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Impact of landscape attributes on the noise reduction effects of heritage landscapes

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Abstract

Heritage landscapes provide a cost-effective solution for mitigating noise and creating adaptable open spaces in urban ecological construction and planning. In this study, we examined 27 distinct landscapes in a city in northern China to assess their effectiveness in reducing traffic-related noise. The acoustic properties of the landscapes, considering various surfaces, slopes, elevations, structures, and topography, were systematically analysed and compared. The findings indicate that vertically rigid descending landscapes exhibit the highest acoustic performance, followed by vertically flexible dense landscapes without slopes. Additionally, the noise reduction effects of horizontal landscapes with rough rigid surfaces surpass those of landscapes covered by low-growing vegetation and landscapes with sparse high-growing vegetation. The insights derived from this study can enhance our understanding of heritage landscapes, provide valuable information for their protection and micro-updates, and support quantitative research in this field.

Keywords Landscape attribute, Noise reduction effect, Horizontal heritage landscape, Traffic noise, Vertical heritage landscape

Introduction

Heritage landscapes represent the symbiotic relationship between human activities and natural processes, encapsulating cultural heritage shaped by extensive historical practices in agriculture, society, industry, and the military. These landscapes serve as invaluable educational resources, enhancing understanding of history, archaeology, and environmental science. Moreover, they contribute to local tourism and recreational activities, serving as economic assets and fostering social cohesion within communities [1].

The impact of traffic noise on heritage sites is multifaceted, involving the deterioration of physical structures due to continuous vibrations and sound waves. This can be particularly detrimental to sites with fragile architecture or materials sensitive to vibrations [2]. Additionally, excessive traffic noise significantly compromises the ambiance and setting integral to the historical and cultural experience offered by these sites, hampering visitors' engagement with the historical context of the site [3]. Moreover, the presence of traffic noise adversely affects wildlife inhabiting some heritage sites, potentially leading to altered natural behaviours and a decrease in biodiversity in the area [4]. Lastly, the soundscape of some heritage sites holds significant conservation value in its own right and will be severely impacted by traffic noise [5].

Therefore, implementing an effective noise reduction strategy for traffic noise is paramount in heritage sites. However, conventional noise reduction methods, such as insulation barriers and rigid noise walls [6, 7], suffer from poor aesthetics and limited functionality in urban planning. Additionally, their unsustainable cost implications can have a detrimental impact on heritage values.

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The method of noise reduction employing the acoustic characteristics of landscapes with micro-adjustments in heritage sites is reasonable. Accordingly, the noise reduction effect in this study is characterised by the absorption, reflection, scattering, and insulation of traffic noise by the heritage landscapes, leading to a reduction in the noise levels of traffic across various frequency bands.

Several studies have investigated the potential acoustic benefits of heritage landscapes in mitigating traffic noise. For instance, roughening the surfaces of intermediate areas or embankments between roads and public spaces has good noise reduction effects because it can effectively reduce the acoustic level of traffic noise [8]. Strategically configuring the perimeters of large open spaces with greenery landscapes contributes to acoustic insulation via the viscoelastic effect. The leaves of tree landscapes can effectively dampen propagating sounds, reducing total noise levels; this effect is more pronounced for high-frequency sounds [9]. Similarly, the exposed soil of vegetation landscapes can cause destructive interference in propagating sound waves [10]. Low-growing vegetation landscapes, by softening the soil and transforming it into a porous sound-absorbing material, can be particularly effective for noises below the 1000 Hz band. An artificial mound with vegetation as part of the heritage landscape can also serve as an effective noise reduction barrier, exemplified by the case of Brooklyn Bridge Park in New York City, which absorbs traffic noise from the Brooklyn Bridge Queens Highway.

Landscape attributes, encompassing the fundamental characteristics of physical, biological, or cultural elements, play significant roles in determining the noise reduction effects of heritage landscapes. Key attributes include structure, function, dynamics, and visual and sensory quality. Structural attributes include the type and form of vegetation, vertical structure, and topography [11]. Previous research has focused on parameters related to tree belts, including visibility [12], length, height, width [13], arrangement [14], flow resistivity, and porosity [15]. Notably, the noise reduction effects of tree belts become evident only when their width exceeds 30 m [13].

However, the impact of landscape attributes on the noise reduction effects of heritage landscapes was not systematically studied. Therefore, this study aims to provide a reliable noise reduction strategy that can alter the direction of traffic-noise transmission, potentially working in conjunction with sound absorption by tree belts.

This study addresses three main questions:

1) What is the impact of the types and forms of heritage landscapes on noise reduction effects?
2) How do noise reduction levels differ with varying vertical structures within heritage landscapes?
3) How does the topography of heritage landscapes affect noise reduction effects?

Materials and methods

Survey site

A preliminary investigation was conducted to categorize landscape types based on their impact on traffic noise. To ensure measurement accuracy and consistency, noise measurement locations were strategically chosen near main traffic roads. These two-way roads, with a minimum of four lanes in each direction, served as the primary sources of traffic sound.

Harbin, a renowned historical and cultural city in China, was selected as the focal point for this study owing to the profound influence of its urban open space heritage landscapes on urban conservation. We selected 27 representative heritage landscapes for measurement based on literature reviews and social media attention. The selection process considered the potential impact of other sound sources, and heritage landscapes susceptible to such influences were excluded within a 20-m radius of the survey site.

The measured landscapes were classified into two categories: horizontal and vertical (Fig. 1), based on their impact on the absorption and reflection of traffic noise, following the approach outlined by Tyagi et al. [16]. Horizontal landscapes, typically used for pavements, artificial ramps, and lower vegetation, had heights of less than 0.5 m. For horizontal landscapes, three materials commonly used in urban open spaces were considered: concrete ground, grass, and flower fields. Vertical landscapes were further divided into three types: vertical flexible landscapes (e.g. tree belts and shrub belts), which primarily absorb traffic sound energy; vertical rigid landscapes (e.g. concrete steps), which mainly reflect traffic sound energy; and vertical mixed landscapes (e.g. earthen mounds with vegetation), which absorb, reflect, and insulate traffic sound energy. Earthen mounds, particularly relevant in city park planning and design, offer elevated recreational spaces for users and can be constructed using recycled construction waste.

