

Research on the Comprehensive Noise Reduction Effectiveness of Plant Communities in Urban Green Spaces

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GRAPHICAL ABSTRACT



ABSTRACT

Noise pollution significantly impacts people's health and quality of life, while urban green spaces not only beautify the environment but also play a crucial role in noise reduction and sound absorption. This study, using the plant communities of waterfront green spaces along Suzhou Creek in Shanghai as a case, innovatively develops a comprehensive evaluation system for physical and psychological noise reduction effectiveness, with 13 indicators. Through field measurements and surveys of 14 urban green spaces with different plant community characteristics, the study found that physical

noise reduction effectiveness is closely related to plant species richness and vertical canopy density. Densely planted trees with thick trunks and tall shrubs significantly improve physical noise reduction effectiveness. When the vertical canopy density is less than 35%, the physical noise reduction effectiveness of waterfront plant communities (with 70% vegetation cover and 30% water cover) outperforms that of terrestrial plant communities (with no water cover) at the same canopy density level. For psychological noise reduction, increasing shrub crown width, height, and

spacing improves visual perception, while enhancing vertical canopy density enriches auditory perception—both of which raise the auditory annoyance threshold. The most effective plant community combination for comprehensive noise reduction is a mix of densely planted trees, shrubs, and ground cover. The noise reduction effectiveness of a waterfront plant community is impacted by vertical canopy density. When it reaches 40% or more, the psychological noise reduction effectiveness will improve as the density increases. This study provides theoretical support and practical guidance for addressing noise issues in urban green spaces and optimizing plant community configurations.

KEYWORDS

Urban Waterfront Green Space; Physical Noise Reduction; Psychological Noise Reduction; Comprehensive Noise Reduction Effectiveness; Plant Community Configuration

HIGHLIGHTS

- Evaluates plant communities' comprehensive noise reduction capacity and quantifies psychological effect
- Explores differences between terrestrial and waterfront plant communities, showing ways to reduce noise
- Provides recommendations for plant community configuration of urban green spaces to mitigate traffic noise

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1 Introduction

Noise pollution is a globally recognized environmental issue. The *Environmental Noise Guidelines for the European Region* issued by the World Health Organization in 2018 identifies environmental noise as the second-largest environmental stressor after air pollution, significantly affecting human health, well-being, and quality of life^[1]. Traffic noise, accounting for over 60% of urban noise, is a major contributor^[2]. Despite the inclusion of noise in China's national regular environmental monitoring since 1980, mitigation efforts in some cities have fallen short^[3]. In 2024, noise pollution remains a primary ecological environmental complaint^[4], posing challenges due to its wide impact, long-time resolution, and complexity.

Urban green spaces serve as key recreational areas while also regulating microclimates, mitigating urban heat island effect, and reducing noise^[5]. Compared with conventional engineering solutions such as noise barriers, vegetation-based noise mitigation offers a low-cost, carbon-reducing alternative^[6]. Through sound reflection and absorption, plant communities provide physical noise reduction while also generating masking effects and enhancing psychological comfort^[7]. However, most related research focuses on either physical or psychological noise reduction alone^{[8][9]}.

This study evaluates the comprehensive noise reduction effectiveness of 14 urban green spaces with varying plant communities along central Suzhou Creek, Shanghai by developing an evaluation framework which integrates physical and psychological dimensions. The framework quantifies the comprehensive noise reduction effectiveness and examines how plant community characteristics influence different aspects of noise mitigation. The findings can support optimal plant community configurations, providing insights and practical guidance for improving plant landscapes in urban green spaces.

2 Theoretical Background

Plant communities, often referred to as “green silencers,” can absorb and block noise. The trichomes and stomata on leaves contribute to noise absorption^[10]. As traveling through greenbelts, sound waves undergo significant attenuation. With mid-to-high-frequency sounds being absorbed and scattered by tree trunks, leaves, and branches, the noise would be reduced. Thereby a well-planned combination of tree species within plant communities can effectively mitigate noise^{[11]~[13]}.

Current research on the physical noise reduction effectiveness

of plant communities primarily falls within the fields of acoustics and plant physiology, focusing on the interactions between sound waves and different mediums during propagation^[14]. Studies indicate that for single-species plant communities, key factors impacting noise reduction include plant type, physical characteristics, and vegetation quantity^[15]. Among different plant types, trees demonstrate the greatest effectiveness in noise reduction^[16], with shrubs showing comparable performance^[17], whereas lawns are significantly less effective in reduction^{[18][19]}. Additionally, plant density, height, and width influence noise attenuation^{[20][21]}. Broadleaf trees generally outperform coniferous trees in unit noise reduction effectiveness^[22] due to their denser foliage, which increases overall noise absorption capacity^[23]. Regarding compound plant communities, planting density, arrangement, and trunk diameter significantly affect noise reduction in fixed-width greenbelts^{[13][24][25]}, with tree–shrub–herb combinations proving to be the most effective^[16].

Beyond physical noise reduction, plant communities also contribute to psychological noise mitigation through acoustic masking effects. Acoustic masking occurs when the presence of a specific sound or a visual focus reduces the perception of other sounds^{[7][26]}. For example, plant communities can physically shield noise sources (e.g., roads, vehicles), reducing direct exposure and increasing tolerance to noise by diverting attention^[27]. Moreover, aesthetically pleasing landscapes shift visitors' focus toward vegetation rather than noise^{[28][29]}. Natural sounds such as birdsong and rustling leaves, as white noise, can mask unwanted sounds and alter the perception of loudness and information content^{[30][31]}. Research on the psychological noise reduction effectiveness of plant communities remains in its early stages. Some studies have applied the membership principle in fuzzy set theory to assess how greenbelts affect psychological distress caused by traffic noise, using survey data to quantify the probability of annoyance caused by environmental noise and establish annoyance thresholds for specific areas^[32]. Others have employed socio-acoustic surveys on subjective annoyance levels from residents near airports to determine noise annoyance thresholds via fuzzy logic functions^[33]. Virtual reality combined with survey methods has demonstrated that richer vegetation colors and higher biodiversity contribute more to reducing noise annoyance^[34]. GIS-based studies have shown that the normalized difference vegetation index (NDVI) and green space coverage influence residents' perceived green space levels, which in turn affect their noise annoyance levels^[35].

In summary, while existing studies have explored both the

physical and psychological noise reduction effectiveness of plant communities, their comprehensive noise mitigation potential remains underexplored due to the complexity and diversity of plant communities.

3 Research Methodology

3.1 Indicator Selection

Based on previous studies and relevant guidelines, this study summarized key plant community characteristics related to noise reduction effectiveness and introduced composite factors. It innovatively established a measurement and evaluation framework, at both physical and psychological aspects, to assess comprehensive noise reduction performance.

3.1.1 Key Characteristics of Plant Communities

According to the *Technical Regulations for County-Level Vegetation Diversity Investigation and Assessment*^[36], vegetation surveys should document community type, stratification, height, canopy closure or coverage, disturbance level, and environmental factors. For trees, species, diameter at breast height (DBH), and height should be recorded; for shrubs, species, height, density, and crown width (coverage) should be documented. Studies have shown that tree species^[37], height^[38], DBH^[39], crown width^[40], clear bole height^[41], vertical canopy density^[42], underlying surface type^[43], and plant community composition^[44] significantly impact noise reduction. Based on differences in vegetation and water coverage (denoted as UP and UW, respectively), this study categorized plant communities into terrestrial (with no water cover) and waterfront (with 70% vegetation cover and 30% water cover) types. The selected characteristics of plant communities include (Table 1): for trees, height (TH), clear bole height (TC), DBH (TB), and planting density (TD); for shrubs, spacing (SS), crown width (SC), and height (SH); and plant species richness (PS) and vertical canopy density (VC) as overall factors. Additionally, based on principles of noise propagation^[45] and plant-based physical noise reduction^[46], this study innovatively introduced two compound factors: TD × TB / TC for trees (Factor A) and SH × SC / SS for shrubs (Factor B).

3.1.2 Evaluation Framework for Comprehensive Noise Reduction Effectiveness

(1) The evaluation indicator for physical noise reduction

The study employed the equivalent continuous A-weighted sound pressure level (LAeq) to characterize the acoustic

Table 1: Characteristic factors of plant communities

Characteristic factor		Definition	
Tree	Single	TH	Average height of trees in the plant community
		TC	Height from the ground surface to the lowest branching point of the tree crown
		TB	Diameter of the main tree trunk at breast height above the ground surface
		TD	Planting density of trees
	Compound Factor A	$TD \times TB / TC$	A compound factor based on characteristic factors related to the effective vertical noise-blocking area of trees
Shrub	Single	SS	Average planting spacing of shrubs
		SC	Width of a shrub crown
		SH	Average height of shrubs in the plant community
	Compound Factor B	$SH \times SC / SS$	A compound factor based on characteristic factors related to the effective vertical noise-blocking area of shrubs
Overall factor	Single	UP	Proportion of vegetation area in the sample site
		UW	Proportion of water area in the sample site
		PS	Number of plant species in the community
		VC	Vertical projected area ratio of plant communities per unit sample site

environment. This metric, standardized according to the international standard for soundscape^[47] and China's *Environmental Quality Standard for Noise (GB 3096-2008)*^[48], quantifies noise exposure and is widely applied in acoustics research. Studies suggest that plant communities reduce noise through both distance attenuation and vegetation absorption^[49]. This study controlled for factors such as measurement scale, duration, and climatic conditions, ensuring that distance attenuation does not impact noise reduction results^{[17][50]}. Therefore, the relative noise attenuation^{[40][51]}—calculated as the difference between the source sound pressure level (SPL) and the SPL after transmission through plant communities—was adopted as the indicator of physical noise reduction effectiveness.

(2) Evaluation indicators for psychological noise reduction

According to acoustic masking theory, individuals' perception, experience, and interpretation of an acoustic environment depend not only on the sound itself but also on visual factors

and their interaction^[52]. Thus, this study constructed a system of psychological noise reduction evaluation indicators encompassing auditory and visual perception.

The semantic differential method is widely used to assess auditory perception^[53]. Common subjective auditory evaluation indicators include "pleasant," "lively," "eventful," "chaotic," "annoying," "monotonous," and "calm"^[53]. Additionally, soundscape assessments frequently consider perceived sound source type^[47], noise annoyance^[54], and quietness^[55]. After removing indicators closely tied to personal experiences and merging redundant items, this study selected 7 auditory perception indicators: quietness, harmony, liveliness, richness, pleasantness, perceived sound source type, and noise annoyance (Table 2).

Based on visual perception theories of landscapes such as prospect-refuge^[56] and stress recovery^[57], sense of color^[58], sense of space^[42], sense of layering^{[56][59]}, sense of atmosphere^[52], attractiveness^[58], diversity^[52], and tranquility^[59] are the common

Table 2: Evaluation system for the comprehensive noise reduction effectiveness of plant communities

Dimension	Indicator		Definition
Physical noise reduction	Relative noise attenuation		Difference in SPL between the noise source at the sample site and the noise after passing through the plant community
Psychological noise reduction	Visual perception	Sense of color	Richness of colors of the plant community
		Sense of space	Degree of spatial enclosure of the plant community
		Sense of layering	Richness of layering of the plant community
		Sense of atmosphere	Plant community's capacity to evoke associative imagery
		Attractiveness	Plant community's capacity to attract people
	Auditory perception	Quietness	Perceived quietness of the sound environment
		Harmony	Degree of coordination between different sound sources
		Liveliness	Amplitude and frequency of changes in the sound environment
		Richness	Diversity of the sound environment
		Pleasantness	Satisfaction degree of the sound environment
		Perceived sound source type	Types of sound sources that can be perceived in the sound environment
		Noise annoyance	Degree of perceived disturbance in the sound environment

visual perception indicators influencing noise tolerance^[60]. These indicators are widely applied in landscape assessment and design. Given the specific focus on plant communities, this study refined the selection to 5 visual perception indicators: sense of color, sense of space, sense of layering, sense of atmosphere, and attractiveness (Table 2).

