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Can urban forests provide acoustic refuges for birds? Investigating the influence of vegetation structure and anthropogenic noise on bird sound diversity

Zezhou Hao[1] · Chengyun Zhang[2] · Le Li[1] · Bing Sun[1] · Shuixing Luo[1] · Juyang Liao[3] · Qingfei Wang[1] · Ruichen Wu[1] · Xinhui Xu[4] · Christopher A. Lepczyk[5] · Nancai Pei[1]

Abstract   As a crucial component of terrestrial ecosystems, urban forests play a pivotal role in protecting urban biodiversity by providing suitable habitats for acoustic spaces. Previous studies note that vegetation structure is a key factor influencing bird sounds in urban forests; hence, adjusting the frequency composition may be a strategy for birds to avoid anthropogenic noise to mask their songs. However, it is unknown whether the response mechanisms of bird vocalizations to vegetation structure remain consistent despite being impacted by anthropogenic noise. It was hypothesized that anthropogenic noise in urban forests occupies the low-frequency space of bird songs, leading to a possible reshaping of the acoustic niches of forests, and the vegetation structure of urban forests is the critical factor that shapes the acoustic space for bird vocalization. Passive acoustic monitoring in various urban forests was used to monitor natural and anthropogenic noises, and sounds were classified into three acoustic scenes (bird sounds, human sounds, and bird-human sounds) to determine interconnections between bird sounds, anthropogenic noise, and vegetation structure. Anthropogenic noise altered the acoustic niche of urban forests by intruding into the low-frequency space used by birds, and vegetation structures related to volume (trunk volume and branch volume) and density (number of branches and leaf area index) significantly impact the diversity of bird sounds. Our findings indicate that the response to low and high frequency signals to vegetation structure is distinct. By clarifying this relationship, our results contribute to understanding of how vegetation structure influences bird sounds in urban forests impacted by anthropogenic noise.

Keywords   Anthropogenic noise · Bird sounds · Urban forests · Vegetation structure

✉ Nancai Pei
  nancai.pei@gmail.com

1   Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangzhou 510520, People's Republic of China

2   School of Electronics and Communication Engineering, Guangzhou University, Guangzhou 510006, People's Republic of China

3   Hunan Botanical Barden, Changsha 410116, People's Republic of China

4   Guangdong Eco-Engineering Polytechnic, Guangzhou 510520, People's Republic of China

5   College of Forestry, Wildlife and Environment, Auburn University, Auburn, AL 36849, USA

Introduction

Urban forests provide crucial habitats for birds to live and breed (Kontsiotis et al. 2019). The presence of a more complex vegetation structure in urban areas is associated positively with an increased avian species richness

within the local community (Kang et al. 2015). However, many forests can also be noisy places that receive various amounts of anthropogenic noise (Slabbekoorn 2013) which has the potential to alter habitat quality and degrade natural acoustic conditions. Since birds rely on vocal communication for territory defense and mating (Slabbekoorn and Ripmeester 2008), predator avoidance (Damsky and Gall 2017) and migratory flight (Damsky and Gall 2017), they are particularly sensitive to human-generated noise (Antze and Koper 2018). As a result, understanding how birds react is critical for developing a better understanding of the role urban forests play in maintaining bird diversity.

Low-frequency, high-energy anthropogenic noise encroaches on the spectrum of bioacoustic resources and, as a result, birds are not only subject to competition for acoustic niches among vocal species, but also human-generated noise encroachment (Shannon et al. 2016), one of the causes of urban biodiversity loss (Kociolek et al. 2011). The acoustic niche hypothesis (ANH; Krause 1993) contends that competitive exclusion among species in natural environments leads to a temporal and frequency differentiation of sounds emitted by different species, enabling efficient utilization of acoustic space. Acoustic spatial partitioning is widespread in bird and insect communities (Henry and Wells 2010), where bioacoustic signals are spatially segregated in both the time and frequency domains (Mullet et al. 2017; Gomes et al. 2021), ensuring effective intraspecific communication. However, urban forests are spaces where people and nature co-exist. Noise from human activities is a constant source of interference in bird habitats (Des Aunay et al. 2014).

The vertical and horizontal structure of vegetation is a fundamental component that can influence bird sound transmission in natural environments (Chen et al. 2021). Based on the acoustic adaptation hypothesis AAH (Morton 1975), the environment filters and retains acoustic signals that travel long distances with little loss of fidelity, so that the sounds produced by birds are adapted to their environment. Previous research has shown that forest structure, such as canopy height variation (Mitchell et al. 2020) and foliage height diversity (Hao et al. 2021), are key factors that positively influences the diversity of bird sounds (Farina et al. 2015). In a study of horizontal structure, canopy opening had a significant effect on bird sounds (Pekin et al. 2012). Scattered branches, trunks, and leaves in the forest can have negative effects in terms of reverberation, absorption, and reflection. Based on the AAH, birds in natural environments use redundant chant repertoires (Forstmeier et al. 2009) or variable syllable lengths (Nemeth et al. 2006) to deal with the effects of vegetation space on their sounds. However, it remains to be tested whether bird sounds are adapted to the vegetation structure of urban forests that are affected by anthropogenic noise.

Human caused noise is a widespread and expanding global pollutant, originating primarily from transportation, industry, construction, and social activities (Barber et al. 2010). Some studies have shown that anthropogenic noise can change animal behavior and thereby affect the distribution of populations and communities of vocal species (Siemers and Schaub 2011; Estabrook et al. 2016). Anthropogenic noise not only directly alters individual animal behavior (Halfwerk et al. 2011), but also changes interspecies relationships and community structure, which impacts the functionality of communities and ecosystems (Francis et al. 2012). Past research on the effects of noise on animals has primarily focused on short-term effects, while research on long-term chronic effects is relatively limited, hindering our understanding of its potential ecological consequences (Senzaki et al. 2020). The vegetation structure of urban forests is an important feature of bird habitats, providing shelter and food sources (Deppe and Rotenberry 2008), while also having a mitigating effect on the spread of human-generated noise (van Renterghem et al. 2014). Therefore, investigating the role of forests in shaping acoustic spaces is a critical aspect of future research in ecoacoustic (Hao et al. 2021; Hong et al. 2021).