Landscape attributes classification

To investigate the impact of heritage landscape types on noise reduction effects, six horizontal landscapes were evaluated, comprising three without slopes (H1-1, H1-2, H1-3; Fig. 1) and three with slopes (H2-1, H2-2, H2-3). The surfaces of landscapes H1-1 and H2-1 were covered by concrete, and landscapes H1-2, H1-3, H2-2, and H2-3 were covered by low-growing vegetation. Examining the effect of the form of heritage landscapes on noise reduction effects, six vertical flexible landscapes with high-growing vegetation were studied. These included

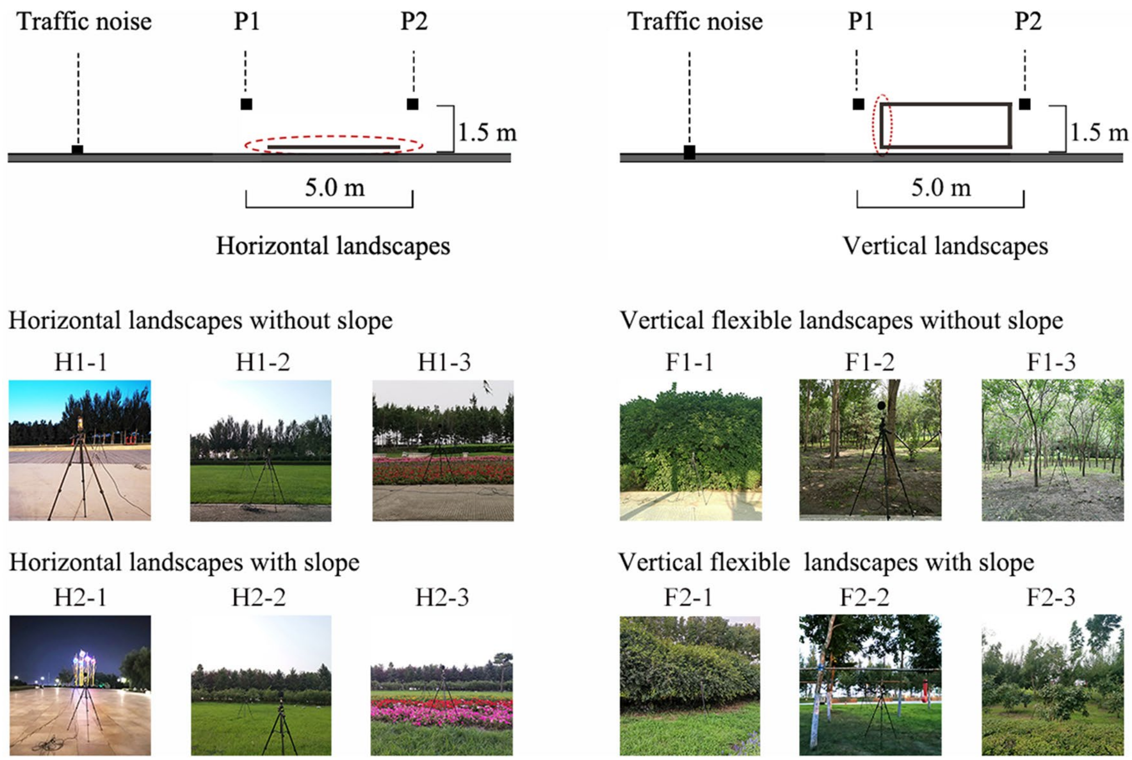

Fig. 1 Sectional views and field measurement photos of horizontal and vertical flexible landscapes. Labels P1 and P2 denote the positions of the acoustic probes

two shrub landscapes with slopes (F1-1; Fig. 1) and without slopes (F2-1), and four tree landscapes with varying slopes and visibilities (F1-2, F1-3, F2-2, F2-3). Notably, the visibilities of F1-2 and F2-2 were higher than those of F1-3 and F2-3.

Regarding the impact of the vertical structure of heritage landscapes on noise reduction effects, three vertical rigid landscapes (R1, R2, and R3 in Fig. 2, with P1 to P4 denoting acoustic probe positions) covered by rigid stone pavements were assessed. These were further divided into six landscapes (R1-1, R1-2, R2-1, R2-2, R3-1, and R3-2). Three landscapes, namely R1-1, R2-1, and R3-1, had different structural forms, whereas the others (R1-2, R2-2, and R3-2) had varying elevations. The elevations of R1-1, R1-2, R2-1, and R2-2 were higher than that of the main road, whereas those of R3-1 and R3-2 were lower. For instance, the elevation of R1-1, with nine steps, was close to 1.2 m; R2-1, with six steps, was 0.6 m; and R3-1, with five steps, was −2.5 m.

To compare the noise reduction effects of heritage landscapes with various topographies, two vertical mixed landscapes (M1 and M2 in Fig. 3) located in the same park, composed of soil with no significant differences in surface material, were selected. Each landscape was approximately 10 m from the main traffic road. The slope of M1 was steeper, whereas M2 had a more gradual slope. These were divided into twelve smaller landscapes (M1-1, M1-2, M1-3, M1-4, M1-5, M1-6, M2-1, M2-2, M2-3, M2-4, M2-5, M2-6, with P1 to P12 denoting acoustic probe positions), each having a depth of 5.0 m. Landscapes M1-1, M1-2, M1-3, M2-1, M2-2, and M2-3 faced the traffic sounds, whereas M1-4, M1-5, M1-6, M2-4, M2-5, and M2-6 were positioned away from the main road.

Noise reduction effect measurement

For on-site measurement of the noise reduction effects of the selected heritage landscapes, a multi-channel sound level recorder (type: SQuadriga II, manufactured in Germany by HEAD acoustics company) was employed to obtain relevant acoustic data. This included the total equivalent A-weighted sound pressure level (L_{Aeq}) and sound pressure level at octave bands (31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz).