3.2 Selection of the Study Area

This study focused on the waterfront green spaces along the central urban section of the Suzhou Creek in Shanghai (Fig. 1). Located in the city's core, this section stretches approximately 21 km from the confluence of Suzhou Creek and the Huangpu River in the east to the Outer Ring Expressway in the west. Flowing west to east through the main urban area, this segment accommodates high-quality commercial, residential, and cultural-recreational spaces^[61] and is also a focal area for urban renewal.

The waterfront connectivity improvement project for recreation and transportation purposes in this section has been largely completed, with enhancements including increased urban road network density, expanded metro capacity, and the introduction of water-based leisure routes^[62], while these initiatives have also brought noise problems. According to Shanghai's noise mapping data, the SPLs along Suzhou Creek, due to the busy traffic, generally exceed 60 dB^[63], surpassing the daytime limit (55 dB) set for Class I acoustic functional zones in *China's Environmental Quality Standard for Noise*. As a result, a diverse range of waterfront green spaces with varied plant communities has emerged and a pervasive traffic noise issue exists along both banks, providing ideal sample sites for this study.

Following a preliminary experiment, 14 sample sites were selected in waterfront green spaces along the central urban section of Suzhou Creek, representing different levels of traffic noise



1. Study area and distribution of sample sites.

exposure and plant community compositions. Among them, two sites are located in Jiuzi Park, two in Butterfly Bay Park, four in Mengqing Garden, and six in Changfeng Park (Fig. 1). The selection criteria for these sites are as follows.

1) Sample sites of terrestrial plant communities were adjacent to urban roads (two-way, single-lane) or internal park roads and kept at least 50 m away from intersections; and waterfront plant community sample sites were situated on the river embankments opposite urban roads. Through on-site verification, site selection was confirmed that the vehicle speeds on the roads adjacent to both types of sites did not exceed 40 km/h—according to previous studies, noise frequency variations remain relatively stable at this speed^[64]. The measured traffic noise SPL was around 60 dB. The traffic flow was steady, without heavy vehicles, and light vehicles accounted for more than 95% of the traffic. The selected roads had no honking and minimal extreme noise disturbances, minimizing variations in distance-dependent noise attenuation, SPLs, and frequency-dependent noise reduction effectiveness.

2) The selected sites covered a wide range of plant community compositions, each with a distribution area exceeding the

designated sampling plot size. To minimize terrain-related variability, all sites were located on flat ground, ensuring intact community compositions and healthy plant growth.

Among the designated sites, site Q0 served as the control group (single-species herbaceous type), sites Q1 ~ Q9 represented terrestrial plant communities (tree-shrub, tree-herb, shrub-herb, and tree-shrub-herb types), and sites Q10 ~ Q13 represented waterfront plant communities (tree-herb and shrub types).

3.3 Research Methods

The experiment was conducted on December 11, 2022, from 13:00 to 17:00, a clear day with no obstructions, rain, snow, or thunderstorms, and with wind speeds below 5 m/s.

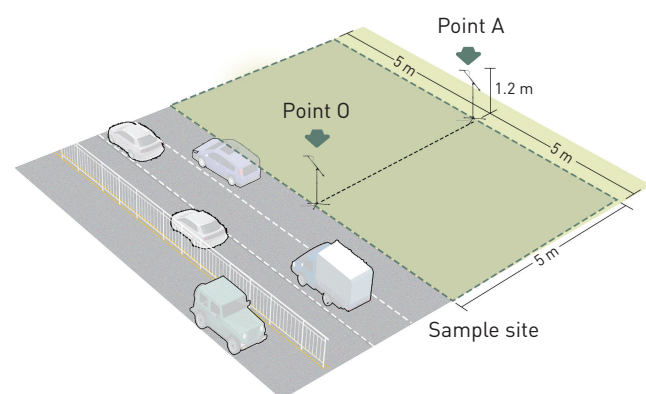
First, plant community sample sites were selected and measured. A 10 m × 5 m sampling plot was delineated at the center of each site. For terrestrial plant communities, the plot covered only the vegetated area; while for waterfront plant communities, the plot also included a 10 m × 1.5 m water surface area. Second, the plant species numbers within each plot were recorded, and a laser rangefinder was used to measure TH, TC, TB, and TD, as well

as SS, SC, and SH. Third, the indicators of VC, $TD \times TB / TU$, and $SH \times SC / SS$ were calculated.

As required by the *Environmental Quality Standard for Noise*^[48], sound environment measurements were conducted at all 14 sample sites. A Class I multi-functional sound level meter (AWA6228+) and a multi-channel signal analyzer (AWVA6290L+) were used to measure the SPLs of plant communities at different locations. The instruments were calibrated before measurement, and the time weighting was set to “fast” response. Based on the definition of noise attenuation, two monitoring points (O and A) were set along the central axis of each sampling plot, both located at the midpoint of the plot’s long axis and spaced 5 m apart (Fig. 2). The primary noise source was traffic noise from adjacent roads. During noise measurement, the sensor was positioned at a vertical height of 1.2 m above ground level. Each monitoring point was measured 5 times, with each measurement lasting 30 s and conducted at 5-min intervals. The average of these measurements was used as the final noise level for each point (α_{O_mean} and α_{A_mean})^[65].

Using the soundwalk method^[66] combined with a questionnaire survey, the psychological noise reduction effectiveness of plant communities was evaluated, with the importance of all indicators in this study assessed to calculate their weights. The questionnaire consisted of three sections. The first section covered participant demographics. The second section focused on the perception of the study site, where participants rated their visual and auditory experiences on the sample site and identified perceived sound sources. The sound source identification section was an open-ended question, while other perception ratings were assessed by a 5-point Likert scale (1 = very dissatisfied, 5 = very satisfied). The

2. Schematic of monitoring points in the sample sites.



third section addressed the importance of different evaluation dimensions, including physical and psychological noise reduction. These ratings were used to determine the weight of each indicator in the comprehensive noise reduction effectiveness of plant communities^[67].

To minimize perception bias caused by individual differences, all survey participants recruited (60 in total) were local university students and received professional training before the experiment, all with normal vision and hearing and no color blindness or hearing impairments. The noise reduction assessment was conducted simultaneously with plant community characterization and physical noise reduction measurements. Participants, guided by the researchers, performed a 5-min soundwalk around Points O and A at each site before completing the questionnaire^[68]. The average scores were used as the psychological perception evaluation results for each site.

3.4 Data Processing

3.4.1 Calculation Method for Physical Noise Reduction Effectiveness

The physical noise reduction effectiveness (F_{phy}) of the plant community within the sampling site is determined by the noise attenuation through the community^[69], calculated using the following formula:

$$F_{phy} = \alpha_{O_mean} - \alpha_{A_mean}. \quad (1)$$

3.4.2 Calculation Method for Psychological Noise Reduction Effectiveness

Based on psychophysical methods and principles of fuzzy mathematics^[32], the concept of annoyance threshold was introduced^①. The annoyance threshold refers to the critical exposure level at which a subject begins to feel annoyed in a specific environment. The difference between this threshold and the actual noise SPL at a given point determines the psychological noise reduction effectiveness of the plant community. Levels of annoyance are divided into equal intervals, and the corresponding subjective annoyance perception membership function (F) is defined as follows:

$$F = \frac{1}{I} + \frac{0.75}{II} + \frac{0.5}{III} + \frac{0.25}{IV} + \frac{0}{V}, \quad (2)$$

① For more information, please refer to the *Acoustics—Methods for the evaluation and prediction of noise annoyance* [GB/T 42473-2023].

where *I, II, III, IV, and V* correspond to the evaluation levels “very strong noise perception,” “strong noise perception,” “moderate noise perception,” “low noise perception,” and “no noise perception,” respectively, with membership degrees of 1, 0.75, 0.5, 0.25, and 0. The membership degree of evaluation level *j* is denoted as μ_j . The probability of annoyance (P_i) at noise SPL *i* is calculated as:

$$P_i = \frac{\sum_j \mu_j \alpha_{ij}}{\sum_j \alpha_{ij}}, \quad (3)$$

where α_{ij} is the frequency of occurrence of evaluation level *j* at noise SPL *i*. Based on this, the annoyance value (*EL*) within the sampling site is calculated as follows:

$$EL = \frac{\sum_i L_{ki} P_i}{\sum_i P_i}, \quad (4)$$

where L_{ki} represents the noise SPL at the monitoring point *k* and noise SPL *i* (in this study, referring to Points O and A).

Finally, the psychological noise reduction effectiveness (F_{psy}) is calculated as:

$$F_{psy} = EL - \alpha_{A,mean}. \quad (5)$$

3.4.3 Calculation Method for Comprehensive Noise Reduction Effectiveness

Based on the importance assessment results from questionnaire participants, weight conversion was performed. To minimize the impact of individual perception bias, the mean value method^[67] was used to determine the importance of indicators. The results indicated that the importance of physical noise reduction is 54%, while psychological noise reduction is 46%. Thus, the comprehensive noise reduction effectiveness (F_{total}) of plant communities was calculated as follows:

$$F_{total} = 1.08F_{phy} + 0.92F_{psy}. \quad (6)$$

4 Results and Discussion

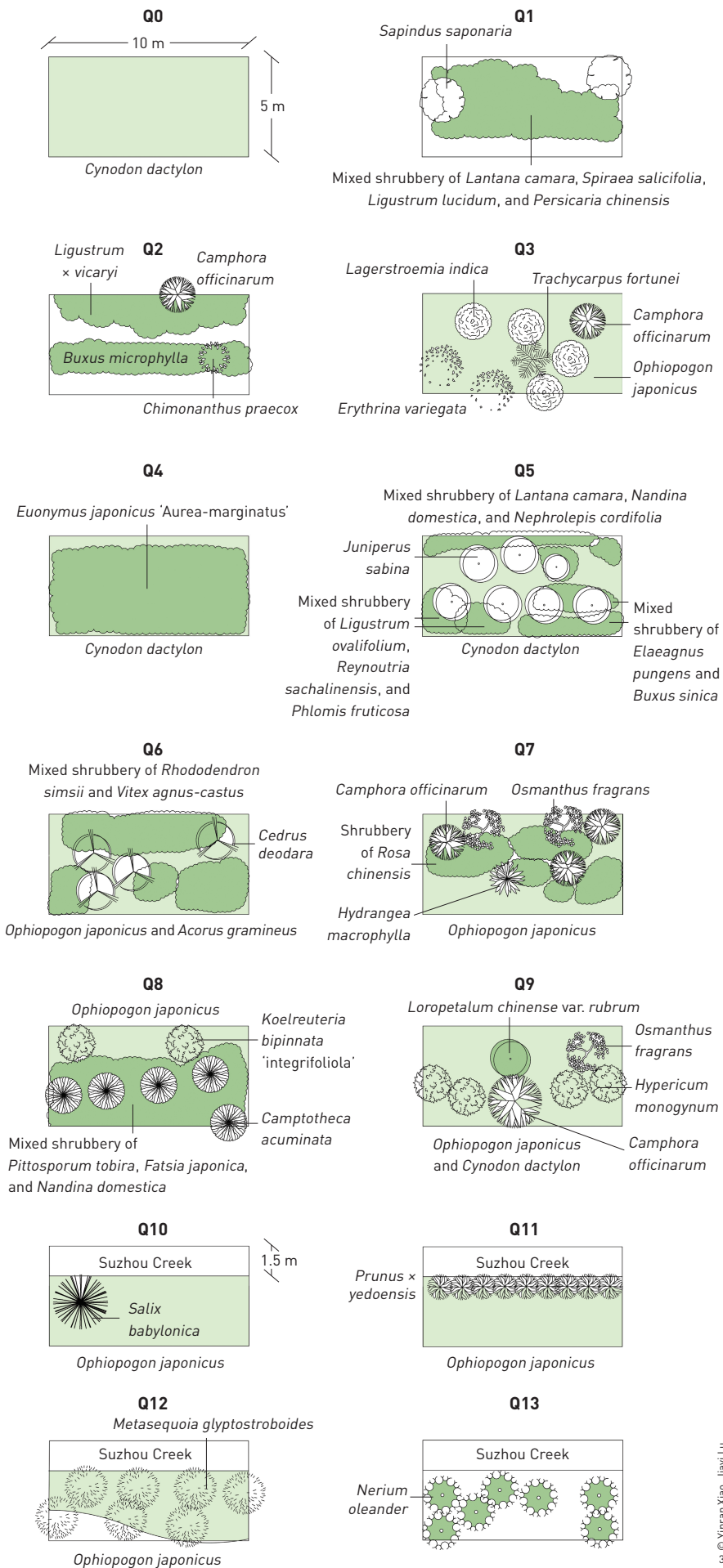
4.1 Characteristics of Plant Communities in the Sample Sites

