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Angaben zur Veröffentlichung / Publication details:

Egerer, Monika, Peter Annighöfer, Sophie Arzberger, Tobias Bahlmann, Stefanie Burger, Michaela Coenen, Andrew Fairbairn, et al. 2026. “Social-ecological relationships on biodiverse and health-promoting city soundscapes.” *Basic and Applied Ecology* 90: 73–88. https://doi.org/10.1016/j.baae.2025.12.007.

Basic and Applied Ecology 90 (2026) 73–88

Contents lists available at ScienceDirect

Basic and Applied Ecology

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

Research Article

Social-ecological relationships on biodiverse and health-promoting city soundscapes

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ARTICLE INFO

Keywords:
Urban green infrastructure
Biodiversity
Human wellbeing
Restoration
Urban planning
Transdisciplinary research
Urban soundscapes

ABSTRACT

Urban soundscapes indicate biodiversity and environmental conditions, including urban stressors. Although relationships among soundscapes, biodiversity, and mental health effects exist, better quantification is needed to inform biodiversity-based health interventions. We present the pilot phase of the CitySoundscapes project, a transdisciplinary effort to develop methods for surveying biodiversity and human wellbeing associated with urban soundscapes. This approach involved citizens and practitioners across conservation, planning and health sectors as well as various urban contexts. In this initial one-year phase of our research, we investigated how soundscape characteristics relate to green space structural complexity, how to measure biodiversity using acoustic monitoring (here, vocal bird species), and people's acoustic perceptions. We also piloted participatory approaches to identify where there are places of high biodiversity, high acoustic comfort and perceived restoration. Our goal was not to deliver exhaustive ecological results, but to test and combine methods from ecology, environmental psychology, and urban planning for feasibility and complementarity. We present these methods and an approach to assess relationships among sound, biodiversity and wellbeing in urban spaces of varying vegetation structure. This case study provides a perspective on how green spaces and their structural features could relate to soundscapes and acoustic comfort and restoration, as well as how green spaces offer habitat for a diversity of sound-producing organisms. This methodological and conceptual contribution offers the groundwork for ecological and inter- and transdisciplinary research. The preliminary insights can inform ecological understanding and practical strategies for healthier, more biodiverse cities.

Introduction

A 'soundscape' can be defined as the entire collection of sounds produced by humans (anthrophonic sounds), by the living environment (biophonic sounds) and by the physical environment (geophonic sounds) (Krause, 2013). In cities, a milieu of various audible stimuli come together in the soundscape to influence the lived experience of urban residents and human health in relation to the built environment,

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https://doi.org/10.1016/j.baae.2025.12.007
Received 31 May 2025; Accepted 10 December 2025
Available online 11 December 2025

as well as to green and blue infrastructure (Pijanowski et al., 2011). Furthermore, the sounds of animals within urban green and blue spaces can be indicators of biodiversity and environmental conditions and can affect human health (Basner et al., 2014). Our work combines conceptual and methodological approaches from an urban ecology and environmental psychology perspective to explore relationships between urban green space structural complexity, biodiversity and human wellbeing. We also include multispecies-oriented approaches to convey a more holistic understanding of soundscapes, particularly in our public outreach work. All three approaches, briefly described here below, stress complementary aspects of soundscapes.

Interdisciplinary perspectives on soundscapes

The field of ecoacoustics investigates the (ecological) role of sounds from both natural and human sources in ecosystems, in which sound can be both a subject of study to understand ecological processes as well as a tool for monitoring biodiversity, assessing habitat characteristics, and determining the effects of human activity on the environment (Farina, 2018). From an urban ecological perspective, natural soundscapes (biophonic and geophonic sounds) indicate trees, wind, and water, as well as sound-producing organisms (e.g., birds, bats, grasshoppers, frogs) that rely on sound to communicate and survey their environments. The biophonic component of soundscapes can be used to assess which species are present within a space and to identify the urban green space structures and also what urban green space structures may be associated with species presence. For example, dense understory vegetation relates to a high diversity of bird sounds whilst also absorbing anthropogenic noise (Uebel et al., 2021). As cities densify and lose vegetation, soundscapes become less audibly diverse and less biophonic due to increasing anthropogenic sounds (Hasegawa et al., 2022; Joo et al., 2011), likely reflecting the decline of sound-producing organisms and the homogenization of urban animal communities. Vegetated spaces can support plant and animal life in cities that are often characterized by imperviousness and green space loss (Perillo et al., 2017). Vegetation structural complexity — "the degree of heterogeneity in biomass distribution in three-dimensional space" (Ehbrecht et al., 2021) — can be an important predictor of urban biodiversity (Beninde et al., 2015).

In the cognitive-psychological dimension, the soundscape concept focuses on how an individual person perceives and experiences the acoustic environment (Kang et al., 2018; Moebus et al., 2020). The international standard definition ((ISO 12913-1:2014)) defines a soundscape as an acoustic environment that is perceived, experienced and/or understood by one or more people in the respective spatial context. While this standard provides a widely applied operational framework, soundscape research more broadly is embedded in multiple epistemological traditions, ranging from cognitive psychology and (eco)acoustics to public health and urban planning. From this cognitive psychology perspective, a soundscape exists specifically in the moment it is perceived by an individual, where preferences for different sounds are variable (Moebus et al., 2020). From a public health perspective, some sounds (traffic, construction) can induce stress and anxiety, and are considered “noise” with both temporary and permanent negative impacts on human health and associated social inequities (Goines et al., 2007). Residents may seek out spaces that are quieter with lower levels of noise pollution from traffic or construction. On the other hand, some sounds (birds twitching, trees in the breeze, flowing water) can facilitate calmness, stress recovery, nature connection, perceived restoration (Berto et al., 2010; Francomano et al., 2022) and in turn enhanced cognitive performance (Buxton et al., 2021). Thus, soundscapes are an important dimension of urban landscapes that relate to perceptions of nature and human health outcomes in cities (Radicchi et al., 2021).

More recent conceptualizations of soundscapes in the humanities, arts and social sciences consider the agency of more-than-human species in the active shaping of shared acoustic worlds, and the responsibility and ethical obligations of humans in the planning of those environments (Ruiz Arana, 2021, 2024). This transdisciplinary perspective and approach to soundscapes aims to de-center soundscape approaches that narrowly focus on human interest and acknowledge that sounds can be meaningful and have effects in a multiplicity of ways across species and individuals (Ogden et al., 2013; Tsing, 2015). As Jordan Lacey proposes in their reflection of ‘the posthuman listener’, “a soundscape is more-than-human insofar as it always exceeds any one person’s apprehension, while at the same time being differentiated by each sensing body into a diversity of listening experiences … Accordingly, sensory attentiveness – ‘the cultivation of skills for both paying attention to others and meaningfully responding’ (Van Dooren et al., 2016) – is positioned here as the ethical and practical foundation for understanding soundscapes” (Lacey, 2024: 274).

Interdisciplinary research on soundscapes

The various disciplinary work on soundscapes has resulted in a diverse body of basic and applied research (Pijanowski, 2024). However, there is still relatively little integrative, inter– and transdisciplinary research on soundscapes. Green and blue space structure and complexity likely influence how auditory sensory experiences relate measures of human wellbeing to measured sounds of biodiversity (Francomano et al., 2022) and thus more biophonic soundscapes (Fisher et al., 2021). But very few empirical studies have linked health metrics related to human-perceived sound of environmental characteristics (e.g., green space complexity, landscape imperviousness) with biodiversity metrics related to sound (Buxton et al., 2021; Markevych et al., 2017). The analysis and systematic evaluation of soundscapes from a human health perspective (e.g., ISO 12,913 series of standards (Sun et al., 2019)) is also still in its infancy. The Perceived Restorativeness Soundscape Scale (PRSS) is one of the few attempts to evaluate the psychological recovery of people through a soundscape (Payne & Guastavino, 2018). Analysis and evaluation are challenging as soundscapes cannot be described by numerical metrics alone but depend largely on human perception. Furthermore, while few studies have found correlations between acoustic indices and perceived biodiversity (bird richness) (Rozario et al., 2025), metrics that are used in ecoacoustics to quantitatively describe soundscapes may not necessarily reflect human perceptions. Individual characteristics of people (e.g., nature-connectedness, age, emotional state) may also mediate these biodiversity–wellbeing effects (Marselle et al., 2021a, b). Thus, soundscapes can have the same quantitative measured level but be perceived very differently by the listener (e.g. 50 dB sound of bird call vs. machine noise) (Jennings & Cain, 2013). Participatory methods and tools with people such as citizen science, crowdsourcing and interactive workshops are also important to assess and understand the influence of the auditory environment on the individual (Payne & Guastavino, 2018). Transdisciplinary approaches in research and praxis that integrate biodiversity, ecoacoustics and public health are lacking, but are needed to measure and promote biodiversity, restorative experiences, and human wellbeing in urban landscape planning and management.