The multi-channel sound level recorder was connected to two external acoustic microphones strategically positioned on opposite sides of the heritage landscape (as illustrated in Fig. 1, with P1 and P2 denoting microphone positions). The distances between traffic sound sources and the landscapes exceeded 1.0 m. The height of each

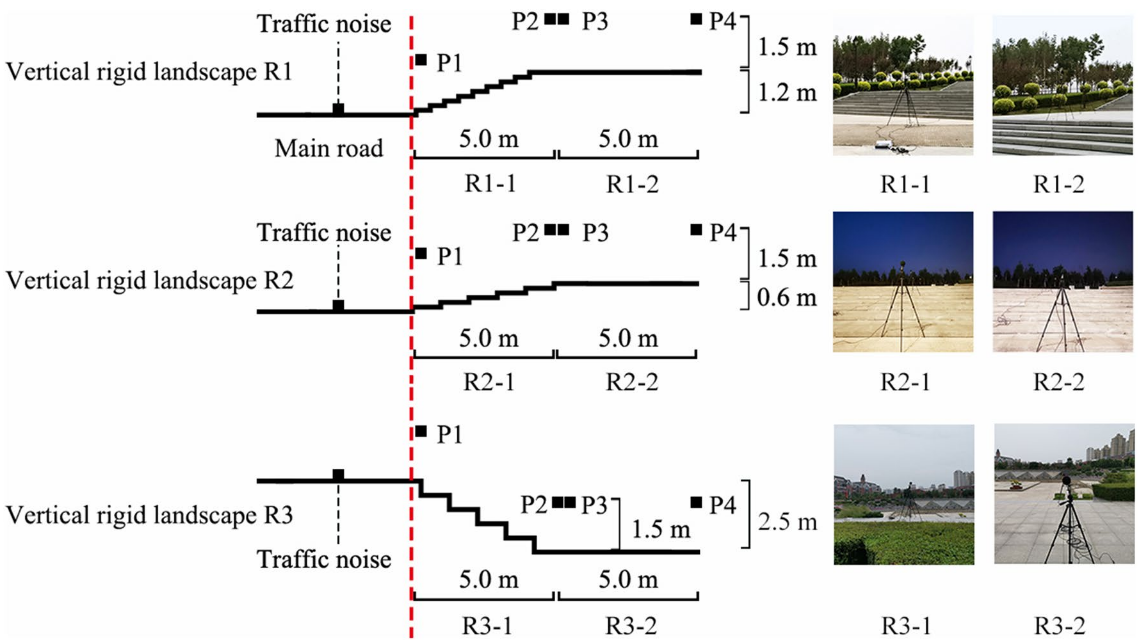

Fig. 2 Sectional views and field measurement photos of vertical rigid landscapes. Labels P1 to P4 denote the positions of the acoustic probes

acoustic microphone was set at 1.5 m, and the distance between the two microphones was 5.0 m [17]. Both microphones were operated simultaneously, continuously recording measurements for a duration of 5 min. Subsequently, the Artemis 12.0 acoustic analysis software was used to analyse and process the acquired acoustic data. In terms of acoustic environment measurement, slow mode and A-weighting were selected, the spectrum was configured to 1/3 octave with A-weighting, and the sampling frequency was set to 48 K. To mitigate the influence of other noise sources, such as surrounding speech, footsteps, and construction sounds, during the measurement, a time period with minimal construction and low crowd activity was selected. Subsequently, the Artemis 12.0 software was utilized to filter out any instantaneous human sounds with prominent waveforms.

In this study, the noise reduction level was employed to assess the noise reduction effects of each landscape. The noise reduction level of each landscape was determined as the reduction in the sound pressure level of traffic noise, calculated by subtracting the value of P1 from P2, recorded by the two microphones. For example, the noise reduction value of landscape H1-1 for traffic noise in the 1000 Hz frequency band was 4.8 dBA, calculated by subtracting 57.8 dBA (P1) from 62.6 dBA (P2).

Figure 4 presents the spectrogram of traffic noise measured on the road near the selected heritage landscapes. The primary acoustic energy of traffic noise is observed to be concentrated in the medium–high frequency bands of 500, 1000, and 2000 Hz. The sound pressure levels in these frequency bands were found to be higher than those in other frequency bands. Consequently, the sound pressure levels in the 500, 1000, and 2000 Hz bands were employed to assess the noise reduction effects of heritage landscapes in this study.

Results

Effects of types of heritage landscapes on noise reduction

Figure 5 illustrates the noise reduction effects of horizontal landscapes in response to traffic sounds. The noise reduction effects of landscapes are influenced by the materials on their surfaces and varying slopes. Sound pressure levels across various frequency bands also differ.

Across each frequency band, landscapes with concrete surfaces and without slopes consistently exhibited higher noise reduction than those with low vegetation and without slopes. For example, the level of noise reduction of landscape H1-1 was 1.1 and 0.8 dBA in the 500 Hz band, 1.0 and 2.0 dBA in the 1000 Hz band, and 1.5 and 5.7 dBA in the 2000 Hz band higher than those of landscapes H1-2 and H1-3, respectively. Consequently, the noise reduction effects of concrete landscapes without slopes were higher than those of low-vegetation landscapes without slopes. The advantage of concrete landscapes on noise reduction was not evident among the landscapes with slopes. For example, the difference in noise reduction levels was minimal (ranging from 0 to 0.1 dBA) between landscapes H2-1 and H2-2 in the 1000 Hz band and between landscapes H2-1 and H2-3 in the 2000 Hz band. It is noteworthy that a variation of