The plant community characteristics of the sample sites are shown in Table 3 and Fig. 3. In terrestrial plant communities, Q0 (herbaceous) is covered solely by *Cynodon dactylon*. Q1 (tree-shrub) features diverse shrubs and relatively large planting spacing. Q2 (tree-shrub) has more formal and densely planted

Table 3: Characteristics of plant communities in the sample sites

Site	Tree					Shrub				Comprehensive factor	
	TH (m)	TC (m)	TB (m)	TD (tree/m ²)	Factor A	SS (m)	SC (m)	SH (m)	Factor B	PS (type)	VC (%)
Terrestrial plant community											
Q0	—	—	—	—	—	—	—	—	—	1	—
Q1	4.0	2.0	0.20	0.04	0.004	0.8	1.0	0.60	0.75	5	33.0
Q2	13.6	1.8	0.25	0.04	0.006	0.5	0.4	0.58	0.46	4	46.0
Q3	3.0	1.5	0.10	0.04	0.003	—	—	—	—	5	27.0
Q4	—	—	—	—	—	0.3	0.3	1.20	1.20	2	70.0
Q5	—	—	—	—	—	0.4	0.6	0.85	1.28	10	62.6
Q6	25.0	5.0	0.20	0.08	0.003	1.0	0.3	1.00	0.30	5	32.8
Q7	12.0	2.0	0.40	0.12	0.024	0.3	0.3	0.70	0.70	5	62.0
Q8	18.0	8.0	0.25	0.14	0.004	1.0	1.0	1.50	1.50	6	53.6
Q9	5.0	2.0	0.20	0.15	0.015	0.8	1.0	1.40	1.75	6	90.0
Waterfront plant community											
Q10	3.0	1.3	0.20	0.08	0.133	—	—	—	—	2	10.0
Q11	3.0	1.0	0.10	0.15	0.015	—	—	—	—	2	40.0
Q12	32.0	2.0	0.20	0.17	0.017	—	—	—	—	2	70.0
Q13	—	—	—	—	—	1.5	1.0	2.0	1.33	2	90.0

shrubs. Q3 (tree-herb) has small and sparsely distributed trees. Both being shrub-herb types, Q4 is a neatly trimmed shrub hedge with denser spacing, smaller individual crown width, and greater height than Q5. Q6 ~ Q9 (tree-shrub-herb) share similar shrub layer characteristics but differ in tree layers—Q6 and Q8 contain only large trees, Q7 and Q9 are dominated by small trees, and Q6 and Q7 have lower planting densities compared with Q8 and Q9. For waterfront plant communities, Q10 ~ Q12 are tree-herb types, with



Q10 having the sparsest and Q12 the densest tree planting. Q13 is a shrub type with large shrubs.

4.2 Analysis of Physical Noise Reduction Effectiveness of Plant Communities and Its Influencing Factors

4.2.1 Results of Physical Noise Reduction Effectiveness

The mean noise SPL at the original noise source, the mean noise SPL after noise reduction by plant communities, and the physical noise reduction effectiveness at the 14 sample sites were listed in Table 4. Results showed that among all sites, Q9 exhibited the highest physical noise reduction effectiveness, reducing noise by 11.34 dB, followed by Q4 and Q5. Sites Q7, Q13, and Q8 had

Table 4: Physical noise reduction effectiveness of sample sites

Site	Average SPL of noise at Point O (dB)	Average SPL of noise at Point A (dB)	Physical noise reduction effectiveness (dB)
Q0	56.06	54.30	1.76
Q1	58.40	55.68	2.72
Q2	60.52	56.12	4.40
Q3	62.34	60.24	2.10
Q4	60.68	49.70	10.98
Q5	71.42	61.08	10.34
Q6	55.62	53.38	2.24
Q7	62.34	55.80	6.54
Q8	59.04	52.66	6.38
Q9	64.06	52.72	11.34
Q10	56.28	52.50	3.78
Q11	56.28	52.40	3.88
Q12	56.28	51.56	4.72
Q13	59.2	52.76	6.44

3. Plan sketch of plant communities in the sample sites.

moderate effectiveness, with reductions of approximately 6.5 dB. The least effective was the control group Q0, which achieved only a 1.76 dB reduction.

4.2.2 Tree-Layer Factors on Physical Noise Reduction Effectiveness

Correlation analysis of Q1 ~ Q3 and Q6 ~ Q9 using SPSS software revealed that tree-layer physical noise reduction effectiveness was significantly positively correlated with planting density ($p = 0.010$), but showed no significant correlation with height ($p = 0.709$), clear bole height ($p = 0.982$), or DBH ($p = 0.062$). However, it was positively correlated with the Factor A ($p = 0.017$), indicating that greater vertical obstruction by plants along the noise path can enhance physical noise reduction effectiveness.

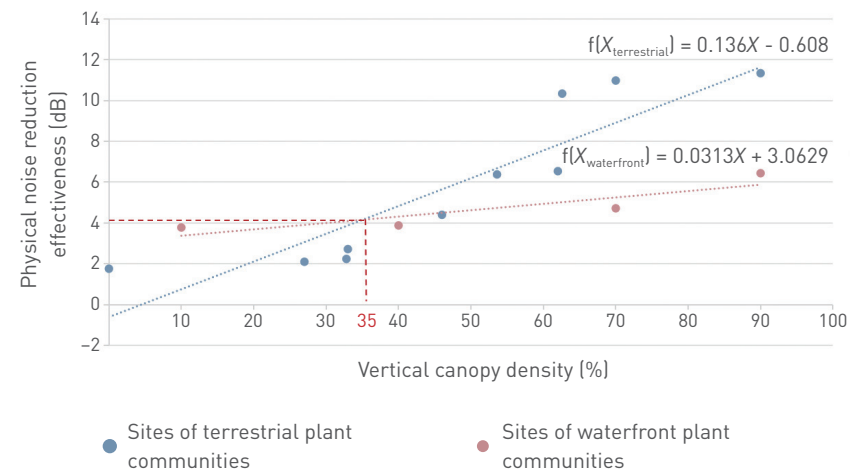
4.2.3 Shrub-Layer Factors on Physical Noise Reduction Effectiveness

Analysis for Q1, Q2, and Q4 ~ Q9 showed no significant correlation between shrub-layer noise reduction effectiveness and spacing ($p = 0.243$), crown width ($p = 0.852$), or height ($p = 0.201$). However, noise reduction was significantly positively correlated with the Factor B ($p = 0.017$), suggesting that shrubs with greater height and crown width, coupled with smaller spacing, exhibited stronger physical noise reduction effectiveness.

4.2.4 Overall Factors Affecting Physical Noise Reduction Effectiveness

To exclude the impact of non-plant factors (water surface proportion), 10 sites with no water cover (Q0 ~ Q9) were analyzed for overall factors of plant community affecting physical noise reduction effectiveness. Correlation analysis using SPSS showed significant relationships between physical noise reduction effectiveness and both plant species richness ($p = 0.033$) and vertical canopy density ($p < 0.001$), with the latter being more significant. This suggests that higher vertical canopy density and species richness can improve physical noise reduction effectiveness.

A comparative analysis between sites with no water cover (Q0 ~ Q9) and 30% water cover (Q10 ~ Q13) generated scatter plots of vertical canopy density versus physical noise reduction effectiveness for these two plant community types (Fig. 4). A linear regression analysis revealed that the slope of terrestrial plant communities ($k = 0.136$) was greater than that of waterfront communities ($k = 0.0313$), indicating that the physical noise reduction effectiveness of waterfront plant communities rose slower than the terrestrial communities as the unit vertical



4. Relationship between noise reduction effectiveness and vertical canopy density of terrestrial and waterfront plant communities.

canopy density grew. Further calculations showed that when the canopy density was below 35%, waterfront plant communities were more effective in reducing noise; above 35%, terrestrial plant communities performed better. This suggests that for plant communities with a vertical canopy density under 35%, incorporating a water surface as the underlying surface will enhance the physical noise reduction effectiveness, while for those exceeding 35%, increasing canopy density is more beneficial.

4.3 Psychological Noise Reduction Effectiveness of Plant Communities and Its Influencing Factors

4.3.1 Psychological Noise Reduction Effectiveness of Plant Communities

A total of 60 questionnaires were distributed, with 59 valid responses. The internal consistency of the questionnaire was tested through Cronbach's α . Using the Analytic Hierarchy Process, the weight of indicators for psychological noise reduction effectiveness was determined, and the overall scores for both visual and auditory perceptions were calculated. Based on the noise annoyance results, the psychological noise reduction effectiveness at the 14 sample sites was calculated (Table 5).

