43.21 and 40.80% respectively, whereas the lowest was recorded in Fuxing Park (UGS-3, 32.04%). The relative visual ratios of herbaceous plants and shrubs varied inconsistently. In Fuxing Park (UGS-3), Century Park (UGS-7), and Expo Culture Park (UGS-8), herbaceous plants slightly surpassed shrubs in visibility, whereas shrubs accounted for a larger share in the remaining six parks. The proportion of flowers was highest in West Bund Nature and Art Park (UGS-6, 2.74%); in all other parks, it remained below 2.00%, with the lowest in Fengxiangzhixiu Park (UGS-5, 0.05%) (Table 5).

The visibility of water bodies also varied considerably among parks. The highest proportion appeared in Quyang Park (UGS-2, 5.12%), followed by Jiangpu Park (UGS-1, 4.43%), while the lowest was in Fuxing Park (UGS-3, 0.53%). When examined by park size category, small parks had the highest average water visibility

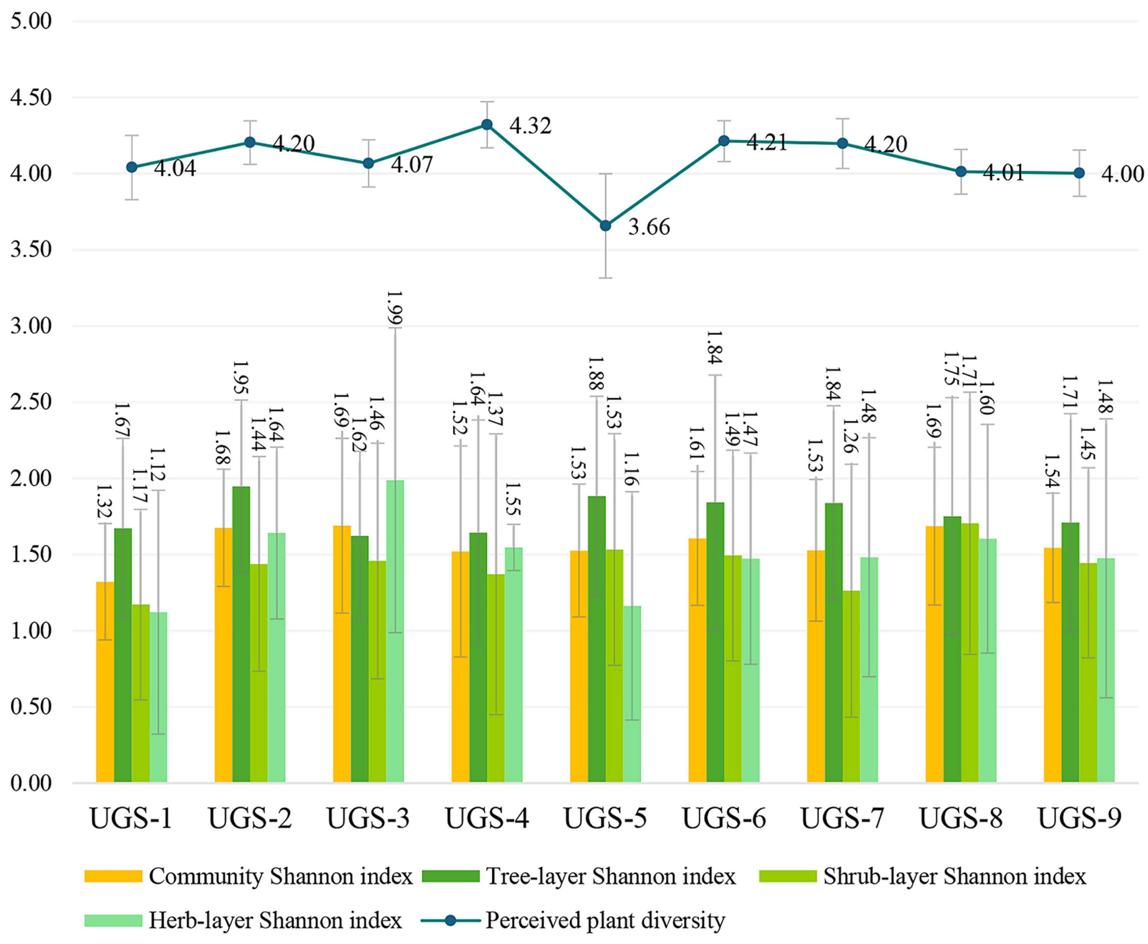


FIGURE 5
Mean value of the measured and people perceived plant diversity.

TABLE 5 Descriptive analysis results of the landscape characteristics.

