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Research article

Mapping and assessing natural soundscape quality: An indicator-based model for landscape planning

Zhu Chen *, Johannes Hermes, Christina von Haaren

Leibniz University Hannover, Institute of Environmental Planning, Herrenhäuser Str. 2, 30419 Hanover, Germany

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ABSTRACT

Natural soundscape quality (NSQ) has been recognized as an essential cultural ecosystem service that contributes significantly to human health and well-being. It also stands as an indispensable component of environmental quality, especially for landscape aesthetic quality. However, an assessment tool for NSQ in landscape planning and environmental impact assessments is still absent. Therefore, this paper aims to address this gap by proposing an indicator-based model for assessing and quantifying NSQ in the Geographic Information System. The model characterizes NSQ based on Calmness and Vibrancy, and employs several indicators, sub-indicators, and respective metrics as proxies to quantify and map them spatially. The evaluation criteria of the model correspond to the general public's preferences for soundscape features. The case study results in Springe municipality, Germany, show that the relative values of NSQ are high in green spaces, including forests, grasslands, and shrublands, whereas they are low in open farmlands. The multiple natural sounds yield higher NSQ scores than the individual ones. The same soundscape compositions in forests and in urban parks exhibit higher NSQ scores than in other land cover types. In addition, the shares of relative values show similar distribution patterns among Calmness, Vibrancy, and NSQ according to land cover types and soundscape compositions. The evaluation results align with public values and preferences for soundscape features. Unlike subjectivist approaches, our user-independent methodology is easily transferable and reproducible. The results are comparable and communicable among the assessed areas. These endow the indicator-based model with the potential to be applied at various planning and management scales. The findings can help to incorporate soundscape evaluation into landscape planning and management systems, supporting sustainable landscape development, and providing valuable information for policy-, plan- and decision-making.

1. Introduction

1.1. Background

The natural soundscape refers to the collection of natural sounds that emanate from ecosystems. It encompasses compositions, interactions, and spatiotemporal properties of natural sounds that reflect ecosystem processes and functions (Pijanowski et al., 2011). Natural soundscapes have been identified as a resource, natural asset, and inherent capability of green spaces (NPS, 2006), essential for promoting environmental quality. They can provide valuable ecosystem services (ES) that contribute to human health and well-being (Chen et al., 2022a; Francis et al., 2017). Given this backdrop, the natural soundscape quality (NSQ) can be understood as the aesthetic pleasure derived from the harmonious state between the imaginative representation of natural soundscapes and people's understanding. It can be regarded as an offered ES, valued by humans but not necessarily utilized currently. NSQ has been recognized as an indispensable composition of landscape aesthetic quality (LAQ) and appreciation (Carles et al., 1999; Wang and Zhao, 2019). It can complement the pleasure that people obtain from the visual experience of nature and landscapes, which is also essential to public psychological and physiological health (Aletta et al., 2018). Contact with high NSQ can foster pleasant experiences and positive mental states (Hong et al., 2020a), aid in attention restoration and cognitive performance (Hong et al., 2019b), and contribute significantly to stress relief, helping recover from depression and fatigue (Hedblom et al., 2019). From this perspective, NSQ serves as the background for many nature-based recreation and outdoor activities in (semi-)natural environments. High NSQ can offer positive masking effects that effectively mitigate the annoyance and adverse effects of noise, improving

* Corresponding author.
E-mail address: chen@umwelt.uni-hannover.de (Z. Chen).

