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Differences in Soundscape Perception of Plants Space in Urban Green Space and the Influence of Factors: The Case of Fuzhou, China

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Abstract: A soundscape can enhance the acoustic environment of urban areas and support the sustainable development of green spaces. This study is based on field research on plant information and a perception questionnaire conducted in 30 urban park sample sites in China. The study analysed the differences in soundscape perception among different plant spaces using three dimensions: sound source dominance degree (SDD), sound source harmony degree (SHD), and soundscape perception evaluation. Additionally, five physical indicators of plant space were selected to quantify the effects of physical characteristics of plant space on soundscape perception in urban green space (UGS). The results indicated that there were impacts on soundscape perception. The evaluation of soundscape perception between different types of plant spaces revealed notable differences, particularly in open and enclosed spaces. All eight indicators demonstrated significant differences, indicating that soundscape perception was influenced by the type of plant space. Additionally, there was a significant correlation between plant space and soundscape perception. The evaluation of soundscape perception in three dimensions was related to several factors, including the degree of spatial enclosure, crown density, average tree height, the proportion of trees and shrubs, and the number of tree species. The dominant factor affecting sound source dominance was found to be the degree of spatial enclosure, followed by the average height of trees. Additionally, the diversity of trees affected the overall soundscape perception.

Keywords: urban green space; landscape; plant space; soundscape; soundscape perception

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1. Introduction

City parks are crucial green spaces for both citizens and tourists to enjoy leisure and comfort. They serve dual functions for ecology and recreation and play a significant role in promoting the protection and improvement of the urban ecological environment [1–3]. Additionally, they are important places for the dissemination of urban culture. Numerous studies have demonstrated that urban green spaces (UGSs) create a natural buffer to the urban environment, providing benefits for human health and well-being [4]. These benefits include stress recovery, attention restoration, improvement of cognitive impairment, improvement of sleep disorders, and more. It is important to note that these evaluations are objective and supported by research [5–8]. The World Health Organization (WHO) states that noise is the second most significant urban environmental stressor affecting people's health after air pollution. One of the objectives of the Environmental Noise Directive (END) [9] is to establish protected quiet zones [10], allowing urban residents to mitigate the harmful effects of environmental noise. Although quiet areas may not always be vegetated, the interaction between vegetation and green spaces is considered a crucial preventive factor for noise-induced stress [11]. Therefore, green spaces are recognised as one of the most important open spaces in cities contributing to reducing the negative effects of exposure to environmental pollutants [10,12]. However, the acoustic environment of urban green space is directly affected by the noise of the surrounding environment, especially in the city centre. The city park is a "natural environment" with high accessibility to urban green space, but its proximity to residential areas, office areas, and urban traffic space leads to an increase in the sound pressure level of the surrounding environment and the intrusion of a variety of complex sound sources, interfering with people's experience in all aspects. This affects people's experience visiting and perceiving the park, which is also detrimental to the public health of city dwellers. Based on this, many researchers have advocated the construction of more UGSs while also using various means to reduce noise or even transform it into a beneficial soundscape [13], and the shift from environmental noise control to soundscape design has provided a fundamental solution to the problem of the acoustic environment and contributed to the creation of a positive, healthy, and diverse urban acoustic environment [14]. Urban well-being and the diversity of urban ecosystems can therefore be promoted by improving the quality of urban ecosystem services; e.g., by using existing acoustic resources in UGSs and by finding ways to make better use of potential acoustic environments in green spaces [15]. The International Organization for Standardization (ISO 12913-1:2014 [16]) defines a soundscape as an acoustic environment that is perceived, experienced, or understood in context by one or more people. An acoustic environment is an environment made up of a variety of sounds and focuses on physical metrics such as acoustics, whereas a soundscape focuses on human perception and relates to a person's memories and emotions [17,18]. In other words, a soundscape is not only about sound composition and sound itself; at the same time, it highlights the perception and feelings of the listener [19]. Therefore, the core elements of a soundscape are the sound, the listener and the environment [20]. At the heart of the soundscape is human perception, which is influenced by factors inside and outside the environment [19], and it is particularly important to clarify how sound characteristics and environmental factors affect people's perception of the soundscape.

Since the emergence of the concept of the soundscape, researchers have wondered how the acoustic and physical environments affect the quality of people's soundscape perception, and how sound can be used in urban planning and design. The number of studies in related fields has grown steadily [21]. Three important clusters have been identified in the language people use to describe soundscape perception: sound sources, sound descriptors and soundscape descriptors. The model of perceived emotional quality proposed by previous researchers has been recommended as a soundscape descriptor [17], an indicator of how people perceive the acoustic environment. Several studies have also been carried out on the relationship between soundscape descriptors and perceptual dimensions [17,22]. Soundscape quality has been identified as an important dimension of environmental perception, with sound source being the most influential dimension in the assessment of the acoustic environment. Sound sources can be recognised and detected [23] and provide important information for the interpretation of the soundscape [24–26]; therefore, the perception and evaluation of sound sources are important parts of the acoustic environment and play an important role in the assessment of the quality of the soundscape [25,27]. Previous studies have confirmed the correlation between major sound sources and the quality of the soundscape [28], and the sound characteristics of urban natural spaces, sometimes featuring sound sources such as birds or fountains, have been recognised as important elements of the urban environment [5,29]. Based on this, many researchers have assessed the perceptual experience of soundscapes, soundscape quality, and its influencing factors. Semantic Difference Analysis, which reveals the overall human perception of the object being assessed, has been widely used to assess human affective perception [30,31]. Researchers classify urban soundscapes based on people's perceptions of acoustic environment parameters, physical perceptual characteristics, or dominant sound source characteristics [32–34]. It has also been found that people's non-auditory perceptions, socio-cultural factors, and personal dimensional characteristics are factors that influence soundscape perception [35,36]; for example, the more frequently people visit parks, the more restorative they perceive the soundscape to be, and individual differences cause differences in soundscape perception [17]. There is a close relationship between landscape features and soundscape perception [37], as the functionality of landscape factors, visual landscape, form, and place; the subjective opinion of the visual landscape; and the composition of landscape elements all show an influence on soundscape perception [38,39]. Large-scale urban morphology also influences physical acoustic metrics and the perception experience of acoustic environments and is particularly sensitive to the functionality of the place (e.g., places for meditation or relaxation [35]), and sound sources that create lively or eventful acoustic environments influence the perception experience of the soundscape and the evaluation of the soundscape [40]. The quality and perception of the soundscape can also be influenced by specific functional spaces in the city, such as parks [41], residential neighbourhoods [42], squares [43], and other monofunctional places.