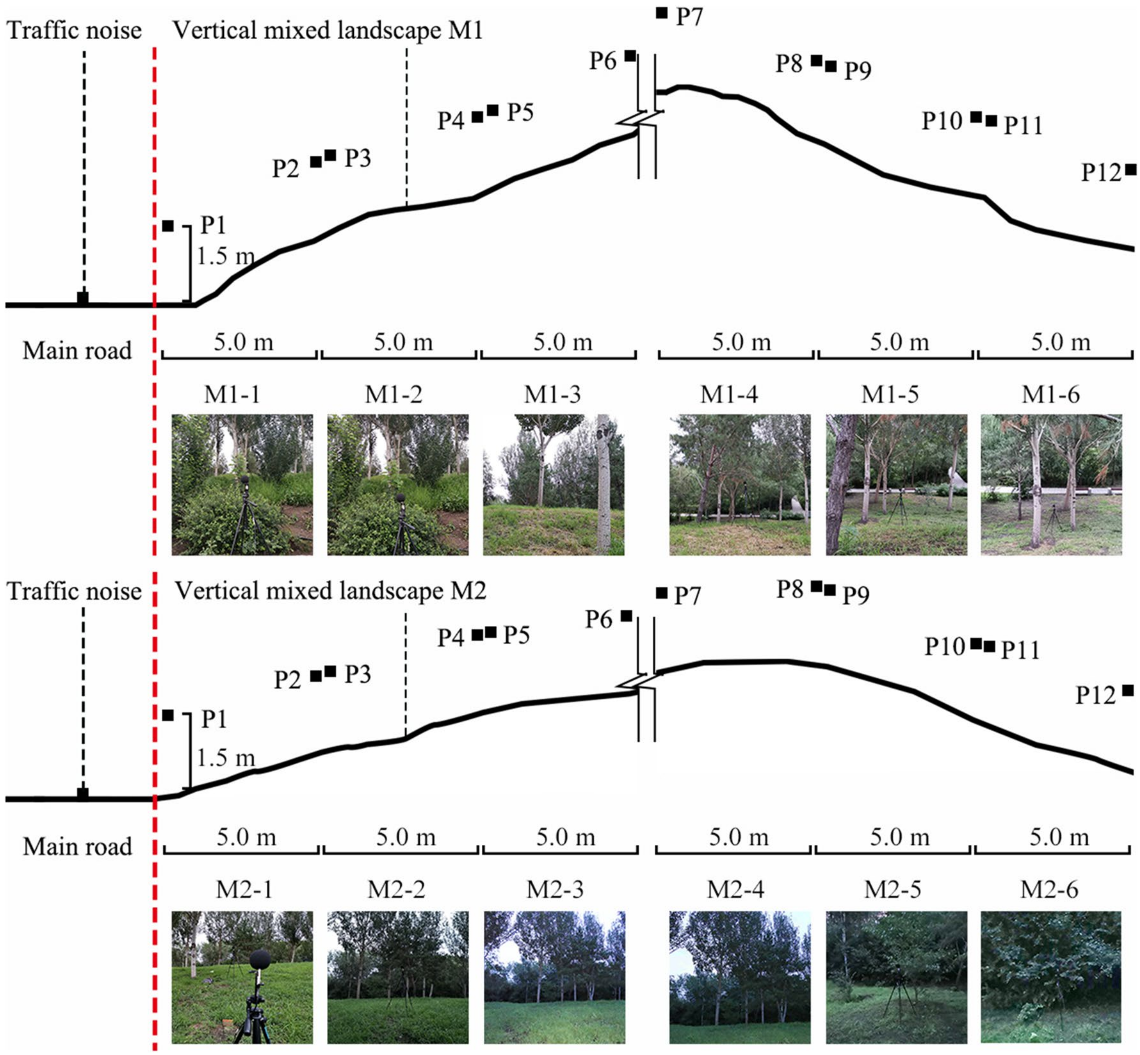

Fig. 3 Sectional views and field measurement photos of vertical mixed landscapes. Labels P1 to P12 denote the positions of the acoustic probes

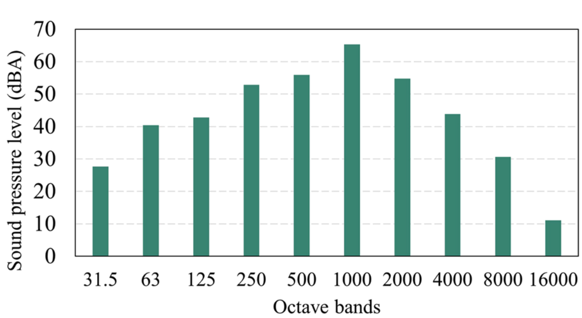

Fig. 4 Spectrogram of traffic noise close to heritage landscapes

0.1 dB is considered insignificant in noise reduction levels. However, notable differences of 3.9 and 4.4 dBA were observed in the 500 Hz frequency band between landscapes H2-1 and H2-2 and between H2-1 and H2-3.

Conversely, the impact of slope on the noise reduction of horizontal landscapes with concrete was not evident. Specifically, the differences in levels between landscapes H1-1 and H2-1 were not substantial, ranging from 0.1 to 0.8 dBA. Similarly, the differences in levels between landscapes H1-2 and H2-2 for traffic sounds ranged from 0.3 to 0.9 dBA.

Effects of form of heritage landscapes on noise reduction

The noise reduction performance at each frequency band is influenced by the form of the landscape. For example, the noise reduction effects of landscapes with shrubs surpassed those of landscapes with trees in the 500 Hz and 2000 Hz bands. Specifically, the noise reduction level of landscape F1-1 was 1.5 dBA higher in the 500 Hz band and 1.3 dBA higher in the 2000 Hz band than that of landscape F1-2, while the noise reduction value of

