Urban Forestry & Urban Greening 124 (2026) 129574

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Garden streets improve urban acoustics: Evidence from a controlled field intervention

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ARTICLE INFO

Keywords:
Street greening
Depavement
Sound propagation
Urban sound
Noise mitigation
Street acoustics

ABSTRACT

Partial street depavement followed by greening enables the creation of so-called garden streets and is known to provide multiple environmental and ecological benefits. Its potential to improve street acoustics, however, has not yet been investigated. In this study, controlled sound propagation measurements were conducted along a street canyon before and after such a greening intervention, using an identical measurement methodology. The results show that the introduction of growing substrates, and their associated sound absorption, leads to additional sound pressure level decays along the street, primarily in the 1 kHz and 2 kHz octave bands, a frequency range highly relevant for common urban noise sources. The magnitude of this effect increases with propagation distance for a fixed sound source. Over an additional propagation distance of 50 m along the street, level reductions at ear height of 2.6 dB and 3.0 dB were observed at the octave bands of 1 kHz and 2 kHz, respectively. Furthermore, reductions in reverberation time (RT20) of 0.2–0.3 s were measured. This effect extends to lower sound frequencies and appears largely independent of receiver distance along the street. Given that the investigated street canyon already exhibits substantial façade scattering, and that the growing substrates likely had a high moisture content during the measurements, the reported acoustic improvements may represent conservative effects.

1. Introduction

Street acoustics can be understood as the outdoor counterpart of room acoustics. Whereas room acoustics studies how sound behaves within enclosed spaces such as concert halls, offices, or classrooms—where the geometry of the space and its materialization largely determine the spatial distribution of sound levels and reverberation—street acoustics examines analogous processes in urban street environments. In streets, the geometry and profile of building façades, ground surfaces, and the broader street layout (e.g., axial shifts and intersections) influence how sound propagates. These elements determine how traffic noise and other urban sound sources are amplified through the multiple reflections between opposing façades and how sound attenuates as it propagates along the street axis.

These processes are particularly relevant in so-called street canyons, which are common in the centres of densely built cities. Although there is no strict definition of a street canyon, the term is used here to describe urban geometries in which the height of the facades (H) exceeds the street width (W), corresponding to an aspect ratio (H/W) greater than 1, and where the building façades are sufficiently continuous along the street to form a well-defined, enclosed space. In such environments, both façade geometry and materialization can strongly influence the street acoustics. This contrasts with wider and more open streets, where reflections play a less dominant role (Heutschi, 1995; Thomas et al., 2013). Understanding these acoustic mechanisms is therefore essential for addressing environmental noise exposure, both at street level and in relation to sound incident on the façades and windows of dwellings. Such knowledge can inform urban design strategies aimed at limiting excessive sound levels while supporting a more pleasant urban soundscape.

From a physical perspective, three main mechanisms can be considered to mitigate sound levels in urban streets. The first approach is to increase sound absorption. By introducing absorbing materials on façades or other urban surfaces, the strength of reflections can be reduced, limiting the cumulative build-up of sound energy caused by multiple reflections and preventing excessively long reverberation within the street canyon.

A second approach is to promote diffuse reflections (Kang, 2000;

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https://doi.org/10.1016/j.ufug.2026.129574
Received 15 March 2026; Received in revised form 22 June 2026; Accepted 22 June 2026
Available online 25 June 2026

Onaga and Rindel, 2007; Picaut and Scouarnec, 2009). In contrast to flat façades, which produce largely specular reflections that direct sound energy along predictable paths, irregular or structured façade elements can scatter sound in multiple directions. Part of this scattered energy may escape the street canyon early (Picaut et al., 2005; Onaga and Rindel, 2007), thereby reducing the amount of sound reaching receivers within the street. However, strongly diffusive surfaces may also produce downward scattering, which can locally increase sound levels near façades (Heutschi, 1995; Kang, 2000; Onaga and Rindel, 2007). This phenomenon is particularly relevant when a significant amount of scattering elements are located at higher storeys but typically leads to limited level increases only. Street furniture and other elements at street level may likewise contribute to the development of a more diffuse sound field.

A third option is the introduction of screening elements, such as low-height noise barriers along pavements or on central reservations. Rigid screens primarily redistribute sound energy within the street rather than reducing it overall, but they can create significantly shielded zones, for example along pedestrian walkways (Horoshenkov et al., 1999; Thorsson, 2002; Baulac et al., 2006; Echevarria-Sanchez et al., 2016). Since the most intensively used parts of the street volume are typically the walkway areas and the façade zone, such localized shielding can already be beneficial. The effectiveness of these measures can be further enhanced when screens incorporate absorbing materials or scattering elements (Echevarria-Sanchez et al., 2016), which help to limit potential increases in sound levels elsewhere in the street.

The use of street vegetation and their associated growing substrates may provide interesting opportunities to increase both sound scattering and absorption in streets. Above-ground vegetation elements can in principle contribute to both mechanisms, although their overall acoustic effect is often limited. A fundamental requirement for efficient scattering is that the size of the scatterers is comparable to the wavelength of the sound (Kuttruff, 2009). While leaves are abundant in trees and shrubs and can thus potentially contribute strongly to scattering, this process mainly affects higher sound frequencies, typically above 3–4 kHz (see e.g. Aylor, 1972; Martens, 1980; Van Renterghem et al., 2014). Most dominant urban noise sources, such as road traffic, contain relatively little acoustic energy in this frequency range, limiting the practical impact of leaf scattering. Visco-thermal absorption at the surfaces of leaves and vibration damping may occur (Aylor, 1972) as well, but such effects are small and likewise affect higher frequencies only (Martens and Michelsen, 1981). Absorption by tree bark may also play a role, particularly for species with more porous and rough bark structures (Reethof et al., 1977; Li et al., 2020). However, in a typical street environment, sparsely populated single rows of trees are most common, so the total bark surface, even in case of mature and bigger trees, remains very limited.

Secondly, and more promising, are the growing substrates associated with urban vegetation. Uncompacted soils in general (see e.g. Attenborough and Van Renterghem, 2021) and substrate layers specifically (Yang et al., 2012; Horoshenkov et al., 2013; Davis et al., 2017) can have good sound absorption properties, often with still reasonable absorption coefficients down to frequencies of a few hundred Hertz.

A number of studies yet looked at how street trees effect sound propagating. In case both the sound source and receiver are positioned below the canopies, a slight increases in the sound pressure level can be expected, relative to the absence of the tree, due to part of the sound field that is scattered downwards by the canopy (Lyon et al., 1977). Jang et al. (2015b) measured a slight level increase of 0.5 dB (as a linear average over frequency bands 100 Hz−4 kHz) in their scale model street with two sparse lines of trees. Similarly, albeit not in a street canyon configuration, Van Renterghem et al. (2012) predicted similar slight level increases between 0.3 and 0.8 dBA for road traffic noise, at typical ear height, behind a vegetation belt of limited depth. In contrast, at a façade receiver above the tree canopies in a street canyon, effective reduction was predicted by Tang and Ong (1988), especially at the higher components of the road traffic noise spectrum (2–3 dB level reduction relative to the absence of trees, starting from 1 kHz).

An urban greening measure that has received considerable attention in the field of environmental acoustics is façade greening. Early field measurements (Aylor & Parlange, 1973) showed that ivy-covered walls (ground-based green façades) could significantly reduce street reverberation, but only in the octave band centred at 4 kHz with no effect at lower frequencies. From an acoustical perspective, non–ground-based systems—commonly referred to as “living walls”—are particularly interesting. These systems typically consist of lightweight and highly porous growing substrates mounted against the façade. Laboratory measurements have shown that such substrates can exhibit strong sound absorption extending to relatively low frequencies (Yang et al., 2012; Horoshenkov et al., 2013; Van Renterghem et al., 2013; Davis et al., 2017). Their potential impact on sound levels in street configurations have been investigated through numerical simulations (Van Renterghem et al., 2013) and physical scale-modelling (Jang et al., 2015a,b). While the acoustic behavior of such substrates can be represented accurately in numerical models (Horoshenkov et al., 2013; Ding et al., 2013; Van Renterghem et al., 2013; Attal et al., 2021), their representation in physical scale models is highly challenging (Horoshenkov et al., 1996). In view of the quiet side concept (see e.g. Öhrström et al., 2006), there has been a main interest in the effect of substrate-based green wall systems deployed in the street, but evaluated at a connected city canyon (Van Renterghem et al., 2013; Jang et al., 2015b). Line source noise reductions, relative to a street without green walls, are reported up to 3.4 dBA (for an urban road traffic noise spectrum, see Van Renterghem et al., 2013) and 2.9 dB (linear average over frequency bands 100 Hz−4 kHz, see Jang et al., 2015b). Jang et al. (2015a,b) also considered receivers in the street canyon itself, leading to 1.8 dB reductions. Although living-wall systems show clear potential for urban noise mitigation, their relatively high installation and maintenance costs may limit their widespread implementation in urban environments.