In addition to this, plants, which are one of the main components of open spaces, also affect the soundscape. The concept of the soundscape, in which plants play an important role, is widely used to reduce noise in urban areas and to improve the comfort of the acoustic environment. Vegetation serves as a buffer against anthropogenic noise and as a source of natural sound [44]. On the one hand, plants have a particularly positive impact on the soundscape in terms of noise attenuation [45]. The physical characteristics of the plants themselves affect sound transmission and the sound quality of the environment; e.g., leaf size, number of leaves, and leaf shape and density—for instance, monocultures, green walls, and hedges reduce traffic noise [46,47]. At the same time, plant assemblages and configurations can absorb noise and improve the quietness of the environment through barrier screening, as well as by creating a favourable ambience that influences people's perception and evaluation of soundscape spaces. The acoustic benefits of vegetation in urban areas therefore include sustainable ways in which vegetation can be used to reduce urban noise and to improve the environmental quality of UGSs [48]. Moreover, plants can create positive soundscape environments and attract the pleasant natural sounds produced by organisms, and studies have found that plant structure influences natural sounds [49] and that plant structure has a significant effect on the activity of vocal animals, such as birds [50]. The acoustic environments of contemporary UGSs have been altered, in part, due to the decrease in natural background noise. The enjoyment of natural sounds in a peaceful setting can be easily overshadowed by external noise pollution.

Planting can effectively reduce noise and improve the overall quality of environmental perception and soundscape comfort, promoting a positive soundscape experience for residents. Soundscape perception itself is a highly subjective process, easily influenced by physical environmental factors, and vegetation is the most important element that constitutes green space. However, the soundscape quality of urban vegetated spatial environments and the impact of soundscape perceptual experience have not yet been specifically examined and compared. Therefore, this study explored the relationship between soundscape perception and plant space from the perspective of plant space, which is important for further improving the soundscape quality of UGSs. This type of research is essential to verify the feasibility of using plants as soundscape design elements and is also important for urban ecosystem quality enhancement and sustainable development.

To achieve these objectives, key factors related to soundscape were extracted based on a literature review. A questionnaire was constructed to assess soundscape in UGSs. A social survey was conducted using the questionnaire to assess the soundscape perception evaluation of different areas in various plant spaces, and an indicator study of on-site vegetation spaces was conducted. To provide a theoretical reference for improving the soundscape quality of urban parks' landscape spaces, this study aimed to achieve the following objectives:

(1) Explore differences in the perception of soundscapes in different plant spaces;
(2) Comprehend the overall relationship between plant space and soundscape perception in UGSs;

(3) Determine the influence of environmental factors on soundscape perception in plant spaces in UGSs.

2. Methodology

2.1. Study Area

The research site was located in Fuzhou City, Fujian Province, China. The green coverage rate of the built-up area is 44.92%, the green space rate is 41.69%, and the city's per capita park green space area is 14.9 square metres per person. Urban parks are the most important UGSs in Fuzhou. These parks are mainly built for the public, and at the same time, they play a role in urban ecosystem protection and biodiversity enhancement. As a research object, they were chosen based on the following criteria: First, they are parks that have existed for a long time and were built on a large scale during the urban development process in Fuzhou. Second, the parks have large flows of people and different vegetation and are of different types. In addition, they have obvious characteristics in terms of geographical location, spatial type, morphological type and urban development function. Six parks in the main urban area of Fuzhou were selected as comparative research objects (Figure 1): Zuohai Park, Hot Spring Park, Niugangshan Park, Gaogaishan Park, Minjiang Park (North Park), and Minjiang Park (South Park). Norman K. Booth [51] divided plant spaces into five basic types: open spaces, semi-open spaces, covering spaces, perpendicular spaces, and enclosed spaces (Table 1). After the field survey, survey samples of five spatial types were selected in each park. In these 30 research plots, field surveys and soundscape status recordings were carried out, and the classification of sound sources was carried out in combination with the classification methods provided by Liu Jiang [30,46] and other researchers. As geophysical sounds such as wind and rain sounds were not present in each plot, they could not be compared, so they were excluded, and in the actual investigation, a sunny, windless, and rainless weather period was selected. Finally, three typical sound sources were identified: biological sound, human sound, and mechanical sound (Table 2).

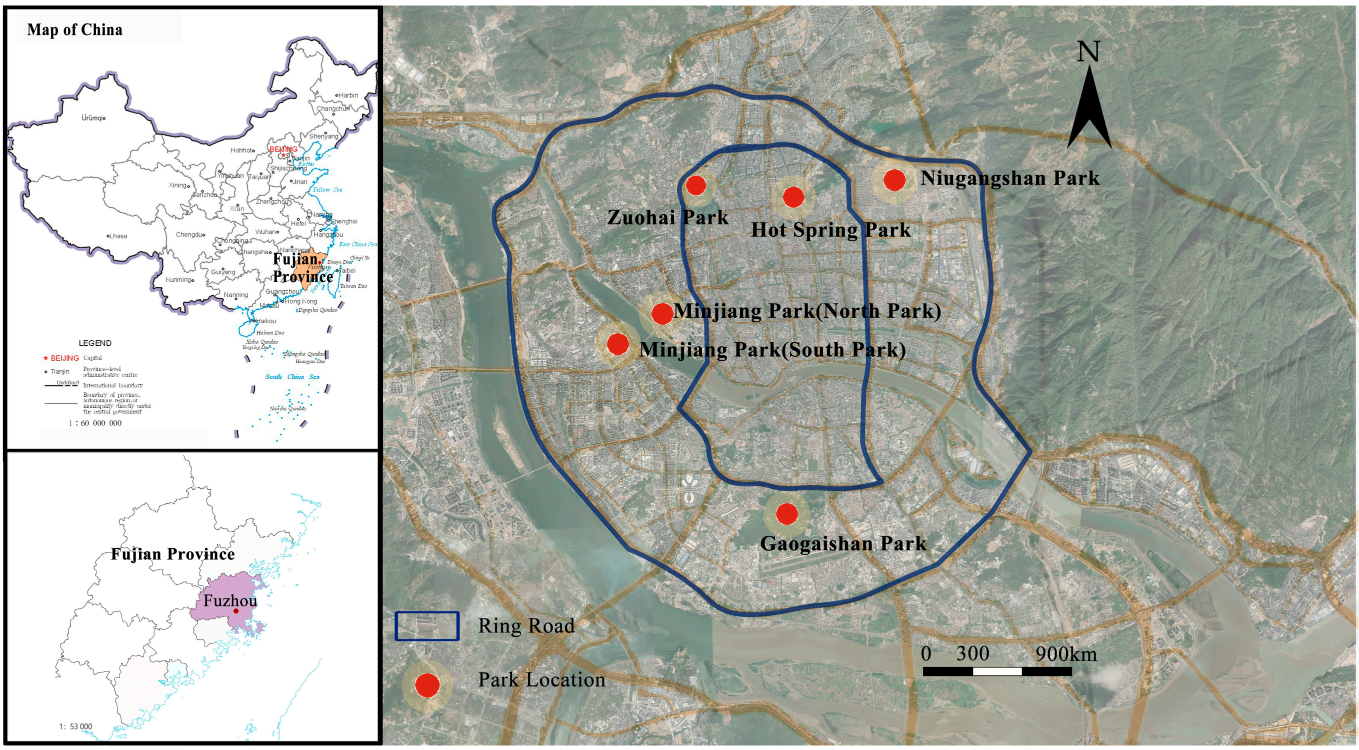

Figure 1. Study area and study sites.