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the quality of environmental experiences (Hong et al., 2020b; Jia et al., 2020). Also, NSQ is a useful indicator for managing and resolving the conflicts between human uses and biodiversity preservation (Francis et al., 2017). These benefits are helpful for growing policy emphasis on biodiversity conservation alongside human welfare (Buxton et al., 2021). Furthermore, awareness of the health benefits brought by nature is likely to expand and diversify public support. The reason is that public opinion is generally shaped by personal emotions and experiences (Sandifer et al., 2015). These imply that NSQ is important to maintain valuable connections with nature, reinforce efforts in biodiversity conservation, and promote public benefits. Landscape planning (LP), as a highly looking-forward measure, is dedicated to improving, protecting and restoring landscape assets, biodiversity, and ESs, generating place-based environmental information, reconciling conflicts between development and conservation, and monitoring cultural and natural assets (Haaren et al., 2019). However, NSQ as a fresh cultural ecosystem service has not yet been identified, quantified, and mapped in LP or reactive instruments such as environmental impact assessment (EIA). Both of them only focus on assessing the disturbing influence of noise in terms of the acoustic environment, with a lack of systematic incorporation in the assessment of the positive effects of natural soundscapes (Haaren et al., 2019). Furthermore, no suitable approach for addressing this aspect is available in their general methodology toolbox.

1.2. State-of-the-art and knowledge gaps

To date, there are several modeling approaches for assessing LAQ with the consideration of acoustic aspects for LP. For instance, Landscape Character Assessments (LCA) in the UK (Swanwick, 2002), Hungary (Boromisza et al., 2011), as well as the Landscape Preferences Spatial Framework (LPSF) applied in Alentejo, Portugal (Ribeiro et al., 2013), evaluate regional tranquility but not positive natural sounds. A user-independent formal assessment of LAQ used in Germany takes the absence of noise as the only indicator reflecting the sound features in assessing LAQ (Hermes et al., 2018). In soundscape studies, soundscape modeling generally tends to anticipate how people perceive the acoustic environment (Lionello et al., 2020). However, psychoacoustic indicators or acoustic indices obtained from on-site measurements or recordings are still needed to capture these perceptions. With such approaches, it is challenging to get spatially explicit results that allow for inter-regional comparisons and supporting decisions for LP or EIA in spatial planning. Moreover, some mapping methods seek to present the spatial distribution of soundscapes, including noise or tranquility mapping (Lesieur et al., 2020; Liu et al., 2020; Watts et al., 2020), as well as soundscape mapping (Chen et al., 2022b; Hong and Jeon, 2017). Nevertheless, the above methods are time-consuming and dependent on subjective data, and the experiments involving human beings may raise ethical issues (van den Bosch et al., 2017), rendering them inadequate for capturing intersubjective or collective preferences. As a result, they are not so well-suited for incorporation into LP across varying scales.

The soundscape assessment in LP and EIA should not rely solely on real-time measured sound data. The emphasis should be on the area's soundscape potential, considering the inherent soundscape characters and qualities. Under this circumstance, the assessment should identify and evaluate natural soundscape characters aligning with human collective preferences (Chen et al., 2022a). It should also exclude components unrelated to natural sounds, like the presence of actual users or human-induced factors. The indicator-based model can analyze and evaluate the state and pressure-specific sensitivity of natural soundscapes by a series of empirical knowledge and easily derived spatial information, allowing for integrating independent pressures (e.g., traffic noise) and the assessment of current soundscape states to model and project future changes in soundscapes. It can be further adapted into the Driving Forces, Pressures, State, Impacts, and Responses (DPSIR) model for exploring and assessing the changes in natural soundscapes over time for LP or in EIA (Albert et al., 2016b; Faseyi et al., 2023). The deduced outcomes of Impacts can inform landscape planners and decision-makers (Haaren et al., 2019). Spatial planning commonly applies the Geographic Information System (GIS) to evaluate landscape states and changes. This tool can implement the assessment model using available geodata (Kempa and Lovett, 2019). Based on this, GIS can visualize the distribution state and value of natural soundscapes, yielding place-specific and comparable results at local or regional scales. Such capabilities could assist in preserving natural resources, improving the tourism potential across regions, and providing complementary insights for LAQ assessment.

1.3. Objectives

This study proposes an indicator-based model for spatially assessing and quantifying NSQ in GIS, and then applies it in a case study. The model employs indicators that (1) align with the mapping knowledge regarding cultural ecosystem services and landscape character assessments, (2) are computational through metrics that represent these indicators, (3) reflect the general public's perception and preferences for certain soundscape features following existing empirical evidence, and (4) are applicable in spatially explicit assessments. The assessment results of this model can offer insights into the landscape capacity or potential to provide an ecosystem service from natural soundscapes.