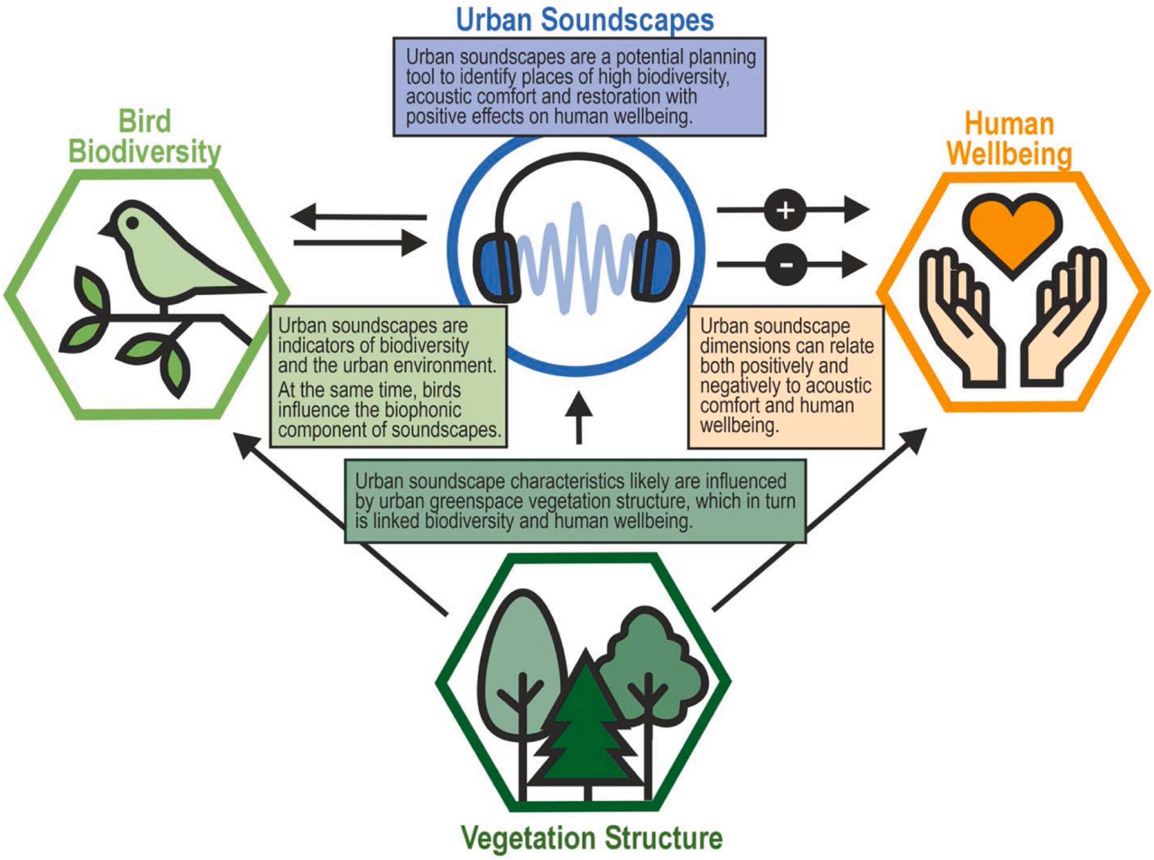
Several studies argue that solutions lie in integrating the concern for soundscapes and focusing on positive effects of soundscapes into the early stages of urban planning and green space design (Farina, 2014; Jaszczak et al., 2021; Lippold & Lawrence, 2019). Yet, most research continues to focus on traditional approaches to noise reduction, avoidance, and abatement (Chen et al., 2022), rather than on soundscapes as the intersection of biodiversity conservation and human health. Nevertheless, the soundscape approach is gaining attention as an innovative method for urban planning with identifying, analyzing, and evaluating existing soundscapes (Haselhoff et al., 2022; Hosseini & Kowkabi, 2023; Jennings & Cain, 2013). Methods implemented include soundwalks, surveys, measurements, mixed reality, and participatory tools (Chen et al., 2022). For example, the ‘Sounding Brighton’ project, launched by the Noise Abatement Society in the UK aims to strengthen the consideration of soundscapes in urban planning and to raise awareness among the public, stakeholders and policy makers (Lavia et al., 2012). Some good practice examples at the site level exist, such as establishing pocket parks to reduce noise in neighborhoods (Guo et al., 2023), to offer a unique soundscape experience, and to blend elements of traditional parks with vibrant public spaces (Jia et al., 2020; Steele et al., 2019a, b). Despite such promising efforts, urban strategies for soundscape planning are still generally missing in most cities. This calls for urban planning measures that relate the topics of ecoacoustics, biodiversity and human wellbeing from a soundscape perspective.

Our research focuses on soundscapes as one quantifiable sensory aspect of urban landscapes to predict the relationship between biodiversity and human restoration in urban areas (Markevych et al., 2017). This relationship is relatively understudied from a combined research, praxis, and public engagement perspective (Fig. 1). This study presents workflows and methods that enable interdisciplinary research into the social-ecological aspects of urban soundscapes. Our questions are: (1) How are the characteristics of urban soundscapes related to urban green space and their proximal structural complexity, as well as to local biodiversity (here, the activity and richness of bird vocalisations)? (2) How are urban soundscapes related to human acoustic comfort and restoration? (3) Where are places with high biodiversity, acoustic comfort and restoration effects? And (4) How can such spaces be fairly promoted in urban planning and administrative processes? To answer these questions, we integrate methods from ecoacoustics and environmental psychology, as well as urban planning and management with the goal to develop recommendations for city planners and policy makers on how to design green spaces that can promote both biodiversity and human wellbeing.

The purpose of this article is to present the initial phase in which we tested and integrated diverse methods including acoustic indices, species detection, vegetation surveys, soundwalks, and community participation to assess their feasibility and complementarities. We position this work as exploratory: while some of our research questions are addressed empirically with pilot data here, others are explored through preliminary insights and other studies. Together, these outcomes aim to provide a foundation for developing an interdisciplinary framework for future research. We demonstrate how we tested methods to characterize soundscapes, and to quantify the relationships among biodiversity in green spaces with a focus on birds, vegetation structural complexity, as well as a method to measure soundscape perceptions and restoration. In addition, we provide first suggestions for public engagement that integrate biodiversity and wellbeing promotion to identify good practice examples that can inform tools to enhance the integration of biodiversity and wellbeing in urban planning and green space management. We reflect on our approaches and make recommendations for their improvement for future soundscape studies. With the rise of interest in social-ecological studies in basic and applied urban ecology, the purpose and strength of this manuscript is in the methods and concepts presented that we hope to be a valuable contribution to an interdisciplinary ecological audience.

Methods

In our pilot project we conducted a case study in the city of Munich, Germany. Here we focus on the methodological framework of the pilot project, in which we explored methods that relate biodiversity, soundscapes and human restoration metrics (Fig. 1). Munich is a relatively big city of Germany with 1.64 million inhabitants in an area of 311 km^2



Urban soundscapes are a potential planning tool to identify places of high biodiversity, acoustic comfort and restoration with positive effects on human wellbeing.

Urban soundscapes are indicators of biodiversity and the urban environment. At the same time, birds influence the biophonic component of soundscapes.

Urban soundscape dimensions can relate both positively and negatively to acoustic comfort and human wellbeing.

Urban soundscape characteristics likely are influenced by urban greenspace vegetation structure, which in turn is linked biodiversity and human wellbeing.

Fig. 1. Conceptual diagram of the relationships among the social-ecological dimensions of urban soundscapes. Urban soundscape characteristics likely are influenced by urban green space vegetation structure, which in turn influences biodiversity. Furthermore, urban soundscapes relate to dimensions of acoustic comfort and human wellbeing (restoration). Key for urban planning is to identify places of high biodiversity, acoustic comfort and restoration with positive effects on human wellbeing that can be equitably promoted in planning and sound-based policies. Graphic by Sophie Arzberger.

(Statistisches Amt München, 2025) that also offers a variety of urban land uses with distinct environmental features as well as green spaces established during different time periods that are characteristic of many central European cities (e.g., English gardens, pocket parks, multifunctional parks). We established a consortium consisting of academic research institutions, civil society organizations and municipal administration to study how soundscapes vary across urban green space and built infrastructure (or 'gray space') gradients. Here we briefly describe our study system and methods in inter– and transdisciplinary research, and how we have approached the analysis of biodiversity and human restoration data. Our primary aim was to test the feasibility and complementarity of multiple methodological approaches rather than to provide comprehensive ecological results. The choices of timing, scale, and sample size were therefore made to balance methodological breadth with practical feasibility.

Establishment of study sites

Munich has a long history of urban green space development including parks and gardens of various ages, sizes and structural characteristics as well as human use (Landeshauptstadt München, 2020). To investigate such effects on biodiversity and wellbeing, we established 93 research sites (44 research plots in 33 green spaces (Arzberger et al., 2024), 14 city squares (Fairbairn et al., 2024), and 32 reference point locations in the built surroundings ('REF') within the central ring (inner city) of Munich as our study system (Fig. 2). The research plots represent a gradient of local vegetation structural complexity as well as urban landscape context and, except for the reference points, were located at least 300 m in distance between one another to reduce spatial autocorrelation (Fontana et al., 2011).

Green space structural complexity, bird diversity and soundscapes

To collect information about vegetation structural complexity and diversity, soundscape characteristics and bird diversity, we piloted the combination of using mobile laser scanning (MLS) with passive acoustic monitoring in urban green spaces (parks) and city squares. The vegetation structure was recorded in each of the green space plots and city square plots using a hand-held MLS (ZEB HORIZON, GeoSLAM Ltd, UK; see Arzberger et al. (2024) for full description of methodology). Vegetation structural complexity was assessed within a 15 m radius around each recorder. We chose this plot size for MLS data collection due to the small size of the squares and because the MLS delivers high-resolution data only on a small scale and is not an appropriate method to cover larger spatial scales. Furthermore, we focused on smaller scale vegetation features here as previous studies on vocal bird diversity in Munich using similar acoustic methods showed the importance of local vegetation features within 100 m rather than the surrounding landscape (i.e., based on NDVI in larger buffers of up to 1 km; Fairbairn et al., 2024, 2025b). Potential limitations around overall habitat complexity and landscape connectivity are discussed below, and subsequent phases of the project will incorporate larger spatial buffers and landscape composition and connectivity measures.

The raw data was processed using the manufacturer-specific software GeoSLAM Connect (version 2.2.0) and the open-source software CloudCompare (CloudCompare, version v2.13.alpha, https://www.danielgm.net/cc/, France). The processed data was analyzed with the software R (version 4.2.6), using RStudio (version 2023.12.1) and the R-package lidR (Roussel et al., 2020). To characterize the vegetation structural complexity of each plot, we calculated ten MLS-metrics hypothesized to predict soundscape characteristics as well as (bird) biodiversity (Table 1). With these vegetation structure metrics, several of which were correlated, we performed a principal component analysis (PCA). The vegetation metrics on the principal components (PCs) were computed to assess which vegetation metrics contributed the most to their respective PCs. Two principal components were calculated to represent vegetation volume and height (PC1) and vegetation vertical structural heterogeneity, from the low shrub layer to higher canopy layer (PC2). The scores of PC1 and PC2 were extracted for each research plot to be used as explanatory variables in our analysis.