Table 1. Types of plant space.

Plant Space Type	Serial Number	Pictures of Sample Sites	Spatial Characterisation
Open space	V1		The space is open, the human line of sight can completely encompass the surrounding scenery of the plant space, no coverage limits, wide vision
Semi-open space	V2		The surrounding area is not fully open, more than two sides are limited by higher plant communities, blocking the overall penetration of the line of sight; i.e., one side of the line of sight is open, one side is blocked, obstructing the effect of the landscape
Perpendicular space	V3		Closed vertical planes, open top planes, low branching points, and small to medium-sized trees with compact crowns or high hedges are often used to emphasise the axial landscape
Covering space	V4		The view is not completely limited; people can walk through or stay in the understory, the space formed by the tall canopy, the dense foliage trees used as the cover, and the lawn base; the top is covered while it is open around the perimeter
Enclosed space	V5		Strong sense of privacy and isolation; use of trees, shrubs, ground cover, and other plants to create a sight limit around the perimeter; surrounded by the top surface of the plant enclosure; sheltered space

Photos are by the author.

Table 2. Typical sound source classification.

Type of Sound Source	Sound Source Name
Biological sound	The sounds of birds, insects, frogs, cicadas
Human activity sound	The sounds of talking, footsteps, singing, entertainment, fitness activities, tourists playing
Mechanical sound	The sounds of musical instruments, the radio, radio music, mobile phone ringtones, electronic equipment, construction, alarms, traffic noise

2.2. Data Collection

2.2.1. Subjective Data for Soundscape Perception

The research was conducted from June to September 2023 in sunny and windless weather on weekends and weekdays, with data collected through questionnaires at 30 sample sites from 7:00to 18:00. The questionnaires were distributed by randomly selecting respondents on the spot (convenience sampling) and confirming that the respondents did not have a hearing impairment. With their consent, respondents were asked to complete the questionnaire after listening for 1 min at the sampling site. The respondents were asked about their basic sociological information, gender (male, female), age (<18, 18–30, 30–45, 45–60, >60), educational level (junior high school and below, senior high school, junior college, bachelor's degree, postgraduate student and above), the duration of the visit (<1 h, 1–2 h, 2–3 h, >3 h), whether they were residents (yes, no), and their evaluation of the typical sound sources and soundscape at the sample site.

Perception assessment. The soundscape rating consisted of two parts: typical sound source perception and overall soundscape perception rating. The typical sound source perception part included the frequency, loudness, and the preference of the tourists among the three types of typical sound sources, while the overall soundscape perception part included the tourists' evaluation of the soundscape environment at the sample site in terms of soundscape pleasure, soundscape richness, and soundscape quietness. A seven-point Likert scale was used for the ratings, where 1 was very low and 7 was very high.

A total of 912 questionnaires were distributed in this study, and screening was conducted to only include questionnaires from respondents who completed all sections of the survey in full, resulting in 903 valid questionnaires. No less than 30 questionnaires were returned for each sample site, and the final number of questionnaires was 180 for the open spaces, 180 for the semi-open spaces, 182 for the vertical spaces, 181 for the covered spaces, and 180 for the enclosed spaces. The testing of the reliability and validity of the questionnaire using SPSS27.01 showed that the Cronbach's alpha values for sound source perception and soundscape perception were 0.790 and 0.842, which were greater than 0.700, indicating that the reliability of the questionnaire was good. Validity was analysed using Bartlett's sphericity test and the KMO value, and the results showed that KMO = 0.749 > 0.6 and the p-value of Bartlett's sphericity was 0.000 ($p < 0.05$), indicating that the questionnaire had good validity. The results of the questionnaire indicated that 57.4% of the total sample were female, while 42.6% were male. The age groups of 18–30 and 30–45 were the most prevalent, accounting for 32.3% and 29.6%, respectively, followed by the 45–60 age group at 18.7%. Those under 18 years old accounted for 11.8% of the sample, while only 7.6% were over 60 years old. Regarding education, almost half of the respondents held a university degree (44.3%), while 10.2% had a postgraduate degree or higher. A higher proportion of respondents had higher levels of education. The majority of respondents were local residents (79.8%) and most visits lasted between 1 and 2 h (62.1%), with the smallest number of visitors staying for more than 3 h (12.3%).

2.2.2. Plant Spatial Objective Factor Data

The degree of spatial enclosure, crown density, average tree height (arbour), tree-to-shrub ratio, and degree of spatial enclosure were selected as five indicators to examine the physical attribute characteristics of the vegetation space. The degree of spatial enclosure refers to the ratio of the length of the plot along the boundary of trees <1.2 m and >1.8 m (vertical height from the ground surface to the lowest branching point of the crown) to the perimeter of the entire spatial boundary; crown density is the degree of shade provided by trees in an area (i.e., the ratio of the projected area of the centre of the crown of trees >1.8 m (vertical height from the ground to the lowest branching point of the crown) to the total area of the forest (stand) in the area).

The survey was conducted from June to September 2023, with 20 m × 20 m vegetation survey sample plots centred on the sampling points. The biological characteristics (species, number, height, diameter at breast height (DBH), and crown width) of all shrub and tree species in the shrub and tree layers of the 30 sample plots were assessed at two levels: (1) species, height (m), and crown height (m) of all woody plants taller than 1.5 m; and (2) species and number of shrubs and trees. To avoid subjective estimation errors, the vegetation surveys were carried out jointly by two plant experts.

Photographs of sample plots were taken avoiding morning or evening hours to reduce the effects of shadows, and the effects of shadows were minimised by choosing less cloudy weather for photography. During the sampling process, the panoramic camera (Insta360

One X) was placed in the centre of the vegetation survey sample plots, and the position of the centre point was used as the calibration point for the automatic gyroscopic correction of the digital photographs to form the panoramic images.