In recent years, urban greening initiatives often referred to as “tile flipping” or “depaving” have gained increasing popularity and are often strongly supported by citizens (Audate et al., 2025). The practice consists of replacing impermeable surfaces such as concrete, asphalt, or pavement with vegetated areas and exposed soil. Such actions are thought to increase urban resilience against climate change—and associated extreme weather events—by mitigating urban heat islands and contributing to improved stormwater management (see e.g. Scalenghe and Ajmone Marsan, 2009; Fini et al., 2017; Murata and Kawai, 2018). Other positive effects associated with depaving are enhancing urban biodiversity due to habitat creation and consequently, providing a natural visual scenery in the street. The latter is known to contribute to human health improvement by stress reduction, attention restoration, social cohesion and physical activity (see e.g. Ulrich et al., 1991; Kaplan, 2001; de Vries et al., 2013; Lu, 2019).

Depaving could also offer opportunities for street noise mitigation. Topsoil and similar substrates have significant sound absorption in the urban sound frequency range as discussed before. Given its relatively simple deployment, and thus potentially wide applicability, the impact of such a greening measure on street sound exposure warrants further investigation.

The current research present a unique real-life measurement campaign in a street canyon, before and after a (partial) depavement. Controlled sound propagation measurements are performed before the greening, and a few years after the greening intervention, following an identical measurement protocol. Not only the sound pressure level decay along the street length axis is analysed, but also how reverberation time is changed by the street greening. Such insertion loss data might be especially useful to showcase effects to urban planners and the public at large given its straightforward concept.

The current work focuses primarily on the physics of sound propagation in urban streets. During the last decade, a significant body of research has been built up on how (visual) greenery improves environmental noise perception, and more specifically self-reported noise annoyance (see e.g. Van Renterghem, 2019, for an overview). Such additional effects from street greening can thus be logically expected, but will not be studied here.

2. Research questions

This naturally leads to the following research questions:

- Does a partial depavement of a street canyon lead to a measurable and significant sound pressure level decay along the street length axis?
- Does a partial depavement lead to measurable and significant changes in the street reverberation times?
- Which frequency bands are mainly affected by this street greening intervention?

3. Methodology

3.1. Site description

3.1.1. Street geometry

The street under study is “De Brouwerstraat”, a 75-m long and 6-m wide street located in the dense inner urban fabric of the city of Antwerp (see Fig. 1). Façade heights are generally uniform along the street and are approximately 7 m. Most houses consist of three storeys, with the upper storey partly integrated into the pitched roof.

As shown by the photographs in Fig. 2, the window sills of the first floor form an almost continuous horizontal line along nearly the entire length of the street. Similarly, the wooden roof overhang used for rainwater drainage, forming the transition between the vertical façade and the pitched roof, presents a significant protrusion and also extends along most of the street.

The vertical façade surfaces feature relatively large recessed areas associated with doors and windows. Apart from garage entrances (all closed), the overall façade structure is generally uniform across the different houses. In some locations, individual houses are approximately 1 m lower than the surrounding buildings. During the measurements, the street under study was closed for traffic, but not the crossing streets.

3.1.2. Greening intervention

The greening intervention (see Figs. 1 and 2) consists of a central reinforced grass strip with a width of 1.10 m extending along the entire length of the street, complemented by 26 individual rectangular depaved patches located adjacent to the façades (see Fig. 1). Each of these patches have a width of 1.55 m and consists of about 1.0 m of exposed soil directly next to the façade and 0.55 m of reinforced grass towards the centre of the street. In total, about 55% of the street surface was depaved.

The reinforced grass surface follows a regular pattern composed of 4 cm wide concrete strips oriented perpendicular to the longitudinal axis of the street, alternating with 4.5 cm open gaps that allow grass growth (see Fig. 2). Two longitudinal strips, each 0.9 m wide, were intentionally left paved to ensure unobstructed vehicle passage along the street.

It should be noted that in the reference situation, a limited amount of informal greening was already present, including plants growing near some façades and occasional flower pots placed on window sills or at ground level in front of certain houses.

3.2. Instrumentation

Test signals were emitted with a dodecahedron loudspeaker, balancing an omni-directional emission while providing sufficient acoustic power (Quested et al., 2014). The dodecahedron has a diameter of 0.3 m, and its centre is positioned at 0.5 m from the street surface. The loudspeaker was positioned at the beginning of the street (see Fig. 1), either in its centre (i.e. at 3 m from the façade), either slightly off axis (i.e. at 2 m from the façade) or around the corner of a crossing street for sound to enter the street in a (partly) diffracted manner.

Ten microphones were positioned along the length of the street at distances of 7.82 m, 24.05 m, 33.75 m, 47.16 m, and 63.11 m, relative to the loudspeaker, in pairs, both at 1 m from the façade (further indicated as the “façade microphones”) and at the centre of the street’s cross section (i.e. at 3 m from the façade, further indicated as the “central microphones”). Type−1 (IEC, 2013) accredited measurement chains were used, consisting of half inch PCB Piezotronics electret microphones, pre-amplifiers and 5-cm diameter spherical windscreens. The height of the actual microphone membrane, relative to the street surface, was each time 1.7 m. Data acquisition was performed with a National Instrument’s PXIe−1082 chassis, driven by a custom made LabView application, allowing synchronized and simultaneous sound emission at the loudspeaker and recordings at the 10 microphones, producing 16-bit .wav files at 48 kHz sampling rate. Calibration was performed with a type−1 (IEC, 2017) Svantek SV30A calibrator producing a 1 kHz pure tone at 94 dB. The calibrator signals were pre-recorded to allow calculating absolute sound pressure levels based on the .wav files.

Meteorological parameters were provided by the official KMI weather station of Deurne, at 2.2 km straight-line distance from the street under study. The data was used to ensure absence of rain during the measurement, to assess wind-induced microphone noise, and to estimate the extent to which the air absorbs sound, determined by air temperature, relative humidity and atmospheric pressure.

3.3. Signal processing

3.3.1. Signal-to-noise ratio

An initial assessment of the signal-to-noise ratio is performed by emitting white noise burst sequences. There, 10-s signals were emitted five times at the same source power level as used for the other measurements (see Sections 3.3.2 and 3.3.3), followed each time by 5 s without signal emission. This allows to check consistency in the sound

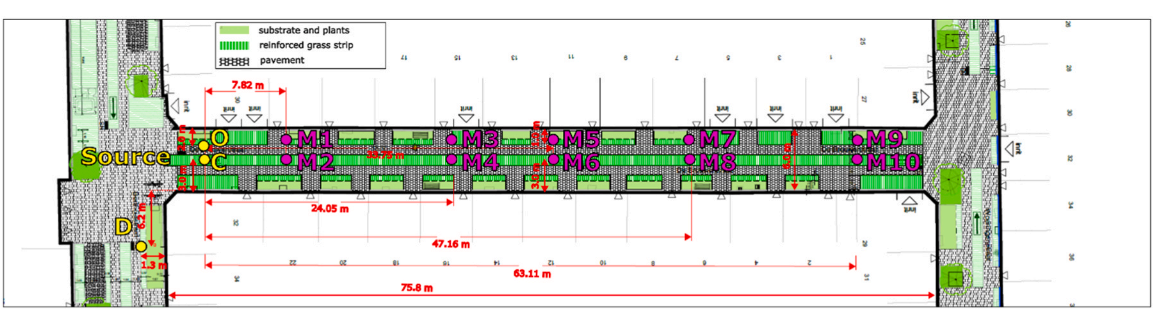

Fig. 1. Plan view of the street under study, including the different source positionings (C=central, O=off-axis, D=diffraction), the façade microphones (M1, M3, M5, M7, and M9) and the central positioned microphones (M2, M4, M6, M8, and M10).

Fig. 2. Photographs showing the street before the greening (upper left), and after the greening interventions (others). The pictures show the dodecahedron loudspeaker used for emitting the test signals (at central positioning, see Fig. 1), the microphones positioned along the length of the street, and a detail of a green patch close to the façade.

pressure levels produced by the loudspeaker, the variability that can be expected with relation to the background noise, and to quantify the difference in sound pressure level between the test signals and the background noise, at close-by and further microphones, at all octave bands.