Visual landscape characteristic	Statistical indicators	UGS-1	UGS-2	UGS-3	UGS-4	UGS-5	UGS-6	UGS-7	UGS-8	UGS-9	Mean
FVR	Mean	1.47%	0.50%	1.49%	1.44%	0.05%	2.74%	1.33%	0.97%	0.47%	1.16%
	Std. dev	2.49%	0.52%	2.74%	2.89%	0.16%	3.92%	2.06%	1.87%	1.79%	/
HVR	Mean	15.94%	12.71%	4.42%	11.23%	14.11%	15.27%	18.26%	7.50%	9.73%	12.13%
	Std. dev	13.00%	8.70%	6.17%	8.74%	9.23%	11.01%	9.76%	7.72%	10.65%	/
ShVR	Mean	12.90%	9.31%	10.05%	8.48%	8.36%	14.67%	14.42%	9.99%	10.15%	10.93%
	Std. dev	11.70%	8.70%	8.01%	8.74%	7.85%	11.01%	9.76%	7.72%	9.16%	/
TVR	Mean	40.80%	36.79%	32.04%	43.21%	34.77%	34.39%	36.91%	35.32%	34.58%	36.53%
	Std. dev	9.61%	10.37%	8.97%	13.53%	10.02%	12.53%	9.18%	10.99%	10.26%	/
WVR	Mean	4.43%	5.12%	0.53%	2.52%	1.66%	1.72%	1.19%	0.78%	0.61%	2.06%
	Std. dev	8.21%	6.73%	1.30%	4.66%	4.02%	4.60%	3.42%	2.11%	2.25%	/
SVR	Mean	16.41%	9.77%	11.61%	16.47%	16.09%	13.66%	11.60%	15.95%	13.46%	13.89%
	Std. dev	6.18%	7.09%	7.03%	8.83%	9.53%	8.64%	6.88%	9.51%	6.16%	/
SPE	Mean	64.44%	72.57%	77.34%	70.92%	71.00%	69.09%	71.09%	75.25%	67.32%	71.00%
	Std. dev	5.33%	8.62%	10.39%	10.89%	10.17%	10.80%	12.44%	11.74%	10.23%	/