The impact of urbanization on biodiversity is a prominent concern within the realm of urban sustainable development. Given the lack of knowledge about how anthropogenic noise may affect biodiversity in urban forests, our objective was to evaluate the impact of vegetation structure on bird sounds under the interference of anthropogenic noise. In natural environments, bird songs have adapted to the surrounding environment, but the intrusion of human-generated noise into bird habitats may lead to changes in bird song ecological niches. The dynamics of bird calls in diverse noise environments offer a unique perspective for understanding the relationship between human activities and biodiversity (Sethi et al. 2020). We hypothesized that: (1) anthropogenic noise occupies the low-frequency space of bird songs and could reshape acoustic ecological niches within urban forests; and (2) vegetation structure still exerts an influence on bird sounds in the presence of anthropogenic noise. Adopting an acoustic perspective to examine the interplay between human activities, vegetation structures, and birds provides a novel analytical framework for further exploring the mechanisms responsible for biodiversity maintenance.

Materials and methods

Study area

The study was carried out in Guangzhou city (7434 km^2), the capital of Guangdong province and one of the four core cities in the Guangdong-Hong Kong-Macao Greater Bay

Area in south China. Subtropical evergreen broad-leaved forests are the main type of vegetation, with secondary forests and plantations covering the hills and mountains. Within the region, there are a few urban areas that have rapidly exspanded over the past several decades. Shimen national forest park in the outer suburbs, Mafengshan forest park in the suburbs, and Dafushan forest park in the city were chosen as case study areas. Mature, stable evergreen broad-leaved forest communities composed of native tree species were selected in each forest park. Based on vegetation community composition and environmental sound composition (Table S1), three recording points were strategically selected within each urban forest park (Fig. 1) to acquire comprehensive and objective acoustic scenes and vegetation structure data. Three principles were followed: (1) monitoring points were spaced at a distance of not less than 200 m to ensure the independence of the data; (2) each point was on approximately the same slope to control for errors caused by topographical differences; and (3) each point was about 20 m from the forest edge to control the influence of the plant community on noise attenuation.

Analyses of sound and schedule of recording

Nine song meter SM4 recorders were used for passive acoustic monitoring (Fig. 1a) and set to record ambient sounds for one minute every ten minutes in each forest (Fig. 1c) over a one-year period (October 19, 2021–October 9, 2022), obtaining 1,296 samples per day. To ensure that the complete natural (biophony) and anthropogenic (anthrophony) sound spectrum was recorded, a stereo set up at 16-bit audio with a 32 kHz sampling rate was used. To avoid ground reverberation on the audio recording equipment, the equipment was fixed to a healthy tree that was ≥ 10 cm DBH. Based on meteorological data, sound observations containing rain and wind sounds were excluded. As a result, 388,368 min of valid data were obtained.
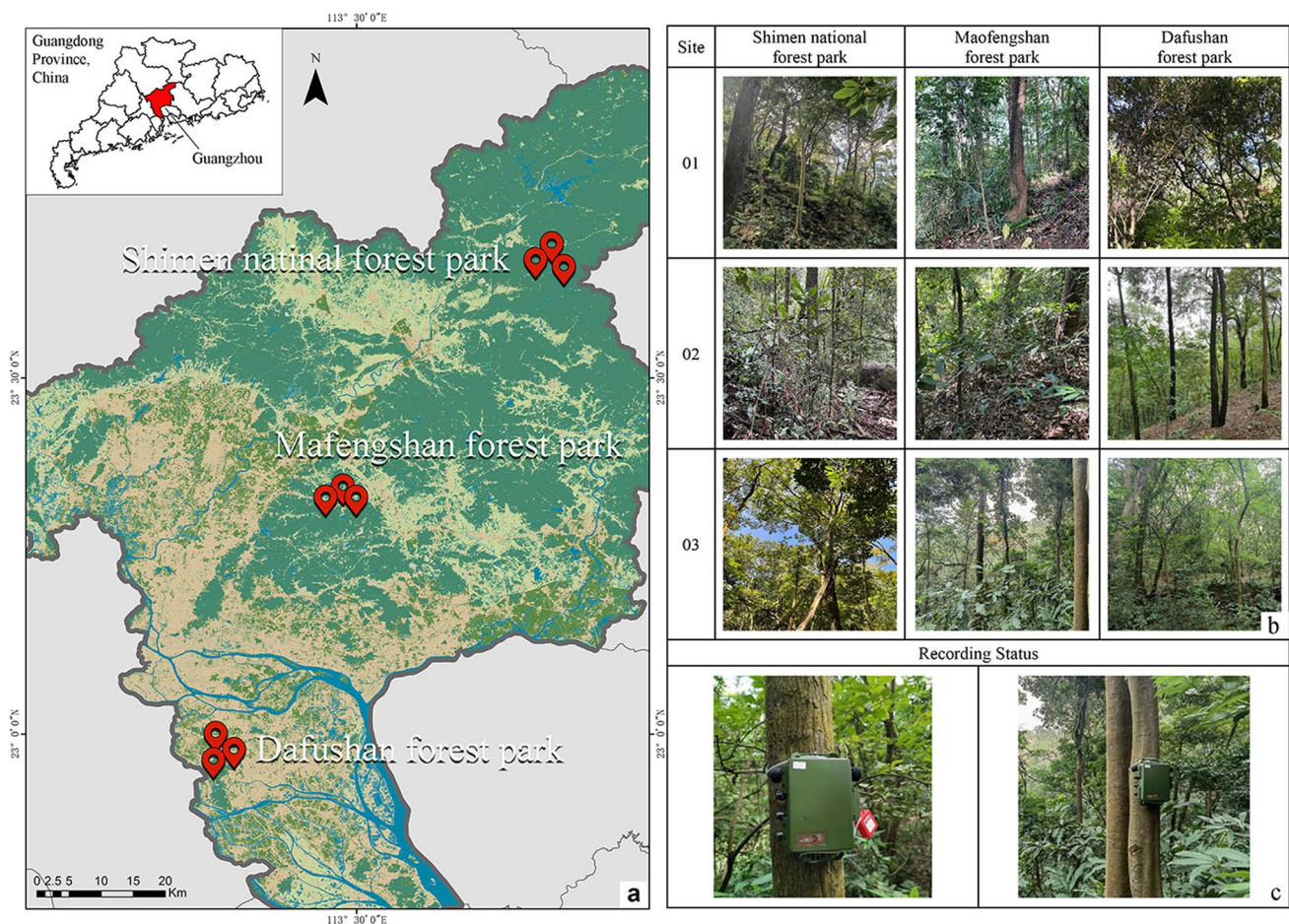
Fig. 1 Study area and distribution of recording sites. **a** Nine urban forests were selected as recording sites and are indicated by red dots; **b** nine recording sites consisted of broad-leaf evergreen forests in the southern subtropics; **c** the Song Meter SM4 recording box in recording plots

Acoustic scene classification model

To evaluate the bioacoustic data, we constructed an acoustic scene classification model using a convolutional neural network (CNN; Hao et al. 2022). An original acoustic scene classification model includes seven types of acoustic scenes: bird, insect, bird-insect, bird-human, insect-human, and human sounds, and silence. Overall, the F1 score (the summed average of precision and recall, with a maximum of 1 and a minimum of 0) of the model was 0.97, the precision was 0.96, and the recall was 0.97. To avoid interference from redundant noise and other biological taxa sounds, bird sounds, bird-human sounds, and human sounds were selected from the classification model's output. For these, the classification accuracy was > 95% (Table 1). The four other sound scenes were not included in this study.