During data processing, the first second of both the signal of interest and background were disregarded to allow building up the sound field in the street, and to avoid including (part of) the reverberant tail while assessing the background noise. The time-domain fragments were first filtered to octave bands, and consequently, absolute levels were calculated using the pre-recorded calibration signals at each microphone.

3.3.2. *Sound pressure level decay along the street*

Sound level decay over the length of the street was assessed in a simple way by means of 60-s pink noise sequences. The recorded time-domain signals were first filtered in octave bands, and consequently, absolute levels were calculated using the pre-recorded calibration signals at each microphone. In a next step, levels were referred to the closest microphones, namely microphone number 1 (see Fig. 1) in case of analysing sound pressure level decay for the façade microphones, and number 2 for the centrally positioned microphones.

The long 60-s pink noise sequences should ensure accurate measurements by intrinsically averaging the acoustic responses over a sufficient time. In this, it is assumed that the sound signals emitted by the loudspeaker are deterministic and constant, while background noise is intermittent and/or of varying spectral content. In addition, the emission of multiple 60-s sequences allows checking the reproducibility of the measurements and its convergence within such a period by calculating standard deviations. Only when there were clear sound disturbances or sound events from sources in the crossing streets (e.g. a car pass-by or people talking) or in the street itself (e.g. windows/door slamming, people exiting their houses), recordings were disregarded.

3.3.3. *Reverberation time*

Calculating reverberation times in a real-life outdoor and thus non-quiet urban environment is particularly challenging. Specific choices were therefore made to ensure high quality assessments.

First, the RT20 reverberation time indicator is used. To calculate, the time required for the sound to decay by 20 dB from – 5 dB to −25 dB, relative to the maximum sound pressure level measured upon exciting a test signal, is first sought. Next, this time interval is linearly extrapolated to a 60 dB decay, defining the reverberation time at a specific microphone location. The use of RT20 takes an intermediate position between early decay time (EDT), where slopes on the level function might not be sufficiently representative for the 60 dB level drop which is aimed at, and RT30, which might not be a measurable level drop at all octave bands in a non-quiet outdoor environment when avoiding excessively intense source power levels.

Secondly, repeated long exponential sweeps were used, with a frequency span covering the octave bands with central frequencies between 125 Hz and 16 kHz. Using this type of source signal excitation, full power can be attributed to each sound frequency. In addition, long test signals of 60 s were used, allowing to average out (accidental) background noise over octave bands. Furthermore, repeated sweeps allow drawing statistics with relation to the obtained reverberation times. Given the interest in octave band analysis, the choice for an exponential sweep over a linear one further ensures an equal amount of acoustic energy emitted in each band and thus providing similar accuracy – at least from the viewpoint of the signal processing – at all bands.

The reverberation time procedure starts from calculating the impulse response, which is obtained by a spectral division of the recorded and (theoretical) source signal after Fourier transforming. Next, octave band decomposition is performed. As the band filtered impulse responses are likely to be contaminated with sound from from environmental noise sources reaching the microphones, start and endpoints need to be carefully estimated. The start point of the response is given by the time when the level function of the impulse response starts to decay, using the backward integration technique (Schroeder, 1965). The endpoint or truncation point is estimated as the intersection between the decaying slope and averaged background noise level of the time-averaged squared band response following Lundeby et al. (1995).

4. Results

Street acoustics measurements were performed in 2018, before the depavement and the associated street greening, and will be referred to as the reference measurements. In the year 2025, an identical measurement methodology was applied, with the same instrumentation and signal processing (see Section 3). At that time, the depavement was fully executed and plants had about 2 years to develop, and will be identified as the post-green measurements.

4.1. Atmospheric absorption

The averaged meteorological parameters during the hours in which the reference and post-green measurements were conducted are presented in Table 1. No rainfall was recorded during the measurements, and moderate-to-low wind speeds were measured at the meteorological station located in an open field at a height of 10 m. It can be reasonably expected that wind speeds within the street canyon were even lower, posing no issues with relation to wind-induced microphone noise.

Differences in air temperature and relative humidity between the two measurement campaigns, and to a much lesser extent atmospheric pressure, result in slightly lower air absorption during the post-green measurements. Therefore, corrections (see Fig. 3) were applied to the post-green measurements to approximate the atmospheric absorption conditions of the reference measurements, following ISO9613–1 (ISO, 1996). The magnitude of these corrections depends on both microphone position and sound frequency and its impact on the results will be analysed further (see Fig. 5).

The aim of this procedure is not to remove atmospheric absorption from either dataset, which would not represent realistic outdoor conditions, but rather to ensure a fair comparison between the reference and post-greening campaigns.

Table 1
Meteorological observations at a closeby meteo station (at 2.2 km from the street under study), during the reference and post-greening measurements.

	reference measurements (30/08/2018)	post-greening measurements (22/10/2025)
Air temperature (°C)	19.2	13.9
Relative humidity (%)	46.1	82.2
Atmospheric pressure (Pa)	102293	99985
Wind speed at 10 m height (m/s)	4.5	3.5
Precipitation: during the measurements (mm)	0	0
Precipitation: 24-h cumulative previous day (mm)	6	15.2

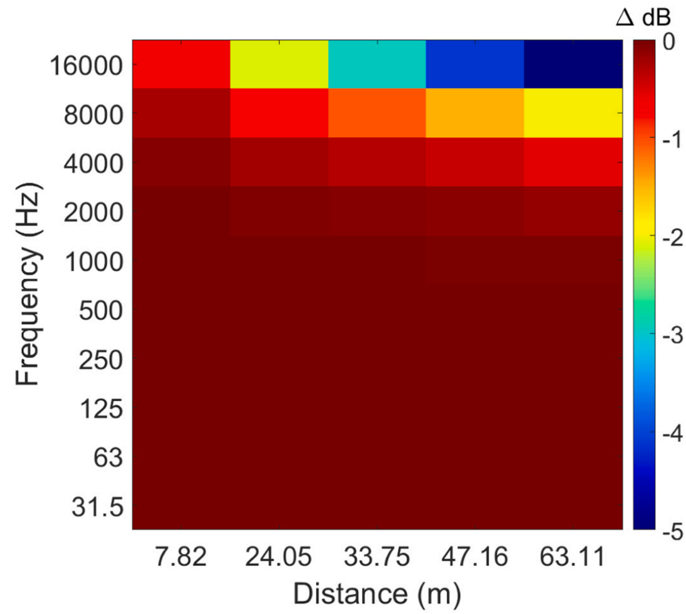

Fig. 3. Atmospheric absorption compensation added to the sound pressure levels measured post-greening to approach similar conditions as during the reference measurements.

4.2. Signal-to-noise ratio

The calculation of the signal-to-noise ratio, in response to repeated white noise bursts, is summarized in Fig. 4. The corresponding absolute level spectra of the emitted signals and background noise, and their variation, can be consulted in Appendix A.

With increasing microphone number (and thus, increasing propagation distance relative to the loudspeaker) the signal-to-noise ratio generally drops. Urban sounds from the surrounding streets can be thought of as being equally relevant at all microphone positions in the street, while more intense test signals are recorded closer to the loudspeaker.

The 63 Hz octave band and below fall outside the emission range of the loudspeaker. At 125 Hz, the SNR at the furthest microphones exceed 10 dB, which could be considered as a minimum SNR for analysis of the level decay along the street in response to emitted noise signals. At 16 kHz, the effect of atmospheric absorption becomes strong, illustrated by the high SNRs at the first microphones, and the much lower SNRs at the furthest microphones due to signal loss while propagating. In the post-greening measurements, at this band, the SNR seems better preserved due to the more limited atmospheric absorption given the higher relative humidity (see Table 1 and Fig. 3). Given the strong importance of atmospheric absorption at the 16 kHz band, and its irrelevance in the spectrum of common environmental noise sources, analysis will be restricted to the octave bands between 125 Hz and 8 kHz.

4.3. Sound level decay

The sound pressure level decay along the street, relative to the closest microphone with respect to the loudspeaker, is presented in Fig. 5. The expected general decay of the test signal over the street length is found at all octave bands. Of main interest here is the difference between the reference and post-green decay curves. The post-greening measurements are shown with (full green lines) and without (dashed green lines) the (simplified) correction for atmospheric absorption as described in Section 4.1. The effect of this compensation is very minor, except at the 8 kHz octave band, where atmospheric absorption seems to explain the main difference between the reference and post-greening decay curve, especially at the microphones towards the end of the street.