2.3. Data Processing

2.3.1. Perception of the Soundscape Subjective Data

Soundscape perception evaluation was divided into sound source perception evaluation and overall soundscape perception evaluation. The overall soundscape perception evaluation was divided into soundscape pleasure (SP), soundscape richness (SR), and soundscape quietness (SQ) to describe the public's perception of the overall sound environment at the sample site. To more comprehensively describe the presence and harmony of sound sources at the sample site, this study introduced two comprehensive sound source perception indicators: sound source dominance degree (SDD) and sound source harmony degree (SHD). Liu Jiang [30,52] and other scholars proposed these indicators in their study of the relationship between sound source perception and tour satisfaction in urban parks. The indicators were based on the three types of sound source perception indicators described above (Table 2). The sound source dominance degree refers to the perceived dominance of a particular sound source in the soundscape. The sound source dominance degree consists of the perceived occurrence of sound (POS) and the perceived sound harmony (SHD). The sound source dominance degree was calculated from the perceived occurrence of sound (POS) and the perceived loudness of sound (PLS); the sound source harmony degree was determined by the sound source dominance degree and the preference for sound (PFS), reflecting the dominance of a particular source and people's preference for that source. The sound source harmony degree was determined from the sound source dominance degree and preference for sound (PFS), reflecting the extent to which the dominance of a sound source matched people's preference for it in the environment.

$$\mathrm{SDD_{ji}} = \mathrm{POS_{ji}} \times \mathrm{PLS_{ji}} \tag{1}$$

where j is the jth sample and i is the ith sound source.

$$\mathrm{SHD_{ji}} = \left(e^{\mathrm{PFS_{ji}} - \sum_{j=1}^{n} \mathrm{PFS_{ji}}/n}\right)\mathrm{POS_{ji}} \times \mathrm{PLS_{ji}} \tag{2}$$

where j is the ith sound source and n is the sample size.

2.3.2. Data Analysis

This study used the one-way ANOVA, correlation analysis, and multiple linear regression method provided in SPSS 27.0.1. One-way ANOVA was used to determine whether there was a difference between the means of three or more independent groups and whether there was a difference in the differences between the before and after changes; $p < 0.05$ meant that there was a significant difference. The Pearson correlation coefficient was used to verify whether there was a significant correlation between the variables; $p \leq 0.05$ meant that there was a significant correlation [53,54]. In addition, regression analysis was employed to elucidate the causal relationship between the variables, studying the correlation between the independent variable and the dependent variable [53]. A VIF < 5 denoted a superior model explanation, whilst an F-test score corresponding to a p-value < 0.05 indicated the model's significance.

3. Results

3.1. Differential Results for Soundscape Perception in Plant Space

3.1.1. Variability of Sound Source Perception in Different Plant Spaces

In this study, one-way ANOVA was used to analyse the differences in sound source perception and overall soundscape perception in different types of plant spaces, and the results are shown in Table 3. Sound source perception showed highly significant differences in different types of plant spaces, including SDD-bio ($p < 0.001$), SDD-hum ($p < 0.001$), SDD-mec ($p < 0.001$), SHD-bio ($p < 0.001$), SHD-hum ($p < 0.001$), and SHD-mec ($p < 0.001$).

Table 3. Analysis of differences in spatial sound source perception and soundscape perception for different plant spaces (n = 30).

	Spatial Type	Mean Value	Standard Deviation	Standard Error	F	Sig
SDD-bio	V1	0.748	0.028	0.011	25.56	<0.001 ***
	V2	0.823	0.027	0.011		
	V3	0.857	0.039	0.016		
	V4	0.882	0.019	0.008		
	V5	0.888	0.019	0.008		
SDD-hum	V1	0.720	0.023	0.009	20.485	<0.001 ***
	V2	0.893	0.043	0.017		
	V3	0.862	0.044	0.018		
	V4	0.815	0.019	0.008		
	V5	0.833	0.040	0.016		
SDD-mec	V1	0.738	0.043	0.017	21.801	<0.001 ***
	V2	0.807	0.056	0.023		
	V3	0.655	0.077	0.031		
	V4	0.602	0.039	0.016		
	V5	0.553	0.044	0.018		
SHD-bio	V1	0.787	0.019	0.008	26.654	<0.001 ***
	V2	0.820	0.037	0.015		
	V3	0.925	0.037	0.015		
	V4	0.903	0.020	0.008		
	V5	0.920	0.032	0.013		
SHD-hum	V1	0.852	0.028	0.011	11.851	<0.001 ***
	V2	0.858	0.035	0.014		
	V3	0.830	0.030	0.012		
	V4	0.907	0.014	0.006		
	V5	0.928	0.033	0.014		
SHD-mec	V1	0.828	0.043	0.018	8.244	<0.001 ***
	V2	0.842	0.056	0.023		
	V3	0.847	0.054	0.022		
	V4	0.932	0.035	0.014		
	V5	0.935	0.029	0.012		
SP	V1	4.670	0.816	0.333	5.433	0.003 **
	V2	5.330	0.516	0.211		
	V3	5.830	0.753	0.307		
	V4	5.500	0.837	0.342		
	V5	6.500	0.548	0.224		
SR	V1	5.000	0.632	0.258	4.367	0.008 **
	V2	4.830	0.408	0.167		
	V3	5.330	0.816	0.333		
	V4	6.170	0.753	0.307		
	V5	6.170	0.983	0.401		
SQ	V1	2.330	0.816	0.333	2.434	0.074
	V2	2.500	0.837	0.342		
	V3	3.000	1.414	0.577		
	V4	3.000	1.265	0.516		
	V5	4.170	1.169	0.477		

V1: open space, V2: semi-open space, V3: perpendicular space, V4: covering space, V5: enclosed space; SDD-bio: biological sound dominance, SDD-hum: human activity sound dominance, SDD-mec: mechanical sound dominance, SHD-bio: harmony of biological sound, SHD-hum: harmony of human activity sound, SHD-mec: harmony of mechanical sound, SP: soundscape pleasure, SR: soundscape richness, SQ: soundscape quietness. ** $p < 0.01$, *** $p < 0.001$

Tukey's post hoc tests were used to compare further the perceived differences between the two groups of plant spaces, and the differences were plotted using Origin data plotting software (https://www.originlab.com/). The results are shown in Figure 2. For SDD-bio, open space was significantly different from the rest of the space; semi-open space was different from open space, covered space, and enclosed space. For SDD-hum, open space was significantly different from the rest of the spaces; semi-open space was different from perpendicular space. For SDD-mec, there were differences between open space, semi-open space, perpendicular space, covering space, and enclosed space. In terms of the identified degree of source dominance, open space was perceived to have the most pronounced differences, with biological sounds, human activity sounds, and mechanical sounds all having significant differences, followed by semi-open space. This suggests that the most prominent sound sources perceived may have been influenced by the spatial composition of the facility.