2. Methodology

To design an indicator-based model of NSQ, we identified key components and indicators, and selected sub-indicators and metrics. Furthermore, we established the evaluation criteria aligning with the general human perception and preferences of specific soundscape features. The knowledge of key components and indicators originates from the systematic literature review of Chen et al. (2022a), supplemented in the present study by additional literature analyses for quantifying these indicators. Hereafter, we selected an exemplary municipality and collected corresponding data to examine this indicator-based model.

2.1. Developing an indicator-based model for natural soundscape quality

2.1.1. Key components

Cain et al. (2013) suggested a 2-dimensional model consisting of the two orthogonal components, Calmness and Vibrancy, as a means for characterizing the emotional dimensions of a soundscape. It is an essential finding of the *Positive Soundscape Project* (Davies et al., 2007). The Calmness-Vibrancy model has been successfully applied in urban and natural environments to evaluate positive soundscapes (Davies et al., 2013; Gale et al., 2021). Also, its practical usability in the planning process has been explained. This model shares the same pleasant region with the Pleasantness-Eventfulness model (Aletta and Kang, 2018), supporting a pleasant soundscape that should either be calm or vibrant. Furthermore, Calmness and Vibrancy straightforwardly contribute to Pleasantness, providing the same information as the soundscape quality (Axelsson, 2015). Therefore, we argue that Calmness and Vibrancy are the most appropriate components in the indicator-based model for characterizing NSQ.

Calmness can be seen as an amalgamation of the valence derived from sounds (Davies et al., 2009, 2013), such as relaxation, comfort, restorativeness, and quietness. It loads heavily onto the overall pleasantness. Importantly, it also pertains to the possibility of encountering and experiencing the sounds characterized by such attributes (Aletta et al., 2016; Aletta and Kang, 2018). Vibrancy can be understood from two aspects: the organization of sounds (Cacophony-Hubbub) and sound changes over time (Constant-Temporal) (Davies et al., 2009, 2013). Building on this notion, we comprise each component with a pair of indicators, and each indicator is further delineated by several sub-indicators (Fig. 1). The metrics are employed to quantify them using available spatial data. As an exploratory indicator-based model, it