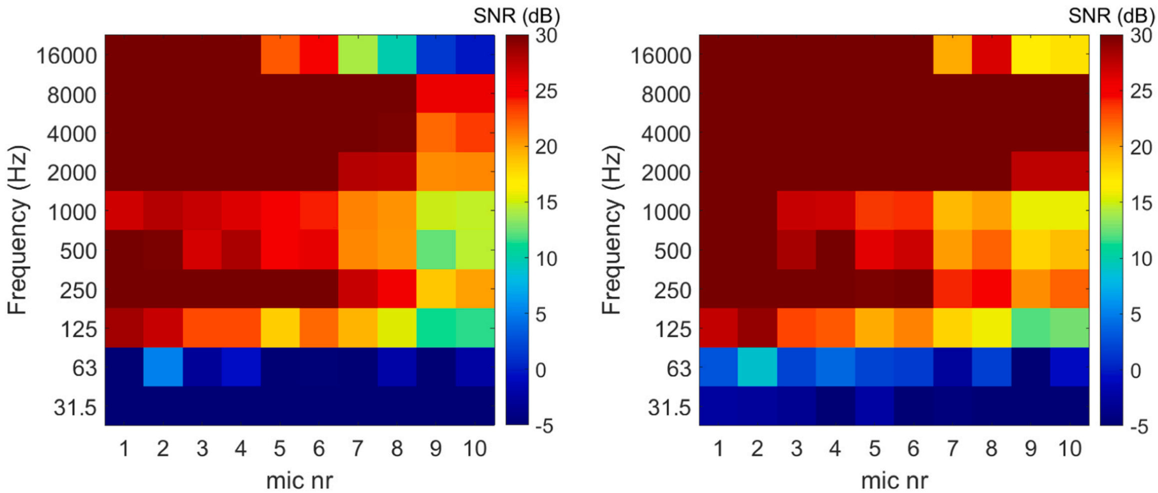

Fig. 4. Mean signal-to-noise ratio at the different microphones, in function of octave band centre frequency, in response to five successive noise bursts. The reference situation is shown in the left figure, the post-greening situation in the right figure.

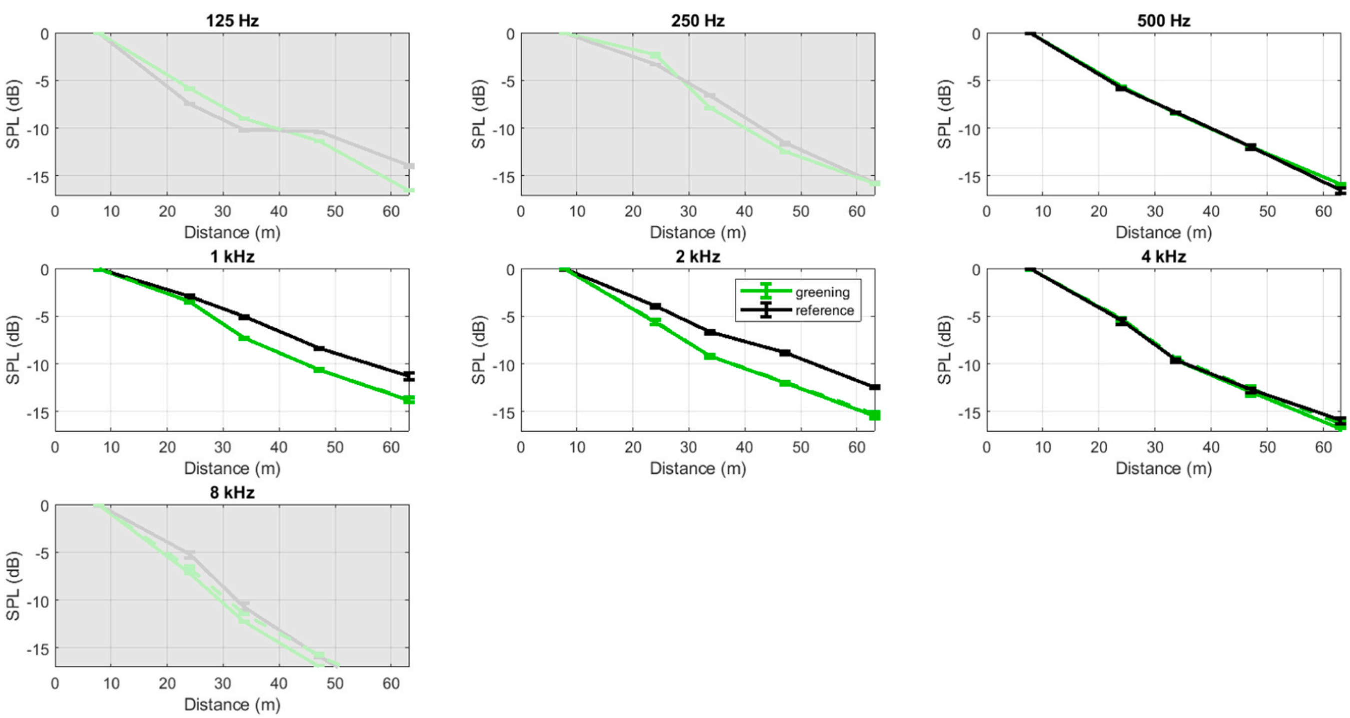

Fig. 5. Mean sound pressure level decay along the street's length for the façade microphones, split up per octave band, in case of a centrally positioned loudspeaker in the street. The decay curves in the reference and post-greening situation are depicted. The errorbars have a total length of 2 times the standard deviation on repeated signal emissions (n = 3 in the reference situation, n = 4 post-greening). The closest microphone (M1, see Fig. 1) is used as a reference level. The dashed lines show additional decay curve not compensating for atmospheric absorption. The subplots with a gray background indicate octave bands where an accurate assessment of the level decay is difficult.

At the 125 and 250 Hz octave bands, the reference and post-green decay curves show a small but somewhat inconsistent behaviour. Supporting simulations using a phase-aware mirror source model (see Appendix B) show that particularly at these bands, microphone positioning errors might be substantial. Distinct modes appear in the street's cross section that remain prominent when averaging to octave bands. Deviations from inexact positioning of the microphones during the reference and post-greening campaign could easily lead to differences of a few decibels. In contrast, at the frequency band of 4 kHz (see Appendix B), e.g., the sound field in the street cross section shows to be much more uniform and consequently, measurements will be much less sensitive to such microphone positioning errors.

At the 500 Hz and 4 kHz octave bands a near-zero effect is observed. This frequency span delineates where accurate and repeatable measurements can be performed. Consistent with the good SNRs as identified earlier in this frequency range, the errorbars in response to repeated signal emissions are small, with only a slight increase with propagation distance, consistent with observations in Fig. 4.

Main effects of the greening operation appear at the 1 kHz and 2 kHz octave bands. With increasing distance travelled, the additional level drop due to the greening intervention increases. At about 63 m from the sound source in the street, the additional noise abatement by the greening is 2.6 dB at 1 kHz, and 3.0 dB at 2 kHz.