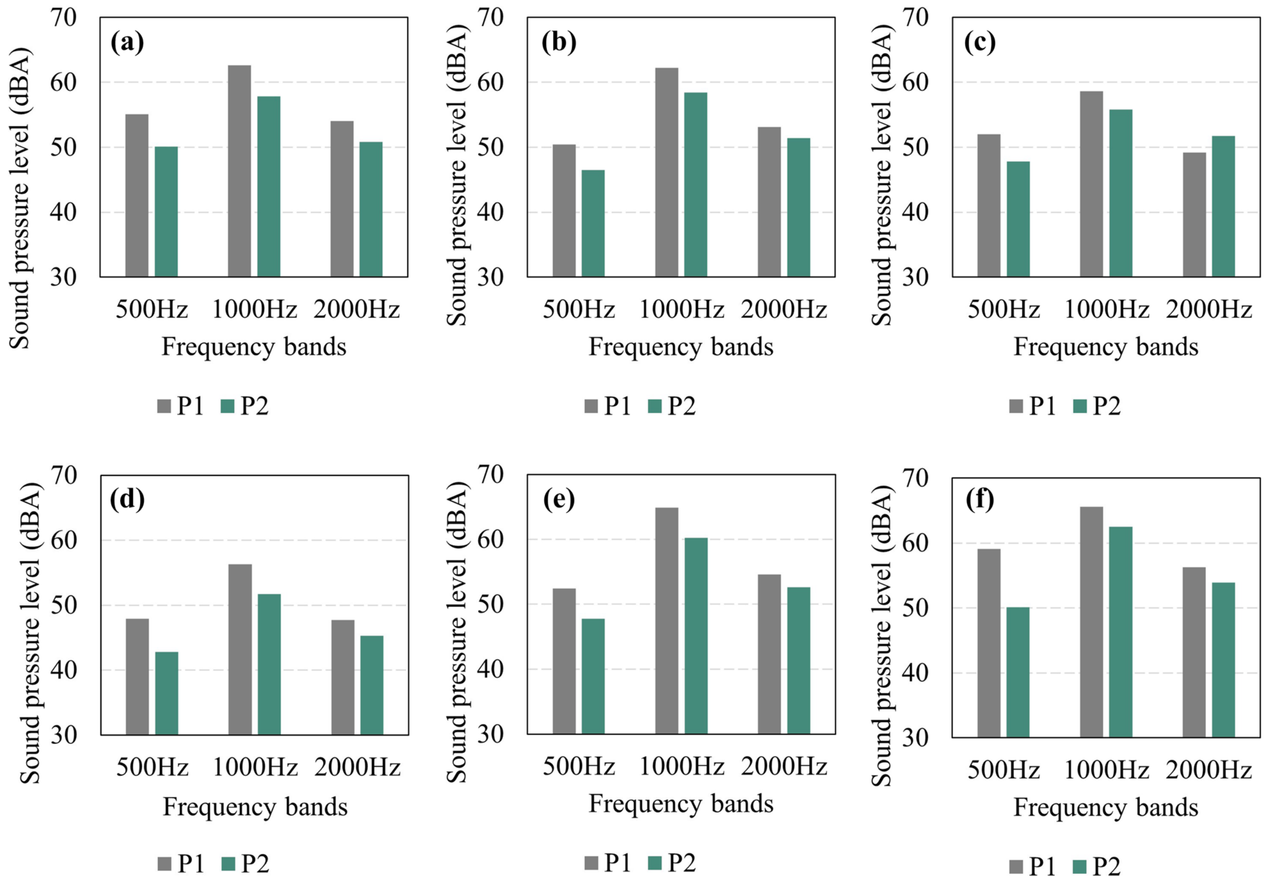

Fig. 5 Sound pressure levels in each frequency band for horizontal landscapes: **a** H1-1, **b** H1-2, **c** H1-3, **d** H2-1, **e** H2-2, **f** H2-3

landscape F1-1 was 0.3 dBA lower in the 1000 Hz band than that of landscape F1-2 (Fig. 6). The noise reduction level of landscape F2-1 was 2.6 dBA higher in the 500 Hz band and 1.7 dBA higher in the 2000 Hz band than that of landscape F2-2, while the noise reduction value of landscape F2-1 was 0.2 dBA lower in the 1000 Hz band compared to landscape F2-2.

The density of vertical flexible landscape also plays a role in influencing the noise reduction effects of landscapes. The noise reduction effects of landscapes with dense trees surpassed those of landscapes with sparse trees. For instance, the noise reduction value of landscape F1-2 was 2.6 dBA higher in the 500 Hz frequency band, 2.9 dBA higher in the 1000 Hz band, and 2.6 dBA higher in the 2000 Hz band than those of landscape F1-3. The noise reduction value of landscape F2-2 was 0.7 dBA higher in the 500 Hz frequency band, 1.1 dBA higher in the 1000 Hz band, and 0 dBA higher in the 2000 Hz band than those of landscape F2-3.

The effects of noise reduction of landscapes were different between dense landscapes with slopes and dense landscapes without slopes. For example, the level of noise reduction of landscape F1-1 was 0.1 dBA higher in the 500 Hz band, 0.5 dBA higher in the 1000 Hz band, and 1.0 dBA higher in the 2000 Hz band than that of landscape F2-1.

Effects of vertical structure of heritage landscapes on noise reduction

In terms of the elevation of vertical rigid landscapes on noise reduction, a lower landscape exhibits better noise reduction effects than a higher landscape. Specifically, the level of noise reduction of landscape R2-1 was 5.1 dBA higher in the 500 Hz band, 1.8 dBA higher in the 1000 Hz band, and 1.4 dBA higher in the 2000 Hz band than that of landscape R1-1 (Fig. 7). However, the noise reduction effects of landscape R1-2 were better than those of landscape R2-2 in the 500 and 1000 Hz band, even if the difference was minimal (ranging from 0.2 to 0.6 dBA).

The difference in noise reduction levels was maximum between landscapes with ascending form and landscapes with descending form. For instance, the noise reduction value of landscape R3-1 was 7.3 and 2.2 dBA higher than those of landscapes R1-1 and R2-1, respectively, in the

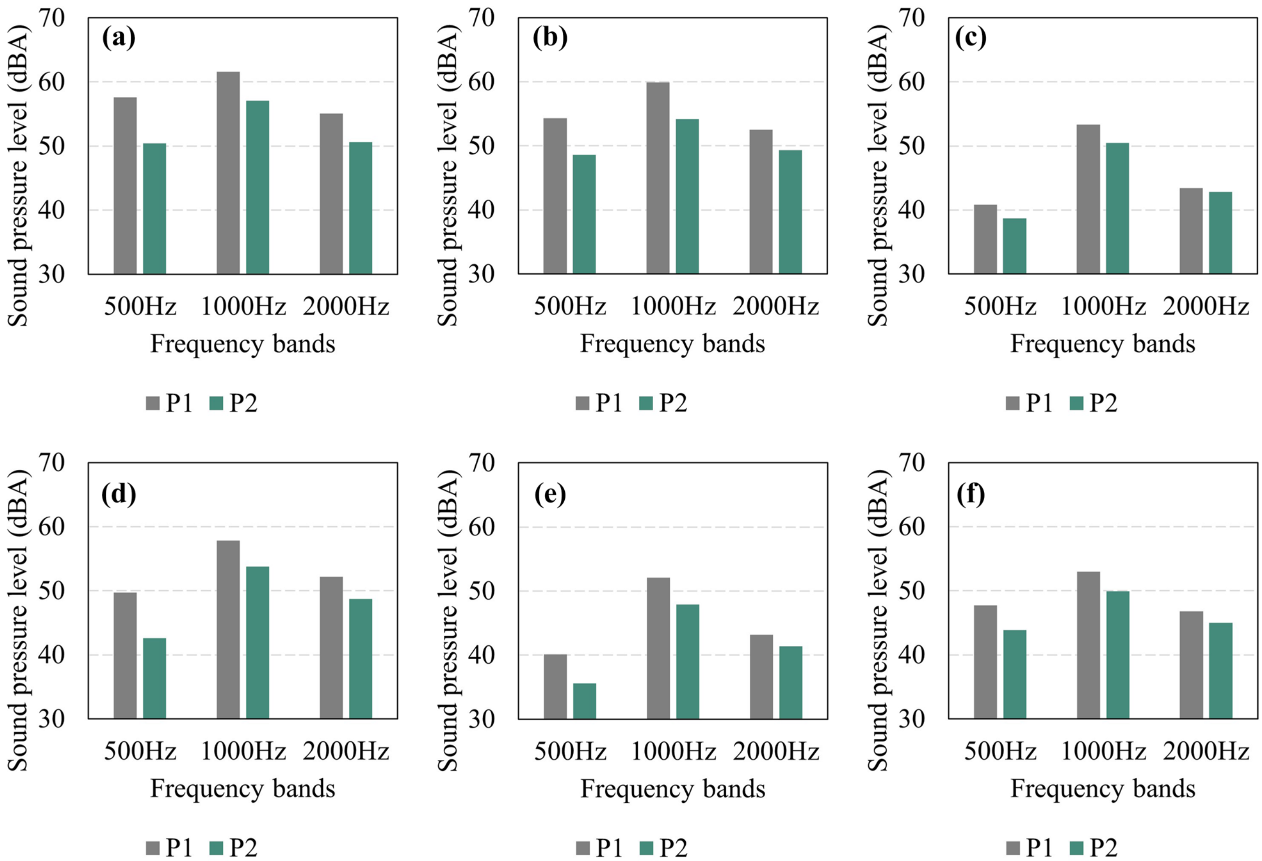

Fig. 6 Sound pressure levels in each frequency band for vertical flexible landscapes: **a** F1-1, **b** F1-2, **c** F1-3, **d** F2-1, **e** F2-2, **f** F2-3