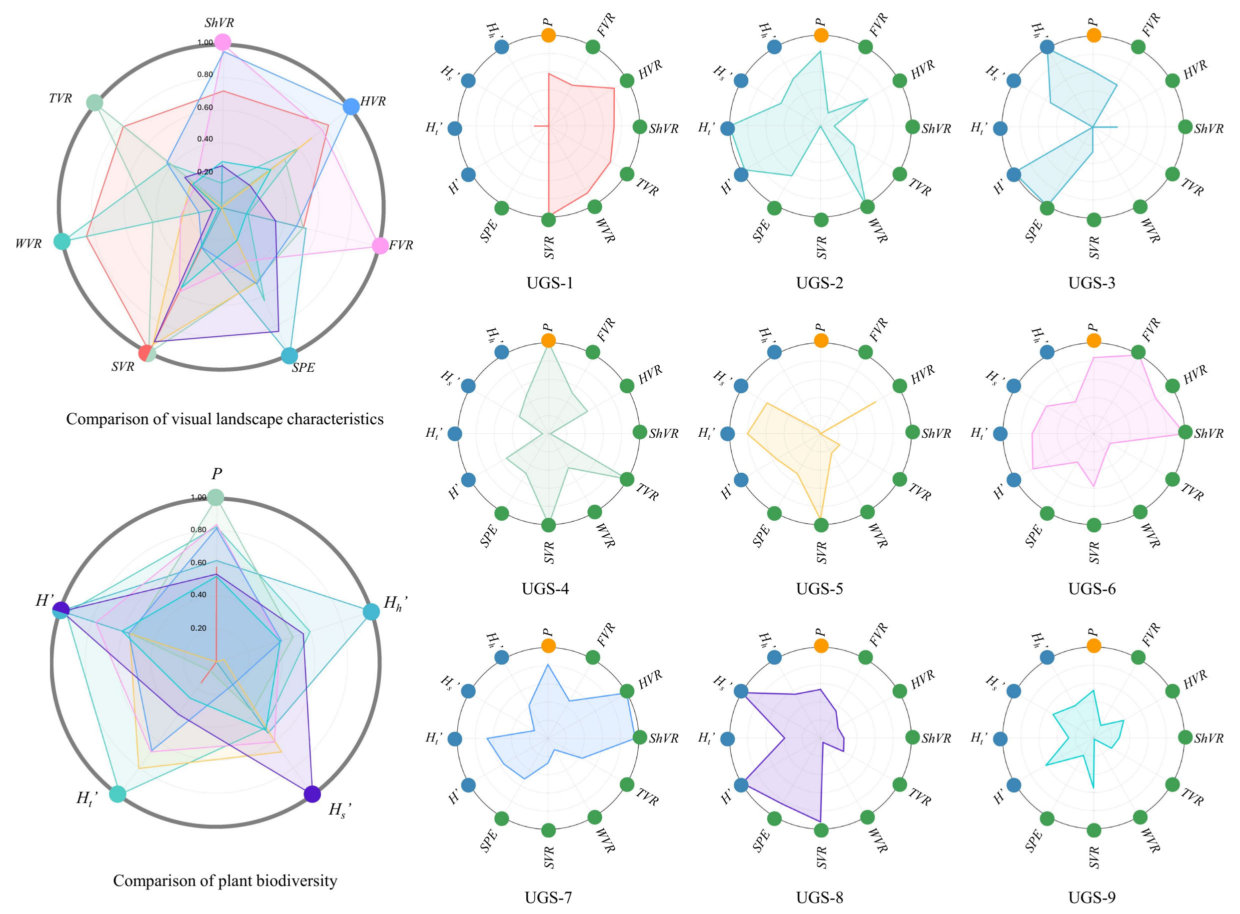


FIGURE 6
Comparison of plant diversity and visual landscape characteristics across UGSs.

(M = 3.36%), followed by medium parks (M = 1.97%), with large parks showing the lowest (M = 0.61%) (Table 5).

Comparative analysis between plant biodiversity and landscape characteristics

The study performed a multidimensional comparison of perceived plant diversity, measured plant diversity, and visual landscape characteristics across the nine parks, based on 12 normalized indicators. The results revealed a pronounced contrast between the visual and ecological dimensions: visual landscape characteristics varied substantially among the parks, with hardly any two sites sharing a similar visual composition. In contrast, plant diversity—both perceived and measured—showed a high degree of consistency across most parks, with only UGS-3, UGS-8, and UGS-9 deviating slightly from the others (Figure 6).

From the perspective of the individual parks, the analysis revealed distinct profiles: UGS-1 exhibited strengths in Sky View Ratio (*SVR*) and Herbaceous View Ratio (*HVR*) but weaknesses in Spatial Enclosure (*SPE*) and all measured plant diversity indices, indicating good visual openness yet low actual diversity; UGS-2 showed advantages in Water View Ratio (*WVR*), overall diversity (H'), and tree layer diversity (H_t') but was weaker in *SVR* and Shrub View Ratio (*ShVR*), reflecting rich aquatic and tree scenery yet less prominent shrub and flowering layers; UGS-3 excelled in SPE, overall diversity (H'), and herb layer diversity (H_h') but performed poorly in *WVR*, *HVR*, and Tree View Ratio (*TVR*), suggesting high enclosure with uniform vegetation structure; UGS-4 was notable for high perceived diversity (*P*), *SVR*, and *TVR* but weaker in tree diversity (H_t') and *ShVR*, corresponding to strong tree presence and subjective richness despite lower arboreal diversity; UGS-5 stood out only in *SVR* while scoring low in *P*, Flower View Ratio (*FVR*), and *ShVR*, denoting an open spatial character with limited shrubs, flowers, and perceived variety; UGS-6 excelled in *P*, *FVR*, and *ShVR* with no clear weaknesses, pointing to well-layered vegetation, abundant flowers, and high public appreciation; UGS-7 was strong in *HVR* and *ShVR* but weak in *WVR*, reflecting rich herbaceous and shrub landscaping without notable water features; UGS-8 performed well in H', shrub diversity (H_s'), and *SVR* but was low in *WVR*, indicating high shrub diversity and open views yet minimal aquatic elements; and UGS-9 had no outstanding indicators and was weak in *WVR*, similarly lacking water-based visual features (Figure 6).

Interactions among visual landscape features

To investigate the interactive effects of independent variables on the dependent variable, this study utilized the "interaction detector" module of the GeoDetector model. Widely adopted in spatial statistical analysis, this method examines how any two independent variables jointly influence the dependent variable. It does not rely on linear assumptions and is capable of detecting complex nonlinear relationships. By comparing the explanatory power of a single factor,

TABLE 6 Results of GeoDetector factor interaction detection.