For visual perception, waterfront plant communities provided a higher overall score ($M = 3.60$) than terrestrial plant communities ($M = 3.48$). Among individual sites, Q8 scored the highest, likely due to the vertically structured trees and lush shrubs creating strong senses of layering and atmosphere. Q10 followed, with open water and *Salix babylonica* enhancing similar senses. Q13, dominated by dense *Nerium oleander*, offered a

Table 5: Visual and auditory perception evaluation results

Site	Visual perception						Auditory perception						Psychological noise reduction effectiveness (dB)		
	V1	V2	V3	V4	V5	OS	A1	A2	A3	A4	A5	OS		PSST	NAV
Q0	3.68	3.68	3.55	3.55	3.34	3.56	3.04	3.32	2.98	3.06	3.08	3.10	Traffic, wind	3.96	-0.13
Q1	3.68	3.47	3.57	3.32	3.36	3.48	2.98	3.25	3.34	3.34	3.13	3.21	Traffic, wind	3.72	1.42
Q2	3.30	3.34	3.38	3.42	3.23	3.33	3.57	3.53	3.26	3.25	3.42	3.41	Traffic, wind, birdsong	3.60	2.37
Q3	3.66	3.57	3.70	3.62	3.57	3.62	3.02	3.04	3.58	3.66	3.35	3.32	Traffic, wind, birdsong, conversation, human activity	3.74	1.09
Q4	3.43	3.43	3.51	3.51	3.36	3.45	3.17	3.42	3.58	3.57	3.36	3.42	Traffic, wind, birdsong, music, conversation, human activity	3.23	6.26
Q5	3.66	3.47	3.58	3.42	3.36	3.49	3.15	3.26	3.43	3.36	3.28	3.30	Traffic, wind	3.25	5.88
Q6	3.45	3.51	3.42	3.32	3.17	3.37	3.21	3.28	3.30	3.28	3.21	3.26	Traffic, wind	3.28	4.62
Q7	3.19	3.17	3.38	3.13	3.02	3.17	3.28	3.23	3.17	3.11	3.26	3.21	Traffic, wind, human activity	3.30	3.66
Q8	3.70	3.74	3.79	3.81	3.66	3.74	3.02	3.14	3.70	3.79	3.60	3.44	Traffic, wind, birdsong, conversation, human activity	3.38	3.54
Q9	3.87	3.53	3.66	3.42	3.47	3.59	3.40	3.49	3.19	3.19	3.23	3.30	Traffic, wind, birdsong, construction	3.15	6.56
Q10	3.70	3.68	3.72	3.74	3.68	3.70	3.57	3.45	3.34	3.26	3.42	3.41	Traffic, wind, water	3.00	2.25
Q11	3.70	3.58	3.68	3.47	3.51	3.58	3.53	3.43	3.28	3.26	3.49	3.40	Traffic, wind, water	3.49	2.11
Q12	3.58	3.42	3.53	3.43	3.26	3.44	3.19	3.48	3.50	3.66	3.40	3.44	Traffic, wind, water, birdsong, conversation, human activity	3.28	2.66
Q13	3.66	3.58	3.72	3.74	3.70	3.68	3.45	3.64	3.53	3.57	3.64	3.57	Traffic, wind, water, birdsong	3.17	3.72

NOTE

V1 = sense of color; V2 = sense of space; V3 = sense of layering; V4 = sense of atmosphere; V5 = attractiveness. A1 = quietness; A2 = harmony; A3 = liveliness; A4 = richness; A5 = pleasantness. OS = overall score; PSST = perceived sound source type; NAV = noise annoyance value.

relatively pleasing visual experience, but lacked senses of color and space compared with Q10. The lowest visual score was for Q7, which had monotonous and oppressive plant colors, weak layering and spatial senses, and lacked attractiveness.

For auditory perception, Q13 had the highest overall score, and Q0 the lowest. Specifically, Q2, Q10, and Q11 were the quietest, while Q13, Q2, and Q9 had the most harmonious sounds. Q8, Q3, and Q4 were the liveliest, whereas Q8, Q3, and Q12 provided

the richest auditory perception. The most pleasant auditory environments were at Q13, Q8, and Q11, whereas the highest noise annoyance values were recorded at Q0, Q3, and Q1. Additionally, birdsong was heard at Q2, Q3, Q4, Q8, Q9, Q12, and Q13, human activity and conversation sounds at Q3, Q4, Q7, Q8, and Q12, and water sounds at Q10 ~ Q13.

Among the 14 sample sites, Q9 and Q4 exhibited the highest psychological noise reduction effectiveness, followed by Q5 and

Q6. The lowest effectiveness was at Q0, with Q3, Q1, and Q11 also performing poorly. For terrestrial plant communities, Q9 was the most effective due to its rich tree–shrub–herb structure and diverse colors, creating a favorable space and visual environment for birds and human activities, thus achieving a higher visual score. Q4 was favourable for its high auditory richness and low noise annoyance. Q5 followed, with balanced scores across all indicators and similarly low noise annoyance. Among waterfront plant communities, Q13 and Q12 had the best psychological noise reduction effectiveness. Q13 featured neatly arranged tall shrubs, while Q12 was dominated by *Metasequoia glyptostroboides*, both benefiting from water and bird sounds that enriched the auditory perception. In contrast, Q10 and Q11 had weaker psychological noise reduction effectiveness, mainly due to their lower liveliness and richness that led to poor auditory perception scores.

4.3.2 Visual Perception Influencing Factors

Correlation analysis of the visual perception scores and characteristics of plant communities showed that, for terrestrial plant communities containing shrubs (Q1, Q2, Q4 ~ Q9, Q13), shrub crown width significantly impacted visual perception. This factor had strong positive correlations with the site’s senses of color ($p = 0.003$), space ($p = 0.044$), and layering ($p = 0.003$), and attractiveness ($p = 0.009$). Shrub height had the strongest positive impact on attractiveness ($p = 0.008$), and also impacted the senses of space ($p = 0.047$), layering ($p = 0.017$), and atmosphere ($p = 0.012$) to some extent. Shrub spacing was positively correlated with the sense of space ($p = 0.039$) and attractiveness ($p = 0.045$). Moreover, the Factor B positively affected the senses of layering ($p = 0.006$) and color ($p = 0.024$), and attractiveness ($p = 0.022$). These findings suggest that overly short shrubs, small canopies, or overly dense planting lead to relatively poor visual perception, thereby reducing the psychological noise reduction effectiveness of the plant communities.

4.3.3 Auditory Perception Influencing Factors

An analysis of auditory perception scores and plant community characteristics across the 14 sample sites revealed a positive correlation between the vertical canopy density and auditory perception richness ($p = 0.043$), as well as the overall score ($p = 0.042$). This suggests that higher vertical canopy density can better accommodate the needs of bird habitats and human activity spaces, enhancing the perception of natural and human-generated sounds, which in turn strengthens the comprehensive auditory perception evaluation.

4.4 Influencing Factors on Comprehensive Noise Reduction Effectiveness

The comprehensive noise reduction effectiveness of plant communities at all sample sites is shown in Table 6. Among them, Q9, Q4, and Q5 exhibited the highest effectiveness, followed by Q7, Q13, and Q8, while Q0, Q3, and Q1 were the least effective.

For terrestrial plant communities, except for Q6, the physical noise reduction effectiveness generally exceeded the psychological effectiveness, and the variation trends of physical, psychological, and comprehensive noise reduction were similar (Fig. 5). Q9 had the best comprehensive effectiveness due to its high vertical canopy density and dense planting, forming an effective physical noise barrier. Additionally, its strong sense of color contributed to high psychological noise reduction effectiveness. Q4 and Q5

Table 6: Results of comprehensive noise reduction effectiveness

Site	Physical noise reduction effectiveness (dB)	Psychological noise reduction effectiveness (dB)	Comprehensive noise reduction effectiveness (dB)
Q0	1.76	-0.13	1.78
Q1	2.72	1.42	4.24
Q2	4.40	2.37	6.93
Q3	2.10	1.09	3.27
Q4	10.98	6.26	17.62
Q5	10.34	5.88	16.58
Q6	2.24	4.62	6.67
Q7	6.54	3.66	10.43
Q8	6.38	3.54	10.15
Q9	11.34	6.56	18.28
Q10	3.78	2.25	6.15
Q11	3.88	2.11	6.13
Q12	4.72	2.66	7.54
Q13	6.44	3.72	10.38

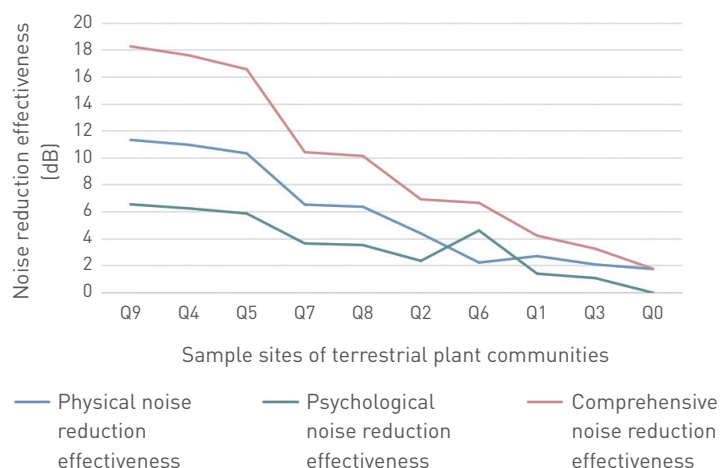
followed, with high canopy density ensuring effective physical noise reduction and low noise annoyance. Q7 and Q8 ranked next, both featuring high vertical canopy density; Q7 had lower noise annoyance, while Q8 benefited from better senses of space, layering, and atmosphere created by the plant enclosures and higher auditory perception richness. Q0 and Q3 exhibited the lowest comprehensive noise reduction effectiveness. Q0, featuring only ground cover with the lowest vertical canopy density, demonstrated the negative psychological noise reduction effectiveness due to the worst overall auditory perception and the highest noise annoyance. Q3 showed relatively low vertical canopy density with only tree and ground cover layers, along with smaller tree DBH, resulting in the poorest auditory harmony. Q1 and

Q6 also had weaker noise reduction effectiveness—Q1 suffered from high noise annoyance and a low overall score of auditory perception, whereas Q6 had poor physical noise reduction effectiveness, which impacted its comprehensive performance.

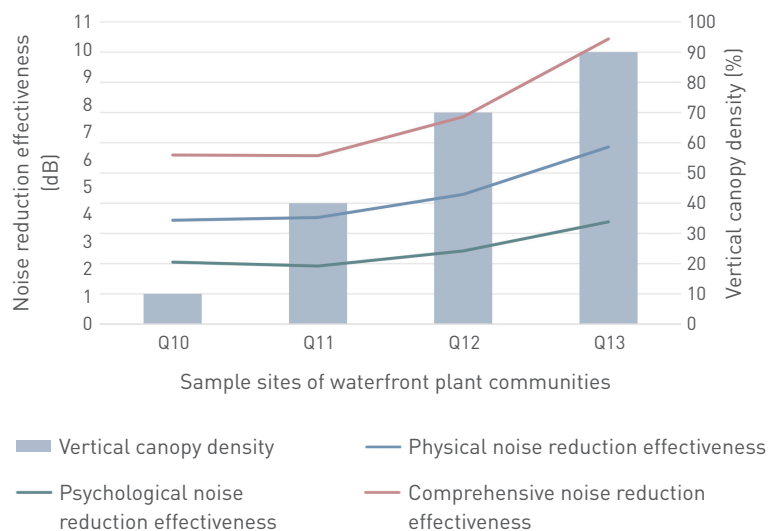
For waterfront plant communities, the comprehensive noise reduction effectiveness showed a certain correlation with the vertical canopy density (Fig. 6). As the vertical canopy density of Q10 ~ Q13 increased, the visual transparency decreased, and the comprehensive noise reduction effectiveness first declined and then rose. Specifically, the physical noise reduction effectiveness increased with rising vertical canopy density. However, in terms of the psychological effectiveness, when the vertical canopy density was 10% ~ 40%, visual transparency was favourable, increased the auditory annoyance threshold, and reduced noise annoyance. When the vertical canopy density reached 40% or more, the psychological noise reduction effectiveness improved as canopy density increased.

5. Noise reduction effectiveness of terrestrial plant communities.

6. Noise reduction effectiveness of waterfront plant communities.



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5 Conclusions and Recommendations

This study examined the waterfront green spaces surrounding the central urban section of the Suzhou Creek in Shanghai, establishing an innovative evaluation framework with 13 indicators to assess the comprehensive noise reduction effectiveness of plant communities from both physical and psychological perspectives. The study selected 14 urban green space sites with different plant community characteristics and used noise attenuation values from field measurements along with visual and auditory perception data from surveys as dependent variables. A model was proposed to explore the effects of single and compound plant structure factors related to tree, shrub, and ground cover layers on physical, psychological, and comprehensive noise reduction effectiveness.