Quantification of sounds

In acoustic scene classification models, the scene types of ambient sound fragments are obtained, but it is still difficult to quantify the intensity of target sounds like biophony and anthropony. Hence, a method for calculating target sound area ratios (TSAR) was devised, in which the decibel mean values are calculated for each frequency point of the spectrogram (Fig. 2). The scale factor is determined to extract the target sound, and its intensity quantified by the ratio of the target sound spectrogram area to the total spectrogram area (Hao et al. 2022). Calculating the TSAR for different frequency bands can help to determine (or help to quantify) how energy is distributed in different acoustic scenes.

Acoustic indices enable a rapid assessment of the dynamic characteristics of acoustic communities. The normalized difference soundscape index (NDSI) is the ratio between biophony (the sounds produced by animals) and anthropony (sounds produced by machinery such as vehicles). The NDSI index is calculated according to the following: (biophony − anthropony)/(biophony + anthropony), where biophony represents the biophony power spectral density (1–11 kHz) and anthropony the anthropony power spectral density (0–1 kHz). NDSI has been found to be closely related to bird diversity in forest environments (Kasten et al. 2012) and can be used to determine the relative importance of biophony and anthropony within a forest (Fuller et al. 2015). NDSI indices were calculated from the "maad.features.soundscape_index" in the alpha acoustic indices module (Ulloa et al. 2021), ported from the seewave (Sueur et al. 2008) and soundecology R packages (Villanueva-Rivera et al. 2018).

Sound pressure level (SPL) is a measure of effective sound pressure compared to a standard value on a logarithmic scale and is typically expressed in decibels (dB). Previous research has shown that attenuation curves for sound in different frequency bands vary significantly (Huisman and Attenborough 1991). Hence, using SPL, it is possible to quantify the frequency-varying energy distribution in biophony and anthropony, with implications for understanding the relationship between complex acoustic signals such as those of birds and their environment. A frequency interval of 1 kHz divided sound fragments into 11 frequency bands (0–1 kHz, 1–2 kHz, and on up to 11 kHz), and the SPL for each frequency band was calculated separately using the Python soundscape analysis toolkit maad (Ulloa et al. 2021).

Vegetation structure parameters

Terrestrial laser scanning (TLS) measurements

Vegetation was measured using a RIEGL VZ-400i terrestrial laser scanner (RIEGL Laser Measurement Systems GmbH, Austria) mounted on a tripod. The VZ-400i operates at a wavelength of 1550 nm with a laser pulse repetition rate

Table 1 Quantity of learning samples used to train an acoustic scene classification model and the performance of the model after training

Acoustic scenes	Description	Learning samples		Model performance		
		Quantity	Total duration (min)	Precision	Recall	F1 score
Bird sound	A sound segment exclusively featuring vocalizations produced by various bird species, encompassing chirps or songs emitted by these birds	1,271	105.92	0.96	0.95	0.96
Human sound	A sound segment exclusively consisting of anthropony, encompassing sounds like car sirens, conversations, music, and construction noises	473	39.42	0.98	0.99	0.99
Bird-human sound	A sound segment with bird sounds and human sounds occurred simultaneously	519	43.25	0.96	0.98	0.98

The learning samples are composed of four-second audio segments with quantity representing the number of learning samples and total duration the total duration of the sample data set for the given acoustic environment, which is calculated in minutes. Precision is the fraction of relevant instances among the retrieved instances, recall the fraction of relevant instances retrieved, and F1 score the harmonic mean of precision and recall. These metrics are used to evaluate the performance of the classification model

set to 1200 kHz and records four returns per outgoing pulse with a range up to 250 m. For each plot, one central scanning position and 'four' other scanning positions were used (Fig. 3). Each recording plot obtained up to 1,200 m^2 of high-resolution point cloud data. The point cloud data from each scan were pre-processed by the automatic registration module in the RiSCAN Pro software (RIEGL Horn, Austria). Pre-processing of the point cloud data by LiDAR 360 software (Green Valley Company, China) included subsampling (minimum points spacing set to 0.001), removing outliers (the number of neighbor points is 10; the multiples of standard deviations is 5), and classifying ground points. We used the TLS seed point editor function in the TLS forest module of LiDAR 360 to manually complete the segmentation of the forest point clouds into individual trees (Fig. 3).

TLS derived parameters

Individual tree structures based on quantitative structure models (QSM) (Calders et al. 2015) were measured to determine a non-destructive estimation of above-ground biomass, with a high agreement with the reference values from destructive sampling. The individual trees within the nine recording plots were segmented using LiDAR 360, followed by calculating the single-number tree attributes (Table 2) from the quantitative structure models using TreeQSM software in MATLAB (Raumonen et al. 2013).

Using a voxel approach, a data frame of 3D voxel information (xyz) with leaf area density (LAD) values from the file described the vertical diversity and density of forest structure at different horizontal heights (resolution = 0.5 m). The voxel dimension allows a fine description of the horizontal component of forest layers. Based on LAD, the leaf area index (LAI) was calculated for six height ranges (< 2 m, 2–5 m, 5–10 m, 10–15 m, 15–20 m, > 20 m). Point cloud data were pixelized, and vegetation structure parameters calculated using the leaf R package (Almeida et al. 2019) in R.

Statistical analysis

To clarify the relationship between anthropogenic noise and bird sounds in terms of frequency distribution and to reveal the acoustic niche pattern of forested ecosystems, we compared the differences in dominance of target sounds across different urban forests using a two-way mixed ANOVA. TSAR in bird sounds, bird-human, and human acoustic scenes was set as the dependent variable, and the recording sites and frequency bands were set as between-subjects (fixed effects) and within-subjects (random effects), respectively, and the interaction effect tested between recording sites and frequency bands on TSAR. For each combination of factor levels, values of the Shapiro–Wilk test were computed. The Levene's and Box's M-tests were used to evaluate the homogeneity of variance and covariance. All analyses were conducted in R using the rstatix package.