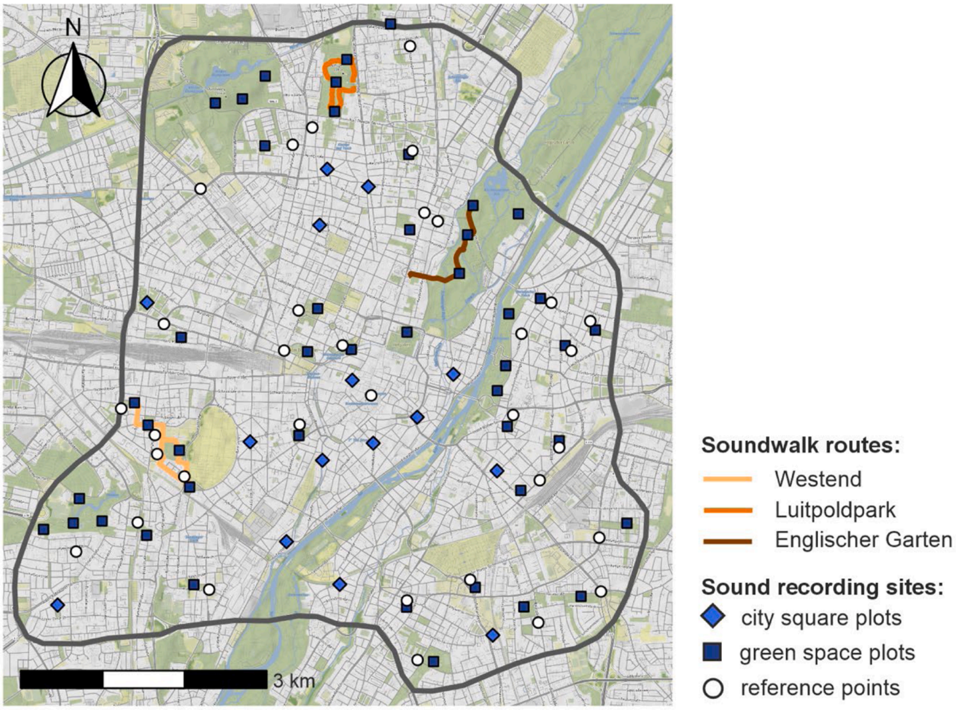


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Fig. 2. Research sites in the inner city of Munich, Germany (as delineated by black line) where sound recordings took place (circles, squares, diamonds) as well as soundwalk routes took place (colored lines). Graphic by Sophie Arzberger.

Table 1
Selected example of structural metrics and their units derived from MLS data and used to create principal components that represent different aspects of vegetation structural complexity, as well as potential hypothesized relevance to bird diversity.

Metric	Explanation	Units	Relevance for bird diversity
Canopy Cover	Ratio between the canopy pixels (threshold height of 3 m) and the total number of pixels within the canopy height model. Indicates how much of the area is covered by the canopy.	Percentage (%)	Canopy cover influences habitat availability, protection from predators, and nesting sites for birds. Higher canopy cover can support more bird species.
Mean Height	The average height of all points in the point cloud. Provides an indication of the general vertical structure of the vegetation.	Meters (m)	Taller vegetation can provide nesting opportunities for different bird species and support greater vertical stratification in habitats.
Box Dimension	A measure of structural complexity calculated using fractal geometry. Higher values indicate more complex structures within the point cloud (Seidel, 2018).	Dimensionless	Structural complexity is associated with diverse microhabitats and resources, which attract a variety of bird species with different ecological needs.
Gini Coefficient	Measure of statistical dispersion to describe the vertical distribution of the vegetation. The Gini coefficient can be used to quantify the density of understory vegetation and the asymmetry of the vertical vegetation profile.	Dimensionless (0–1)	Height inequality reflects vertical habitat heterogeneity, which can support diverse bird species by providing various feeding, nesting, and roosting opportunities.
Clark-Evans Aggregation Index	A metric indicating spatial point distribution: values ⟨ 1 suggest clustering, values = 1 indicate random distribution, and values ⟩ 1 suggest regular spacing.	Dimensionless	Aggregation patterns of vegetation influence the spatial distribution of birds. Clustered vegetation can support bird species that prefer dense habitats, while regular spacing may favor those needing open areas.
Point Density	Ratio between the number of points in the point cloud and the number of points in a predefined cylinder based on the plot-specific maximum canopy height. Provides insight into vegetation density.	Percentage (%)	Dense vegetation often correlates with increased availability of cover and food resources, which attract more birds and provide protection.
Density at DBH	Ratio between the point density of the diameter at breast height layer (1–2 m) in comparison to the point density of the layer with the maximum point density. Related to the shrub and understory layer	Percentage (%)	The density of vegetation within 1 to 2 m from the ground (e.g., shrubs) can be important for birds that forage or nest near the ground or on tree trunks (e.g. woodpeckers, small passerines.

We conducted continuous 24-h acoustic recordings within each of the research plots during two recording rounds of seven days each in all study sites including urban green spaces, city squares and reference points (Round 1: 11.08.2023 – 18.08.2023; Round 2: 24.08.2023 – 30.08.2023 (168 h of recordings for each plot)). We recorded in August as part of our coordinated pilot phase; we acknowledge that bird vocal activity often peaks in spring and early summer, however we can still measure the vocal bird community for a relative assessment across sampled sites. Relating vegetation structure to acoustic indices in this dataset is therefore exploratory and provides information on bird vocalization and thus bird communities in the time we surveyed. We used passive acoustic monitoring devices from Frontier Lab (BAR & BAR LT) placed three to four meters above the ground on lamp posts or trees depending on available infrastructure and physical conditions. Recordings were taken at a sample rate of 48 kHz, a bit depth of 16 and a gain of 40 dB (Fairbairn et al., 2024b). During preliminary analyses we identified that one site was dominated by running water in a nearby fountain; this site was removed from the analyses. At two sites, data storage was compromised, and no data could be retrieved. Analyses were based on 90 sites.

From the collected acoustic data, we derived four different acoustic indices to characterize the urban soundscapes (Fairbrass et al., 2017). This included the Acoustic Diversity Index (ADI), Acoustic Evenness Index (AEI), Bioacoustic Index (BI), and the Normalised Difference Soundscape Index (NDSI) (Table 2). Hourly means were calculated for all indices for the entire recording period (168 recording hours per site) using the *seewave* and *soundecology* packages in their default settings in R (Sueur et al., 2008; Villanueva-Rivera & Pijanowski, 2018). In addition, we subset the data to focus on daytime (diurnal) soundscapes where organisms of focus (vocal birds) are most dominant as well as when people are most likely to experience soundscapes (04:00 to 20:00).

We derived local songbird biodiversity using BirdNET, a deep artificial neural network that can identify vocal bird species by call in 3-s segments (Kahl et al., 2021). Bird vocal activity was analyzed using BirdNET Analyzer, with overlap 0, sensitivity 1, and i including week of the year and location for species filtering via BirdNET and eBird. We followed the settings for BirdNET suggested by Fairbairn et al. (2025a) to produce the highest dataset resolution to validate results, keeping only detections with a confidence of 0.8 or above. BirdNET detections were validated by checking species detected ten times or fewer across all sites and those detected only one time per site were removed for being considered incidental and not resident to the site. We then calculated alpha diversity (vocal bird species richness), a vocal Shannon's Diversity index (a standardized index that measures species diversity), and bird species vocal activity rate (VAR; Pérez-Granadados et al., 2019) for each site for each recording round. VAR was used for the calculation of vocal Shannon's Diversity.

To test for differences in vocal bird diversity and soundscape indices between urban green spaces, city squares, and reference points, we applied the Kruskal–Wallis test followed by pairwise Wilcoxon rank-sum tests as post hoc analyses, as not all variables were normally distributed. We built generalized linear models to test the relationships between vegetation structural complexity (PC1, PC2) and the four soundscape acoustic indices derived from the acoustic recordings. Response values

Table 2

Description of the three acoustic categories (biophony, geophony, anthrophony), based on e.g., Krause (2013) and Pijanowski et al. (2011), and the four acoustic indices calculated here to characterize the urban soundscapes in study sites in Munich, based on Fairbrass et al. (2017): the Acoustic Diversity Index (ADI), Acoustic Evenness Index (AEI), Bioacoustic Index (BI), and the Normalised Difference Soundscape Index (NDSI).

Acoustic information or index	Description
Biophony	Acoustic signals produced by non-human organisms (e.g., bird song, insect stridulation, mammal calls). In our analysis, these were primarily detected in the mid-frequency range (~2–10 kHz), where most avian and insect vocalizations occur.
Geophony	Non-biological natural sounds generated by geophysical processes (e.g., wind, rain, flowing water). These were typically concentrated in lower frequencies (<2 kHz for wind and water flow) but can overlap with higher bands during rainfall.
Anthrophony	Human-produced sounds associated with human activities including mechanical, industrial, and social activity (e.g., traffic, aircraft, voices, construction). These can dominate low to mid frequencies (typically 20 Hz–2 kHz for traffic and machinery) but also can extended into higher frequencies for human speech (~0.3–6 kHz), especially in cities.
Acoustic Diversity Index (ADI)	ADI measures the diversity of frequency and amplitude distribution between a distinct time window; it is based on Shannon Diversity Index (SDI).
Acoustic Evenness Index (AEI)	AEI measures the concentration of dispersion of energy amongst frequency bins; like the ADI but uses Gini-coefficient instead of SDI (Reserve ADI).
Bioacoustic Index (BI)	BI measures the amplitudes in the biophonic frequency range of 2–10 kHz; it is a function of both amplitude and number of occupied frequency bands (in 1 kHz steps) between a defined frequency range. Values are relative to the quietest 1 kHz frequency band; higher values indicate greater disparity between the loudest and quietest bands.
Normalised Difference Soundscape Index (NDSI)	NDSI measures the ratio of amplitudes within the ranges of biophonic (2–10 kHz) and anthrophonic (1–2 kHz) sounds, estimates anthropogenic disturbance.

were the hourly values for all sites from the entire recording period (7 days, 168 recording hours per site) and then the average value per site. All analyses were performed in the R Statistical Environment version 4.4.3.

Soundwalks to measure soundscape perceptions, acoustic comfort, and restoration

We carried out a feasibility study to test a method to conduct "soundwalks" to measure soundscape perceptions, acoustic comfort, mood and restoration. In environmental psychology and acoustic soundscape research, the soundwalk methodology is a research method for investigating environmental sounds, in which human participants stop along a defined route, consciously listen to the acoustic environment, and evaluate the soundscape according to different standardized question sets (Behrendt, 2018). We conceptualized two German-language questionnaire variants based in the DIN ISO/TS 12,913–2 conceptual framework that links soundscape experience to human restoration for data collection.