500 Hz frequency band. In the 1000 Hz frequency band, it was 6.4 and 4.6 dBA higher, and in the 2000 Hz frequency band, it was 4.4 and 3.0 dBA higher than those of landscapes R1-1 and R2-1, respectively. Consequently, a descending form landscape has an advantage over an ascending landscape in terms of noise reduction.

Effects of topography of heritage landscapes on noise reduction

A significant difference exists in the noise reduction effects between vertical mixed landscapes facing the main road and vertical mixed landscapes backing the main road. The levels of noise reduction for landscapes facing the main road were significantly lower than those for landscapes backing the main road. For example, landscape M1-4 exhibited a 3.2 dBA higher level than that of landscape M1-1 in the 500 Hz frequency band, a 2.6 dBA higher level in the 1000 Hz frequency band, and a 1.5 dBA higher level in the 2000 Hz band (Fig. 8). Landscape M1-5 exhibited a 4.5 dBA higher level than that of landscape M1-2 in the 500 Hz frequency band, a 5.9 dBA higher level in the 1000 Hz frequency band, and a 6.5 dBA higher level in the 2000 Hz band.

A comparison of the section facing the main road of landscapes M1 and M2 indicates that the total noise reduction effects of landscapes with a gradual slope, comprising M2-1, M2-2, and M2-3, were better than those of landscapes with a steep slope, including M1-1, M1-2, and M1-3 (Fig. 9). For example, the noise reduction value of landscape M2-1 was 1.5, 2.3, and 2.4 dBA higher than those of landscape M1-1 in the 500, 1000, and 2000 Hz frequency bands, respectively. Additionally, landscape M2-3 exhibited a 2.2 dBA higher level than that of landscape M1-3 in the 500 Hz frequency band, a 3.3 dBA higher level in the 1000 Hz frequency band, and a 0.5 dBA higher level in the 2000 Hz band.

Conversely, the total noise reduction effects of the section of landscape M1 away from the main road, consisting of M1-4, M1-5, and M1-6, were better than that of the section of landscape M2 away from the main road, including M2-4, M2-5, and M2-6. For example, the noise reduction value of landscape M1-4 was 2.8 and 4.4 dBA higher than that of landscape M2-4 in the 500 Hz and 2000 Hz band. Landscape M1-5 exhibited a 2.3 dBA noise reduction, surpassing that of landscape M2-5 in the 500 Hz band, a superior noise reduction of 3.8 dBA in

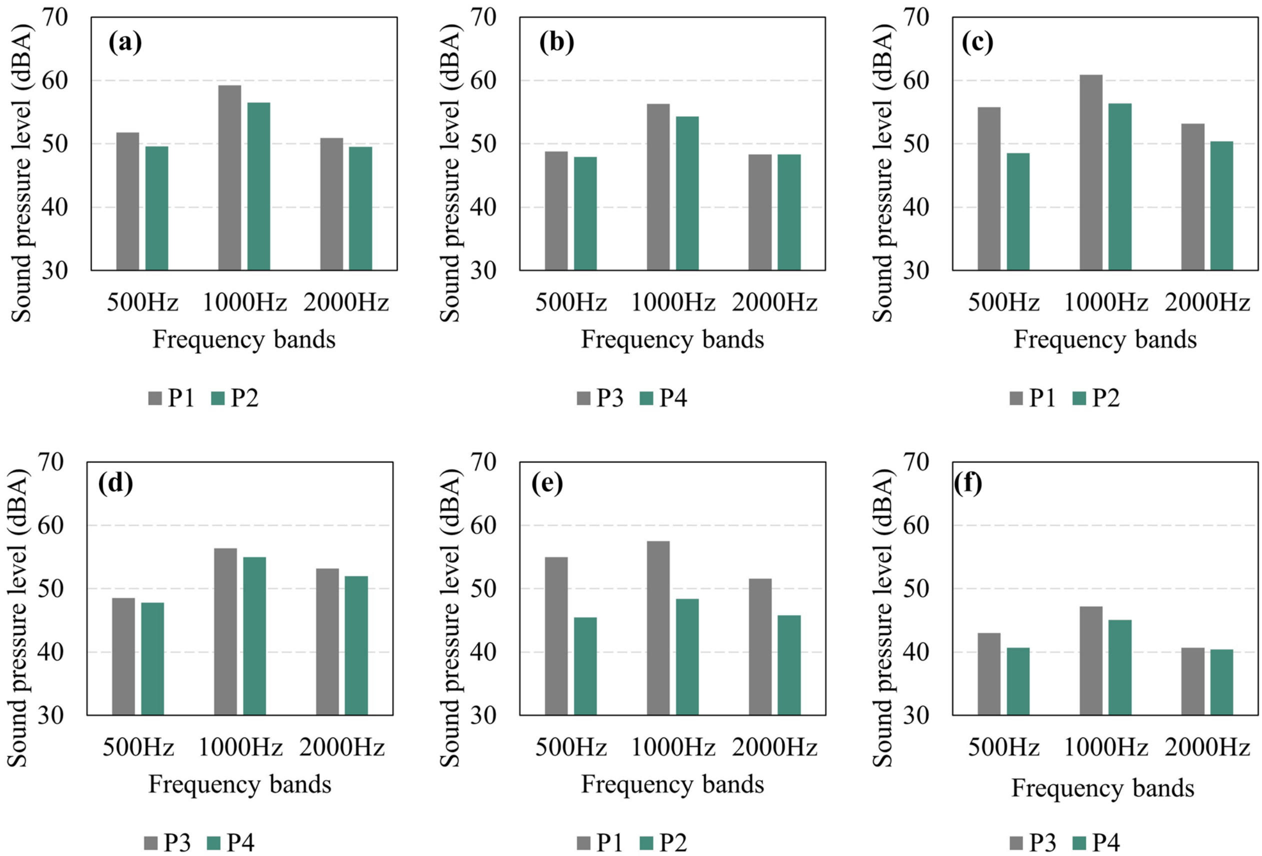

Fig. 7 Sound pressure levels in each frequency band for vertical rigid landscapes: **a** R1-1, **b** R1-2, **c** R2-1, **d** R2-2, **e** R3-1, **f** R3-2

the 1000 Hz band, and a more pronounced reduction of 5.2 dBA in the 2000 Hz band. The level of noise reduction of landscape M1-6 was 2.2, 2.9, and 2.7 dBA higher than that of landscape M2-6 (500, 1000, and 2000 Hz).