The results indicate that in the direction of noise propagation, richer plant species and denser vertical canopy can significantly enhance physical noise reduction effectiveness. Densely planted trees with low clear bole height and large DBH, along with tall-big shrubs, improve physical noise reduction. When the canopy density exceeds 35%, increasing it further enhances overall physical noise reduction; however, when below 35%, increasing the ratio of water surface and vegetation coverage is more effective. For psychological noise reduction effectiveness, increasing shrub crown width, height, and spacing can effectively strengthen visual perception, raising the auditory annoyance threshold. Additionally, higher vertical canopy density enriches auditory perception and the overall experience. Among all sites,

plant communities combining densely planted trees, shrubs, and ground cover exhibited the highest comprehensive noise reduction effectiveness. For waterfront plant communities, variations in vertical canopy density affected visual transparency, which influenced comprehensive noise reduction effectiveness. When the canopy density is at least 40%, richly layered plant communities contributed more significantly to psychological noise reduction; below 40%, reducing it will improve visual transparency and lower noise annoyance.

Understanding the relationship between plant communities and noise reduction from a perspective of plant configuration is crucial for improving urban green spaces. Based on the findings, the results can be applied to mitigating traffic noise in various urban settings. Considering the current conditions of green spaces, the following recommendations are proposed.

1) For terrestrial green spaces with sufficient planting area, a community planting model combining densely planted trees, tall shrubs, and ground cover is recommended. Trees should be low-branching, dense-foliaged, and large in diameter, while tall shrubs should have broad canopies—both of them to be densely planted. Maximizing vertical canopy density can provide diverse wildlife habitats and increase natural sounds. Additionally, it is advisable to intersperse other tall shrubs with large canopies to highlight the shape of individual shrub plants, enhance visual perception, and further improve noise reduction effectiveness.

2) For terrestrial green spaces with limited planting area, a high-density shrub and ground cover combination is recommended. Shrubs should be large-canopied evergreen species to ensure year-round physical noise reduction. Scattered large-canopy tall shrubs can enhance visual experience, improving psychological noise reduction effectiveness.

3) For waterfront green spaces with sufficient planting area, a high-effectiveness noise reduction model similar to terrestrial vegetation should be adopted—densely planted trees, tall shrubs, and ground cover—with a vertical canopy density exceeding 40% to enhance both physical and psychological noise reduction.

4) For waterfront green spaces with limited planting area, where increasing vertical canopy density is not feasible, adjusting the proportion of water and vegetation cover can enhance physical noise reduction. Meanwhile, reducing plant density to improve visual transparency and optimize the river and water landscape, while maintaining vertical canopy density below 40%, can enhance psychological noise reduction.

This study has certain limitations. First, only 59 valid samples were collected in the psychological noise reduction survey, making

the sample size relatively small and some conclusions preliminary. Second, the plant community patterns along the Suzhou Creek do not encompass all green space types. Future studies could expand the scope and increase the number of sampling sites for more comprehensive and precise data, improving the scientific validity and generalizability of the findings. Furthermore, although this study initially identified the influencing mechanisms of waterfront plant communities on comprehensive noise reduction effectiveness, the researched sample sites for waterfront plant communities were relatively few and this field remains exploratory. Future research should further investigate underlying mechanisms and refine the theoretical framework. Overall, this study aims to provide practical theoretical support and guidance for mitigating traffic noise in urban green spaces and creating multi-sensory healthy urban environments.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at <https://doi.org/10.15302/J-LAF-0-020027>.

Competing interests | The authors declare that they have no competing interests.

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城市绿地植物群落综合降噪效能研究

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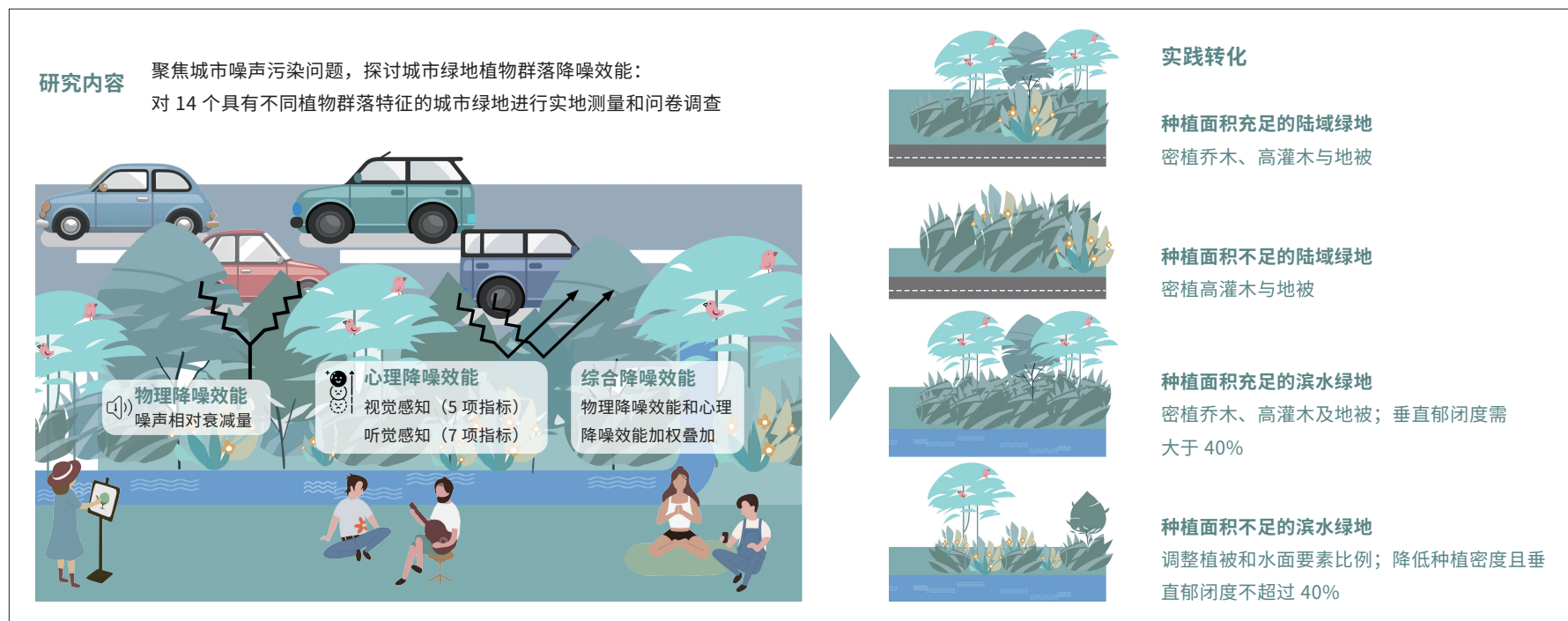
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图文摘要



摘要

噪声污染严重影响人们的健康和生活质量, 而城市绿地不仅美化环境, 还起到降噪吸声的重要作用。本研究以上海苏州河滨水绿地植物群落为例, 创新性地构建了基于物理与心理降噪效能的综合评估体系, 共包括 13 项评价指标。通过对 14 个具有不同植物群落特征的城市绿地进行实地测量和问卷调查, 研究发现, 植物群落的物理降噪效能与植物物种丰富度、垂直郁闭度密切相关, 密植且枝干较大的乔木和高大灌木能显著增强物理降噪效能。当垂直郁闭度小于 35% 时, 相同郁闭度下, 滨水植物群落 (植被占比 70%、水面占比 30%) 的物理降噪效能优于陆域植物群落 (不包含水面要素)。在心理降噪效能方面, 增加灌木的冠幅、高度和间距有助于提升视觉感知; 增加垂直郁闭度则能提升听觉感知的丰富度, 两者均有助于提高听觉烦恼度阈值。综合降噪效能最佳的植物群落类型为密植乔木与灌木及地被的组

合, 而滨水植物群落的降噪效能受到垂直郁闭度变化的影响, 当垂直郁闭度不低于 40% 时, 可通过提升郁闭度来优化心理降噪效能。研究为改善城市绿地空间中的噪声问题提供了理论支持和实践指导, 有助于优化城市绿地植物群落配置。

关键词

城市滨水绿地; 物理降噪; 心理降噪; 综合降噪效能; 植物群落配置

文章亮点

- 使用综合降噪效能评估植物群落的降噪效果, 量化心理降噪效能
- 探讨陆域和滨水植物群落差异, 发现提升综合降噪效能新途径
- 为缓解城市交通噪声提供城市绿地植物群落配置建议

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1 引言

噪声问题是全球公认的重要环境问题之一。2018年世界卫生组织发布的《欧洲环境噪声指南》显示，环境噪声是仅次于空气污染的第二大环境压力源，严重影响人们的健康、福祉和生活质量^[1]。交通噪声是城市环境噪声的重要组成部分，占城市噪声总量的60%以上^[2]。自1980年中国正式将噪声纳入全国环境常规监测项目以来，部分城市噪声污染防治措施仍未达到预期效果^[3]。2024年，噪声问题仍是生态环境污染举报的重点^[4]，且面临着牵涉面广、解决周期较长、治理难度大等困境。

城市绿地是居民休闲游憩的重要场所，具有改善城市小气候、缓解城市热岛效应、降低噪声等多重功效^[5]。相较于传统的声屏障等工程降噪措施，利用绿地植物进行降噪是一种低成本且减碳的方法^[6]。由于植物对声波具有反射和吸收作用，植物群落不仅能起到类似声屏障的物理降噪作用，还能通过声景的营造产生声掩蔽效应，从而实现心理降噪的功效^[7]。但目前有关植物降噪效能的研究多集中于植物的单一物理或心理降噪效能方面^{[8][9]}。

本研究以上海苏州河流域中心城段14个具有不同植物群落特征的城市绿地为例，从物理和心理降噪两个维度构建评价体系，对植物群落的综合降噪效能进行量化，深入分析植物群落特征对物理、心理和二者综合降噪效能的影响，探究植物群落配置的优化方案，为城市绿地空间的植物景观改造提升提供参考和支撑。

2 相关理论发展

植物群落被称为“绿色消音器”，能够吸附、阻滞噪声；植物的叶片绒毛和气孔对噪声有良好的吸附作用^[10]。声波在传播过程中经过绿带时会呈现明显的衰减趋势；中高频声音可被树木的枝干或叶片、枝茎等

吸收和散射，从而减弱噪声。因此，通过植物群落中不同树种的合理搭配，可以有效降低噪声^{[11]-[13]}。

目前，关于植物群落物理降噪效能的研究大多集中在声学 and 植物生理学等领域，聚焦于声波在传播中遇到不同形式的介质而产生的反应机制^[14]。现有研究成果表明，对于单一类型植物群落来说，影响其降噪效果的植物要素包括植物种类、物理特性、绿量等^[15]。不同类型的植物中，乔木林的降噪效果最为显著^[16]，灌木带的效果与乔木相近^[17]，且显著高于草坪的效果^{[18][19]}；同时，植物群落的密度、高度和宽度等物理特性也会影响降噪效能^{[20][21]}；而阔叶树比针叶树的单位降噪效能更强^[22]，这是由于浓密的枝叶具有更高的植物绿量，从而提高了树木的单位吸声量^[23]。就复合植物群落的降噪效能而言，种植间距和形式，以及树干直径等因素对固定宽度植物群落的降噪效果有显著影响^{[13][24][25]}；乔灌草相结合的形式对噪声的削减作用最为明显^[16]。