Focusing on the 1 kHz and 2 kHz behavior, Fig. 6 shows decay curves

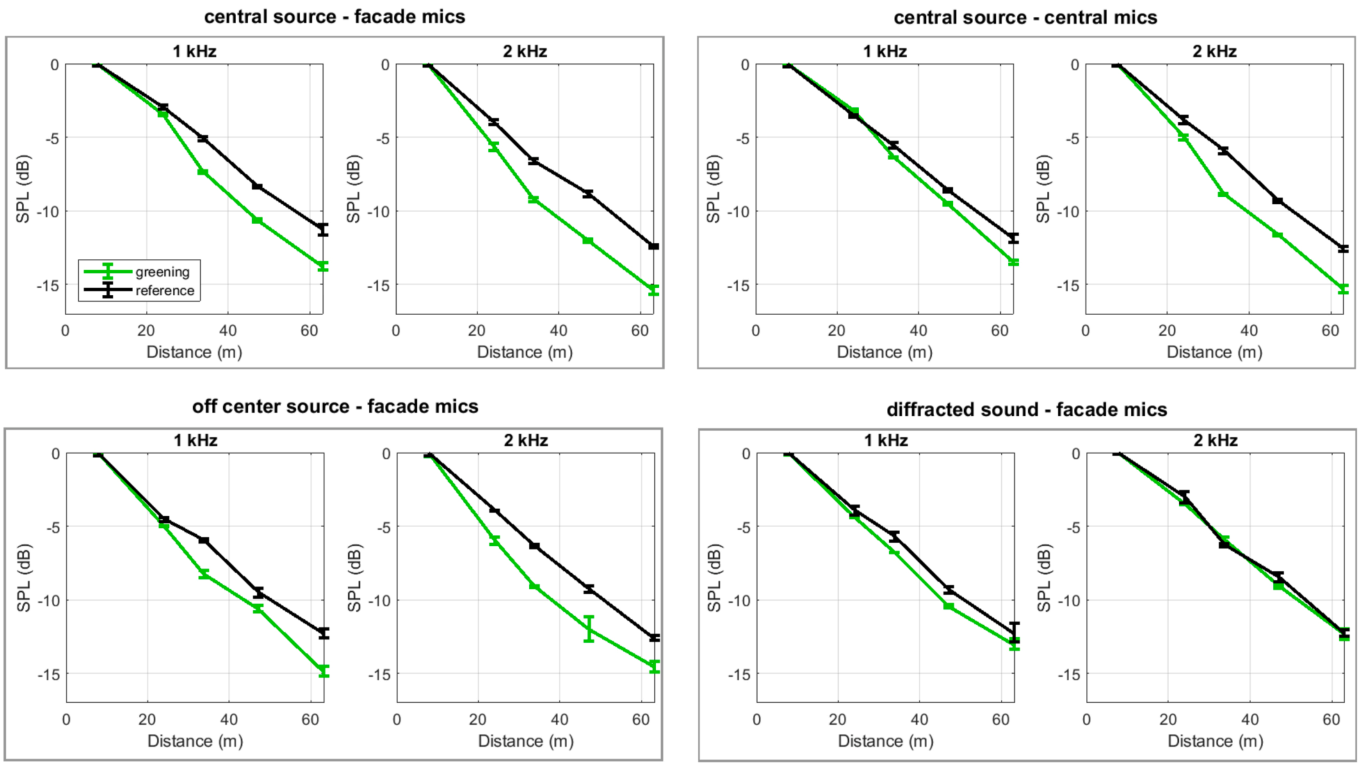

Fig. 6. Mean sound pressure level decay along the street's length for the octave bands of 1 and 2 kHz. The data show different combinations of source positionings (central source, off-centre source, source positioned outside the street and thus representing partly diffracted sound entering the street). The decays in the reference situation and post-greening are depicted. The errorbars have a total length of 2 times the standard deviation on repeated signal emissions (n = 3 or 4). The closest microphones are used as a reference level (more precisely, M1 in case of façade microphones, M2 for central positioned microphones).

for central source positioning in combination with façade and central microphones, for the sound source moved 1 m closer to the façade (off-centre, see Fig. 1), and for the sound source moved outside the street (see Fig. 1), forcing the sound to (partly) diffract while entering the street (see also Appendix C, Table C1). For the configurations with the sound source inside the street, findings are similar as described before,

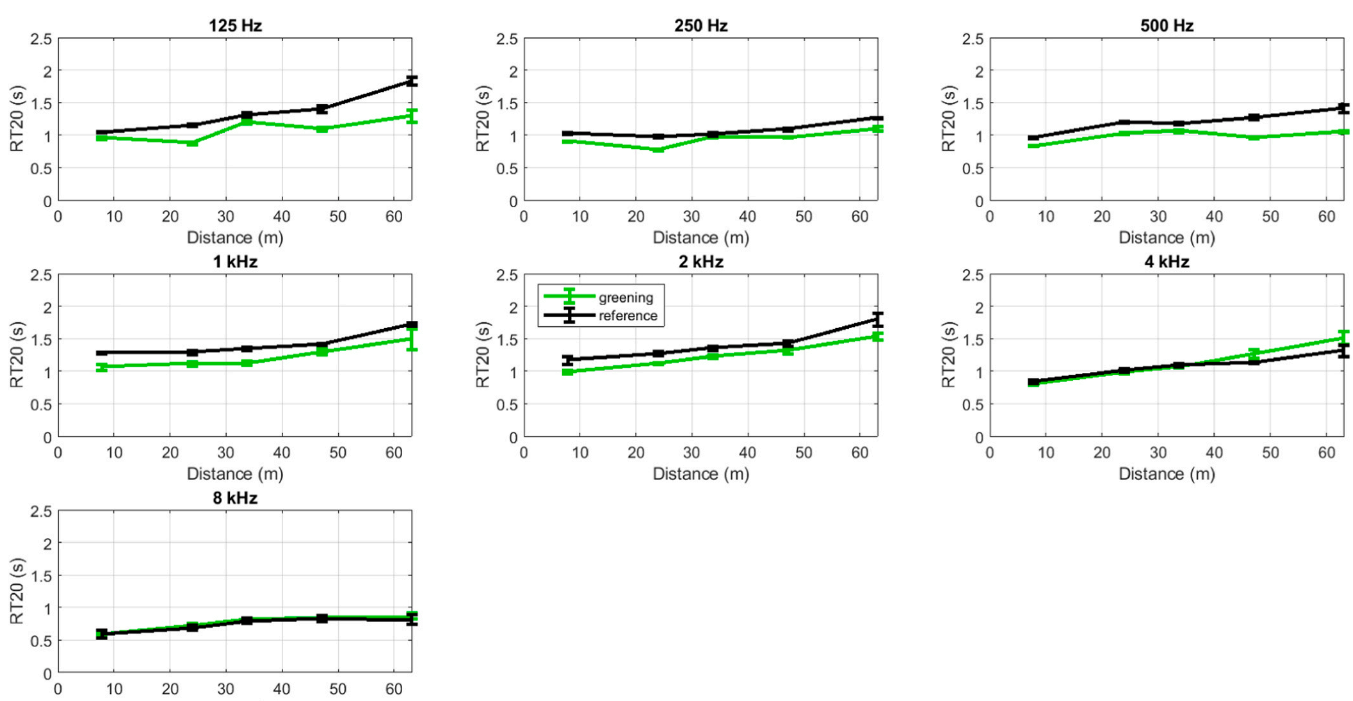

Fig. 7. Reverberation times (RT20) along the street's length, in function of frequency, for the façade microphones and central source positioning, before and after the greening. The errorbars have a total length of 2 times the standard deviation on repeated signal emissions (n = 5 in the reference situation, n = 6 post-greening).

although the reductions might differ somewhat. In case of a diffracted sound field entering the street, a smaller effect is observed for the façade microphones at 1 kHz (up to 1 dB). At 2 kHz, noise abatement seems absent.

4.4. Reverberation time

The measured reverberation times seem to increase somewhat with distance along the street, and decrease overall when going to higher octave band centre frequencies. RT20 values are found between 0.5 s and 2 s.

The greening reduces the reverberation times with about 0.2 s to 0.3 s (see Fig. 7, and Appendix C, Table C2), and effects are observed up to and including the octave band of 2 kHz, although deviations from this behavior can be observed at particular frequency bands and distances. Also at low frequencies, reverberation time reductions are observed by introducing the greenery, in contrast to level decays along the street. The observed reduction in reverberation time due to the greening does not seem to generally depend on distance.

At the 4 kHz octave band and in case of larger distances relative to the loudspeaker, the greening seems to slightly increase the reverberation time, although errorbars of the reference and post-greening measurements partly overlap. At 8 kHz, reverberation times stay below 1 s, and no net effect of the greening is observed.

5. Discussion

Performing sound propagation experiments in real-life urban environments, which are inherently non-quiet, remains challenging and therefore requires tailored measurement approaches. The methodology applied in this study demonstrates good reproducibility and enables the detection of relatively small effects of greening interventions on street acoustics.

The sound pressure level reductions associated with an additional 50 m of propagation along the street range between 10 dB and 15 dB for frequency bands between 500 Hz and 4 kHz. This frequency range corresponds to the span in which the most reproducible decay measurements could be obtained in the present 6-m-wide street canyon. These values are consistent with real-life measurements reported by Picaut et al. (2005), who observed similar level decreases for 1/3-octave bands between 250 Hz and 5000 Hz in a straight street that was 7.9 m wide and 18 m high. Likewise, Thomas et al. (2013) reported in-situ level reductions ranging from approximately 10 dB (at the 250 Hz octave band) to 15 dB (at the 4 kHz octave band) in a street with a width of 10.7 m and a building height of 17 m.