Paired indicators	q(X1∩X2)	q(X1)	q(X2)	Interaction type	Basis for judgment
FVR∩ShVR	0.286	0.143	0.076	Enhance, nonlinear-	q(X1∩X2) > q(X1) + q(X2)
FVR∩TVR	0.269	0.143	0.082	Enhance, nonlinear-	q(X1∩X2) > q(X1) + q(X2)
FVR∩SVR	0.257	0.143	0.043	Enhance, nonlinear-	q(X1∩X2) > q(X1) + q(X2)
FVR∩SPE	0.137	0.143	0.087	weaken, nonlinear-	min(q(X1), q(X2)) < q(X1∩X2) < max(q(X1), q(X2))
ShVR∩TVR	0.194	0.076	0.082	Enhance, nonlinear-	q(X1∩X2) > q(X1) + q(X2)
ShVR∩SVR	0.272	0.076	0.043	Enhance, nonlinear-	q(X1∩X2) > q(X1) + q(X2)
ShVR∩SPE	0.184	0.076	0.087	Enhance, nonlinear-	q(X1∩X2) > q(X1) + q(X2)
TVR∩SVR	0.102	0.082	0.043	Enhance, bi-	max(q(X1), q(X2)) < q(X1∩X2) < q(X1) + q(X2)
TVR∩SPE	0.190	0.082	0.087	Independent	q(X1∩X2) = q(X1) + q(X2)
SVR∩SPE	0.127	0.043	0.087	Independent	q(X1∩X2) = q(X1) + q(X2)

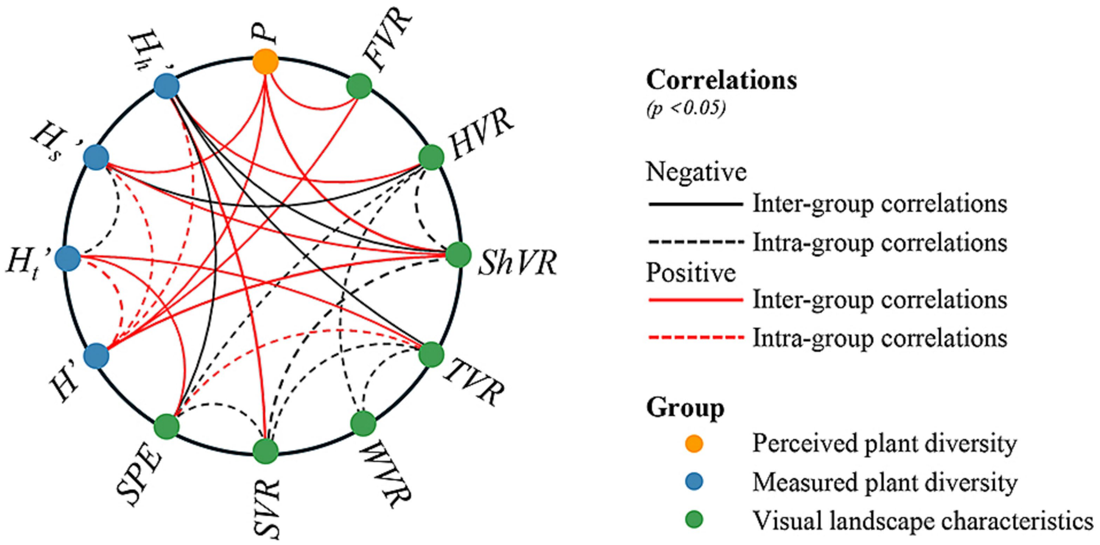


FIGURE 7
Cross effects of visual landscape characteristics and plant diversities.

expressed as q(X), with the combined explanatory power of two factors, expressed as q(X1∩X2), the interaction type between the two factors can be determined (Wang et al., 2010).

The results of the interaction analysis are summarized in Table 6. Interactions between the following pairs—*FVR∩ShVR*, *FVR∩TVR*, *FVR∩SVR*, *ShVR∩TVR*, *ShVR∩SVR*, and *ShVR∩SPE*—all showed nonlinear enhancement. This indicates that their combined explanatory power for perceived plant diversity is not only stronger than that of either factor individually, but also exceeds the sum of their individual effects. In contrast, the interaction between *FVR∩SPE* displayed nonlinear weakening, implying a mutually inhibitory effect when these two factors act together. The combined influence of *TVR∩SVR* demonstrated a positive synergistic effect on explanatory power. Finally, the interactions between *TVR∩SPE* and *SVR∩SPE* were found to be mutually independent, suggesting no significant interaction between these variable pairs.

Cross effects between plant biodiversity and landscape characteristics

Cross effects were then checked within three groups of indicators: the measured and perceived plant diversity, and visual landscape characteristics. It was found that 26 pairs of indicators to be significantly related to each other, including 11 pairs of external positive correlations, four pairs of external negative correlations, four pairs of internal positive correlations and seven pairs of internal negative correlations. A total of two pairs of inter-group positive correlations were identified between perceived plant diversity and measured plant diversity, while two pairs were observed between perceived plant diversity and visual landscape characteristics. Additionally, seven pairs of inter-group positive correlations were found between measured plant diversity and visual landscape characteristics. Similarly, negative external correlations (four pairs) were all observed between these two groups.