To assess the influence on each acoustic scene and NDSI, we constructed a random forest regression model to screen vegetation factors affecting acoustic indices and to evaluate the explanatory power of various vegetation and structural factors on acoustic indices. In the random forest regression model, NDSI was the dependent variable, while individual tree parameters and forest structural parameters were independent variables. A substitution test (N = 99) was used to calculate the explanatory power (R^2) and significance (p-value) of vegetation factors on the NDSI model. NDSI was calculated by ranking increase in MSE (%IncMSE) as the importance ranking for the independent variables. The relative importance and significance of vegetation factors were calculated based on the IncMSE index. The optimal number of attempts (ntry) for fitting the different models was determined by a recurrent function based on iterative calculations of out-of-bag (OOB) data. The analytical analysis was implemented using the randomForest, rfUtilities, and rfPermute packages in R.

Redundancy analysis (RDA) was employed to test the potential differences in bird sound responses to vegetation structure among different frequency intervals. The environmental data were transformed with the Hellinger transformation. According to the results of the RDA, the short gradient along the first axis was < 3, which meant that RDA was a better fit for our data than canonical correlation analysis. SPL in each frequency band (N = 11) were treated as species variables and used to determine the distribution of target sounds in different frequency bands. Model performance was determined by adjusted R2, and the model, axes, and explanatory variables were evaluated by Monte Carlo (MC) permutations (N = 99). RDA were conducted using the vegan and rdacca.hp (Lai et al. 2022) packages in R.
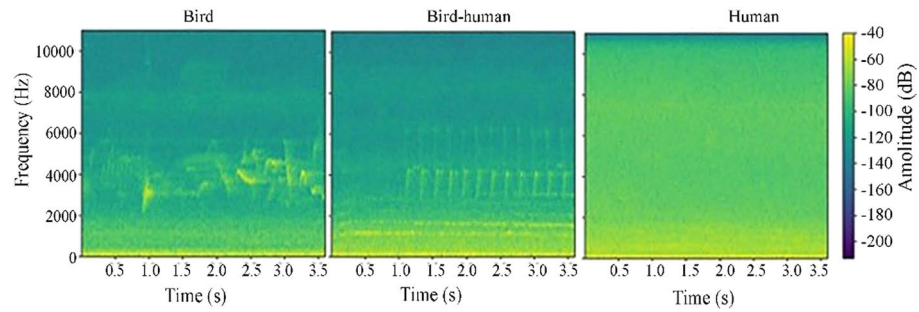
Results

Acoustic scene dominance

The three acoustic scenes (bird, bird-human, and human) exhibited different TSAR distributions. The frequency distribution in the human sound scene showed that anthrophony was predominantly located at lower frequencies (1–2 kHz). In comparison, the TSAR peaks at 3–4 kHz for bird and bird-human scenes had higher values in the 2–4 kHz range for the bird scene but lower ones in the 4–7 kHz range compared to bird-human scene (Fig. 4). This indicates that anthropogenic noises affect the acoustic niche of birds.

The TSARs in the bird-human scene were significantly different between frequency bands ($F_{10, 60} = 56.85$, $p < 0.001$), but the interaction between recording sites
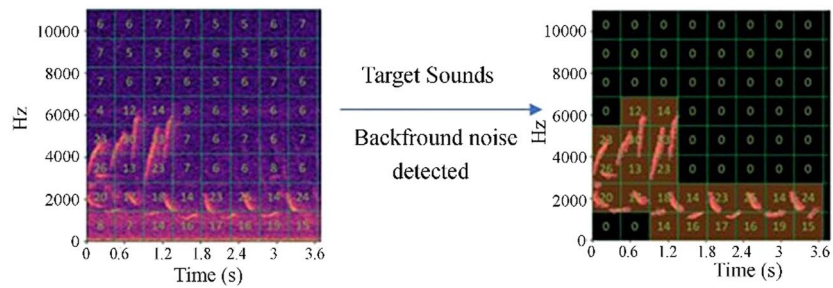
Step 1:
Sound recording
& pre-processing

4 s   4 s

Sample 1   Sample 2   Sample 3   ......
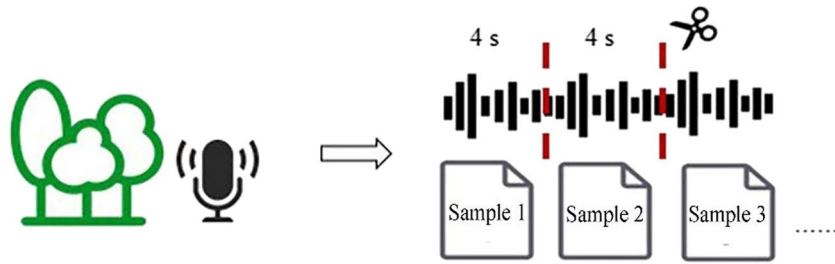
Step 2: Acoustic
scene
classification
model

Bird   Bird-human   Human

(1) Target sound area ratio (TSAR)

Target Sounds

Backfround noise
detected

(2) Normalized difference soundscape index (NDSI)

Step 3:
Sound analysis

Biophony (β):   Sum of the PSD in 1-11 kHZ

$$NDSI = \frac{\beta - \alpha}{\beta + \alpha}$$

Anthrophony (α)   Sum of the PSD in 0-1 kHz
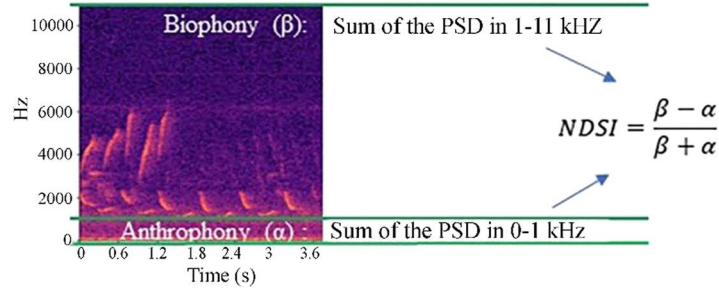
(3) Sound pressure level (SPL) in each band