此外，植物还可通过声掩蔽效应实现心理层面的降噪。声掩蔽效应指由于某种声音或视觉焦点的出现，使人们对其他声音的感知能力下降^{[7][26]}。例如，植物群落能够直接对噪声源（如公路、汽车等）产生遮挡，避免人们直观感受到噪声源的存在，通过转移注意力提高人们对噪声的容忍度^[27]；植物群落通过形成优美的景观空间，将人们的关注点转移至植物景观，并因此减少对噪声的关注^{[28][29]}；此外，植物群落所带来的鸟鸣、风吹树叶等白噪声可引发声掩蔽效应，从而影响人们对声音响度和信息量的判断^{[30][31]}。当前关于植物群落心理降噪效能的研究尚处于起步阶段。例如，利用模糊语言的隶属度原则讨论绿化带对交通噪声引起的心理烦恼度的影响，通过问卷调查得出了环境噪声引起的烦恼概率，进一步计算给定区域内的烦恼阈值，以此来量化植物群落的心理降噪能力^[32]；通过社会声学调查方法，对机场周围的村庄居民开展飞机噪声的主观烦恼问卷调查，采用隶属度函数计算确定了机场噪声的烦恼阈值^[33]；运用虚拟现实技术与问卷调查方法，指出植被色彩丰富度及生物多样性越高，越有利于减少居民的噪声烦恼度^[34]；基于GIS数据，发现归一化植被指数（NDVI）与绿地占比可通过影响居民的感知绿地水平，影响其噪声烦恼度水平^[35]。

综上，尽管对植物群落的物理和心理降噪效能已有初步研究，但由于植物群落的多样性和复杂性，其在物理与心理层面的综合降噪效能仍需进一步探讨。

3 研究方法

3.1 指标选取

在既往研究和规范的基础上，本研究归纳了与降噪效能相关的植物群落特征要素，并提出了复合要素；创新性构建了基于物理和心理层面的测量与评价体系，以评估综合降噪效能。

3.1.1 植物群落特征要素

根据《县域植被多样性调查与评估技术规定》^[36]，植物群落调查需查明区域内的植物群落类型、群落层次、群落高度、郁闭度或盖度、干扰程度和环境因素等；乔木需记录其物种、胸径和树高；灌木需记录其种名、高度、株数和冠幅（盖度）。国内外研究表明，树木种类^[37]、树高^[38]、胸径^[39]、冠幅^[40]、枝下高^[41]、垂直郁闭度^[42]、下垫面^[43]及植物群落结构^[44]等因素是影响植物群落降噪效能的重要指标。本研究根据植被和水面占比的差异，将植物群落分为陆域植物群落（不包含水面）和滨水植物群落（植被占比70%、水面占比30%）。选择以下要素作为植物群落特征要素（表1）：乔木层指标为高度、枝下高、胸径和种植密度；灌木层指标为间距、冠幅和高度；综合要素为植物物种丰富度和垂直郁闭度。此外，根据噪声传播^[45]和植物物理降噪^[46]的原理，本研究创新性地提出两项复合要素，即乔木的种植密度×胸径/枝下高（复合因子A）和灌木的高度×冠幅/间距（复合因子B）。

3.1.2 植物群落综合降噪效能评价体系

（1）物理降噪效能评价指标

研究选取等效连续A计权声压级（ L_{Aeq} ）来描述场地的声环境特征。该指标是声景国际标准^[47]和中国《声环境质量标准（GB 3096—2008）》^[48]中用于测量环境声压级的规范指标，可表达声音的暴露水平，目前已被广泛运用于声学研究。相关研究表明，植物群落对噪声的衰减作用通常可分为距离衰减和绿化衰减两个方面^[49]。本研究在实验过程中对样地的尺度、测量时间、气候环境等影响要素进行了统一控制，可排除距离衰减对样地噪声相对衰减量的影响^{[17][50]}。因此，本研究选择测量样地噪声源声压级和噪声通过植物群落后的声压级差值，即噪声相对衰减量^{[40][51]}作为植物群落物理降噪效能的评价指标。

（2）心理降噪效能评价指标

基于声掩蔽理论可以发现，个体或群体在某一场景下感知、经历和/或理解的声学环境，不仅受到声环境本身的影响，还会受到视觉环境及两者交互作用的影响^[52]。因此，本研究基于听觉感知和视觉感知两个维度构建心理降噪效能评价指标。

语义差异法是听觉感知研究中常用的描述和评价方法^[53]。听觉主观评价的常用指标包括愉悦、活跃、事件性、杂乱、烦人、单调和平静^[53]；此外，声景评价常用指标还包括声源感知类型^[47]、噪声烦恼^[54]、安静^[55]等。通过去除与个人阅历相关的指标并合并词义相反或相似的指标，本研究最终确定了安静、和谐、活跃、丰富、愉悦、声源感知类型和噪声烦恼共7项听觉感知评价指标（表2）。

基于瞭望—庇护^[56]、压力舒缓^[57]等景观视觉感知理论，可归纳出色彩感^[58]、空间感^[42]、层次感^{[56][59]}、氛围感^[52]、吸引力^[58]、多样性^[52]和静谧感^[59]等与提升人对噪声承受阈值相关的视觉感知指标^[60]——这些指标已

表1：植物群落特征要素

特征要素		定义	
乔木层	单因子	高度	植物群落中乔木的平均高度
		枝下高	乔木从地表到树冠最下分枝点的垂直高度
		胸径	乔木主干离地表胸高处的直径
		种植密度	乔木的种植密度
复合因子A	种植密度 × 胸径 / 枝下高	由与乔木对噪声垂直阻挡有效面积相关的要素构成的复合指标	
灌木层	单因子	间距	灌木的种植平均间距
		冠幅	灌木最宽处横向距离的长度
		高度	植物群落中灌木的平均高度
复合因子B	高度 × 冠幅 / 间距	由与灌木对噪声垂直阻挡有效面积相关的要素构成的复合指标	
综合	单因子	植被占比	样地中植被面积占比
		水面占比	样地中水面面积占比
		植物物种丰富度	群落所含植物物种的数量
		垂直郁闭度	植物群落在单位样地立面上的垂直投影面积所占比例

被广泛应用于景观评估与设计。本研究结合植物群落的特殊性，并去除与听觉感知因素直接关联的指标和语义重复指标，最终确定色彩感、空间感、层次感、氛围感和吸引力共5项视觉感知评价指标（表2）。

3.2 研究区域选取

本研究以上海苏州河流域中心城段周边滨河绿地为研究对象（图1）。苏州河中心城段位于上海中部核心区域，东起苏州河—黄浦江河口，西至上海外环高架，全长约21km，自西向东穿越主城区，该段流域是重要的高品质商业居住和文化休闲空间^[61]，也是旧城改造集中区域。

截至目前，该区段已经基本完成滨水活动空间及道路的贯通工程，并适当增加了主城区范围内的局部路网密度、轨道交通运量和水上休闲航线^[62]。尽管这些举措为市民的出行提供了便利，但也带来了相应

表 2: 植物群落综合降噪效能评价体系

评价维度	评价指标		定义
物理降噪	噪声相对衰减量		样地噪声源声压级和噪声通过样地植物群落后的声压级差值
心理降噪	视觉感知	色彩感	植物群落的色彩丰富程度
		空间感	植物群落的空间围合程度
		层次感	植物群落的层次丰富程度
		氛围感	植物群落引发相关联想的丰富程度
		吸引力	植物群落对人的吸引程度
	听觉感知	安静	主观感知声环境的安静程度
		和谐	不同类型声源之间的协调程度
		活跃	声环境变化的幅度及频度
		丰富	声环境的丰富程度
		愉悦	声环境令人满意的程度
		声源感知类型	可感知的声源类型
		噪声烦恼度	声环境令人烦躁的程度

的噪声问题。上海市噪声地图显示,受复合交通的影响,苏州河沿岸的声压级普遍高于60dB^[63],超过了《声环境质量标准》中规定的1类声环境功能区昼间的限值(55dB)。基于此,苏州河两岸拥有大量功能各异的滨河绿地和种类丰富的植物群落,且存在着普遍交通噪音问题,为本研究提供了合适的测量样地。

经过预实验,本研究最终在苏州河流域中心城段周边滨河绿地内选取了14个受不同程度交通噪声影响、具有不同植物群落结构的测量样地,其中2个位于九子公园、2个位于蝴蝶湾公园、4个位于梦清园,6个位于长风公园(图1)。样地选择基于以下标准。

1) 陆域植物群落样地应靠近城市支路(双向单车道)或公园内部车行道路,且距离十字路口50m以上;滨水植物群落样地应位于城市支路对岸的河堤上。经现场确认,两类样地所在道路的车速应低于40km/h(根据相关研究,在该速度下,车辆产生噪声的频率变化不明显^[64]);

交通噪声声压级为60dB左右,流速平缓稳定,无大型车辆通行,轻型车占95%以上;此外,该路段禁止鸣笛,无极端噪声干扰,排除了声传播的距离衰减、不同声压级及频率的噪声衰减效率差异等对实验的影响。

2) 涵盖多种植物群落结构类型,且每类植物群落的分布范围大于样方划定面积。为减少地形差异影响,所选群落均位于平地,且结构完整、植物长势良好。

在划定的样地中,样地0(Q0)为对照组(物种单一的草本型),样地1~9(Q1~Q9)为陆域植物群落(乔灌型、乔草型、灌草型和乔灌草型),样地10~13(Q10~Q13)为滨水植物群落(乔草型和灌木型)。

3.3 研究方法

实验选择在无障碍物、无雨雪、无雷电的晴天进行,当日风速低于5m/s,于2022年12月11日13:00~17:00展开。

首先,选取和测定植物群落样地,以测量点位为中心划定10m×5m的样方。其中,陆域植物群落样方仅覆盖植物生长区域,而滨水植物群落样方需包含10m×1.5m的水域面积。其次,记录样方内的植物物种数量,并使用激光测距仪测量乔木高度、枝下高、胸径和密度,以及灌木间距、冠幅和高度。再次,计算植物群落的垂直郁闭度、复合因子A和B等指标。

同时,依据《声环境质量标准》中对环境噪声的检测要求^[48],对上述14个样地的植物群落声环境进行实测。实验选用1级多功能声级计(AWA6228+)和多通道信号分析仪(AWVA6290L+)测量不同植物群落下各点位的声压级。测量前已对仪器进行校准,测量仪的时间计权特性为“快”响应。根据噪声衰减的定义,在每个样地沿中轴线布置监测点O和A,分别位于植物群落的长轴中点,相距5m(图2)。测量的噪声声源主要为每个样地周边的道路产生的交通噪声。测量噪声时,仪器的传感器距离地面垂直高度为1.2m,每个监测点重复测量5次,单次测量时长为30s,每次测量间隔5min,并取平均值作为该点位的噪声测量结果($\alpha_{0均}$ 和 $\alpha_{A均}$)^[65]。

依托声漫步法^[66]结合问卷调查的方法展开植物群落的心理降噪效能评估,同时对本研究各项指标的重要性进行评价,用以计算指标权重。问卷主要分为三部分:1)参与者基本信息;2)参与者对样地的视觉和听觉感知评价,以及对声源类型的感知——声源类型感知为半开放填空题,其余评价均采用李克特5级量表(1为“极不满意”,5为“非常满意”);3)参与者对物理降噪和心理降噪两个评价维度各指标进行重要性判断,以用于计算各指标对植物群落综合降噪效能的影响权重^[67]。

为控制个体差异可能引发的感知偏差,问卷调查的参与者统一招募自本地大学生群体,并进行了专业培训。共招募60人,所有参与者均具备良好的视力和听力,无色弱或听力障碍等问题。降噪效能评估与植物群落特征和物理降噪指标测量同步进行。参与者在研究人员的带领下,