TABLE 7 Correlation analysis results between plant diversities and landscape visual indicators.

Variable	Statistical indicators	*FVR*	*HVR*	*ShVR*	*TVR*	*WVR*	*SVR*	*SPE*	H'	H_t'	H_s'	H_h'
P	*r*	0.311**	−0.073	0.305**	−0.079	−0.018	−0.154	0.057	0.336**	−0.13	0.565**	0.12
	p-value	0	0.387	0	0.347	0.829	0.067	0.503	0	0.122	0	0.154
FVR	*r*	1.000**	−0.143	0.15	−0.084	−0.15	−0.067	−0.048	0.188*	0.003	0.308**	0.011
	p-value	0	0.089	0.073	0.32	0.074	0.428	0.569	0.024	0.973	0	0.895
HVR	*r*	−0.143	1.000**	−0.549**	−0.078	−0.170*	0.133	−0.227**	0.123	0.003	−0.349**	0.517**
	p-value	0.089	0	0	0.357	0.042	0.114	0.006	0.145	0.972	0	0
ShVR	*r*	0.15	−0.549**	1.000**	0.024	−0.051	−0.237**	0.14	0.276**	−0.024	0.690**	−0.183*
	p-value	0.073	0	0	0.78	0.542	0.004	0.097	0.001	0.774	0	0.029
TVR	*r*	−0.084	−0.078	0.024	1.000**	−0.195*	−0.748**	0.733**	−0.055	0.242**	−0.047	−0.250**
	p-value	0.32	0.357	0.78	0	0.02	0	0	0.515	0.004	0.578	0.003
WVR	*r*	−0.15	−0.170*	−0.051	−0.195*	1.000**	0.161	−0.057	−0.068	−0.096	−0.032	0.004
	p-value	0.074	0.042	0.542	0.02	0	0.055	0.5	0.419	0.253	0.706	0.967
SVR	*r*	−0.067	0.133	−0.237**	−0.748**	0.161	1.000**	−0.789**	0.015	−0.146	−0.149	0.286**
	p-value	0.428	0.114	0.004	0	0.055	0	0	0.863	0.082	0.075	0.001
SPE	*r*	−0.048	−0.227**	0.14	0.733**	−0.057	−0.789**	1.000**	−0.082	0.212*	0.026	−0.336**
	p-value	0.569	0.006	0.097	0	0.5	0	0	0.33	0.011	0.753	0
H'	*r*	0.188*	0.123	0.276**	−0.055	−0.068	0.015	−0.082	1.000**	0.551**	0.495**	0.658**
	p-value	0.024	0.145	0.001	0.515	0.419	0.863	0.33	0	0	0	0
H_t'	*r*	0.003	0.003	−0.024	0.242**	−0.096	−0.146	0.212*	0.551**	1.000**	−0.1	0.116
	p-value	0.973	0.972	0.774	0.004	0.253	0.082	0.011	0	0	0.233	0.169
H_s'	*r*	0.308**	−0.349**	0.690**	−0.047	−0.032	−0.149	0.026	0.495**	−0.1	1.000**	−0.056
	p-value	0	0	0	0.578	0.706	0.075	0.753	0	0.233	0	0.505
H_h'	*r*	0.011	0.517**	−0.183*	−0.250**	0.004	0.286**	−0.336**	0.658**	0.116	−0.056	1.000**
	p-value	0.895	0	0.029	0.003	0.967	0.001	0	0	0.169	0.505	0

* $p < 0.05$; ** $p < 0.01$.

Regarding intra-group positive correlations, three pairs emerged among the four indicators of measured plant diversity, and one pair was identified within the seven indicators of visual landscape characteristics. Furthermore, six pairs of intra-group negative correlations were detected within the seven indicators of visual landscape characteristics, with an additional pair observed among the indicators of measured plant diversity (Figure 7).

Constructing the prediction model of people perceived plant diversity

The study aims to construct regression models using both measured and perceived plant diversity and landscape characteristics obtained from sample plots. This approach will facilitate the prediction of user-perceived plant diversity in subsequent research based on measured plant diversity and landscape features that are easier to acquire and measure on a large scale. A Pearson correlation analysis was first conducted on the four measured plant diversity indicators, seven visual landscape characteristic indicators, and people perceived plant diversity evaluation of the sampled parks. The results revealed that the shrub diversity index ($p < 0.05$) and the overall community plant diversity index ($p < 0.05$) among the measured plant diversity indicators, as well as the flower visibility rate ($p < 0.05$) and shrub visibility rate ($p < 0.05$) among the visual landscape characteristics, demonstrated a significant positive correlation with the perceived plant diversity evaluation results (Table 7).