1000 Hz

SPL caculated to each
frequency band

Bands	SPL
0-1	65.8
1-2	57.3
2-3	45.1
3-4	51.5
4-5	54.3
5-6	46.1
...	...
8-9	33.2
9-10	27.1
10-11	18.5
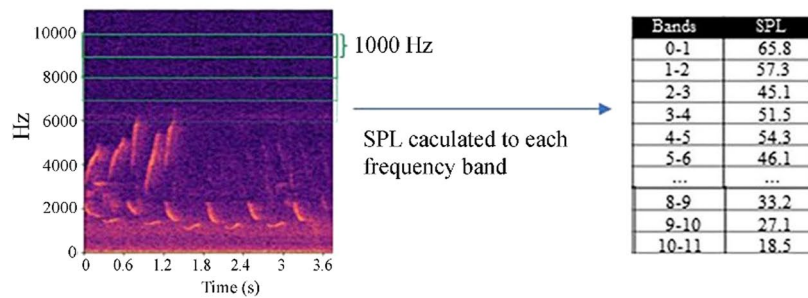
◄**Fig. 2** Workflow steps used to assess the soundscape information in different acoustic scenes. In step 1, each original sound file recorded is cut into 4 s segments. In step 2, each segment is subjected to an acoustic scene classification model. The acoustic scenes of bird, bird-human, and human were selected from the results of all sound classifications for this study. In step 3, TSAR, NDSI, and SPL quantified the characteristics of sound signals in the frequency domain and energy for the three acoustic scenes

and frequency bands was not significant. The frequency bands in the bird-human and human scenes (bird-human: $F_{10, 60} = 213.78$, $p < 0.001$; human: $F_{10, 60} = 3004.07$, $p < 0.001$) were significantly different, and the interaction between recording sites and frequency bands were also significant (bird-human: $F_{20, 60} = 4.19$, $p < 0.001$; human: $F_{20, 60} = 9.54$, $p < 0.001$).

Effects of vegetation structure on bird sounds

From the perspective of model interpretation in random forests (R-squared values), the influence of vegetation on NDSI in the three acoustic scenes was > 0.50 and ranked in the following order: bird-human (0.59), bird (0.57), and human (0.53). Trunk volume, number of branches, and LAI1115 (height range 11–15 m) had the greatest impact on NDSI for bird and bird-human sound scenes (Fig. 5). The NDSI of the human scene was influenced by three primary vegetation factors: trunk volume, crown base height, and number of branches. Branch volume, trunk area, tree height, LAI, and DBH were secondary factors.

The normalized differences soundscape index (NDSI) is primarily influenced by trunk volume and number of branches in various acoustic scenes (Fig. 6). The biophony power spectral density increased with trunk volume in all three scenes but decreased with number of branches, which were shown to have a negative impact on high-frequency sounds (e.g., bird song), whereas trunk volume had a positive impact.

Response of sound frequency and pressure to vegetation factors

Redundancy analysis detected relationships between the sound pressure level (SPL) in different frequency bands and vegetation factors (Table 3, Fig. 7). Vegetation factors had high explanatory power for the SPL in different frequency bands of acoustic scenes, including explaining more than 40% of the variation in bird, bird-human, and human scenes. The vegetation factor had the highest R^2 at 0.48 for explaining bird sounds in different frequency bands by permutation test.

The SPL in different frequency bands across acoustic scenes was obviously correlated with vegetation factors, but patterns varied slightly (Fig. 7). In the bird sound scene, the SPL distribution in the 1–3 kHz frequency range showed a significant negative correlation with LAI1115, LAI1620, LAI2135, branch length, total length, and number of branches. In the bird-human sound scene, the SPL in the 2–4 kHz frequency range showed significant correlation with LAI1115, LAI1620, and LAI2135 and positive correlation with branch volume, and the SPL in the human sound scene was significantly correlated with branch volume in the 0–1 kHz frequency range. Combined with the relationship between SPL and vegetation factors at 0–1 kHz in different sound scenes, the LAI-related parameters and height-related parameters showed positive correlations, while there was a negative correlation with volume. Accordingly, the results of the RDA and random forest models on the vegetation factors at low and high frequencies are consistent, indicating that the vegetation structure affect the sound in different frequency bands and have significant differences at the same time.

Discussion

Acoustic methods reveal the encroachment of urban noise on low-frequency space, as direct evidence of the negative impact of anthropogenic noises on urban biodiversity. The soundscapes of different acoustic scenes are an important component of urban forests, providing proof of how bird songs change over space and time and respond to human activities. Our findings indicate that the TSAR distribution of bird sounds in the 1–3 kHz range is higher in pure bird sound scenes compared to scenes with both bird and human sounds, regardless of low or high-energy anthropogenic noise. This finding is consistent with previous studies that showed that birds adjust to noise caused by human activities by changing the frequency distribution of song energy (Cooke et al. 2020). Further, our findings suggest that bird vocalizations exhibit different frequency distributions under anthropogenic noise compared to undisturbed conditions, indicating a possible adaptation strategy (Nemeth and Brumm 2010). Our research found that birds adjust the energy in low frequency ranges to reduce overlap with anthropogenic noise, but such adjustments may impact the efficiency of vocalizations in complex environments (Tarrero et al. 2008). As a result, bird species that are susceptible to alterations in the acoustic environment may decrease in number or leave green spaces (Halfwerk et al. 2011). Future studies should integrate species-specific song recognition models to further clarify how different bird species adapt to human noise. City managers should develop appropriate noise control policies or establish quiet areas to protect wild animals in urban forests.