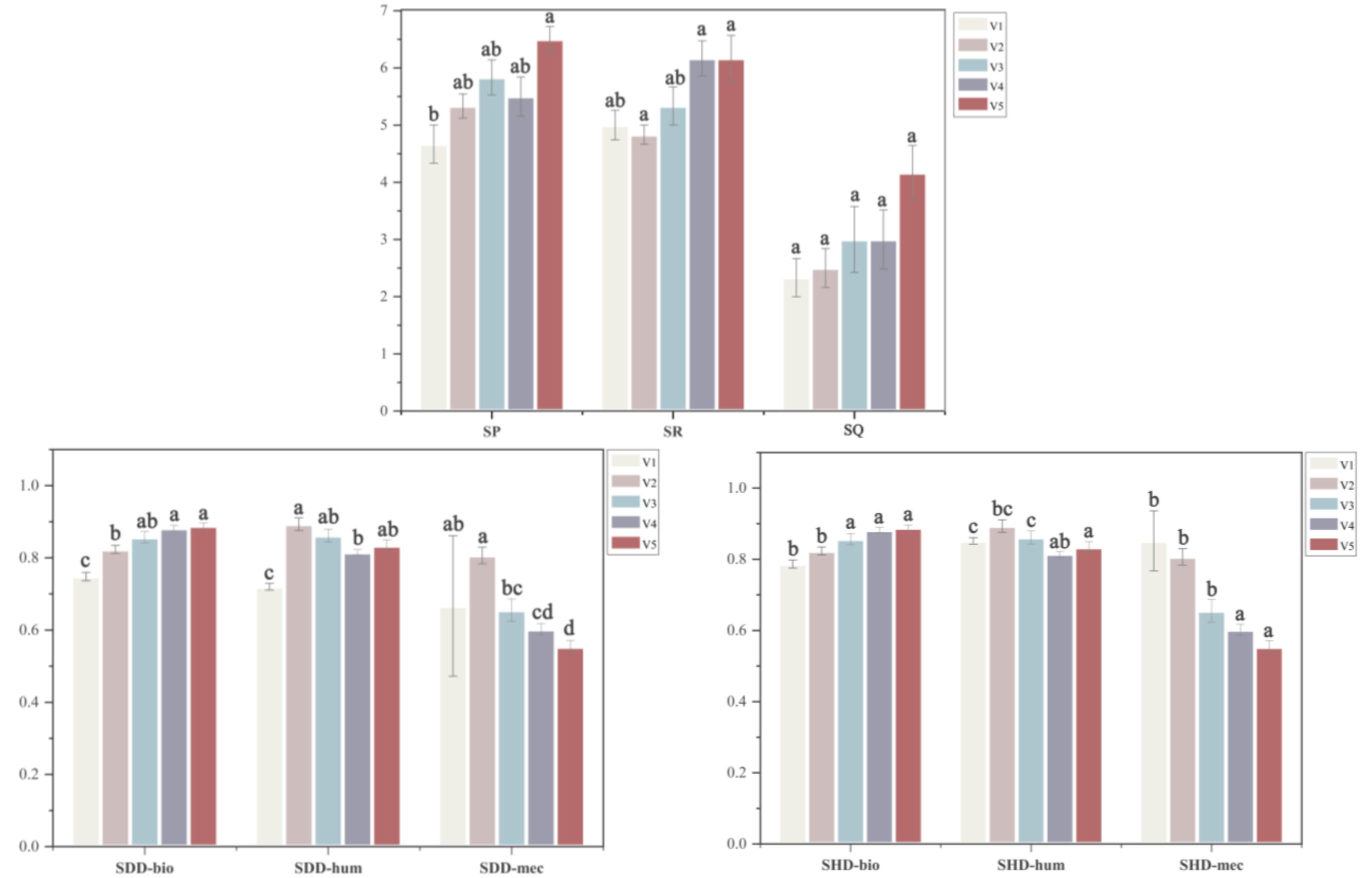

Figure 2. Differential visualisation of soundscape perceptions in different plant spaces (where there is a letter with the same label, the difference is not significant, and where there are letters with different labels, the difference is significant). V1: open space, V2: semi-open space, V3: perpendicular space, V4: covering space, V5: enclosed space.

For SHD-bio, there were differences between open space and semi-open space and vertical space, covered space, and enclosed space. For SHD-hum, there were differences between open space, semi-open space, and covered space and enclosed space and open space. For SHD-mec, there were differences between open space, semi-open space, covering space, and enclosed space. Since the degree of source dominance was the frequency and number of times that the most prominent source was perceived, the degree of source harmony was determined by dominance and preference. If a space had more occurrences of preferred biological sound [55] and was less noisy, then the dominance of the biological sound source in the space was likely to be higher. Open spaces and semi-open spaces had fewer natural elements, such as plants, and less human activity, which may have been the reason for their significantly different performance in terms of SDD and SHD.

3.1.2. Variability in Overall Soundscape Perception across Plant Spaces

Compared to the sound source perception, the differences in the dimensions of the overall soundscape perception were not obvious. Table 3 shows that overall soundscape perception differed only in terms of SP ($p < 0.05$), for which there were differences for open and enclosed spaces (Figure 2), which was consistent with the previous results for differences in sound source perception.

3.2. Relationship between Plant Space and Soundscape Perception

Using Pearson's correlation coefficient (r) to indicate the strength of the correlation, it was found that the plant spatial factor had a statistically significant ($p \leq 0.05$) correlation in soundscape perception. As shown in Figure 3, the degree of spatial enclosure of plants had a statistically significant positive correlation ($p \leq 0.05$) with SDD-bio (r = 0.83, $p \leq 0.05$), SDD-hum (r = 0.48, $p \leq 0.05$), SHD-mec (r = 0. 87, $p \leq 0.05$), SP (r = 0.63, $p \leq 0.05$), SR (r = 0.41, $p \leq 0.05$), and SD (r = 0.42, $p \leq 0.05$) and a negative correlation with SDD-mec (r = −0.61, $p \leq 0.05$). The results showed that plant enclosure was correlated with eight indicators, and the trends of change for seven indicators were consistent. It is worth noting that when the sense of plant enclosure was stronger, the frequency and number of perceived mechanical sounds were lower.