于每个样地的监测点O和A附近漫步感受5min后填写问卷^[68]，取各项的平均值作为该点位的心理感知评价结果。

3.4 数据处理

3.4.1 物理降噪效能计算方法

实验样方内植物群落的物理降噪效能 ($F_{物}$) 为通过该群落的噪声衰减量^[69]，公式为：

$$F_{物} = \alpha_{O均} - \alpha_{A均}。 \quad (1)$$

3.4.2 心理降噪效能计算方法

基于心理物理学方法和模糊数学原理^[32]，研究引入听觉烦恼度阈值概念^①。烦恼度阈值即感受主体在某一特定环境中感到烦恼的临界暴露水平，该临界值与特定点位实际噪声声压级的差值即为植物群落的心理降噪效能。研究采用等间隔划分烦恼度等级，并定义相应的主观感知烦恼度的隶属函数 (F) 为：

$$F = \frac{1}{I} + \frac{0.75}{II} + \frac{0.5}{III} + \frac{0.25}{IV} + \frac{0}{V}， \quad (2)$$

式中，I、II、III、IV和V分别表示评价等级“噪声感知非常强烈”“噪声感知强烈”“噪声感知一般”“不大能感受到噪声”和“感受不到噪声”，1、0.75、0.5、0.25和0为各评价等级的隶属度。评价等级j的隶属度记为 μ_j 。此时，噪声声压级i下的烦恼概率 P_i 的计算公式为：

$$P_i = \frac{\sum_j \mu_j \alpha_{ij}}{\sum_j \alpha_{ij}}， \quad (3)$$

式中， α_{ij} 为噪声声压级i下评价等级j出现的频度。在此基础上，样地内的烦恼值 (EL) 的计算公式如下：

$$EL = \frac{\sum_i L_{ki} P_i}{\sum_i P_i}， \quad (4)$$

式中， L_{ki} 表示该样地内第k个监测点在第i级噪声下的声压级（本研究中指监测点O和A的噪声声压级）。

最终，基于烦恼值计算心理降噪效能 ($F_{心}$)，计算公式为：

$$F_{心} = EL - \alpha_{A均}。 \quad (5)$$

3.4.3 综合降噪效能计算方法

基于上述问卷参与者对各指标的重要性判断结果进行权重换算。为避免参与者的感受差异造成影响，通过平均值法^[67]计算得出物理降噪对

参与者噪声感知影响的重要性为54%，而心理降噪为46%。因此，对物理降噪效能和心理降噪效能进行加权叠加，并统一系数，可得植物群落的综合降噪效能 ($F_{总}$) 计算公式为：

$$F_{总} = 1.08F_{物} + 0.92F_{心}。 \quad (6)$$

4 结果与讨论

4.1 样地植物群落特征

各样地的植物群落特征如表3和图3所示。在陆域植物群落中，Q0为草本型，仅包含草本植物狗牙根 (*Cynodon dactylon*)；Q1为乔灌型，灌木种类丰富，种植间距较大；Q2为乔灌型，其灌木层种植形式更为规则和密集；Q3为乔草型，乔木体量较小且分布稀疏；Q4和Q5为灌草型，Q4为规则修剪的灌木篱，种植间距与Q5相比更密集，单株植被冠幅更小但更高；Q6~Q9为乔灌草型，各样地灌木层群落特征相近，主要差异在乔木层——Q6和Q8仅种植大乔木，Q7和Q9以小乔木为主，而Q6和Q7的种植密度小于Q8和Q9。在滨水植物群落中，Q10~Q12为乔草型，乔木种植Q10最为稀疏，Q12最为密集；Q13为灌木型，灌木植株高大。

4.2 植物群落物理降噪效能及影响因素分析

4.2.1 物理降噪效能结果

14个样地的噪声原点声压级均值、植物降噪后的声压级均值，以及物理降噪效能如表4所示。从实测结果显示的物理降噪效能来看，所有植物群落样地中Q9最佳，可有效降噪11.34dB；其次是Q4和Q5；Q7、Q13和Q8次之，降噪效能均在6.5dB左右；降噪效能最差的是对照组Q0，仅为1.76dB。

4.2.2 物理降噪效能乔木层影响因素分析

通过SPSS软件对Q1~Q3及Q6~Q9样地进行的相关性分析结果显示，乔木层的物理降噪效能与种植密度显著正相关 ($p=0.010$)，而与高度 ($p=0.709$)、枝下高 ($p=0.982$) 和胸径 ($p=0.062$) 等单因子特征要素无显著相关性，同时与复合因子A呈正相关 ($p=0.017$)。这表明，植物在噪声传播路径上垂直方向的遮挡越多，其物理降噪效率越强。

4.2.3 物理降噪效能灌木层影响因素分析

对Q1、Q2、Q4~Q9样地展开的相关性分析结果显示，灌木层的降噪效能与间距 ($p=0.243$)、冠幅 ($p=0.852$) 和高度 ($p=0.201$) 无显著

① 详见《声学 噪声烦恼度的评价和预测方法 (GB/T 42473—2023)》。

表 3: 各样地植物群落特征

样地	乔木层					灌木层				综合	
	TH (m)	TC (m)	TB (m)	TD (棵/m ²)	复合 因子 A	SS (m)	SC (m)	SH (m)	复合 因子 B	PS (种)	VC (%)
陆域植物群落											
Q0	—	—	—	—	—	—	—	—	—	1	—
Q1	4.0	2.0	0.20	0.04	0.004	0.8	1.0	0.60	0.75	5	33.0
Q2	13.6	1.8	0.25	0.04	0.006	0.5	0.4	0.58	0.46	4	46.0
Q3	3.0	1.5	0.10	0.04	0.003	—	—	—	—	5	27.0
Q4	—	—	—	—	—	0.3	0.3	1.20	1.20	2	70.0
Q5	—	—	—	—	—	0.4	0.6	0.85	1.28	10	62.6
Q6	25.0	5.0	0.20	0.08	0.003	1.0	0.3	1.00	0.30	5	32.8
Q7	12.0	2.0	0.40	0.12	0.024	0.3	0.3	0.70	0.70	5	62.0
Q8	18.0	8.0	0.25	0.14	0.004	1.0	1.0	1.50	1.50	6	53.6
Q9	5.0	2.0	0.20	0.15	0.015	0.8	1.0	1.40	1.75	6	90.0
滨水植物群落											
Q10	3.0	1.3	0.20	0.08	0.133	—	—	—	—	2	10.0
Q11	3.0	1.0	0.10	0.15	0.015	—	—	—	—	2	40.0
Q12	32.0	2.0	0.20	0.17	0.017	—	—	—	—	2	70.0
Q13	—	—	—	—	—	1.5	1.0	2.0	1.33	2	90.0

注

TH= 高度; TC= 枝下高; TB= 胸径; TD= 种植密度。SS= 间距; SC= 冠幅; SH= 高度。PS= 植物种类; VC= 垂直郁闭度。

相关性, 但与复合因子B显著正相关 ($p=0.017$)。这意味着同时具备更大高度、冠幅及更小种植间距等特征的灌木层表现出了更强的物理降噪效能。

4.2.4 物理降噪效能综合影响因素分析

为了排除非植物要素 (水面占比) 对物理降噪效能的影响, 选取不

包含水面要素的样地Q0~Q9共10处, 来分析植物群落综合特征要素对物理降噪效能的影响。利用SPSS软件进行的相关性分析结果表明, 植物群落的物理降噪效能与植物物种数量 ($p=0.033$) 和垂直郁闭度 ($p<0.001$) 均存在显著相关性, 且后者更为显著, 即植物群落的垂直郁闭度越高、植物物种越丰富, 其物理降噪效能越强。

综合对比不包含水面要素的Q0~Q9样地与水面要素占比30%的Q10~Q13样地, 生成两类植物群落垂直郁闭度与物理降噪效能的散点图, 并对各自的线性关系函数进行拟合 (图4), 分析植物群落构成要素对物理降噪效能的影响。如图所示, $f(X_{陆})$ 的斜率 ($k=0.136$) 高于 $f(X_{水})$ 的斜率 ($k=0.0313$), 即受水面要素影响, 单位垂直郁闭度上升时, 滨水植物群落物理降噪效能的增加速度缓于陆域植物群落。当郁闭度小于35%时, 滨水植物群落的物理降噪效能更优; 而郁闭度大于35%时, 则反之。据此可推断, 当植物群落郁闭度小于35%时, 使用水面要素作为植物群落的下垫面更有助于整体提升其物理降噪效能;

表 4: 各样地物理降噪效能

样地	监测点 O 噪声声压级 测量均值 (dB)	监测点 A 噪声声压级 测量均值 (dB)	物理降噪效能 (dB)
Q0	56.06	54.30	1.76
Q1	58.40	55.68	2.72
Q2	60.52	56.12	4.40
Q3	62.34	60.24	2.10
Q4	60.68	49.70	10.98
Q5	71.42	61.08	10.34
Q6	55.62	53.38	2.24
Q7	62.34	55.80	6.54
Q8	59.04	52.66	6.38
Q9	64.06	52.72	11.34
Q10	56.28	52.50	3.78
Q11	56.28	52.40	3.88
Q12	56.28	51.56	4.72
Q13	59.2	52.76	6.44

当垂直郁闭度大于35%时，提升郁闭度更有助于提升整体的物理降噪效能。

4.3 植物群落心理降噪效能及影响因素分析

4.3.1 心理降噪效能分析

本次调研共发放问卷60份，共回收有效问卷59份。问卷内容均通过内部一致性（Cronbach's α ）检验。利用层次分析法计算植物群落心理降噪效能指标权重，并在此基础上计算视觉感知和听觉感知各自的综合评分，根据噪声烦恼指标评价结果计算得到14个样地的心理降

噪效能（表5）。

就视觉感知评价结果而言，相较于陆域植物群落的综合评分均值（ $M=3.48$ ），滨水植物群落的体验（ $M=3.60$ ）总体更优。在单个样地中，Q8的视觉体验最佳，可能由于垂直生长的乔木和茂盛的灌木形成了良好的层次感和氛围感；其次为Q10，开阔的水域与垂柳（*Salix babylonica*）同样形成了良好的层次感和氛围感；Q13的视觉体验亦较好，该样地主要为密植的夹竹桃（*Nerium oleander*），但色彩感和空间感较Q10稍弱；视觉综合评分最低的样地是Q7，其植物色彩感单一且压抑，层次感和空间感较弱，且缺乏吸引力。

表 5: 各样地视觉和听觉感知评分结果

样地	视觉感知						听觉感知						心理降噪效能 (dB)		
	色彩感	空间感	层次感	氛围感	吸引力	综合评分	安静	和谐	活跃	丰富	愉悦	综合评分		声源感知类型	噪声烦恼度
Q0	3.68	3.68	3.55	3.55	3.34	3.56	3.04	3.32	2.98	3.06	3.08	3.10	交通声、风声	3.96	-0.13
Q1	3.68	3.47	3.57	3.32	3.36	3.48	2.98	3.25	3.34	3.34	3.13	3.21	交通声、风声	3.72	1.42
Q2	3.30	3.34	3.38	3.42	3.23	3.33	3.57	3.53	3.26	3.25	3.42	3.41	交通声、风声、鸟鸣声	3.60	2.37
Q3	3.66	3.57	3.70	3.62	3.57	3.62	3.02	3.04	3.58	3.66	3.35	3.32	交通声、风声、鸟鸣声、谈话声、人群活动声	3.74	1.09
Q4	3.43	3.43	3.51	3.51	3.36	3.45	3.17	3.42	3.58	3.57	3.36	3.42	交通声、风声、鸟鸣声、音乐声、谈话声、人群活动声	3.23	6.26
Q5	3.66	3.47	3.58	3.42	3.36	3.49	3.15	3.26	3.43	3.36	3.28	3.30	交通声、风声	3.25	5.88
Q6	3.45	3.51	3.42	3.32	3.17	3.37	3.21	3.28	3.30	3.28	3.21	3.26	交通声、风声	3.28	4.62
Q7	3.19	3.17	3.38	3.13	3.02	3.17	3.28	3.23	3.17	3.11	3.26	3.21	交通声、风声、人群活动声	3.30	3.66
Q8	3.70	3.74	3.79	3.81	3.66	3.74	3.02	3.14	3.70	3.79	3.60	3.44	交通声、风声、鸟鸣声、谈话声、人群活动声	3.38	3.54
Q9	3.87	3.53	3.66	3.42	3.47	3.59	3.40	3.49	3.19	3.19	3.23	3.30	交通声、风声、鸟鸣声、施工声	3.15	6.56
Q10	3.70	3.68	3.72	3.74	3.68	3.70	3.57	3.45	3.34	3.26	3.42	3.41	交通声、风声、水声	3.00	2.25
Q11	3.70	3.58	3.68	3.47	3.51	3.58	3.53	3.43	3.28	3.26	3.49	3.40	交通声、风声、水声	3.49	2.11
Q12	3.58	3.42	3.53	3.43	3.26	3.44	3.19	3.48	3.50	3.66	3.40	3.44	交通声、风声、水声、鸟鸣声、谈话声、人群活动声	3.28	2.66
Q13	3.66	3.58	3.72	3.74	3.70	3.68	3.45	3.64	3.53	3.57	3.64	3.57	交通声、风声、水声、鸟鸣声	3.17	3.72