Urban forests are an important habitat for urban wildlife. Further, our study shows that vegetation structure is a key
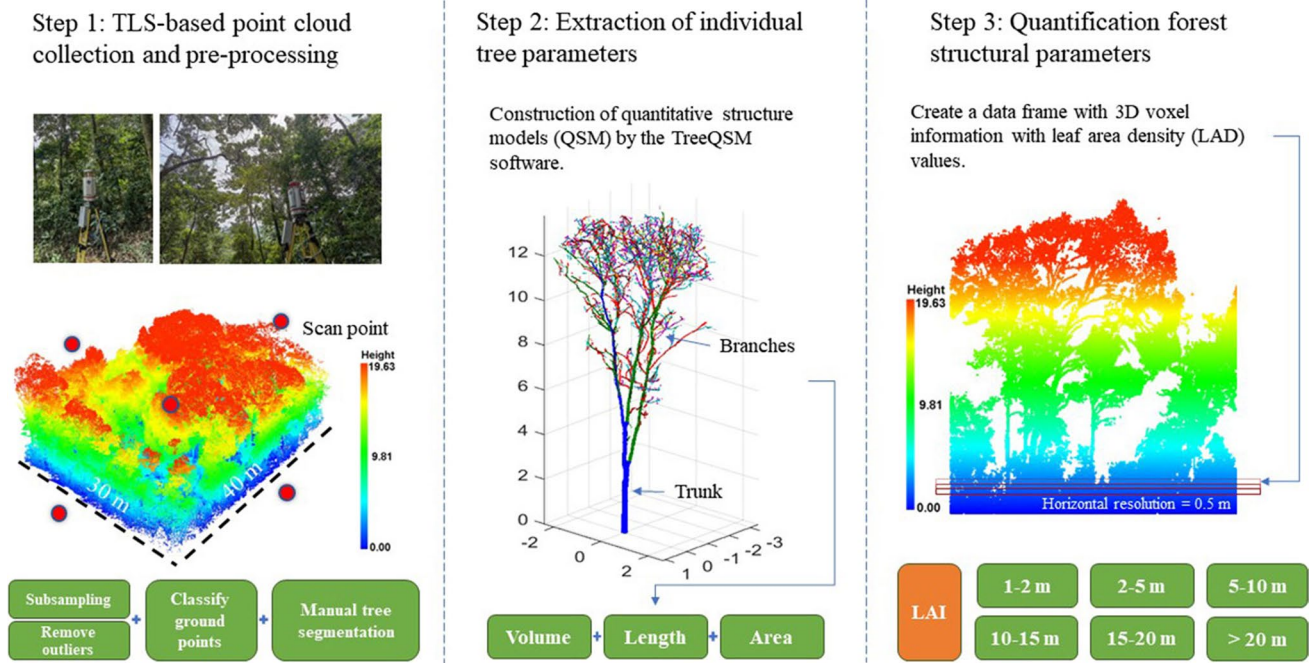
Fig. 3 Process of collecting, processing, and estimating the metrics of individual trees and forest structures with the TLS-based point clouds

Table 2 Glossary of the vegetation structural variables

| Type	Variables	Description
Volumes	Trunk Volume	Volume (L) of the stem
	Branch Volume	Volume (L) of all branches
Length	Tree Height	Height (m) of the tree
	Total Length	Total length (m) of all branches and stem
	Trunk Length	Length (m) of the stem
	Branch Length	Total length (m) of all branches
	Crown Base Height	Crown's base height (m) from the ground
	DBH	DBH (m), the diameter of the cylinder in the QSM
Area	Trunk Area	Total surface area (m^2) of the stem
	Branch Area	Total surface area (m^2) of the branches
Density	LAI	LAIs calculated from the LAD within the six height ranges (LAI12: 1–2 m, LAI35: 3–5 m, LAI610: 6–10 m, LAI1115: 11–15 m, LAI1620: 16–20 m, LAI2135: > 20 m)
	Number of Branches	Number of branches

Considering that sound transmission in forests may be affected by factors such as trunks, branches, and leaves (Tarrero et al. 2008; Slabbekoorn et al. 2007), twelve structural variables were selected based on the calculations of the TreeQSM model. These variables were derived from TLS, and the metrics were estimated for each scan and then averaged across all scans

factor affecting song adaptation of birds. Volume-related (trunk and branch volumes) and density-related metrics (number of branches and LAI) both had significant influence on bird sounds. The structural components of plants such as leaves, trunks, and branches can impede the transmission range of bird vocalizations and impair individual recognition capabilities, thereby impeding effective inter-bird communication (Richards and Wiley 1980; Slabbekoorn et al. 2002). Vegetation structure is a crucial factor in shaping the vocal environment of birds in habitats with interference from anthropogenic noise (Velez et al. 2015). In comparison to the acoustic scenes that contain a mixture of

Fig. 4 Distribution of TSAR in different frequency bands for bird, bird-human, and human scenes; box plots show the distribution of TSAR only in the 1–7 kHz range
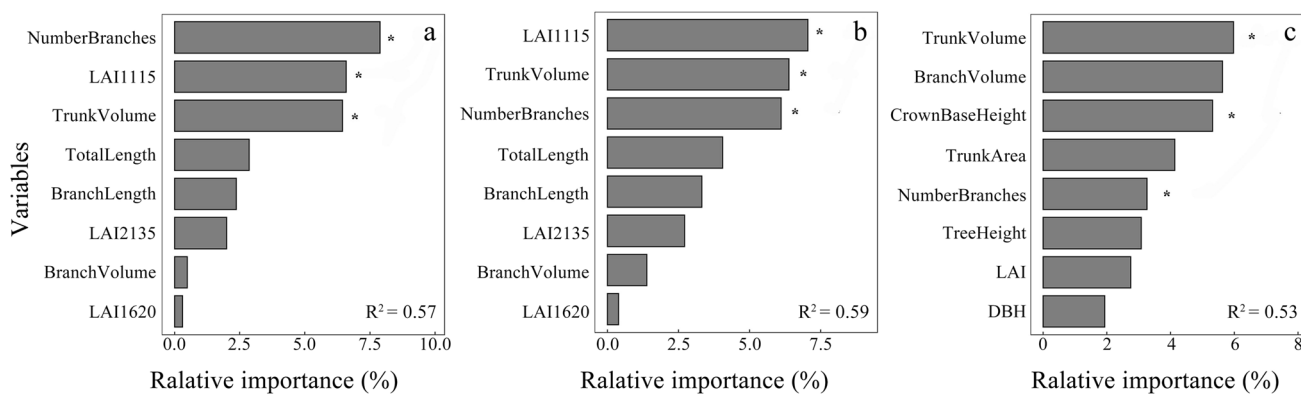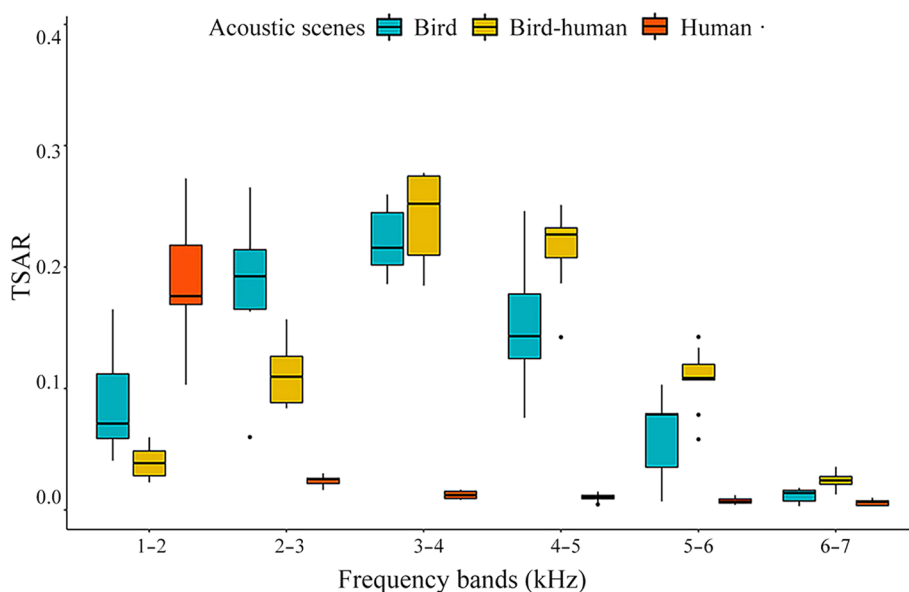