Although a direct comparison is not possible due to differences in street geometry—particularly street width, which is a dominant factor governing sound propagation along streets (Heutschi, 1995; Thomas et al., 2013)—the present results are broadly consistent with these previous in-situ street experiments. Such measurements remain relatively scarce, highlighting the value of additional field studies in real urban environments.

The effect of street greening on sound level decay is mainly observed in the 1 kHz and 2 kHz octave bands. Moreover, the magnitude of the effect increases with propagation distance. Longer propagation paths within the street increase the likelihood of interactions with, and absorption by, the exposed soil surfaces present in the depaved patches. After 50 m of propagation along the street, for a centrally positioned source and façade microphones, the greening-related insertion losses reached 2.6 dB at 1 kHz and 3.0 dB at the 2 kHz octave band.

Comparable results were obtained for other source–receiver configurations, except in cases where sound waves entered the street in a partially diffracted manner. Under these conditions, the observed effects were considerably smaller. From a practical standpoint, this indicates that sounds originating from a crossing street—where the source is not directly visible from within the street—are only minimally attenuated by the depavement intervention considered here. This finding suggests that targeted absorption near the street entrance may offer a more effective mitigation strategy, analogous to approaches used for noise control at road traffic tunnel portals (Jonasson and Storeheier, 2001). However, a more detailed analysis would require full-wave numerical simulations, which fall beyond the scope of the present study.

Reported data on the random-incidence absorption characteristics of exposed topsoil and similar substrates (Yang et al., 2012; Yang et al., 2013; Davis et al., 2017) indicate that sound absorption decreases at both low (<200 Hz) and high (>2500 Hz) frequencies, with maximum absorption generally occurring at intermediate frequencies. For example, Yang et al. (2013) reported an absorption coefficient of approximately 0.8 at 1 kHz for a 20 cm layer of topsoil (with a moisture content of 17%).

When the soil is wet, however, absorption properties change markedly. Given the heavy rainfall on the day preceding the post-greening measurements (see Table 1), elevated soil moisture levels can reasonably be expected during the experiments, although not actually measured. Under such conditions, absorption coefficients become very small at low and high frequencies (<0.1), and the peak absorption at intermediate frequencies is substantially reduced. For instance, Yang et al. (2013) reported that for a 20 cm layer of topsoil with a moisture content of 29%, the absorption coefficient at 1 kHz decreases to approximately 0.2.

Although soil moisture was not measured in situ in the present study, these findings suggest that the greening-related insertion losses reported here likely represent conservative (minimum) estimates of the potential acoustic effect.

The multi-modal sound level distribution across the street at the low-frequency octave bands of 125 Hz and 250 Hz makes sound pressure level measurements highly sensitive to the exact microphone positioning. Small inaccuracies in (re)positioning can therefore easily lead to differences of several decibels (see simulations in Appendix B) between the reference and post-greening measurements, as the inconsistent results in Fig. 5 at these very low frequencies seem to suggest.

In addition, the absorption of the greened patches is expected to be very limited at these low frequencies. Although reliable measurements appeared possible at 4 kHz, the decay curve is nearly identical to that obtained during the reference measurements (see Fig. 5), suggesting only minimal absorption by the greened patches. A similar observation applies to the 8 kHz band, where a more precise correction for atmospheric absorption (see further) may be required to account for the small differences observed in Fig. 5.

Although currently only effects at the octave bands of 1 and 2 kHz could be reported, this is nevertheless a frequency range of high relevance for most urban sound sources (such as road traffic, outdoor ventilation units, people talking, etc.). In addition, human hearing is most sensitive in this frequency range.

To account for the different meteorological conditions during the reference and post-greening measurements, a simple correction procedure was applied to adjust the post-greening data to the same air absorption conditions as those present during the reference measurements. Given the use of continuous noise sequences, this correction was implemented in a simplified manner based on the first arrivals, which represent the dominant component of the sound field.

It should be noted that the objective was not to remove all atmospheric absorption from the measurements, as this would lead to unrealistic outdoor conditions. Although methods for full de-absorption have been proposed in the literature (e.g., Picaut et al., 2005; Hornikx and Forssén, 2008), applying such approaches in non-quiet outdoor environments carries a clear risk of amplifying residual environmental noise. This risk is particularly relevant for field experiments such as those conducted in the present study.

In the present work, the primary focus was on sound level decay along the street, as reducing noise exposure remains a central objective in most urban noise policies. Reverberation time may serve as an additional descriptor of street acoustics. It is plausible that reverberation characteristics are linked to noise perception and soundscape pleasantness, although this relationship still requires further investigation. More broadly, the use of street reverberation time, or related parameters, as a predictor of urban noise levels has previously been proposed by several authors (e.g., Heutschi, 1995; Thomas et al., 2013; Penteado et al., 2018). From a theoretical perspective, a relationship exists between sound level decay and reverberation time, although this relationship is not necessarily straightforward.

The measured reverberation times in case of the single and fixed sound source increase with distance from the source, consistent with the measurements reported by Picaut et al. (2005) and the simulations presented by Onaga and Rindel (2007). Picaut et al. (2005) reported reverberation times in the 1/3-octave bands between 250 Hz and 5 kHz ranging from 1.1 to 1.4 s near the source, and from 1.3 to 1.6 s after 50 m of propagation. Similar values were observed in the present study, although a stronger decrease in reverberation time with increasing frequency was found. This difference can likely be attributed to two factors. First, Picaut et al. (2005) synthetically removed atmospheric absorption from their measurements. Second, the façades in their study were considerably higher, which would lead to increased downward scattering, particularly at higher frequencies. This interpretation is supported by simulations from Onaga and Rindel (2007), which showed that, for identical street widths and similar absorption and scattering coefficients, higher façades result in longer reverberation times.

The greening intervention generally reduced the reverberation time by approximately 0.2–0.3 s. This reduction is largely independent of source-receiver distance and is also observed at lower frequencies. Whereas sound pressure level decay is mainly governed by direct sound and early reflections, reverberation time is influenced by a much larger number of reflections. As a result, even relatively small absorption contributions can become significant when sound undergoes many successive interactions with the environment.

The observed distance independence of the greening can be interpreted in light of classical room acoustics theory (Kuttruff, 2009), where the reverberation time is primarily determined by the total absorption area in the space and is inversely proportional to it, while the source-receiver distance plays a much less important role. Nevertheless, the analogy between an enclosed room and a street canyon, approached as a room with an open or perfectly absorbing ceiling, clearly has its limitations.

The street greening consists of reinforced grass, exposed topsoil, topsoil covered with low-growing plants, and climbing vegetation along the walls. Some of these green elements are continuous along the street, such as the central strip of reinforced grass, while others occur only locally and are therefore more discontinuous. These different green features may interact with sound in different ways.

Exposed soil and the same soil covered with plant material have previously been shown to exhibit different acoustic absorption characteristics (Ding et al., 2013; Yang et al., 2013). The central strip of reinforced grass may introduce complex soft-ground effects (Attenborough and Van Renterghem, 2021). In particular, the alternation between rigid pavement and grass strips can lead to pronounced impedance discontinuities, which may further influence sound propagation (Attenborough and Van Renterghem, 2021). Vegetation on the walls may also introduce additional scattering. However, this effect is likely of minor importance, given the near absence of additional level decay or reverberation time reduction at 4 kHz, where such leave scattering effects might be expected (Aylor and Parlange, 1973). However, the current dataset does not allow to disentangle the relative contributions of these different greening elements to the observed acoustic changes in the street.

A visual inspection of the façades indicates that a substantial amount of scattering was already present in the reference situation, due to the large fraction of façade surfaces occupied by recessed doors and windows. In such conditions, it is well known that introducing additional absorption—here through the depaved patches—tends to be less effective in enhancing level decay along the street or reducing reverberation time. This behavior is illustrated by the simulations of Onaga and Rindel (2007), which examined combinations of scattering and absorption coefficients for receivers located near a façade in a street canyon with a single fixed source. Although only qualitatively assessed here, this moderate degree of façade scattering, together with the assumed wet soil absorption spectra, suggest that the greening-related effects reported here represent rather conservative estimates.

The present findings indicate that the mere presence of greenery is not, in itself, a reliable predictor of acoustic impact at street level. Instead, the properties of the growing substrate—and, to a lesser extent, the vegetation cover—govern the sound absorption achieved at depaved patches. In addition, potential interactions with street and façade geometry are likely to play a role, but could not be assessed here, as the experiments were conducted in a single street configuration.