The questionnaire had the following main components: (1) an 'affect grid' (9 × 9 square grid) to evaluate two different dimensions of mood states: horizontal dimension: pleasure or displeasure (from left to right; 1–9) and vertical dimension: arousal versus sleepiness, where arousal refers how "activated" someone feels (from bottom to top; 1–9) (Russell et al., 1989); (2) standardized soundwalk questions following either variant (i) DIN ISO/TS std 12,913–2 (ISO/TS 12913-2, 2018) or variant (ii) "Perceived Restorativeness Soundscape Scale" (PRSS) (German-language translation) following Payne (2013); (3) a graphical query of ones' relation to nature (Kleespies et al., 2021); (4) two questions on disturbing or perceived restorative ambient sound; and (5) sociodemographic questions. Part 2 asked how soundscapes and multisensory aspects are experienced including questions to be answered on a Likert scale, including: "*There is a lot for me to explore in this sound environment*"; "*I find this sound environment fascinating*"; "*I like to spend time in sound environments like this one*"; "*The sounds come together to create a harmonious sound environment*". The DIN ISO/TS 12,913–2 questionnaire measures different psychoacoustic parameters, like sharpness, tonality, roughness or fluctuation strength which can be correlate to the individual perception and assessment of environmental noise sources, e.g. road traffic noise (ISO/TS 12913-2, 2018). Part 2 measures eight affective attributes will be used to calculate a rating in the main dimensions of pleasantness and eventfulness. The second soundscape questionnaire was the German non-validated translation of the PRSS, which consists of 44 items, rated by a 9-point Likert Scale (0 = not at all; 9 = completely). The scale is designed to assess perceptions of a soundscape's potential to provide psychological restoration based on the attention restoration theory by Kaplan and Kaplan (1989).

For both questionnaires, different psychoacoustic indicators can be calculated that related to the restorative potential of environmental soundscapes. The survey was available either via a paper-based questionnaire or smartphone. We then conducted qualitative interviews after the soundwalk with volunteers to ask for their feedback to improve the quality of the soundwalks for the future. The pilot survey in the original German format as well English translation (note: the survey was only conducted in German) can be found in Appendix A, 1.1.

We tested the soundwalk design in three different green spaces in Munich (Fig. 2) over six soundwalks with 27 volunteer residents that were recruited using posters and flyers in local businesses, social network platforms, and networks of civil society organizations. The feasibility study enabled us to test tools (surveys, site selection, route design) and to study how residents perceive soundscapes. The three soundwalk study sites were selected from the same sites as 2.2. to represent different green space contexts of varying structural complexity and biodiversity (Fig. 2): Westend Park (lower structural complexity), Luitpoldpark (middle structural complexity), and Englisher Garten (high structural complexity). Along these routes, participants stopped for five minutes in three to four listening locations as well as a reference control area, such as subway stations that were the initial meeting point for the walks and completed the survey questions. Each of the listening locations were also respective data collection points for structural complexity data as well as acoustic monitoring. The routes ranged from 1.6 to 3.3 km and were 60 to 90 min in duration.

Data were collected and managed using REDCap (Research Electronic Data Capture) hosted at the Department of Medical Information Processing, Biometry, and Epidemiology – IBE at LMU Munich. REDCap is a secure, web-based software platform designed to support data capture for research studies, providing: (1) an intuitive interface for validated data capture; (2) audit trails for tracking data manipulation and export procedures; (3) automated export procedures for seamless data downloads to common statistical packages; and (4) procedures for data integration and interoperability with external sources (Harris et al., 2009, 2019). For data analyses, we summarized all soundwalk questionnaires per listening location across all respondents. For the affect grid, we calculated the frequency of each x- and y-values for each listening spot and soundwalk track from the 9 × 9 square grid. Because of the two dimensions (positive/negative affect and arousal/sleepiness) both dimensions were accumulated separately. A neutral emotional state is represented in the center of the grid. Any positive feelings are characterized by a high value in dimensions. For the DIN-ISO questionnaire as well as for the PRSS questionnaire, different acoustic indices for restoration can be and were calculated (e.g., traffic noise or fascination).

Interactive and participatory approaches

In parallel, we piloted small-scale interactive and participatory approaches designed to engage residents with sound environments, to raise awareness of soundscapes, and to test the feasibility of integrating more interactive practices into soundscape research. Here we tested participatory mapping methods, citizen science for acoustic data on bird song and interactive activities to qualitatively engage people in the monitoring, learning and shaping of their urban soundscapes. With these formats, we wanted to explore the contribution of biodiverse environments to urban soundscapes as experienced directly by people through their emotional and multisensory encounters with sounds and subsequent sound-based biodiversity. In addition, we sought to raise awareness of people's capacity and role in designing health-promoting soundscapes that support human wellbeing but also connect to the needs of other species. While not systematically evaluated in this phase, qualitative feedback indicated strong public interest, and we discuss these preliminary outcomes as inspiration for future, more structured interactive approaches below.

We piloted the methods in an "Urban Sound Lab," a free walk-in workshop hosted at the BIOTOPIA Lab (Munich) on four separate days in 2023. Publicity was done via social media (Instagram), press releases, newsletters, and the museum's event program, resulting in ~100 visitors. The main aim of the workshop was to trial the suitability of the participatory formats from participant and scientist perspectives, using visitor feedback regarding the usability and exploratory observation of the process. The three interactive stations were offered: (1) participatory soundscape mapping using qualitative methods; (2) an immersive audio station; and (3) an introduction to citizen science digital tools to monitor and crowd source acoustic data on soundscapes.

With the participatory mapping exercise, we followed an analogous, multisensory oriented participatory cartographic approach (Fagerholm et al., 2021; Korpilo et al., 2023) by asking people to spatially locate, name and evaluate the visual and audible qualities that make up favorable and unfavorable acoustic environments in the city of Munich from their actual experiences. For this we used a physical map on which participants could mark places with a sticker and attach a written description as to how the specific place sounds to them as well as their emotional state when they are there. We analyzed these text responses using structuring qualitative content analysis (Mayring, 2014; Kuckartz, 2014). This approach involves systematically coding responses into thematic categories that are either theory-driven (from prior literature) or emerge inductively from the material. Codes are then aggregated into categories, and their presence and frequency are assessed as indicators of subjective relevance. This method was chosen because it allows ecologically oriented data (place, sound type) to be meaningfully combined with experiential and affective dimensions, producing both qualitative depth and semi-quantitative indicators that can inform planning and ecological research.

With the immersive audio station, we exposed people via headphones connected to a digital platform with a range of acoustic recordings taken across Munich. Here we used two types of soundscapes that were presented to participants: (i) more 'natural' soundscapes (selected from our acoustic recording database for having relatively more biophonic sounds including bird song within green spaces in Munich (Fairbairn et al., 2024)); (ii) more 'urban' soundscapes (selected from our acoustic recording database for having relatively more anthrophonic sounds including traffic and construction within gray spaces in Munich Fairbairn et al., 2024). We then asked participants to record voice messages that qualitatively describe what they hear and how it makes them feel. Here the participants did not get any specifications, other than to record their feelings freely to learn about the descriptive words that people use to capture soundscapes and their sensations towards them. People were also allowed to listen to responses from other participants as a way of building a sense of the city as a shared soundscape that can be experienced very differently based on personal perceptions and experiences. The qualitative analysis of the audio recordings followed Saldana (2013). The mentioned words were classified into the categories "High stress", "Moderate stress" and "No stress" and into "Positive", "Neutral" and "Negative". As a follow-up, we asked people to complete a survey including demographic information, an affect grid (as in 2.3) and some questions regarding the methodology of the station itself.

With the citizen science digital tools station, we offered an interactive introduction to digital apps and platforms that people can use to collect acoustic data on soundscapes around the world. As an example, we used the citizen science *Dawn Chorus Project* (see: https://dawn-chorus.org/). We introduced participants to the *Dawn Chorus* App and taught them how to document 60-s soundscape recordings, as well encouraged them to explore the *Dawn Chorus* soundmap – a virtual map of global citizen science recordings of early morning birdsong, with many examples from Munich to engage with the recordings made locally in Munich. Collectively, these formats provided different modes of listening to soundscapes with different emphasis on the aspects of technology and citizen science in soundscapes.

Results

Vegetation structural complexity, soundscapes and bird diversity

A total of 15,624 h of recordings were collected across all study sites with 168 h per site. The recordings captured 53 vocal bird species and 206,866 individual calls across all sites, with an average of 28 distinct vocal bird species per site and 476 vocalizations per hour across all sites. The vocal Shannon Diversity Index ranged from 1.5 to 3.5, with an average of 2.4 per site. The most vocally active bird species across all sites included the Carrion Crow (*Corvus corone)*, Short-toed Treecreeper (*Certhis brachydactyla)*, and Great Spotted Woodpecker (*Dendrocopos major)* (Appendix A, 1.2).

NDSI and AEI were higher in green spaces in comparison to REF sites, but ADI was significantly higher in the REF sites (Fig. 3). There was no significant difference in BI among urban green spaces, squares and REF sites. The bird species richness was significantly higher in green spaces compared to the other sites, but the difference between the squares and REF sites was insignificant. We observed no significant linear relationship between the soundscape indices and the vegetation structure (Fig. 4).

Soundwalk feasibility, perceived soundscapes, acoustic comfort, mood and restoration

Fig. 5 provides an overview of a sample selection from the collected data of the pilot study, including values of one item from ISO/TS 12,913–2, namely 'traffic noise' (a; response to "*To what extent do you presently hear the following four types of sounds?: traffic noise (e. g. cars, busses, trains, air planes)"*), as well as a dimension of the *Perceived Restorativeness Soundscape Scale,* namely 'fascination' (b; response to "*I find this soundscape fascinating*"). Study participants reported that both instruments were appropriate for the planned study on soundwalks and the perception of the acoustic environment. The participants were able to classify the standardized questionnaires, relate them to their environment and provide plausible assessments. However, when completing the *Perceived Restorativeness Soundscape Scale* questionnaire, more frequent queries and comprehension problems were noted compared to ISO/TS 12,913–2. The anthropogenic noise quality of the three sites was different: Westpark had a moderate anthropogenic noise intensity (approx. 50 dB), Luitpoldpark was temporally noise-polluted due to landscape gardening work, Englischer Garten was tranquil and anthropogenic noise signatures were seldom perceived.