When constructing the regression model, factors with low correlation or collinearity issues were progressively eliminated through partial correlation analysis and collinearity diagnostics. The excluded variables include herb visibility ratio, water visibility ratio, the overall community diversity index, herb layer diversity index, and arbor layer diversity index. Factors with substantial contributions were retained to establish an evaluation model for perceived plant diversity using Equation 4. The final regression model equation is as follows:

$$\begin{aligned} P = 3.997 + 1.282 \times FVR - 0.570 \times ShVR - 0.690 \times TVR \\ -0.788 \times SVR + 0.220 \times SPE + 0.215 \times H_s' \end{aligned} \quad (4)$$

Where,
P = perceived plant diversity;
FVR = flower visibility ratio;
$ShVR$ = shrub visibility ratio;
TVR = tree visibility ratio;
SVR = sky visibility ratio;

TABLE 8 Model prediction test results.

Predictor variable	Unstandardized coefficients		Standardized coefficients	*t*	*p*	Collinearity diagnosis	
	B	Standard deviation	*Beta*			VIF	Tolerance
FVR	1.282	0.791	0.116	1.621	0.107	1.148	0.871
ShVR	−0.57	0.271	−0.201	−2.106	0.037*	2.034	0.492
TVR	−0.69	0.273	−0.283	−2.532	0.012*	2.783	0.359
SVR	−0.788	0.414	−0.242	−1.904	0.059	3.588	0.279
SPE	0.22	0.285	0.091	0.772	0.442	3.071	0.326
H_s'	0.215	0.034	0.617	6.34	0.000**	2.102	0.476
R^2	0.388						
Adjusted R^2	0.361						
F	F (6,136) = 14.376, p = 0.000						
D-W value	1.47						

* $p < 0.05$; ** $p < 0.01$.

SPE = spatial enclosure;

H_s' = Shrub-layer Shannon index.

The model demonstrates a satisfactory overall fit, with a coefficient of determination (R^2) of 0.388 and an adjusted R^2 of 0.361, indicating that the six selected independent variables collectively explain 36.1% of the variance in perceived plant diversity. Results from the analysis of variance (ANOVA) show that the regression relationship is highly significant [F (6, 136) = 14.376, $p < 0.001$], confirming the statistical validity of the model.

Significance tests for each predictor variable revealed the following (Table 8). The Shrub-layer Shannon index exhibits a highly significant positive predictive effect on perceived plant diversity ($\beta = 0.617$, $t = 6.340$, $p < 0.01$). With the highest standardized regression coefficient, it is identified as the most critical factor influencing perceived plant diversity. Both shrub visibility ratio ($\beta = -0.201$, $t = -2.106$, $p < 0.05$) and tree visibility ratio ($\beta = -0.283$, $t = -2.532$, $p < 0.05$) show significant negative influences on perceived diversity. Although flower visibility ratio ($p = 0.107$), sky visibility ratio ($p = 0.059$), and spatial enclosure ($p = 0.442$) did not reach statistical significance, the direction of their regression coefficients may still offer valuable directional insights.

To evaluate the statistical validity of the model, diagnostic tests for multicollinearity and residual independence were conducted. Variance inflation factor (VIF) values for all independent variables ranged from 1.148 to 3.588 (all well below 10), and tolerance values exceeded 0.2, indicating no severe multicollinearity and confirming the stability of the model structure. The Durbin–Watson statistic was 1.47, suggesting a low degree of residual autocorrelation. While this may lead to a slight overestimation of the significance levels of the predictors, the estimated coefficients, their directional signs, and the relative importance of the variables remain reliable (Liu and Wang, 2014). Overall, the regression model satisfies key assumptions—significance and absence of severe multicollinearity—and, though explaining a limited portion of variance, demonstrates a robust statistical structure that effectively captures the mathematical relationship between perceived plant diversity and objective landscape attributes.

To further assess the model's generalizability and potential overfitting, a 10-fold cross-validation was performed. The full dataset ($n = 143$) was randomly divided into 10 non-overlapping subsets. In each iteration, nine subsets (≈128 samples) were used for training, and the remaining subset (≈15 samples) for testing, ensuring every sample was predicted exactly once. The cross-validation yielded a mean test-set R^2 of 0.358 and a root mean square error of 0.113. The mean test-set R^2 closely aligns with the adjusted R^2 from the full model (0.361), with a difference well below the common threshold of 0.05. The explanatory power demonstrated exceeds the established threshold for a 'large' effect size within behavioral science (Cohen, 1988). This finding is consistent with the variance typically accounted for in analogous environmental perception research (Chen et al., 2016; Meng et al., 2024), thus robustly confirming the influence of key visual features.