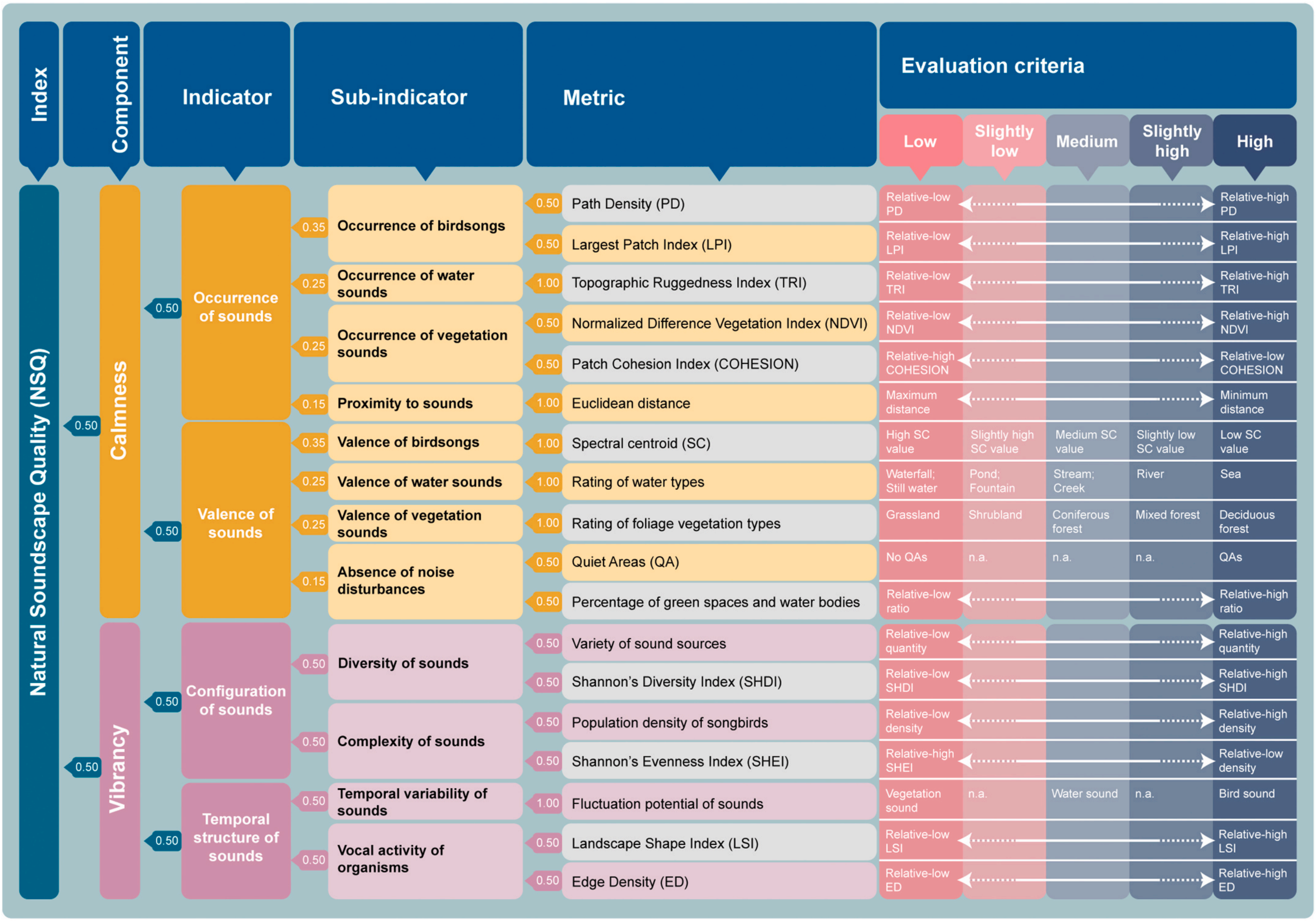

Fig. 1. Key components and indicators compiling the indicator-based model for natural soundscape quality, and an overview of corresponding sub-indicators, metrics, and evaluation criteria used to quantify the indicators, with their respective weights.

currently encompasses natural sounds from songbirds, water, and foliage vegetation. These natural sounds are widely accepted as the most valuable for human health and well-being (Jaszczak et al., 2021a; Krzywicka and Byrka, 2017; Liu et al., 2019; Pérez-Martínez et al., 2018). The detailed explanations are outlined in the following section.

All weights of the model were evenly assigned, inspired by the LAQ model (Hermes et al., 2018; Kalinauskas et al., 2021), except for the sub-indicators for the occurrence of sounds and valence of sounds. We further adjusted these weights based on a ranking of natural sounds (Chen et al., 2022a). The ranking indicates that bird, vegetation, and water sounds are scored from high to low. Nevertheless, the final value for vegetation sounds does not account for the "reduced effect" data, potentially resulting in a higher overall score. We, therefore, argue that the sub-indicators for vegetation and water sounds can have the same weight. Additionally, compared to the sub-indicators for specific natural sounds, the proximity to the sounds was deemed less relevant to the occurrence of sounds. Likewise, the absence of noise was considered to have a lower impact on the valence of sounds. Following these considerations, we fine-tuned the weights based on the average of 0.25 by transferring 0.1 scale point of the weight of proximity to sounds and absence of noise to the two birdsong-related sub-indicators, respectively.