Another limitation is the absence of meteorological measurements within the street canyon itself. Instead, meteorological data from a nearby official weather station were used to estimate atmospheric absorption and to exclude an influence of wind-induced microphone noise. Also refraction of sound during propagation along the street axis is unlikely given the expected low wind speeds (and consequently, weak vertical wind speed gradients) inside the street canyon. This is further backed up by the high repeatability of the acoustic measurements, not only within, but also between the repeated experiments. Meteorological measurements within the street canyon would nevertheless have allowed a more direct verification of the local meteorological conditions during the experiments.

Some further limitations should be noted. Measurements were conducted at a single receiver height (1.7 m, representative of ear level), and may therefore not reflect façade exposure at higher elevations, such as bedroom windows.

The current measurements show the potential for additional sound pressure level reduction during propagation through the depaved street, in octave bands of high relevance for environmental noise sources, such as (loud) voices (see e.g. Ballesteros et al., 2014) and outdoor devices of air-conditioning units (see e.g. Crocker et al., 2004). However, the use of a single and fixed loudspeaker, positioned close to the street surface, does not directly allow drawing conclusions on the impact on the actual sound exposure in the street. In realistic urban road traffic conditions, e.g., there will be distributed and moving sources. In such a case, the nearest vehicle can dominate the sound field, and its emitted sound may not sufficiently interact with the depaved surfaces to yield substantial attenuation.

6. Conclusions

Although challenging in real-life, non-quiet urban environments, the effect of partial depavement followed by greening could be reliably measured in the frequency range between 500 Hz and 4 kHz. The additional sound pressure level decay in case of a single and fixed sound source is mainly observed in the 1 kHz and 2 kHz octave bands and increases with propagation distance. Over an additional distance of 50 m along the street, level reductions at ear height of 2.6 dB and 3.0 dB were measured at 1 kHz and 2 kHz, respectively, with minor deviations depending on the source–receiver positioning relative to the façades, on condition the source is present inside the street itself. The greening intervention also reduced the reverberation time (RT20) by 0.2–0.3 s. In contrast to the level decay, this effect extends to lower frequencies and is largely independent of receiver distance along the street. The introduction of growing substrates, and their associated sound absorption, appears to be the main mechanism underlying the observed acoustic changes.

CRediT authorship contribution statement

Pieter Thomas: Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Timothy Van Renterghem:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to enhance readability, optimize text flow, and condense the writing. Only individual paragraphs were separately submitted, with explicit instructions not to alter the content or intended meaning. All AI-assisted revisions were subsequently reviewed and, where necessary, edited by the author. The authors takes full responsibility for the final content of this publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the city of Antwerp for (partly) funding this study and facilitating the two measurement campaigns.

Appendix A. Absolute level spectra in response to successive noise bursts

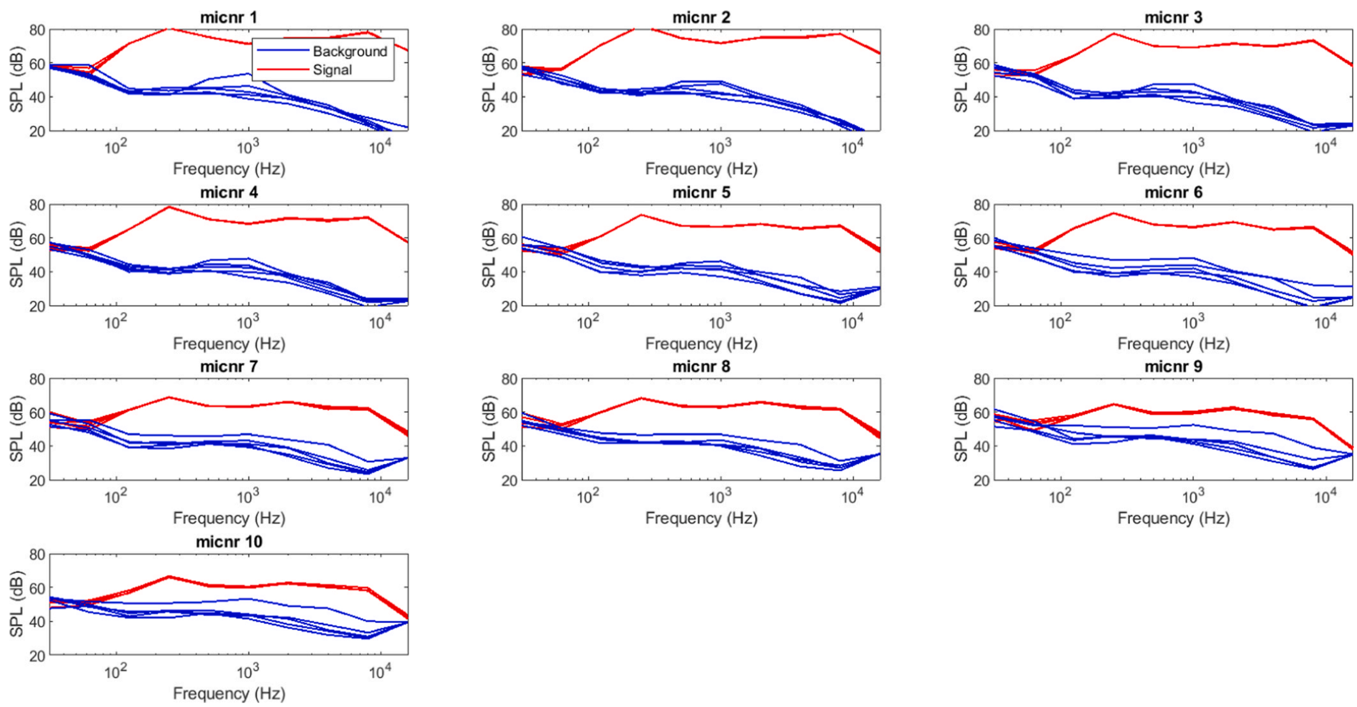

Fig. A1. Absolute sound pressure level spectra in the reference situation at the different microphones along the street's length, in response to 5 successive 10-s noise bursts (including background sounds), followed by 5 s (pure) background sounds.