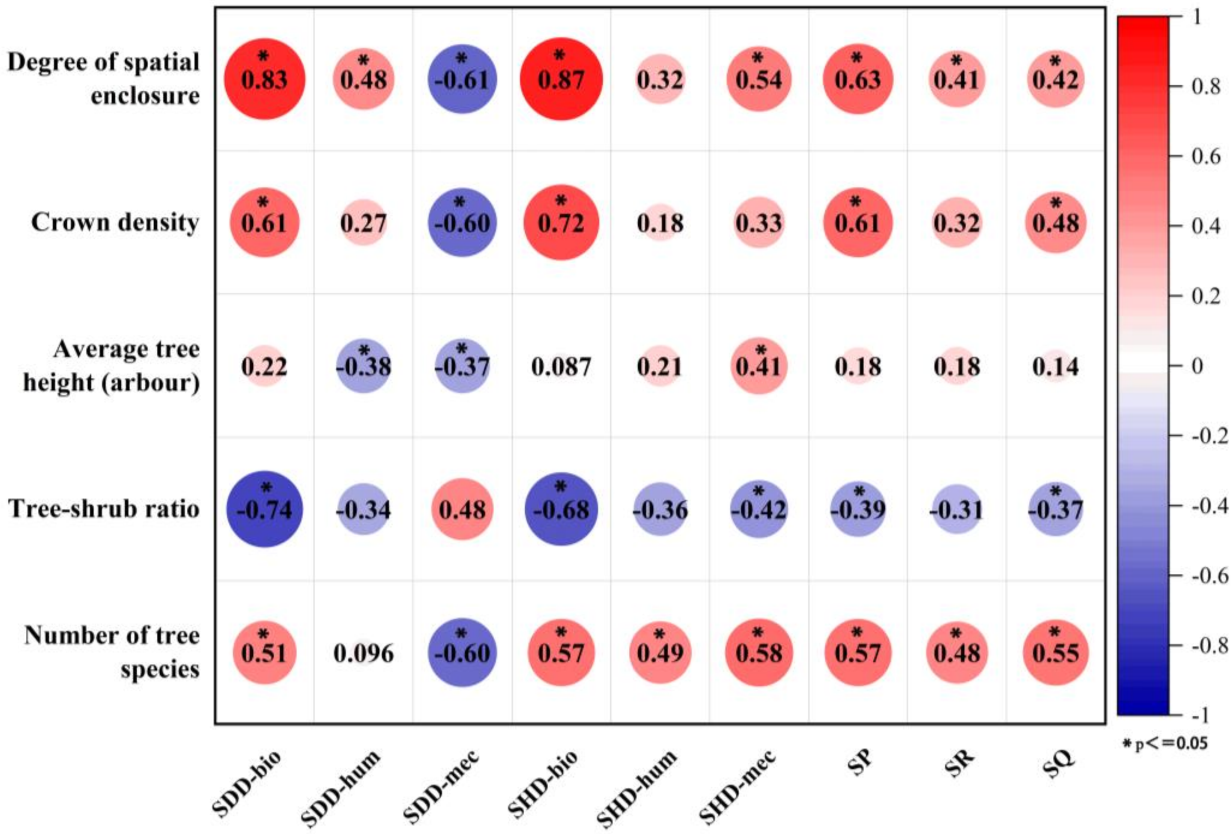

Figure 3. Plot of correlation coefficients between plant space and soundscape perception. The colours on the right side represent the coefficient score of the pairwise correlation between plant spatial factors and soundscape perception: the deeper the colour, the greater the coefficient value and the stronger the correlation. Red is positively correlated, blue is negatively correlated, and $p \leq 0.05$ indicates a significant correlation.

The crown density of the plants was positively correlated with SDD-bio (r = 0.61, $p \leq 0.05$), SHD-bio (r = 0.72, $p \leq 0.05$), SP (r = 0.61, $p \leq 0.05$), and SQ (r = 0.48, $p \leq 0.05$) and negatively correlated with SDD-mec (r = −0.27, $p \leq 0.05$). In contrast to the positive tendency of the other perceptual indicators, the greater the crown density of the plant was, the lower the perceived mechanical sound frequency was.

Average tree height (arbour) had a negative correlation with SDD-hum (r = −0.38, $p \leq 0.05$) and SDD-mec (r = −0.37, $p \leq 0.05$) and a positive correlation with SHD-mec (r = 0.41, $p \leq 0.05$). The results showed that the greater the plant height was, the less pronounced the perceived anthropogenic and mechanical sounds were and the lower people rated the degree of conformity of mechanical sounds in the environment.

The tree-to-shrub ratio had a negative correlation with SDD-bio (r = −0.74, $p \leq 0.05$), SHD-bio (r = −0.68, $p \leq 0.05$), SP (r = −0.39, $p \leq 0.05$), and SQ (r = −0.37, $p \leq 0.05$) and a positive correlation with SDD-mec (r = 0.48, $p \leq 0.05$). This means that when the ratio of trees to shrubs increased (when there were more trees), more biological sound was produced, and this result was similar to the degree of spatial enclosure of plants and the crown density of plants, so a similar explanation for the relationship between the ratio of trees to shrubs and SDD-bio and SDD-bio is also applicable.

The degree of spatial enclosure was similar to the previous results, showing a positive correlation with SDD-bio (r = 0.51, $p \leq 0.05$), SHD-bio (r = 0.57, $p \leq 0.05$), SHD-hum (r = 0.49, $p \leq 0.\ 05$), SHD-mec (r = 0.58, $p \leq 0.05$), SP (r = 0.57, $p \leq 0.05$), SR (r = 0.48, $p \leq 0.05$) and SQ (r = 0.55, $p \leq 0.05$). There was a negative correlation with SDD-mec (r = −0.60, $p \leq 0.05$). The number of tree species was closely related to soundscape perception, except for a significant correlation with human activity sounds. Similarly, as the number of tree species increased, perception of mechanical sounds decreased.

3.3. Influence of Vegetation Spatial Characteristic Factors on Soundscape Perception in UGSs

3.3.1. Analysis of the Effect of Vegetation Spatial Characteristic Factors on Soundscape Perception

Using SDD and SHD as dependent variables and the degree of spatial enclosure, crown density, average tree height, tree/shrub ratio, and number of tree species as independent variables, multiple stepwise linear regression was used to construct a model. The regression results are presented in Table 4. The F-test with the six regression models used $p < 0.05$, indicating that a model was meaningful. The covariance test used VIF < 5, indicating there was no covariance, and the model explained better. R^2 represents the goodness of fit of the regression model.