Affect grid results from the soundwalks (Fig. 6) showed varying

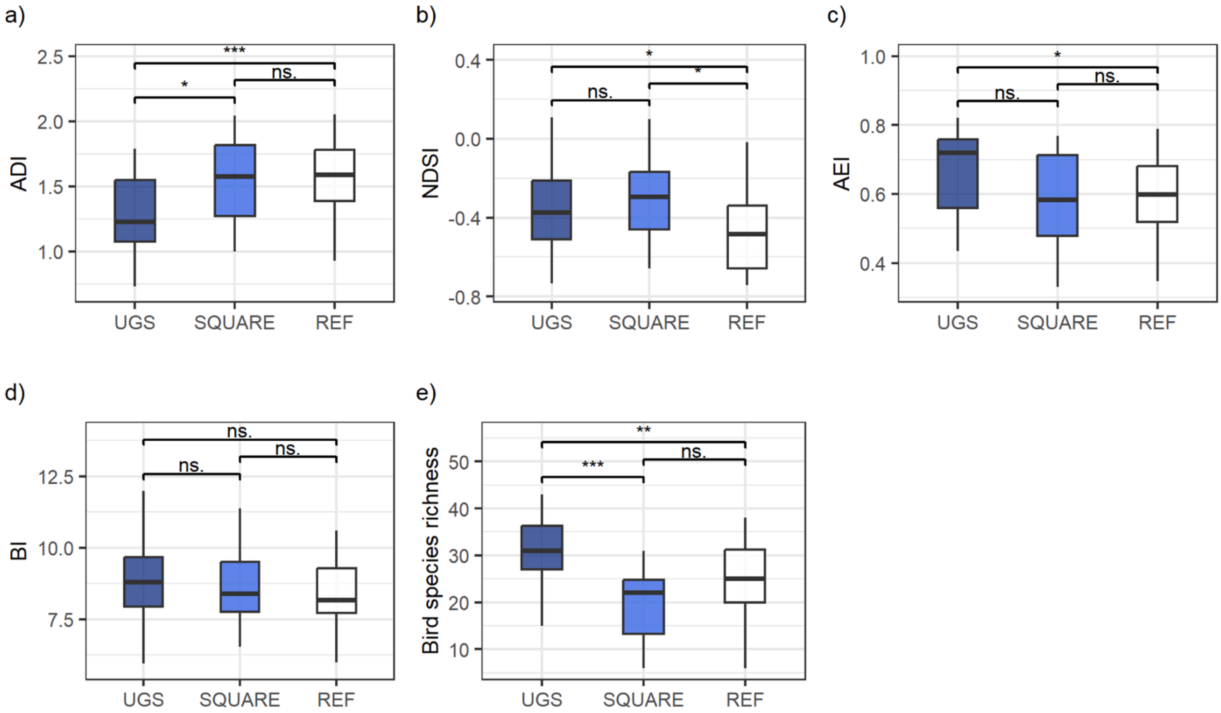

Fig. 3. Box plots show differences in soundscape indices (a-d; ADI, NDSI, AEI, BI (hourly values for all sites from the entire recording period of 7 days (168 recording hours per site) and then the average value per site) and (e) vocal bird species richness (total) between the urban green space study sites (UGS), city square study sites (SQUARE) and reference study sites (REF) (*** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$; ns = non-significance).

patterns in emotional responses across the three soundwalk sites. The concentration of responses in the lower right quadrant suggests that the acoustic environment quality in green spaces is more associated with a positive and relaxed state of mind . Several responses indicated stress and unpleasantness in both left quadrants, indicating the influence of urban noise sources such as traffic or landscape gardening work at these hearing spots (Fig. 6a). Especially at the different control listening spots of each site, negative affect or stressful noise impacts were obvious (left upper corner) compared to the green spaces, but we also observed some relaxing responses (right lower corner) (Fig. 6d). In Westend (Fig. 6a), responses were distributed across the mid-range of the grid, with frequency clusters around moderate arousal and mixed valence (both pleasant and unpleasant), with some participants reporting unpleasant and stressful states. This reflects that participants perceived the acoustic environment as somewhat stimulating but not consistently restorative based on the nearby perceived traffic noise. In Luitpoldpark (Fig. 6b), responses clustered toward lower to mid-arousal range with moderately pleasant valence, indicating moderately pleasant and calm experiences. The positive acoustic experiences were partially disturbed by selective garden working activities on the soundwalk day. Englischer Garten (Fig. 6c) elicited the most restorative responses, with a strong clustering in the pleasant–relaxing quadrant, with many participants reporting low arousal and high pleasantness. These differences mirror ecological measurements: Englischer Garten generally had the highest vegetation complexity and bird species richness, while Westend exhibited the lowest levels of vegetation complexity among our three sites.

Interactive and participatory approaches

Of ∼100 visitors, approximately two-thirds ($n \approx 65$) engaged with all three stations, while the remainder participated selectively. Families with children and younger adults were particularly active in the audio station, while older visitors tended to engage more with the mapping exercise. In the participatory mapping exercise, 15 locations were marked on the city map and participants provided feedback on the mapping method. The qualitative content analysis found that pleasant places were associated with positive sentiments such as “comfortable soundscapes” as "calming," "beautiful," and "cozy," and these pleasant places were associated with green spaces such as the Englisher Garten and natural features such as trees, meadows, water, and the Isar river. Natural sounds, including "rustling leaves" and "birdsong," were associated with a calming and restorative effect, and contrasted with urban sounds like "engine noise" and "stadium chants". Visual elements such as "many trees," "waterfalls," and park landscapes were also positively evaluated for their aesthetic appeal. Participants related these elements to feelings of "relaxation," "joy," and "serenity," and as a "calm oasis" amid urban stress. Positive personal connections were also noted, often tied to memories of "childhood," "youth," and "friends." Unpleasant places clustered along traffic-heavy roads, construction zones, and crowded squares, with urban sounds like "engine noise" and "freight train screeching," and descriptors such as “loud,” “stressful,” or “overwhelming.” Overall, the analysis showed a preference for natural over urban environments, with nature perceived as significantly enhancing wellbeing and emotional health. The usability survey for the mapping survey that aimed to identify preferred map types found that participants would prefer digital maps in everyday use due to their convenience and functionality, though analog maps were favored for special activities such as this one in the Urban Sound Lab.

The immersive audio experience station collected a total of 34 voice notes (53 % ($n = 18$) for the biophonic-dominant soundscapes and 47 % (16) for the anthrophonic soundscapes from adults; recordings from children were not evaluated due to guided instruction by the researcher that may have introduced bias as well as data privacy issues ($n = 18$)). For the biophonic soundscapes, participants mentioned words associated with “No stress” (e.g., “vacation”, “relaxation” and “rest”) 50 % of the time ($n = 9$), “Moderate stress” (e.g., “everyday life”, “curiosity” and “yearning”) was mentioned 27 % ($n = 5$) and “High stress” (e.g., “stress”, “confrontation” and “fight”) 22 % of the time ($n = 4$). Words associated with “Positive” feelings (e.g., “positivity”, “rest” and “curiosity”) were mentioned 61 % of the time ($n = 11$), “Neutral” words (e.g., “mixed

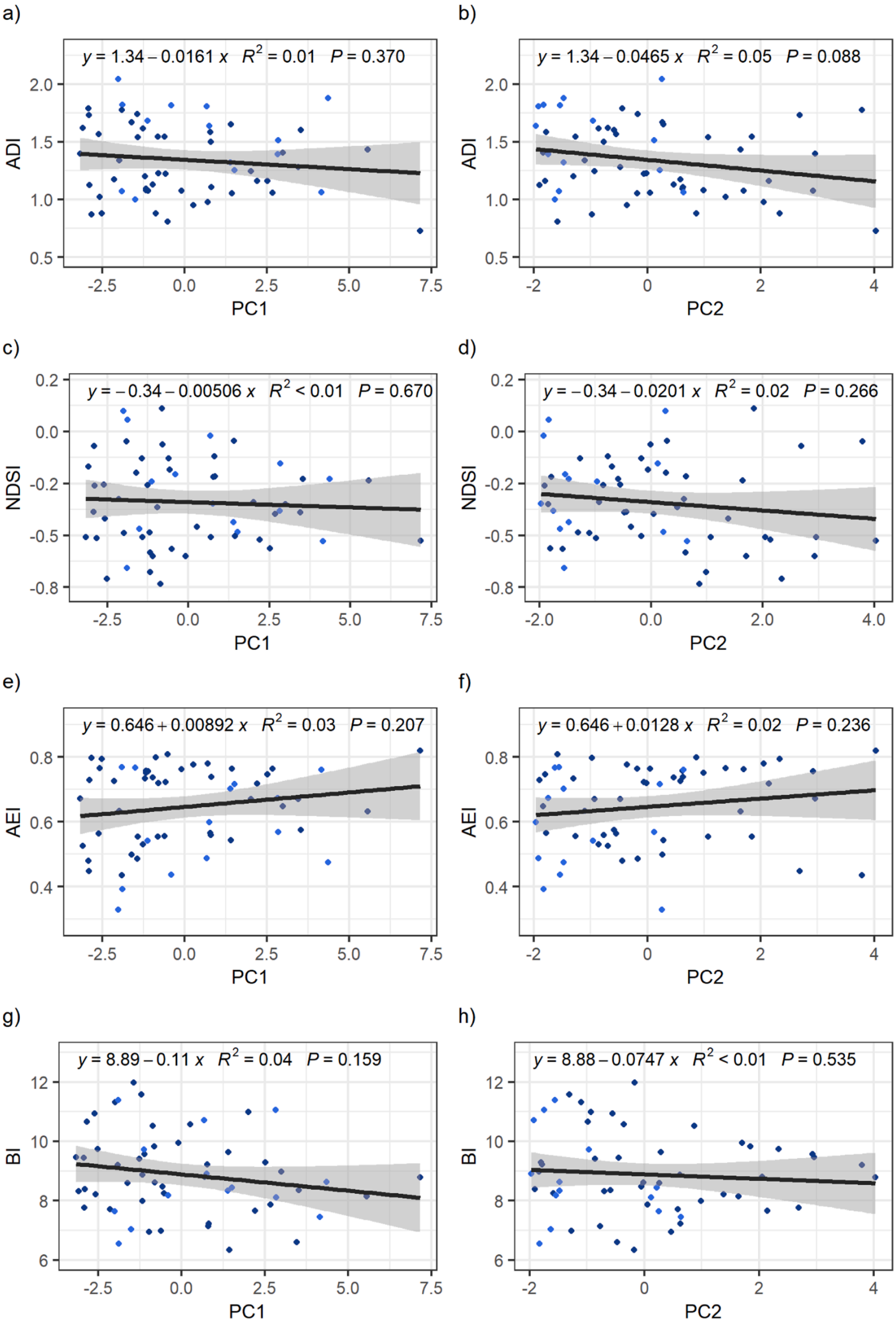

Fig. 4. Regressions show the relationships between acoustic-derived soundscape indices (a-b) ADI; c-d) NDSI; e-f) AEI; g-h) BI) and vegetation volume and height (PC1) and vegetation vertical structural heterogeneity (PC2). Each point represents the site average of the daily mean of the hourly means during the data collection period. Dark blue dots represent urban green space study sites, while lighter blue dots represent city square study sites.