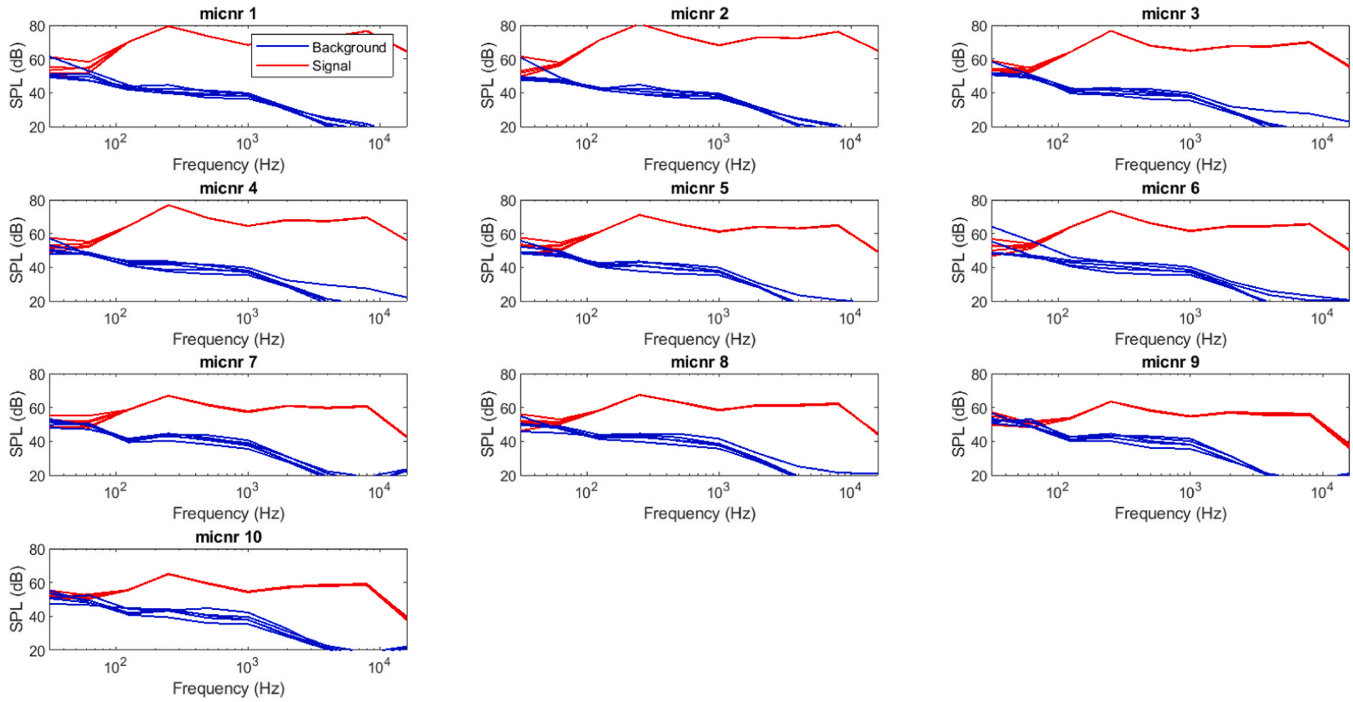

Fig. A2. See caption of Fig. A1, but now post-greening

Appendix B. Idealized sound pressure level distribution over the street canyon

In Figs. B1 and B2, the predicted spatial distribution over an idealized straight street with infinitely high and flat facades is provided, as an example, for the 250 Hz and 4 kHz octave bands, respectively. The modelled street has the same width (6 m) as the street where the measurements took place. The simulations rely on a mirror source model, similar to the model presented in Kang (2000), but making it phase-aware while assuming fully specular facades. The façade sound pressure reflection coefficient was set to 0.9 and the ground's sound pressure reflection coefficient to 1. Atmospheric absorption corresponding to the meteorological conditions during the reference measurements (see Table 1) were explicitly included. The model used 100 mirror sources, and 50 individual frequencies were considered to constitute the octave band response, leading to convergence. Using an (x;y;z) coordinate system, the (point) source is positioned at (0;3;0.5) m and receivers at (x;y;1.7) m which correspond to the centre of the dodecahedron loudspeaker, and the microphone heights, respectively. Spatial sampling is performed at one tenth of the smallest wavelength in each octave band.

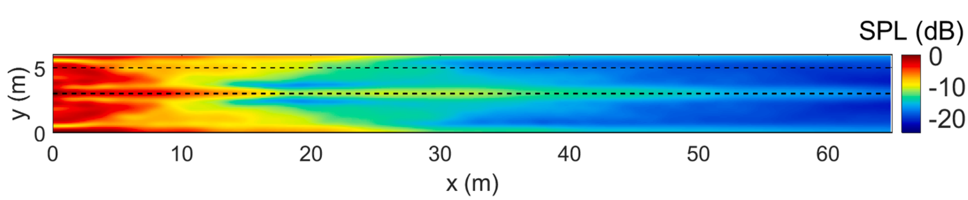

Fig. B1. Sound pressure level distribution over the street, at the microphone height at 1.7 m, for the 250 Hz octave band. Levels are referred to the maximum found along the receiver plane. The dashed lines show the façade (at y=5) and central (at y=3) microphone positioning lines

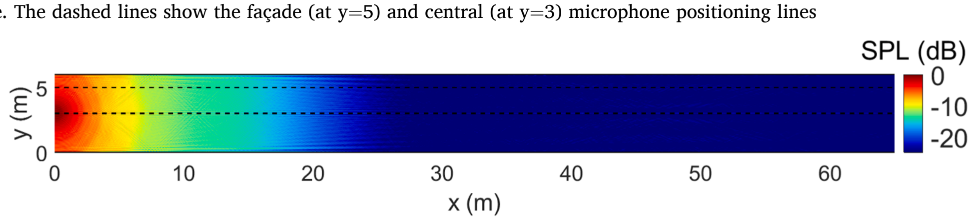

Fig. B2. See caption of Fig. B1, but now for the 4 kHz octave band.

Appendix C. Sound level decays and reverberation times in the reference and greening condition

Table C1
Mean sound pressure level decay (in dB) along the street's length for the octave bands of 1 and 2 kHz at different source and receiver positionings, in the reference and greening condition. The values in between brackets are the standard deviations on repeated signal emissions (n = 3 or 4). The closest microphones are used as a reference level (more precisely, M1 in case of façade microphones, M2 for central positioned microphones)

	Central source - facade mics				Central source - central mics			
	1 kHz		2 kHz		1 kHz		2 kHz	
Distance (m)	Reference	Greening	Reference	Greening	Reference	Greening	Reference	Greening
7.82	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)	0.0 (0.2)	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)
24.05	−2.9 (0.2)	−3.4 (0.1)	−4.0 (0.2)	−5.6 (0.3)	−3.5 (0.1)	−3.1 (0.1)	−3.8 (0.3)	−5.0 (0.2)
33.75	−5.1 (0.1)	−7.3 (0.1)	−6.6 (0.2)	−9.2 (0.1)	−5.5 (0.2)	−6.3 (0.0)	−5.9 (0.2)	−8.8 (0.0)
47.16	−8.3 (0.1)	−10.6 (0.1)	−8.8 (0.2)	−11.9 (0.1)	−8.6 (0.1)	−9.5 (0.1)	−9.3 (0.1)	−11.6 (0.1)
63.11	−11.3 (0.4)	−13.7 (0.3)	−12.4 (0.1)	−15.3 (0.3)	−11.9 (0.3)	−13.4 (0.2)	−12.5 (0.2)	−15.2 (0.2)
	Off center source - facade mics				Diffracted sound - facade mics			
	1 kHz		2 kHz		1 kHz		2 kHz	
Distance (m)	Reference	Greening	Reference	Greening	Reference	Greening	Reference	Greening
7.82	0.0 (0.2)	0.0 (0.1)	0.0 (0.2)	0.0 (0.3)	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)
24.05	−4.5 (0.1)	−5.0 (0.0)	−3.9 (0.0)	−5.9 (0.2)	−3.9 (0.3)	−4.4 (0.0)	−3.0 (0.4)	−3.5 (0.0)
33.75	−5.9 (0.1)	−8.2 (0.2)	−6.3 (0.1)	−9.0 (0.0)	−5.7 (0.3)	−6.8 (0.0)	−6.3 (0.1)	−5.9 (0.2)
47.16	−9.5 (0.3)	−10.6 (0.2)	−9.2 (0.2)	−11.9 (0.8)	−9.3 (0.2)	−10.4 (0.1)	−8.5 (0.3)	−9.0 (0.1)
63.11	−12.3 (0.3)	−14.9 (0.3)	−12.6 (0.2)	−14.4 (0.4)	−12.3 (0.6)	−13.0 (0.4)	−12.3 (0.2)	−12.2 (0.3)

Table C2
Reverberation times (RT20) along the street's length (in s), in function of frequency, for the façade microphones and central source positioning, in the reference and greening condition. The values in between brackets are the standard deviations on repeated signal emissions (n = 5 or 6)

Reference **Distance (m)**	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**
7.82	1.05 (0.01)	1.03 (0.02)	0.96 (0.01)	1.29 (0.01)	1.18 (0.06)	0.84 (0.03)	0.59 (0.06)
24.05	1.15 (0.02)	0.98 (0.02)	1.21 (0.01)	1.29 (0.03)	1.27 (0.03)	1.02 (0.03)	0.68 (0.04)
33.75	1.31 (0.04)	1.02 (0.03)	1.18 (0.02)	1.36 (0.03)	1.36 (0.03)	1.10 (0.03)	0.79 (0.04)
47.16	1.41 (0.05)	1.10 (0.02)	1.27 (0.03)	1.42 (0.02)	1.43 (0.04)	1.13 (0.01)	0.83 (0.05)
63.11	1.83 (0.05)	1.26 (0.01)	1.41 (0.06)	1.72 (0.02)	1.80 (0.10)	1.32 (0.08)	0.81 (0.07)
Greening **Distance (m)**	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**
7.82	0.96 (0.02)	0.91 (0.01)	0.83 (0.01)	1.07 (0.04)	0.99 (0.03)	0.81 (0.01)	0.59 (0.01)
24.05	0.88 (0.02)	0.78 (0.02)	1.03 (0.01)	1.12 (0.04)	1.12 (0.02)	0.99 (0.03)	0.73 (0.03)
33.75	1.20 (0.03)	0.98 (0.02)	1.06 (0.02)	1.13 (0.04)	1.23 (0.03)	1.07 (0.02)	0.82 (0.01)
47.16	1.10 (0.03)	0.97 (0.01)	0.97 (0.02)	1.30 (0.05)	1.32 (0.05)	1.27 (0.07)	0.85 (0.02)
63.11	1.30 (0.10)	1.10 (0.03)	1.05 (0.02)	1.50 (0.16)	1.53 (0.05)	1.52 (0.10)	0.86 (0.05)

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