Discussion

Based on subjective and objective data obtained from small-scale quadrats in UGSs, this study constructs a mathematical model that utilizes objective environmental cues to evaluate perceived plant diversity. By analyzing the relationships among perceived plant diversity, measured plant diversity, and visual landscape characteristics, the model enables cost-effective and large-scale prediction of perceived plant diversity in UGS settings.

Support for and further elaboration on the "human-biodiversity paradox"

The study found significant discrepancies between all four metrics describing measured plant diversity (arbor, shrub, herbaceous, and community diversity index) and perceived plant diversity. This finding further corroborates the "human-biodiversity paradox" and supports existing research suggesting only a weak, or even non-existent, direct link between perceived and measured plant diversity. Previous studies have indicated that measured biodiversity is merely one factor influencing public perception, not a decisive one; although the two are related, measured plant diversity cannot be directly equated with the experiential benefits gained by the public (Rozario et al., 2025). In most cases, perceptions of biodiversity are characterized by a notable systematic underestimation and considerable individual variation (Bele and Chakradeo, 2021). When UGSs are designed to serve human needs, design strategies focused solely on maximizing species count often fall short of expectations. It is essential to integrate considerations of how other life forms are perceived by people. In addition, the regression model indicated that the Shannon diversity index of the shrub layer positively predicted perceived plant diversity, as shrubs are positioned at eye level and include a greater variety of flowers compared to the arbor and herbaceous layers, making them more noticeable to visitors and thereby influencing their assessment of perceived plant diversity.

Furthermore, the investigation into the relationships among the measured plant diversity, perceived plant diversity, and visual landscape characteristics indirectly supports the mediating role of perceived plant diversity in the human-biodiversity relationship. While numerous studies have confirmed the impact of visual landscape features on human health and well-being, this study identifies flower visibility ratio, shrub visibility ratio, tree visibility ratio, sky visibility ratio and spatial enclosure as significant positive and negative predictors of perceived plant diversity. Research suggests that perceived diversity does not arise in a vacuum but is grounded in objective reality, filtered and reconstructed through the visual channel (Ha et al., 2025). When landscape features exert a strong influence on visual perception (e.g., flowering plants within a scene), the link between measured and perceived plant diversity is typically stronger and exerts a positive influence. Conversely, for species that are less directly observable or visually inconspicuous (e.g., woodland of trees with high branching points), this connection tends to be weaker (Southon et al., 2018) or can even exhibit a negative influence. Therefore, when exploring the impact of biodiversity on mental health, it is crucial to integrate visually relevant environmental features related to perceived plant diversity into the mechanistic framework.

Visual landscape characteristics as quantifiable and adjustable design cues

Perceived biodiversity is a multi-sensory experience, yet vision undoubtedly plays the dominant role. Regression analysis result revealed that visual landscape characteristics were more effective predictors of perceived plant diversity than measured plant diversity itself. Specifically, the flower visibility ratio (*FVR*) and spatial enclosure (*SPE*) emerged as key positive predictors. Among all predictors, *FVR* had the highest regression coefficient, indicating that even a small presence of flowers within the visual field can significantly elevate perceived diversity. This aligns with findings suggesting that colorful meadows elicit stronger perceptions of diversity (Hoyle et al., 2018).

A higher spatial enclosure, coupled with a lower sky visibility ratio, implies a habitat type more closely resembling a pristine, dense forest, leading visitors to perceive the area as having greater plant richness. This suggests that people may perceive and appreciate biodiversity more keenly in naturalistic landscapes (Johansson et al., 2014), while tending to overlook it in manicured park environments. This phenomenon resonates with dimensions of Kaplan's Attention Restoration Theory regarding the mechanisms of perceived biodiversity (Wilkie et al., 2020), where people appear to equate an environment's sense of naturalness with a greater variety of plants.

To further investigate the complex interplay between these visual predictors, this study employed the GeoDetector method. The interaction analysis revealed that 6 out of 10 factor pairs—including $FVR \cap ShVR$—demonstrated "nonlinear enhancement," meaning their combined explanatory power substantially exceeded the sum of their individual effects. This synergy suggests that combinations like *FVR* and *ShVR* are likely to create richer visual information through complementary colors and forms. Conversely, the interaction between *FVR* and *SPE* exhibited "nonlinear weakening," indicating that in highly enclosed spaces, the positive contribution of flowers to diversity perception may be inhibited—highlighting the design importance of spatial openness. Other interactions, such as $TVR \cap SVR$, showed "bivariate enhancement," while $TVR \cap SPE$ and $SVR \cap SPE$ were "mutually independent," suggesting that spatial enclosure operates through a different perceptual pathway than vegetation structure, allowing for more independent design control. While GeoDetector effectively detects interaction types, it does not specify the underlying mathematical mechanisms, pointing to a valuable direction for future research.