feelings" and "everyday life") were mentioned 17 % of the time ($n = 3$) and "Negative" feelings (e.g., "stress", "disruption" and "fight") were mentioned 22 % of the time ($n = 4$). For the more anthrophonic soundscapes words associated with "High stress" (e.g., "restless", "nervous" and "hurry") were mentioned 50 % of the time ($n = 8$), "Moderate stress" words (e.g., "hostile" (in German: Lebensfeindlich) and "tedium" (Langeweile)) were mentioned 50 % of the time ($n = 8$). There were no descriptions of words associated with "No stress". "Negative" words (e.g., "run away", "negative" and "tense") were mentioned 81 % of the time ($n = 13$), whereas "positive" words (e.g., "hope") were only mentioned once and "neutral" words (e.g., "surprised") only twice. Overall, natural/biophonic sounds were strongly preferred over urban/anthrophonic sounds. Natural soundscapes were rated high for pleasantness (7 out of 10 on the affect grid) and moderate for arousal (4), while urban soundscapes were rated low for pleasantness (2) and high for arousal (7), indicating that they were perceived as more stressful and less restorative.

When asked about the methodology of the station itself, the average

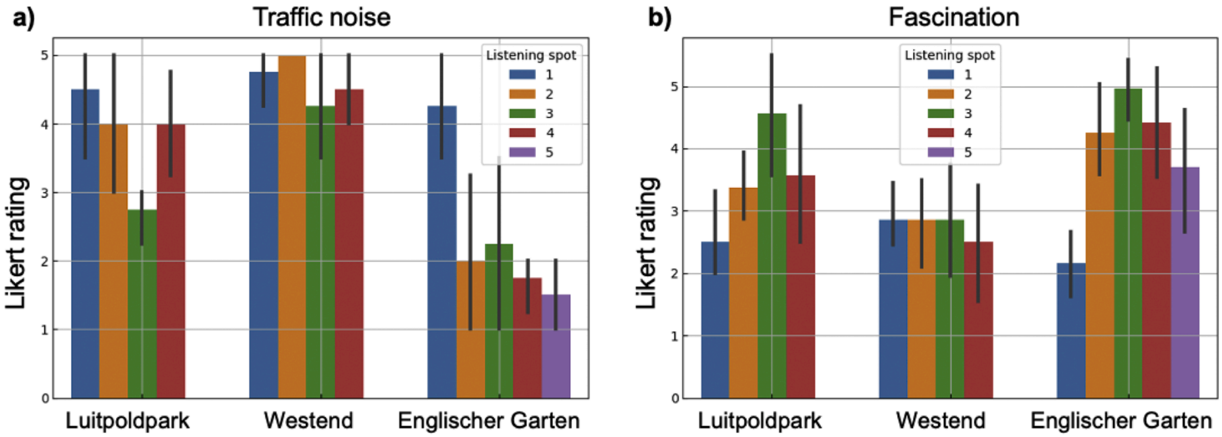

Fig. 5. (a) Perception of the extent of perceived traffic noise including e. g. cars, busses, trains, airplanes (scale 1 = not at all to 5 = dominates completely) according to the *ISO/TS 12,913–2* (n = 12). (b) Soundscape dimension "Fascination" (Scale 1 = not at all to 7 = completely) according to the *Perceived Restorativeness Soundscape Scale* (n = 15). Here the arithmetic mean values and 95 % confidence intervals are presented for each listening location. Listening spot 1 (blue) refers to a reference grey area in the immediate vicinity of the urban green spaces (Luitpoldpark, Westend, Englisher Garten) and respective listening spots (2–5). Note that in (a), there is no error bar in listening spot 2 of Westend because all participants unanimously gave it the highest rating regarding traffic noise. This can happen with a small sample (n = 27 participants). Note that in (b), where the error bars expand over the horizontal line of y = 5, Fascination was rated on a seven-point scale, not on a five-point Likert scale as in (a) because of the different assessment instruments used (see Appendix A, 1.1).

value for the approval of the statement "*I had fun doing this activity*" was 4.1 out of 5 (Likert scale 1 = strongly disagree; 5 = strongly agree). The average value for the approval of the statement "*This activity was interesting*" was 4.6 out 5. The average value for the approval of the statement "*This activity was boring*" was 1.9. The average value for the approval of the statement "*This activity was frustrating*" was 2 out of 5. The average value for the approval of the statement "*This activity was understandable*" was 4.1 out of 5. The average value for the approval of the statement "*In the future I will be more mindful about my feelings in different soundscapes*" was 4 out of 5. And the average value of the approval of the statement "*It was interesting to hear other people's audio recordings*" was 3.8 out of 5. Recommendations of participants included: provide a written form instead of the audio recording; better sound quality with noise cancelling headphones and shorter audios of the soundscapes; and a more comfortable station with the option to sit down. Overall, 14 of the 18 participants would visit a similar station if it would be standing autonomously in the city. The average value for the approval of the statement "*I would like to hear this soundscape more often*" was 3.7 for the more biophonic soundscapes and 2.8 for the more anthrophonic soundscapes.

At the citizen science station, approximately 40 participants actively tested the *Dawn Chorus* App during the sessions. Feedback indicated curiosity about contributing to biodiversity research, though some participants noted barriers such as the need for early morning recording or limited technical familiarity. Nevertheless, several participants downloaded the App during or after the workshop. Informal feedback from participants suggested that participants valued the opportunity to share subjective experiences of sound and to learn about biodiversity connections. Participants emphasized that communal listening and subsequent conversations enhanced their awareness, while technological elements (soundmaps, apps) served as useful entry points for engagement.

Discussion

This initial research demonstrates the feasibility and value of combining ecoacoustic monitoring, public health research, and participatory approaches. The pilot phase already provides useful insights for inter– and transdisciplinary ecological and public health research with applied outcomes for urban planning. Below we provide initial insights on urban soundscapes and how to relate green space structural complexity, soundscapes, biodiversity and soundscape-related dimensions to human restoration. In addition, we summarize recommendations to measure sound-related biodiversity or human perceptions within urban spaces and contrast our quantitative data with public listening interventions that educate about and cultivate the multiplicity of ways in which the city of Munich can be experienced acoustically.

Ecological considerations

From an ecological perspective, vegetation complexity and biodiversity offer valuable insights into habitat availability and structure, influencing how urban green spaces support biodiversity. We observed that indices of NDSI and AEI were higher in green spaces in comparison to gray spaces, while ADI was significantly higher in the gray spaces. ADI measures overall acoustic diversity without distinguishing biological from anthropogenic sources. The elevated ADI in gray spaces, therefore, may partly result from a greater variety of human-made sounds such as traffic and voices, but this interpretation requires caution given the index's lack of source discrimination. Green spaces exhibit higher soundscape-derived bird species richness compared to adjacent gray spaces, and vocal bird species richness in Munich is positively related to the local amount of surrounding habitat vegetation (Fairbairn et al., 2025b) Together, this underscores the significance of urban vegetation for urban biodiversity, such as for birds (Huang et al., 2015), which need various habitat features for food and shelter (Mühlbauer et al., 2025). Our pilot study suggests that even limited temporal recordings can differentiate biodiversity between green and gray spaces. Given that seasonality and patch size are expected to strongly affect ecological detectability, future work should implement repeated seasonal sampling (spring and summer), combine indices with species-specific detections, and test larger spatial scales to capture habitat connectivity. Furthermore, future research can further explore the positive effects of vegetation complexity beyond simple land surface measurements (Fairbairn et al., 2025b) – specifically, investigating how vegetation can buffer against anthropogenic noise and modify soundscape characteristics.