The SDD results showed that the degree of spatial enclosure of plants ($p < 0.01$, $R^2 = 0.683$) significantly influenced SDD-bio. The degree of spatial enclosure of plants ($p < 0.01$, $R^2 = 0.376$) and average tree height ($p < 0.01$, $R^2 = 0.376$) had significant effects on SDD-hum. The degree of spatial enclosure of plants ($p < 0.01$, $R^2 = 0.420$) and average tree height ($p < 0.05$, $R^2 = 0.420$) affected SDD-mec. The results showed that the coefficients of determination (R^2) predicting the direction of the SDD were high, ranging from 0.350 to 0.700, and all had $p < 0.01$, meaning there was 99% confidence that there was an influential relationship between the SDD and plant spatial factors. This means that plant enclosure, and average tree height as a predictor, can play an influential role in sound source perception. The degree of spatial enclosure of plants was high (between 0.376 and 0.683), so it can be concluded that the degree of spatial enclosure of plants plays an important role in influencing the perception of sound sources in the direction of SDD.

The SHD results showed that the degree of spatial enclosure of plants significantly affected SHD-bio ($p < 0.01$, $R^2 = 0.741$), the number of tree species significantly affected SHD-hum ($p < 0.01$, $R^2 = 0.211$), and the average tree height ($p < 0.05$, $R^2 = 0.390$) and number of tree species ($p < 0.01$, $R^2 = 0.390$) affected SHD-mec. In the case of SHD-bio, the variation in the variance was better explained when plant enclosure was the predictor ($R^2 = 0.741$).

Table 4. Results of stepwise regression analysis (n = 30).

Dependent Variable	Independent Variable	Standardized Coefficient	t	p	Collinearity Diagnostics		R^2
		Beta			VIF	F	
SDD-bio	Constant	-	43.604	0.000 **	-	-	
	Degree of enclosure	0.833	7.976	0.000 **	1.000	p = 0.000	0.683
SDD-hum	Constant	-	12.074	0.000 **	-	-	-
	Degree of enclosure	0.532	3.601	0.001 **	1.016	p = 0.001	0.376
	Average tree height	−0.442	−2.991	0.006 **	1.062	p = 0.001	0.376
SDD-mec	Constant	-	8.962	0.000 **	-	-	-
	Degree of enclosure	−0.570	−3.996	0.000 **	1.016	p = 0.000	0.420
	Average tree height	−0.303	−2.125	0.043 *	1.016	p = 0.000	0.420
SHD-bio	Constant	-	44.399	0.000 **	-	-	-
	Degree of enclosure	0.866	9.173	0.000 **	1.000	p = 0.000	0.741
SHD-hum	Constant	-	40.492	0.000 **	-	-	-
	Tree species	0.488	2.961	0.006 **	1.000	p = 0.006	0.211
SHD-mec	Constant	8.914	8.962	0.000 **	-	-	-
	Average tree height	2.074	−3.996	0.048 *	1.042	p = 0.000	0.390
	Tree species	3.534	−2.125	0.001 **	1.042	p = 0.000	0.390
SP	Constant	-	11.518	0.000 **	-	-	-
	Degree of enclosure	0.626	4.246	0.000 **	1.000	p = 0.000	0.222
SR	Constant	-	11.130	0.000 **	-	-	-
	Tree species	0.485	2.931	0.007 **	1.000	p = 0.007	0.235
SQ	Constant	-	2.547	0.017 *	-	-	-
	Tree species	0.550	3.482	0.002 **	1.000	p = 0.002	0.370

SDD-bio: biological sound dominance, SDD-hum: human activity sound dominance, SDD-mec: mechanical sound dominance, SHD-bio: harmony of biological sound, SHD-hum: harmony of human activity sound, SHD-mec: harmony of mechanical sound, SP: soundscape pleasure, SR: soundscape richness, SQ: soundscape quietness. * $p < 0.05$, ** $p < 0.01$.

3.3.2. Analysis of the Effect of Vegetation Spatial Characterisation Factors on Overall Soundscape Perception

With SP, SR, and SQ as the most dependent variables and the degree of spatial enclosure, canopy density, average tree height, tree/shrub ratio, and number of plant species as independent variables, a model was constructed using multiple stepwise linear regression. F-tests ($p < 0.05$, VIF < 5) with the three regression models with small R^2 indicated that, although the models were meaningful and explanatory, the predictive power of the study was insufficient due to the diversity of factors affecting soundscape perception. The results indicated that the degree of spatial enclosure of plants ($p < 0.01$, $R^2 = 0.222$) significantly affected SP ($p < 0.01$, $R^2 = 0.222$), the number of tree species ($p < 0.01$, $R^2 = 0.235$) significantly affected SR, and the number of tree species ($p < 0.05$, $R^2 = 0.370$) affected SQ. The results showed that there was at least 99% certainty ($p < 0.01$) that the degree of spatial enclosure and number of tree species had a significant influence on SDD.

4. Discussion

4.1. Analysis of Differences in Spatial Soundscape Perception of Different Plant Spaces in UGSs

It is easy to perceive the differences in the soundscapes between the open space and the enclosed space in urban parks, both in the degree of typical sound source dominance for the three categories and in the harmony of the three typical sound sources, indicating that sound source perceptions change with the plant spatial environment. In particular, the semi-open space also showed significant differences in the degree of dominance of mechanical sound sources compared to the other spaces. Compared to perpendicular space, covering space, and enclosed space, open spaces and semi-open spaces have fewer plants to provide shade and animal habitats [56]. Additionally, having the lowest level of plant cover makes it difficult to form a natural noise barrier, increases the interference of other sounds, and results in fewer living organisms and human activities, leading to more pronounced mechanical sounds. Furthermore, the pleasure ratings of soundscapes exhibited significant disparities between open and enclosed spaces. The physical characteristics of these two types of plant spaces are vastly dissimilar, and the physical environment affects the soundscape [57,58]. This implies that plant space disparities affect people's perceptions of soundscapes.