在听觉感知方面, Q13的综合评分最高, Q0最低。具体而言, Q2、Q10和Q11最为安静; 听觉感知最为和谐的为Q13、Q2和Q9; Q8、Q3和Q4活跃度较高; Q8、Q3和Q12的听觉感知最为丰富; 愉悦度最高的是Q13、Q8和Q11; 噪声烦恼度较高的是Q0、Q3和Q1。此外, Q2、Q3、Q4、Q8、Q9、Q12和Q13可听到鸟鸣声; Q3、Q4、Q7、Q8、Q12可感知到人群活动声和谈话声, Q10~Q13可感知到水声。

综合对比14个样地, Q9和Q4的心理降噪效能最佳, 其次是Q5和Q6; 心理降噪效能最低的是Q0, 较差的包括Q3、Q1和Q11。具体而言, Q9丰富的乔灌木结构及色彩感为鸟类和人群活动提供了良好的空间和视觉环境, 因而视觉综合评分较高; Q4的声环境丰富度感知评分较高, 且噪声烦恼度较低; Q5所有指标评分均处于平均水平, 噪声烦恼度同样较低。而在滨水植物群落样地中, Q13和Q12的心理降噪效能较优, 前者为规则高灌木, 后者大部分为水杉林 (*Metasequoia glyptostroboides*), 相较于其他样地, 水声和鸟鸣声提供了更为活跃且丰富的听觉体验; Q10和Q11的心理降噪效能较弱, 主要由于听觉感知的活跃度和丰富度较低, 导致其综合评分稍低。

4.3.2 视觉感知影响因素分析

针对植物群落的视觉感知评分结果和特征要素进行的相关性分析表明, 在含有灌木的陆域植物群落样地 (Q1、Q2、Q4~Q9、Q13) 中, 灌木冠幅对视觉感知影响较大, 该指标与样地的色彩感 ($p=0.003$)、空间感 ($p=0.044$)、层次感 ($p=0.003$) 和吸引力 ($p=0.009$) 均具有较强的正相关性; 灌木高度对吸引力 ($p=0.008$) 的正向影响最为强烈, 同时也在一定程度上影响着空间感 ($p=0.047$)、层次感 ($p=0.017$) 和氛围感 ($p=0.012$); 灌木间距与样地的空间感 ($p=0.039$) 和吸引力 ($p=0.045$) 也具有一定的正相关性; 而灌木复合因子B又会对层次感 ($p=0.006$)、色彩感 ($p=0.024$) 和吸引力 ($p=0.022$) 产生积极影响。综上所述, 灌木高度过低、冠幅过小或种植过密均会带来相对较差的植物群落视觉感知, 进而削弱植物群落的心理降噪效能。

4.3.3 听觉感知影响因素分析

对14个样地植物群落的听觉感知评分结果和特征要素进行相关性分析, 结果显示, 植物群落的垂直郁闭度与听觉感知的丰富度 ($p=0.043$) 及综合评分 ($p=0.042$) 呈正相关, 这或许是因为随着植物群落垂直郁闭度的增大, 可更好地满足鸟类生境和人类活动的空间需求, 可感知的自然声和人群活动声更多, 听觉感知的综合评分也随之提升。

4.4 综合降噪效能影响因素分析

经计算, 14个实验样地中植物群落的综合降噪效能如表6所示。其

中, 综合降噪效能最佳的是Q9、Q4和Q5, 其次是Q7、Q13和Q8, 最差的是Q0、Q3和Q1。

在陆域植物群落样地中, 除Q6外, 植物群落的物理降噪效能总体优于心理降噪效能, 且物理、心理和综合降噪效能的变化特征相似 (图5)。其中, 综合降噪效能最佳的是Q9, 其垂直郁闭度较高, 植物种植密集, 形成了良好的物理噪声屏障, 同时色彩感较好, 心理降噪效能较高。其次是Q4和Q5, 这些样地较高的植物郁闭度既保证了良好的物理降噪效果, 又降低了噪声烦恼度。综合降噪效能次之的是Q7和Q8, 其垂直郁闭度均较高, Q7的噪声烦恼度较低, 而Q8植物群落围合形成的空间感、层次感和氛围感更优, 且听觉感知丰富度更高。综合降噪效能最差的样地是Q0和Q3, 前者仅有地被层植被, 垂直郁闭度最低, 植物群落形成的听觉环境综合感知最差, 噪声烦恼度最高, 心理降噪效能为负; 后者垂直郁闭度较低, 仅包含乔木层和地被层, 且乔木胸径较细, 听觉感知的和谐程度最差。降噪效能较弱的还包括Q1和Q6——Q1由于噪声烦恼度较高, 听觉综合评分较低, 心理降噪效能较差; 而Q6的物理降噪效

表6: 各样地综合降噪效能

样地	物理降噪效能 (dB)	心理降噪效能 (dB)	综合降噪效能 (dB)
Q0	1.76	-0.13	1.78
Q1	2.72	1.42	4.24
Q2	4.40	2.37	6.93
Q3	2.10	1.09	3.27
Q4	10.98	6.26	17.62
Q5	10.34	5.88	16.58
Q6	2.24	4.62	6.67
Q7	6.54	3.66	10.43
Q8	6.38	3.54	10.15
Q9	11.34	6.56	18.28
Q10	3.78	2.25	6.15
Q11	3.88	2.11	6.13
Q12	4.72	2.66	7.54
Q13	6.44	3.72	10.38

能较差，影响了其综合降噪效能。

滨水植物群落的综合降噪效能与垂直郁闭度呈现一定的相关性（图6），随着Q10~Q13样地垂直郁闭度的上升，其视线通透性相应下降，综合降噪效能呈先降后升的趋势。具体而言，滨水植物群落的物理降噪效能随垂直郁闭度的上升而增强。而在心理降噪效能方面，当垂直郁闭度为10%~40%时，降低垂直郁闭度可增加视线通透性，进而提升噪声的听觉烦恼度阈值，降低噪声烦恼度；当垂直郁闭度不低于40%时，该类植物群落的心理降噪效能随垂直郁闭度上升而增强。

5 结论与建议

本研究以上海苏州河流域中心城段周边滨河绿地为例，从物理降噪和心理降噪两个维度，创新性构建了植物群落综合降噪效能评估框架，共包括13项评价指标。研究选择了14处具有不同植物群落特征的城市绿地，将实地测量获取的噪声相对衰减量及问卷调查获取的视觉和听觉评价数据作为因变量，提出了植物群落综合降噪效能计算模型，探索了植物群落乔木层、灌木层、地被层、综合特征要素下单因子和复合因子对物理、心理及综合降噪效能的影响。

研究结果表明，在噪声传播方向上，植物群落的物种越丰富，垂直郁闭度越高，物理降噪效能越显著；密植枝下高较低、胸径较粗的乔木和高大的灌木可显著增强物理降噪效能。当植物群落的郁闭度高于35%时，进一步提升郁闭度有助于增强整体的物理降噪效能；反之，增加水面和植被要素之间的比率更有利于提升物理降噪效能。在心理降噪效能方面，增加灌木的冠幅、高度和间距可有效提升视觉感知，进而提高听觉烦恼度阈值；而增加植物群落的垂直郁闭度则可有效提升听觉感知的丰富度和整体体验。在所有样地中，密植乔木与灌木及地被相组合的类型具有更强的综合降噪效能。此外，在滨水植物群落中，因垂直郁闭度变化导致的视线通透性差异可影响植物群落的综合降噪效能——当垂直郁闭度不低于40%时，层次丰富的植物群落更有助于提升心理降噪效能；当垂直郁闭度低于40%时，则可通过降低垂直郁闭度来形成通透的视线，减少噪声感知。

从植物配置的角度探讨植物群落与降噪之间的关系，对进一步提升城市绿地的环境品质具有重要意义。基于本研究结果，结合各类城市绿地面临的交通噪声问题和绿地现状，提出以下建议。

1) 针对种植面积充足的陆域绿地，建议采用密植乔木与高灌木及地被相组合的群落种植模式。选择枝下高较低、枝叶茂密、胸径较大的乔木及冠幅较大的高灌木进行密植；应尽量提升植物群落的垂直郁闭度，为动物提供多样化的生境，增加自然声。此外，可适当点缀其他大冠幅的高灌木，以突出单颗灌木植株的形态，提升视觉感知，进一步增强降

噪效能。

2) 针对种植面积不足的陆域绿地，建议采用密植高灌木与地被相结合的群落种植模式，灌木应使用冠幅较大的常绿高灌木类，以保证四季的物理降噪效果；同时适当点缀大冠幅的高灌木植株，以形成良好的视觉感受，提升植物群落的心理降噪效能。

3) 针对种植面积充足的滨水绿地，可采用降噪效能更优的陆域植被种植模式——密植乔木、高灌木及地被相组合，同时营建垂直郁闭度大于40%的植物群落，以同步提升物理和心理降噪效能。

4) 针对种植面积不足、无法通过提升垂直郁闭度来提升综合降噪效能的滨水绿地，建议通过调整水面和植被要素比例来提升物理降噪效能；同时，降低植物种植密度，增加视线通透性，优化河流水域景观，并将植物群落的垂直郁闭度控制在40%以下，进而提升心理降噪效能。

本研究亦存在一定的不足。首先，在心理降噪效能问卷调查阶段，仅收集到59份有效样本，样本量相对有限，导致部分结论的准确性受到一定影响，结论仅能提供初步的判断。其次，苏州河两岸绿地的植物群落模式尚未覆盖所有绿地类型，未来研究可扩大范围，增加样地的选取，以获取更全面、更精确的植物群落综合降噪效能数据，提升研究的科学性和普适性。此外，尽管本研究初步揭示了滨水植物群落特征要素对其综合降噪效能的独特影响机制，但滨水植物群落样地相对较少，且这一领域仍处于探索阶段，未来仍需进一步挖掘其内在规律，完善相关理论体系。总体而言，本研究期望为缓解城市绿地空间中的交通噪声问题及构建多感官健康城市空间提供更具实践意义的理论依据和指导建议。

补充材料

可通过<https://doi.org/10.15302/J-LAF-0-020027>查看本文补充材料。

图 1. 研究区域及样地分布图

图 2. 实验样地监测点设置示意图

图 3. 样地植物群落平面示意图

图 4. 陆域及滨水植物群落降噪效能与垂直郁闭度的关系示意图

图 5. 陆域植物群落降噪效能分析图

图 6. 滨水植物群落降噪效能分析图