We observed very few significant relationships among soundscape indices and measures of vegetation complexity. This confirms work showing that acoustic indices are largely biased in urban contexts (Fairbrass et al., 2017). The time in which soundscapes were captured or overlapping sounds comprising the indices may complicate meaningful conclusions from acoustic indices, especially regarding biophonic diversity and biodiversity; while many biophonic sounds (e.g., birdsong) occupy distinct frequency bands from anthropogenic noise (e.g., traffic),

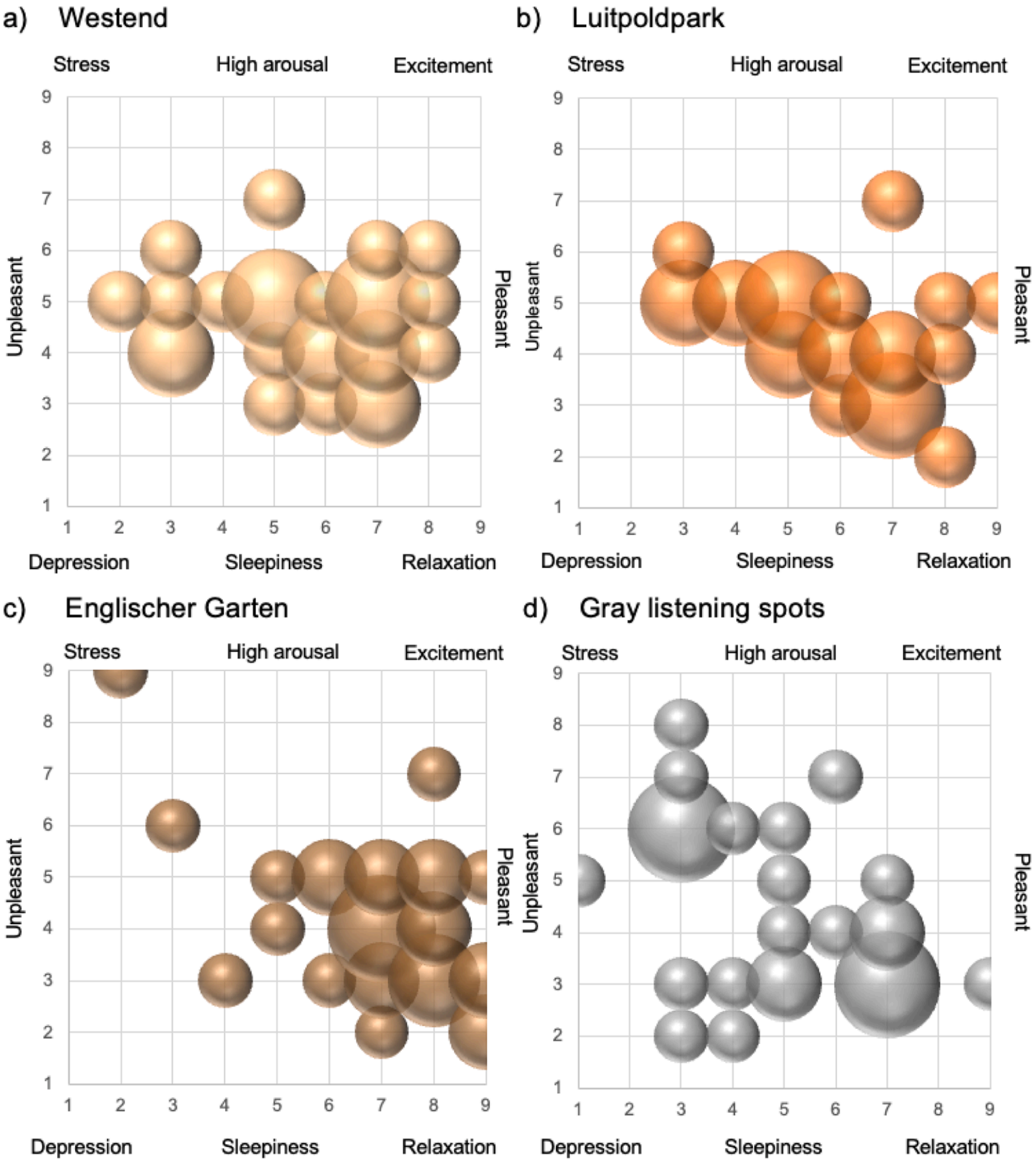

Fig. 6. Affect grid responses from soundwalk participants ($n = 27$) in the different soundwalk locations (a) Westend, (b) Luitpoldpark and (c) Englisher Garten and (d) control ‘gray’ sites (REF) within each area in Munich (see Fig. 1). The grids show participants’ reported emotional states during the soundwalks at the listening spots, with x-axis represents mood states related to valence (unpleasant → pleasant) and y-axis represents mood states related to arousal (sleepiness/depression → stress/excitement/high arousal). The bubble size reflects frequency of responses.

making them detectable despite lower sound pressure levels, acoustic indices may not capture biophonic sounds due to overlapping anthropogenic and geophonic sounds. To address this, we recommend employing a multi-index approach with prior filtering to the accuracy of acoustic indices in urban ecological studies (Lawrence et al., 2022; Fairbrass et al., 2017). Without such filtering, acoustic indices likely cannot be used to analyze biophonic diversity in urban contexts, nor to accurately measure biodiversity. Recent work highlights the need to combine indices with manual or AI-assisted sound identification, as indices alone may misrepresent vocal activity in noisy urban settings (Fuller et al., 2015; Sueur & Farina, 2015). Our testing confirms that indices should be interpreted cautiously and paired with targeted ecological indicators. Here, advancing AI-driven algorithms and deep learning techniques can improve biodiversity and soundscape assessments (Arzberger et al., 2025), and which is why we derived actual estimates of vocal bird diversity metrics to provide a better picture of local biodiversity. Beyond just acoustic indices, identifying individual sounds such as species-specific biophony or specific landscape geophony aspects could be interesting to explore over space and time in relation to human perceptions, as urban soundscapes are not static across the year but rather dynamic, and pleasantness and fascination will likely also vary.

Expanding the vegetation measurement radii and increasing the diameter of the computation cylinder for vegetation structural metrics beyond 15 m (e.g., to 100 m) could also provide a better assessment of vegetation volume and height effects and account for bird mobility (i.e., as in Fairbairn et al., 2025b). However, this may be difficult with MLS approaches that are more suited for small but fine scale measurements, which informed our pilot approach. Studies in Munich using similar acoustic monitoring methods to derive bird diversity have found that vegetation measures (NDVI) at larger spatial scales $>$ 100 m are not strong predictors of vocal bird diversity within a habitat (Fairbairn et al., 2025b). Additional predictors, including tree age, green space size, management practices, neighborhood characteristics, landscape green-space connectivity, and anthropogenic disturbances, should also be integrated into future studies to improve our understanding of urban biodiversity. In sum, best practice for future ecoacoustic monitoring in cities can include: (i) stratified sampling across seasons, (ii) multi-scale vegetation and landscape connectivity metrics, and (iii) validation of automated species detection with manual subsets (e.g., Fairbairn et al., 2025a). These steps will support higher ecological inference from soundscapes as well as comparability across studies.

Public health considerations and interactive approaches

Our study tested instruments during soundwalks in three locations to measure the restorative potential of green spaces. Specifically, parks such as the Englischer Garten — an older, structurally complex green space — elicited relaxation and pleasant emotions based on a perceived low level of anthropogenic noise. Questionnaires used during the soundwalks proved valuable for assessing the relationship between soundscapes, restoration and affect, mood states related to arousal and emotions. Comparing the differences between gray spaces and green spaces in terms of arousal and emotion show qualitative differences between these two — with generally more pleasant responses than unpleasant in the green spaces. The results on arousal and emotion were supported by the participants' qualitative interview statements, who felt significantly more relaxed after the soundwalk. Despite limitations related to sample size and the number of soundwalks, our findings align with prior research on the restorative benefits of urban green spaces (e.g., Wood et al., 2018; Liu et al., 2022) and relationships with their soundscapes (Ueble et al., 2021).

Regarding the recruitment process, we used a variety of participant recruitment strategies but with limited success. The implementation of posters in the designated areas of supermarkets and information points, in conjunction with personal invitations extended to elderly residential facilities, resulted in limited participant outcomes. The most effective recruitment strategy was online media and digital tools including neighbourhood online community platforms along with personal e-mail invitations to colleagues and friends. It may be that the concept or idea of soundwalks is not yet well-known to the general public; in the next phase of our work, greater emphasis will be placed on explaining the concept and its value to public health research and practice to attract more participants across sociodemographic groups. Furthermore, the implementation of additional online advertising initiatives, using university media channels, and inviting school classes are expected to enhance the effectiveness of the recruitment strategy.

The findings on arousal and emotions provide a first indication of how ecological characteristics of green spaces translate into perceived restorative benefits. Participants in the structurally complex and biodiverse Englischer Garten tended to report a relatively high frequency of pleasant and relaxing mood states, whereas responses from the more urbanized Westend were mixed, with also reports of stress and unpleasantness. Luitpoldpark fell between these two, which could be due to a more intermediate vegetation complexity as well as noise pollution from landscape gardening work that occurred during one of the soundwalks. These initial trends suggests that biodiversity and vegetation complexity can support restorative processes, but anthropogenic noise can dampen these effects. Other studies have found that noise sensitivity can be modified by environmental factors or by a persons' individual characteristics to influence sound perceptions, assessment and restoration (Ojala et al., 2019). Interestingly, some participants were relatively relaxed and not particularly bothered by traffic or anthropogenic noise at the gray reference spots that served as our control, suggesting that this may be because, as city dwellers, they are already accustomed to or acclimated to such background noise daily. Nevertheless, as in other studies (Aletta et al., 2025; Irvine et al., 2009), most respondents benefitted from the presence of green spaces. Future studies can examine biodiversity–soundscape–restoration relationships across broader temporal scales with larger participant groups and assess how anthropogenic disturbances influence the restorative potential of urban soundscapes. Future research can also incorporate other environmental variables (e.g., temperature, seasonality) to control for confounding effects, and accommodate children and the elderly (e.g., as in Li et al., 2025) to increase inclusivity in soundscape research. In sum, our pilot study shows the feasibility of using short, mobile-friendly instruments (affect grids, short Likert scales) during soundwalks and future studies can combine these with physiological indicators (e.g., heart rate, stress biomarkers) where feasible to triangulate subjective wellbeing and restoration with objective measures (Hartig et al., 2014).

As a takeaway from our pilot work on interactive participatory soundscape activities, we are now further developing workshop formats of *listening together* Sound Salons (in German 'HörSalons') – a public and practice-based approach where we share different forms of listening to and with others and other species, providing a multiplicity of access points and contact zones across Munich. This approach does not expect participants to be research subjects submitting data, but rather to: (i) give back knowledge about urban bio- and ecoacoustics in a less cognitivist way; (ii) create a shared sense of sonic placemaking; and (iii) appropriate the research tools (field recordings, apps, biomonitoring tools) so that they can be made more accessible. Sharing knowledge can be transformative itself (Gabrys, 2022). The ongoing Sound Salons, realized together with local creative and environmentally engaged communities are not necessarily about data generation but about the creation and the sharing of transformative knowledge — knowledge which is both sensory and factual, sensitive to multispecies attunement, and tied to a sonic sense of space. It is thus subjective and embodied yet conceptually informed. The Sound Salons also draw attention to the idea of multispecies stakeholders: organisms such as birds, bats, insects and the vegetative communities that contribute to, and are affected by, urban soundscapes. Considering non-human contributors as stakeholders shifts some research and management questions for future research investigations — for example, to protecting vocal niche space for sensitive species, or to designing structural habitat connectivity that supports species-specific acoustic behaviors. While our empirical focus here remains on human perception and biophonic measurements, we suggest that future studies can explicitly integrate multispecies wellbeing metrics (e.g., breeding success, call rates across seasons, habitat connectivity indices) when designing soundscape-sensitive urban interventions.