Discussion

This study classified heritage landscapes based on their acoustic characteristics and investigated their noise reduction effects, addressing a critical research gap concerning the relationship between landscape attributes and noise reduction effects. Some interesting findings emerged as follows:

Concerning horizontal landscapes, the total noise reduction effect of concrete landscapes is more pronounced than that of grass and flower landscapes. The possible reason is that the surface of concrete landscapes is rough. A rough surface can reduce acoustic energy, which is consistent with results from a previous study [8]. The noise reduction effect of flower landscapes was notable in the 500 Hz band. This is because the size of the flowers was close to the wavelength of the sound wave in the 500 Hz band. Consequently, flowers consumed more sound energy due to acoustic resonance.

In vertical flexible landscapes, they can be considered as sound-absorbing material. The noise reduction effects of dense landscapes were superior to those of sparse landscapes. This is because dense landscapes have more leaves to absorb traffic sound energy than sparse landscapes [9].

Another interesting finding is that the noise reduction effects of vertical rigid landscapes with a descending form exceeded those of vertical rigid landscapes with an ascending form. This may be due to the difference in acoustic characteristics between descending and ascending landscapes. Specifically, ascending landscapes reduce noise levels by reflecting sound energy, while microphones on ascending landscapes have more opportunities to capture traffic noise. In contrast, descending landscapes act as sound insulation materials, isolating traffic noise from the main road and preventing it from reaching the microphones. As a result, there is less direct and reflected sound recorded by the microphones.

Landscapes backing the main road exhibited superior noise reduction effects compared to landscapes facing the main road. One possible reason is that direct traffic noise was insulated by the section of landscape

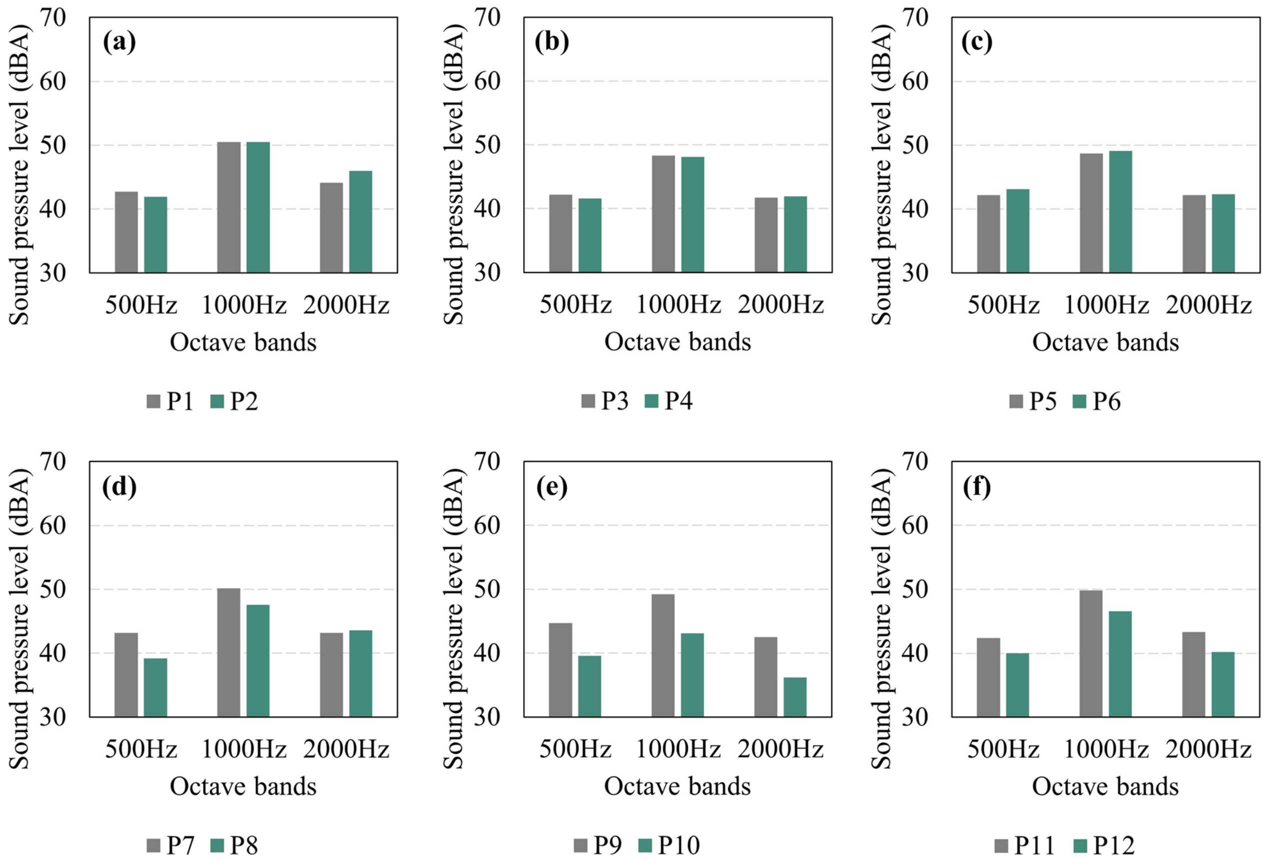

Fig. 8 Sound pressure levels in each frequency band for vertical mixed landscape M1: **a** M1-1, **b** M1-2, **c** M1-3, **d** M1-4, **e** M1-5, **f** M1-6

backing the main road. It should be noted that the noise reduction effects of landscapes with a slight slope were better than those of landscapes with a steep slope. The possible reason is that the elevation of landscapes with a steep slope was higher than that of landscapes with a slight slope, resulting in more traffic noise being recorded by microphones, which is consistent with the rationale for vertical rigid landscapes.