Fig. 5 Relative importance of vegetation factors in **a** bird, **b** bird-human, and **c** human acoustic scenes. The asterisks indicate the vegetation structure variables that were statistically significant in the models

bird and human-made sounds (bird-human acoustic scenes) and acoustic scenes that only contain a single sound source (either bird or human), the results show that acoustic scenes with bird signals exhibit a significant correlation with trunk volume, number of branches, and LAI for various height ranges. Among them, volume-related vegetation factors, such as trunk volume, had a positive effect on biophony, whereas the number of branches and LAI had a negative effect across various height layers. However, an acoustic scene containing both human and bird sounds had a higher frequency band of energy distribution compared to one with only bird sounds. Previous studies have shown that leaf and branch absorption and scattering of acoustic signals increase with frequency (Francomano et al. 2021). Even though birds can adjust the way they distribute their sound energy in response to anthropogenic noise, the modified frequency of their sounds may still be negatively impacted by the

vegetation structure (Velez et al. 2015). Bird vocalizations in noisy environments shift towards mid- to high-frequency communication, with weaker transmission efficiency compared to low-frequency sounds (To et al. 2021). Our findings suggest correlations between tree trunks, branches, and bird sounds, indicating that habitats with open understory spaces and large trees are ideal for vocalization. When managing urban forests, it is important to consider protecting and creating diverse vegetation structures to support biodiversity and improve acoustic environments.

The effect of vegetation structure on different frequency ranges of sounds is inconsistent, with anthropogenic noise having a contrasting relationship compared to bird sounds in terms of trunk volume, number of branches, and LAI for various heights. Highly dense vegetation has limited impact on the attenuation of low-frequency and high-energy anthropogenic noise (Ow and Ghosh 2017), and
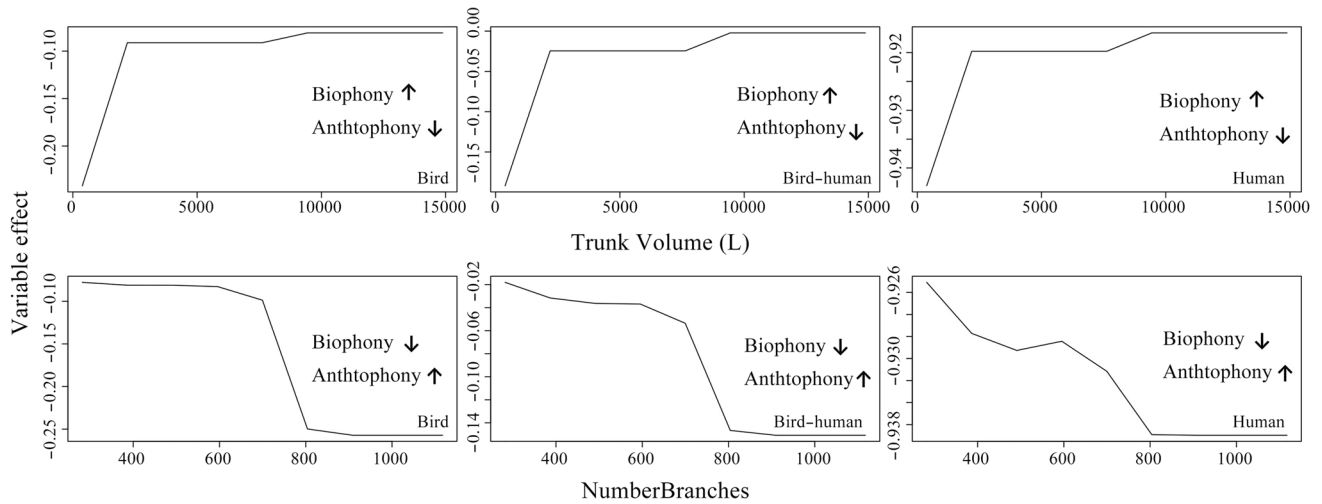
Fig. 6 Partial dependence plots of NDSI for trunk volume and number of branches. An increase in trunk volume resulted in an increase in biophony and a decrease in anthrophony for bird, bird-human, and human scenarios, while an increase in number of branches resulted in a decrease in biophony and an increase in anthrophony. Note: biophony represents the sum of power spectral densities in the 1–11 kHz interval, and anthrophony the sum of power spectral densities in the 0–1 kHz interval