Applied considerations

Soundscapes remain underrepresented in urban planning (Herranz-Pascual et al., 2016), despite growing recognition of their importance for environmental quality and public health (European Environment Agency, 2014; Radicchi et al., 2021; Haselhoff et al., 2022; Guo et al., 2023). Our pilot study combined with insights from the literature show that while promising examples exist — such as sound planning for city parks (Jaszczak et al., 2021) — systematic integration into planning practice is still rare (Lavia et al., 2018; Lippold et al., 2019). Barriers include a lack of understanding of awareness (e.g., of soundscape concepts) among planners, limited assessment tools that are both of high scientific quality as well as user-friendly (Benocci et al., 2023a, 2023b; Kang et al., 2018), and limited stakeholder engagement in soundscape planning (Steele et al., 2020). Furthermore, there is a need for clear targets, standards, and spatial designations for soundscapes (European Environment Agency, 2014; ETC-ACM, 2016).

Considering soundscapes in applied environmental research and urban planning offers the opportunity for planners, designers and sound experts to work together to improve city soundscapes (Steele et al., 2020).

Building on our findings and existing knowledge of best practices, we recommend some directions for soundscape-oriented urban ecological, environmental and social-ecological research and urban planning:

1. **Capture and assess soundscape diversity:** cities should define, map, and monitor soundscapes across sociodemographic and infrastructural contexts. Assessments must include quantitative as well as qualitative approaches with a diversity of city residents and thus perspectives across sociodemographic groups (Soares & Coelho, 2016; Kang et al., 2018; Steele et al., 2020). The literature highlights participatory mapping projects (Radicchi et al., 2021) such as "Sounds in the City" in Hannover (see for examples: https://www.tonspur-stadtlandschaft.de/), which integrate citizen-generated data into planning frameworks. Our own participatory mapping pilot confirmed the feasibility of such methods: residents were able to locate, describe, and emotionally evaluate acoustic qualities of places. This confirms the feasibility of such approaches in research and planning contexts. Future studies should combine qualitative (soundwalks, mapping, interviews) and quantitative approaches (indices, acoustic monitoring, GIS integration) to capture both ecological and social soundscape dimensions.
2. **Go beyond noise reduction:** Traditional planning often treats sound primarily as a nuisance to be mitigated (ETC-ACM, 2016). A soundscape approach can reframe sound as both a stressor and as a resource (Van Renterghem et al., 2020, 2021), aligning with WHO (2018) calls for promoting "acoustic comfort" rather than only reducing exposure. Projects such as "Sounding Brighton" (Lavia et al., 2012, 2014) shows that soundscapes can support place-making by associated acoustic environments with social and cultural activities. Here, in such mapping processes, residents can identify how sound is linked to a place (Lavia et al. 2012). Similarly, the project Quiet Parks International has developed recognition schemes for quiet spaces that combine local experiences with international standards (see: https://www.quietparks.org/quiet-places). Soundwalk feedback in our study suggests residents value natural sounds as much as low noise, supporting the argument for designing not just quieter but more biodiverse soundscapes.
3. **Recognize sound as a health-promoting resource:** Restorative soundscapes (biophony, flowing water, wind in trees) contribute to stress recovery, positive affect, and cognitive functioning (Payne, 2013; Liu et al., 2022; Buxton et al., 2021). Preventative measures in urban planning and consideration of health promotion aspects should aim to reduce stressful soundscapes while promoting relaxing or restorative soundscapes (Van Renterghem et al., 2020). At the same time, species respond to urban soundscapes in ways that may either support or hinder their persistence (Francis et al., 2011; Francis & Barber, 2013). Furthermore, it is important to consider that species may be attracted to or repelled by certain soundscapes or that the specific species combination within a biophonic soundscape may be perceived as most pleasing by people. Important is to identify positive and negative feedback loops between people and non-human life and minimize negative relationships. Planning should therefore consider both human and multispecies wellbeing by protecting vocal niche space for sensitive taxa and designing green spaces that enhance acoustic diversity (Zhao et al., 2025).
4. **Design soundscape interventions and sound-oriented nature-based solutions:** Nature-based solutions (NbS) are a mainstreamed concept in urban greening and sustainability that are readily being adopted in municipalities as interventions to improve ecological and social conditions (Adams et al., 2023). Studies suggest that vegetation, running water, and habitat elements can be designed not only for ecological benefits but also for their acoustic qualities (Aletta et al., 2016; Van Kamp, 2017). Thus, we see the potential for 'soundscape interventions' — a site-specific design aimed at preserving or improving the acoustic environment (Moshona et al., 2023) — to be considered within the NbS toolbox. For example, tree species may provide pleasant rustling sounds, while water features can mask traffic noise and attract biodiversity. Embedding best practices in soundscape design and soundscape-related measures into NbS could relate urban greening as an intervention more directly to both ecological functioning and health promotion, recognizing the multisensory experience of city residents. This approach may include elements such as running water, selecting tree species that produce complementary sounds of leaves in the breeze, and integrating vegetation that attracts wildlife to create more biophonic- and geophonic-rich and engaging soundscapes (Levenhagen et al., 2021; Moshona et al., 2023). Additionally, addressing sources of noise pollution — such as reducing road traffic, implementing speed limits, and minimizing disruptive construction sounds — can help to mitigate disturbances and enhance urban soundscapes for acoustic comfort.
5. **Digitalize soundscape data for planning and management:** GIS-based approaches and participatory digital mapping tools are emerging as effective platforms for incorporating sound into urban spatial planning at city's digital cartographic libraries (Radicchi et al., 2021; Aletta et al., 2025; Aletta & Van Renterghem, 2021). Examples include using mobile phones for measuring sound data including urban noise pollution in large-scale participatory sensing campaigns in cities that can be used to generate a sound map (e.g., in Paris, London, Amsterdam, Prague and Milan; Aumond et al., 2017; Xie et al., 2021), as well as the Think About Sound crowdsourced data collection and interactive map in the UK (Craig et al., 2017). Our Urban Sound Lab experience suggests that citizens are enthusiastic about contributing sound recordings and thus digital sound databases, pointing to the feasibility of building long-term participatory soundscape databases that can be used in practice. This data can be triangulated to provide cities across geographic contexts with a proper overview of how to define and manage soundscapes of their cities over the long term (Lavia et al., 2018; Xie et al., 2021). These could be institutionalized as part of city planning departments' digital infrastructures, providing dynamic soundscape layers alongside land use, mobility, and biodiversity data (Kang et al., 2018).
6. **Integrate geo- and biophonic soundscapes in urban green infrastructure strategies:** Beyond noise avoidance or just quiet zone designation, cities can set measurable goals for maintaining or enhancing biodiverse soundscapes (Levenhagen et al., 2021). Scandinavian cities, for example, have piloted "sound quality indicators" in sustainability assessments (Nilsson & Berglund, 2006). Future interdisciplinary research should explore how ecoacoustic measures, environmental psychology indicators, and planning standards can be linked into soundscape-sensitive green infrastructure policies (Lawrence et al., 2025). This includes prioritizing habitat features that may support desired vocal species and acoustic diversity, such as structurally complex vegetation, varied water elements like streams and brooks, and refuges from anthropogenic noise through landscape architecture practices that work with natural elements such as hedges. Measures or standards could serve as acoustic indicators in sustainability certifications or urban health indexes (Levenhagen et al., 2021). Future research should test how soundscape-based planning tools can be institutionalized, for example through integration into environmental impact assessments, health audits, or urban greening activities.

Conclusion

Understanding the social-ecological dimensions of city soundscapes requires combining ecoacoustics, environmental psychology, participatory interfaces, and landscape planning and management. Work in this area is growing – new technologies such as cheaper automated recording devices, deep learning-based measurement tools, participatory research that integrates diverse stakeholders, and urban planning processes can design and implement soundscape interventions for both improving environmental quality and human health. Soundscapes are also a sensorial way in which multispecies relationships are experienced and shaped. They constantly surround us. Both city residents as well as urban planners can consider ways in which city environments and soundscapes could be designed or optimized to positively improve the quality of human and non-human life in urban environments. Multisensory experiences with urban nature through soundscapes can be heightened and harnessed for biodiversity awareness, nature conservation, and health promotion. The persistent challenge in such research-praxis spaces will be to understand complex human-nature relationships as well as integrating the various perceptions of diverse stakeholders effectively and meaningfully across a city landscape. From a methodological perspective, our pilot study demonstrates that inter- and transdisciplinary soundscape research requires ecological sampling, paired with participatory approaches that sensitize diverse stakeholders to the biodiverse soundscapes that surround them by offering tools for attentive listening and reflection. Best practice involves combining acoustic indices with species-level data, relating subjective wellbeing and restoration with objective health measures, and embedding participatory approaches into long-term monitoring. By advancing such integrative methods, future research can provide actionable knowledge for planners and policymakers seeking to identify, protect, and design biodiverse, health-promoting city soundscapes.

Funding

The project on which this paper is based was funded by the German Federal Ministry of Education and Research within the Research Initiative for the Conservation of Biodiversity (FEdA) under the funding code 16LW0385, the Technical University of Munich, the Ludwig-Maximilians-Universität München, and the Technical University of Berlin. The responsibility for the content of this publication lies with the authors.

Data availability

Data will be made available upon publication in Zonodo and upon request.

CRediT authorship contribution statement

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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.

Acknowledgments

We thank the City of Munich for supporting the initial phases of this work, including the Department for Climate and Environmental Protection, as well as the volunteer participants in our soundwalks and Urban Sound Labs. Finally, we acknowledge the support and collaboration of the Biotopia Lab in Munich and the Dawn Chorus project. Their commitment to connecting science, art, and public participation enriched our research and outreach efforts.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.baae.2025.12.007.

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