4.2. Analysis of Plant Spatial Factors Affecting Soundscape Perception in UGSs

The results of this study show that the degree of spatial enclosure of plants is the most important factor influencing the degree of dominance of sound sources, followed by the average height of trees. Plant enclosure played a significant role in influencing the dominance of biological sound, anthropogenic sound, and mechanical sound. This was also consistent with previous findings showing that the composition of biotopes is strongly influenced by the surrounding environment and that vegetation is one of the key factors [59]. From open grasslands in parks to densely wooded forests, a higher degree of spatial enclosure results in a better ability to provide a habitat for acoustic fauna, such as birds and insects, and a slightly more independent and secluded space, as well as a greater number of and more diverse vegetation types and leaf physical characteristics, such as leaf size and density, and more complex vegetation [60–63]. The complexity of vegetation is the most important influence on and predictor of biodiversity results [64–66]. Areas of dense vegetation (high spatial enclosure, average tree height, high number of trees) provide a comfortable gathering space for visitors to engage in recreation. Trees can regulate the outdoor microclimate and improve the thermal environment of public green spaces through the shading areas provided by their canopy and their evapotranspiration [67], and the attenuation of solar radiation by tall trees is a very important aspect of the microclimate [68].

The degree of spatial enclosure, the number of tree species, and the average height of plants affect the degree of harmony of the sound source. The number of tree species affects the sounds of human activities and mechanical sounds, and the effect is more obvious with a higher number. Consistent with the previous results for sound source dominance degree, among the different types of sound sources, natural sounds were more abundant, and thus the harmony degree was higher due to people's preference for the sounds of natural organisms (e.g., birds singing, beetles singing, frogs singing) [69,70]. Enclosed and canopied areas can be found in high-density forests and help to cool the area and regulate the microclimate by creating a shaded area, which also increases the sound of human activities. A high number of trees and high degree of enclosure can reduce noise pollution in environments where mechanical noise dominates [71], and the edge areas of dense trees can block out some external noise [72] so that the peripheral traffic noises and mechanical noises perceived by people are reduced [73]. Mechanical sounds are one of the unpopular sound sources [74], and the frequency and loudness of mechanical sounds should be low to improve the harmony of mechanical sounds.

The degree of plant enclosure, the number of tree species, and soundscape pleasure showed a significant influential relationship. Previous studies have proven that the amount and density of greenery have a close relationship with the evaluation of soundscape perception [75], which is consistent with the results of this study. This can also indicate that plant or vegetation space is an effective soundscape design strategy. As the degree of plant enclosure and the number of trees increase, the frequency of sounds increases, and at the same time, some of the annoying mechanical sounds from outside are blocked, leading to higher comfort and pleasure ratings.

4.3. Limitations of the Study and Future Research

This study provides insight into the mechanisms influencing plant space and soundscape perception. However, the results may have been influenced by the limited diversity of the sample sites and the chosen methodology. The findings are only applicable to the sample site types in this study. The study focused on results for soundscape perception, revealing which plant spatial environmental factors trigger specific soundscape perceptual experiences. It did not take into account the overall mechanism leading from the physical spatial environment to subjective perception; i.e., how plant spatial environmental factors trigger the corresponding soundscape perception. Further research is required to fully understand the influence of multi-sensory perception on the spatial experience of plant landscapes. Additionally, there is a need to increase the number of plant spatial indicators and their generalizability. The relationship between human social/demographic characteristics and soundscape perception should also be explored to better understand the interaction between hearing and other perceptual indicators and landscape factors. The sample used in this study may be considered biased due to the low representation of individuals over the age of 60 (only 7.6% of the sample) and the over-representation of individuals in the high-education stratum. In future studies, it is recommended to consider the variability in the population's personal behavioural and demographic characteristics, as well as the relationship between these characteristics and the perception of soundscapes in UGSs. Factors such as educational background, age, the time of the visit, personal preferences, location attachment, and visit patterns are likely to influence the perceived experience of soundscapes.

Future studies should consider seasonal changes in different types of vegetation, such as deciduous trees, evergreen vegetation, and shrub vegetation, which may affect the soundscape. This study was conducted during the summer, and it is important to take into account the changes in other seasons, particularly in winter when many trees lose their leaves. Furthermore, to enhance the validation and effectiveness of soundscape design, it is recommended to include corresponding objective acoustic metrics in the study of perceived soundscape perception. These metrics may include the sound pressure level, sound spectrum metrics, and recording and analysis of sound waves for scientific and comprehensive corroboration of the results.

5. Conclusions

There is a growing recognition of the importance of the acoustic environment in UGSs, and the design of urban parks often focuses on landscaping plants, ignoring the interaction between vegetation and the acoustic environment. The design of active and healthy green spaces needs to be approached in a more scientific and multifaceted way, and this study highlights the following conclusions with this aim in mind:

(1) The perception of soundscapes in different types of plant spaces is mainly reflected by the degree of sound source dominance and sound source harmony. The perception of the three types of sound sources in open spaces was significantly different from that in other plant spaces. Furthermore, this study highlights the significant differences in sound source and soundscape perception between open and enclosed spaces. The differences were most noticeable in sound source perception, indicating that the design of green spaces has a significant impact on public soundscape perception. This conclusion reinforces the importance of considering the characteristics of the space when designing soundscape elements.

(2) The study revealed a strong correlation between plant spatial characteristics and soundscape perception evaluation. Specifically, the degree of spatial enclosure of plants was found to be the factor most closely related to soundscape perception, as indicated by eight out of nine perception indicators. Moreover, the numbers and proportions of tree species and shrubs should be considered when planning. Plants can be used to create an appropriate enclosure space, but it is important to choose the right species. It is also important to maintain a proper scale. Research has shown a positive correlation, but the specific degree of enclosure has not been determined.

(3) The spatial closeness of plants had an impact on all six perceptual indicators, while the number of tree species affected four perceptual indicators. Additionally, the average tree height had a significant effect on three perceptual indicators. The perception

of sound sources and overall soundscapes can be affected by the degree of spatial enclosure, number of tree species, and average tree height. Therefore, it is important to consider the characteristics of the plant species in the soundscape when creating and regulating it. This conclusion confirms that soundscape creation should consider the spatial characteristics of the plant type. The improvement of soundscapes can be controlled by plants; for example, by increasing the number and frequency of biological sounds through plant enclosure. The influence of the sound source dominance degree can also be affected by plant enclosure.

This study confirms the influence of plant space on soundscape perception and that there is an influential relationship between the two. This study should encourage consideration of the role of plant space creation when planning soundscapes in UGSs. Urban planners and landscape designers can maximise the creation of good potential soundscape environments in UGSs by promoting plant diversity and increasing the number of plants in the park. Plant vegetation should be strategically based on the natural resources of the area. For example, the mix of trees, shrubs, and evergreens can create a permanent barrier effect, with different heights for different types of tall trees and dwarf shrubs used to create space and a sense of enclosure. Alternatively, different types of plant space can be combined in the park design to achieve a variety of acoustic experiences for residents along the tour route, and the best acoustic environment for the tour route can be developed according to the acoustic experience of different types of plant space.

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