Furthermore, our previous research has indicated that sound pressure levels are associated with the psychology of users in urban open spaces [18]. Notably, negative psychological responses were observed when the sound pressure level of traffic noise in urban open spaces exceeded 54.1 dBA. This negative mood, involving both cognitive and affective dimensions [19, 20], is expected to impact evaluations (affect congruent judgments) and the description of additional information related to heritage places [21]. Consequently, the study emphasizes the importance of examining the noise reduction effects of heritage landscapes, as they influence not only the psychological assessment of heritage landscapes but also the evaluation of their heritage values.

Micro-updates do not compromise the heritage value of landscapes; instead, they can significantly improve the acoustic environment of heritage sites. Based on the findings of this study, the following five micro-update strategies for landscapes in heritage sites are proposed:

1. Roughing horizontal rigid landscapes is more effective in reducing traffic noise compared to the alternative approach of planting low-growing vegetation.
2. Planting dense vegetation is more advantageous for noise reduction than planting sparse vegetation.
3. A planting combination of trees and shrubs may be more advantageous for noise reduction than planting only one type of vegetation.
4. Designing descending steps is better for reducing traffic noise than designing ascending steps.
5. Optimal placement of crowd activity spaces, such as squares, entertainment areas, and alleys, is on the mound backing to the main road rather than on the mound facing the road.

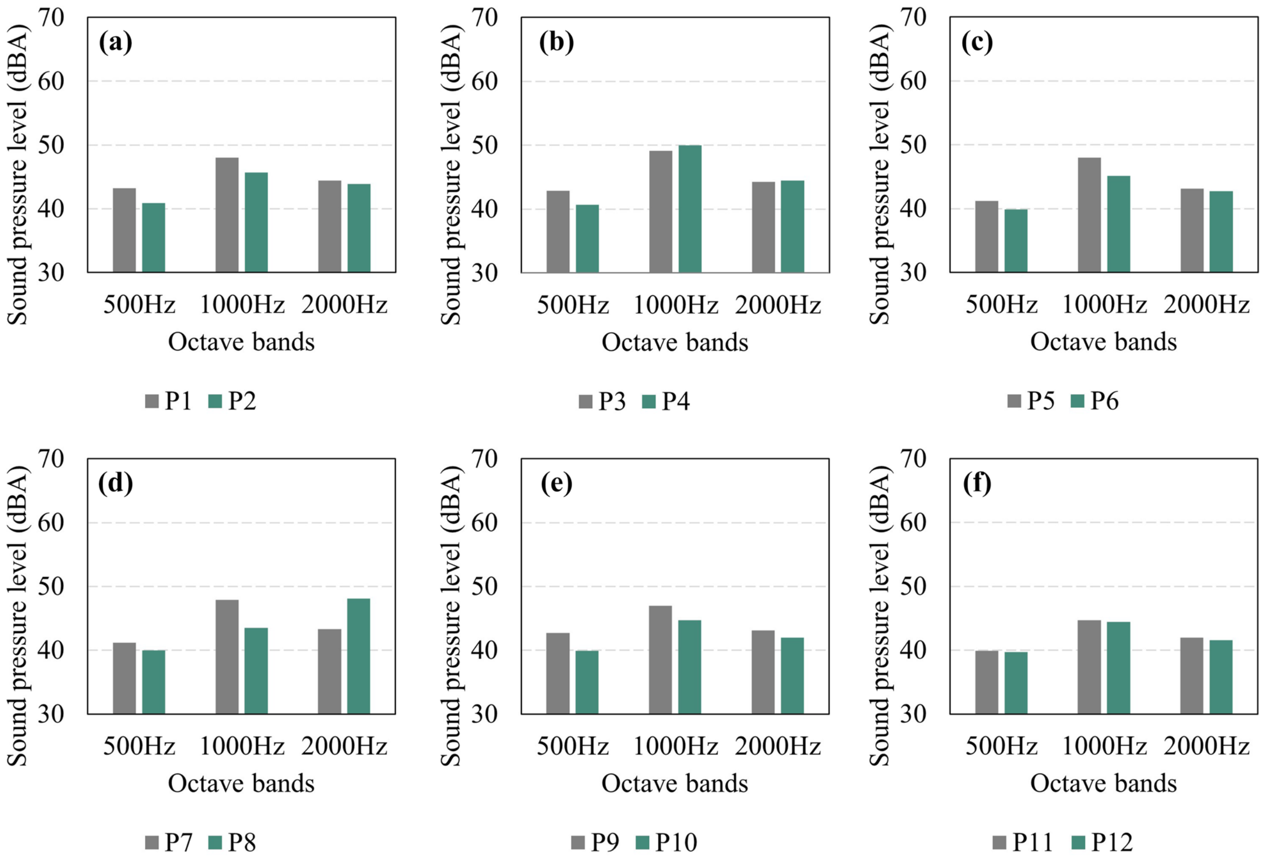

Fig. 9 Sound pressure levels in each frequency band for vertical mixed landscape M2: **a** M2-1, **b** M2-2, **c** M2-3, **d** M2-4, **e** M2-5, **f** M2-6

Conclusions

This study introduces a novel landscape classification method based on acoustic characteristics and investigates the attributes of horizontal and vertical landscapes with diverse slopes, surfaces, elevations, structures, and topography in the context of traffic sounds, relying on on-site measurements. The key findings can be summarized as follows: First, landscape attributes, including surfaces of horizontal landscapes, sparsity, and varieties of vertical flexible landscapes, significantly influence the noise reduction effects of landscapes. Second, the noise reduction effects are more pronounced in descending landscapes, followed by ascending landscapes with lower elevations, and then ascending landscapes with higher elevations among vertical rigid landscapes. Finally, the noise reduction effects of vertical mixed landscapes with a more gradual slope facing the main road are superior to those of landscapes with a steeper slope, while the opposite is true on the side backing away from the main road.

This study provides valuable insights to address knowledge gaps in the field of heritage values. The findings serve as a foundation for optimizing design strategies aimed at protecting heritage landscapes in open urban spaces. Additionally, these findings offer a database for designing and planning green spaces based on heritage soundscape creation. Despite these contributions, the scope of the study was confined to a limited set of landscape types, rendering the investigation of more generalized cases challenging. To address this, future research endeavours will focus on acoustic environment simulation and modelling, leveraging the outcomes of this study. Furthermore, while earthen mounds are acknowledged for their significance in optimizing the acoustic environment of urban open spaces, their detailed investigation was limited in this study. Therefore, future studies should incorporate a more thorough examination of earthen mounds.

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Author contributions

SZ: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft, writing—review and editing; visualization, supervision, project administration. LZ: Conceptualization, writing—review and editing, supervision, project administration. ZC: Writing—review and editing. LC: Writing—review and editing.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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