having a higher crown base height actually facilitates the transmission of noise through the vegetation structure. The findings of this study support previous research that suggests that green spaces composed of a mixture of tree, shrub, and grass components effectively reduce noise compared to pure tree or shrub structures (Martinez-Sala et al. 2006). However, the results of this study revealed a negative growth in the normalized difference soundscape index with an increase in branch density, potentially attributed to the attenuation of bioacoustic intensity within high-density vegetation environments. It is worth noting that anthrophony energy exhibited an opposite trend compared to previous research findings, highlighting the need for further investigation into the influence of branches on anthropogenic noise mechanisms. While such habitats may be conducive to sound propagation, they may be suboptimal for many bird species due to limitations in foraging and nesting opportunities. Anthropogenic noise, characterized by low frequencies ranging from 0 to 2 kHz, and bird sounds, characterized by high frequencies ranging from 2 to 5 kHz, differ in terms of their frequency-time domain composition and their response to vegetation structure. The domina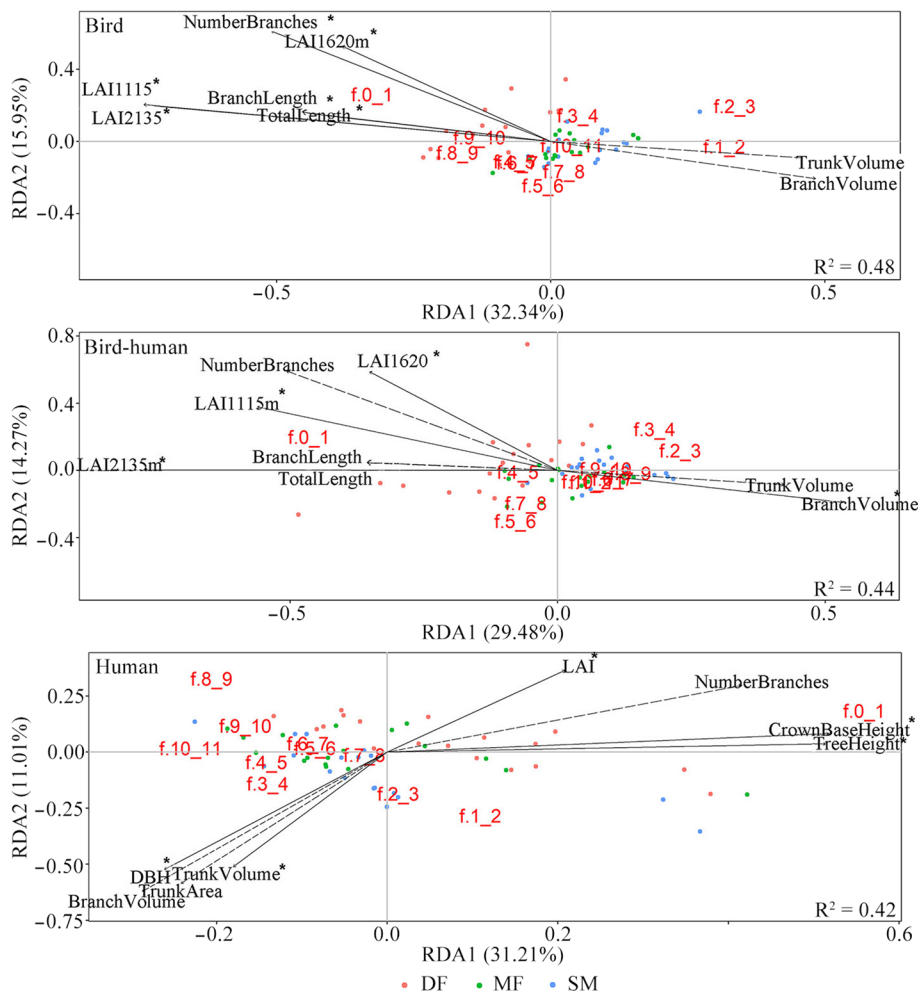nt form of anthropogenic noise in this study was low-frequency traffic sounds, the most prevalent type of anthropogenic noise (Proppe et al. 2013). The traffic sound energy of the signal is mainly concentrated in the frequency of 500–2000 Hz, and it exhibits low frequency and extended duration characteristics (Kern and Radford 2016). According to previous research, bird calls react differently to different types of anthropogenic noise (Shannon et al. 2016), suggesting that the relationship between anthropogenic noise and bird calls should not be solely studied in the context of traffic noise (Nemeth et al. 2013).

Sensing and protecting urban biodiversity through the perspective of sound may become a new research topic in the future. Some countries have established national acoustic observation networks and collected acoustic resource data using automatic recording sensors (Roe et al. 2021). Passive acoustic monitoring technology and artificial intelligence-based sound analysis have become a focus of numerous laboratories and companies (Lahoz-Monfort and Magrath 2021). By integrating smart city technologies with sound-related monitoring data (Du et al. 2019) or developing mobile sound collection applications (Green and Murphy 2020), it may be possible to discover and utilize more environmental sound data. By accumulating these data, we can gain a more comprehensive understanding of noise sources, propagation mechanisms, and environmental impacts in forest ecosystems. Laser scanning platforms, such as satellites, aircraft, drones, and ground mobile platforms, can provide multi-temporal and spatial monitoring and facilitate the analysis of forest structure (Newnham et al. 2015). Further monitoring and evaluation of environmental data on sound and plants can be useful in better understanding the

Table 3 Permutation tests of variance explained by vegetation factors in RDAs

Acoustic scenes	Df	F-value	p value	Adjusted R²
Bird	8	3.89	0.001	0.48
Bird-human	8	3.07	0.001	0.44
Human	8	4.82	0.001	0.42

Fig. 7 RDA and the relationship between vegetation factors and SPL in different frequency bands; asterisks indicate the significance of the vegetation structure variable in the RDA

Conclusions

Urban forests play a crucial role in maintaining ecological balance and promoting biodiversity within cities. However, the presence of anthropogenic noise and often inadequate vegetation structure in these forests may result in adverse effects on urban biodiversity. Therefore, it is important to determine how designed vegetation structures can effectively mitigate the impacts of noise pollution while providing suitable habitats for urban wildlife. In this study, we found that vegetation structure played a significant role in shaping bird sounds and that the response to low frequency signals, such as anthropogenic noise, and high frequency signals, such as bird calls, to vegetation structure is distinct. By reducing the impact of anthropogenic noise and creating suitable habitats for birds, vegetation structure in green spaces can be strategically designed to effectively conserve urban biodiversity. The acoustic vision provides a valuable addition to traditional visually based analyses of urban forests. An acoustic-based approach can provide urban planners and

impacts of human activities on wildlife and ecosystems and the potential of forests in creating healthy, safe, and comfortable acoustic spaces.

The results of this study have provided evidence of the impact of vegetation structure and anthropogenic noise on bird vocalizations in urban forests, but we acknowledge that there are some limitations in this study. The investigation of the urbanization gradient in this study still presents certain deficiencies. Future research should aim to examine vocalization responses across additional passive acoustic monitoring sites, encompassing a wider range of urbanization gradients and extending over longer periods. This may be more conducive to understanding the complex effects of chronic noise on urban wildlife during urbanization. Additionally, future research might also consist of playback experiments of bird sounds or anthropogenic noise to verify the distance of sound propagation in different urban forests, which may allow further elaboration of the role of vegetation structure in constructing the acoustic space of urban forests.

municipal administrators with the key indicators necessary to create better green spaces that engage multiple senses, and to evaluate the effectiveness of bird habitat restoration efforts in urban forests worldwide.

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