Traditionally, assessing the perception of plant diversity in UGSs has relied heavily on labor-intensive questionnaire surveys, whose reliability can be susceptible to environmental interference (Austen et al., 2021). This study establishes a link between perceived biodiversity and quantifiable visual landscape characteristics, implying that perceived diversity can be evaluated on a large scale using minimal on-site surveys combined with batch processing of panoramic imagery. This approach lays the groundwork for applications in large-scale urban planning and green space management.

The findings offer clear practical value: UGS management and design can be strategically enhanced by optimizing key visual cues to boost public perception of plant diversity, thereby maximizing associated health benefits. These feature-focused strategies are often more cost-effective and actionable than simply increasing species richness, particularly in resource-limited urban settings. Critically, as the interaction analysis confirms, design interventions must account for the complex synergistic or inhibitory relationships between visual features. Ultimately, this research provides planners with an evidence-based tool to help balance ecological conservation with public needs.

Limitations

Although the research findings largely met expectations, this study has several limitations that suggest directions for future work. Regarding research design, the conclusions are based on data from nine urban parks in Shanghai. Consequently, their generalizability to other types of green spaces—such as street greenery and community gardens—or to cities with different sizes, climates, and cultural contexts requires further validation. Future studies could expand the geographical scope and incorporate cross-cultural comparisons. Additionally, the participant pool may not fully represent the spectrum of park users. Although a range of individuals was surveyed, systematic differences likely exist between casual visitors and regular users, whose perceptions may be shaped by familiarity and repeated exposure. Investigating these user-type differences is a valuable direction for comparative research. In terms of methodology, two specific constraints should be noted. First, although predefined criteria guided the manual selection of field quadrats, some degree of subjective researcher bias is inevitable. Future work could employ remote sensing and GIS techniques for preliminary, large-scale habitat classification to inform a more objective and stratified sampling strategy. Second, the study was designed to capture perceptual effects within a consistent seasonal context, with all data collected in a single month (October). This approach controlled for the confounding effects of major seasonal changes in plant phenology—such as flowering, leaf coloration, and senescence—which can dramatically alter visual cues and perceived biodiversity even when species composition is stable (Qin et al., 2025). While this provides a controlled snapshot, it limits the temporal generalizability of the findings. Future research should prioritize multi-seasonal or longitudinal assessments to disentangle the effects of permanent landscape features from transient seasonal dynamics on human perception (Koji et al., 2023). Concerning data analysis, linear regression models were employed to maintain simplicity and preserve the interpretability of variable relationships. However, this approach may overlook potential non-linearities and complex interaction effects. Future models could leverage advanced algorithms such as Random Forest or XGBoost, which impose fewer distributional assumptions and can automatically capture such patterns (Genuer et al., 2008; Li, 2022), potentially yielding more accurate predictions. Finally, a broader perceptual limitation stems from the focus on the visual channel. While vision is dominant, a more comprehensive simulation of on-site experience could consider the integration of other sensory information—such as auditory cues (e.g., birdsong) and olfactory elements (e.g., floral scents)—to better understand how multi-sensory experiences collectively shape the perception of biodiversity.

Conclusion

The health benefits of biodiversity for people largely depend on the level of biodiversity that they perceive. Therefore, it is essential to better understand how people perceive biodiversity, through which primary pathways such perception is formed, and what relationship exists between measured biodiversity and perceived biodiversity. This study focuses on plant diversity in UGSs, exploring the links between perceived plant diversity, measured plant diversity, and visual landscape characteristics. It reveals that perceived plant diversity can be significantly moderated by plant-related landscape features. For urban parks whose primary aim is to enhance health benefits in modern cities, this insight offers a practical and implementable design strategy that is relatively straightforward to implement and yields perceptible results more quickly—compared to measures focused on enhancing actual biodiversity, which typically require longer timeframes to demonstrate effects. The study provides a deeper understanding of the interplay among the measured plant diversity, perceived plant diversity, and environmental characteristics. This knowledge can serve as a leverage point for promoting human interaction with biodiversity, as well as offer evidence to inform the development of nature-based management strategies that support both human well-being and biodiversity conservation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

YY: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. BL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. QC: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that Generative AI was not used in the creation of this manuscript.

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