2.1.2. Quantifying indicators

2.1.2.1. Occurrence of sounds. Four sub-indicators were applied to quantify the occurrence of sounds (OS): occurrence of birdsongs (OBS), occurrence of water sounds (OWS), occurrence of vegetation sounds (OVS), and proximity to sounds (PTS). OBS is linked to the arrangement of green spaces (Bormpoudakis et al., 2013), especially in fragmented landscapes (Liu et al., 2014a). It is evaluated using the Patch Density (PD) and Largest Patch Index (LPI) of green spaces, which can reflect the fragmentation degree of given areas (Liu et al., 2014b) OWS typically hinges on the interaction between water bodies and their surroundings (Galbrun and Ali, 2013). Terrain variability has been identified as a significant factor influencing the generation of running water sounds (Wang and Zhao, 2019), quantified using the Terrain Ruggedness Index (TRI). TRI is derived from the elevation differences between neighboring pixels (Riley et al., 1999; Stojilković, 2022) OVS is commonly prominent in areas with dense vegetation or fragmented landscapes (Hong et al., 2019c; Liu et al., 2013). These characteristics can be measured by the Normalized Difference Vegetation Index (NDVI) and Patch Cohesion Index (COHESION) separately (Kowe et al., 2021). PTS also affects the perception of sound occurrence (Jaszczak et al., 2021b), which can be quantified by the Euclidean distance between sound emitter and receptor (Balaji and Bapat, 2007).

2.1.2.2. Valence of sounds. The valence of sound (VS) serves as a descriptor of sound positiveness based on preferences (Davies et al., 2009). VS mapping involves valence of birdsongs (VBS), valence of water sounds (VWS), valence of vegetation sounds (VVS), and absence of noise disturbances (ANB). VBS can be quantified using spectral centroid (SC), a metric commonly employed to assess the brightness of birdsongs. SC aligns with human perception and preferences for birdsongs, where a low value indicates a soft timbre inducing calmness and pleasure, while a high value signifies an acute sound quality evoking a sense of aggressiveness (Hong et al., 2021; Kendall et al., 1999; Xu et al., 2020b). VWS evaluation can rely on the type of water bodies, as the preferences for the sounds from different water types have been previously studied (Galbrun and Ali, 2013; Rådsten-Ekman et al., 2013). Values are assigned to different water body types to reflect the valence of water sounds. VVS considers the leaf state of foliage vegetation as the primary determinant (Jaszczak et al., 2021a), given that leaves produce sound through structural vibrations caused by intermittent contact with neighboring elements (van Renterghem, 2019). Values are attributed to various foliage vegetation types according to the preferences of vegetation sounds deduced from Hong et al. (2019c), van Renterghem (2019), and Jaszczak et al. (2021b). ANB evaluation involves Quiet Areas (QA) and percentages of green spaces and water bodies (Hedblom et al., 2017; Watts et al., 2020; Watts and Marafa, 2017). QA can be identified based on the maximum impact distance of different noise sources (Votsi et al., 2012). The percentage of green spaces and water bodies can be assessed by the proportion of these land covers in the evaluated area.

2.1.2.3. Configuration of sounds. The quantification of the configuration of sounds (CS) comprises two sub-indicators: diversity of sounds (DIS) and complexity of sounds (COS). DIS considers sound diversity based on the absolute quantity and relative abundance of natural sound sources. These can be measured by the variety (quantity) of natural sounds and Shannon's Diversity Index (SHDI) of green spaces. The variety of natural sounds, following human preferences for soundscapes (Hong et al., 2021; Pérez-Martínez et al., 2018), is calculated using the absolute number of potential natural sound sources in the area. SHDI involves mathematical operations on the relative abundances of species within a community (Wu, 2000), exhibiting positive correlations with the species abundance and sound diversity in green space (Gunnarsson et al., 2017; Ha and Kim, 2021; Ricotta, 2002). COS evaluation depends on the population density of songbirds and Shannon's Evenness Index (SHEI) of green spaces. Bird population density significantly affects the complexity of acoustic communication in an area (Farina, 2013; Hilje et al., 2017). SHEI of green spaces gauges vegetation evenness, which negatively correlates with sound complexity (Farina et al., 2015).

2.1.2.4. Temporal structure of sounds. The temporal structure of sounds (TS) depends on the natural rhythms and biological processes (Bian et al., 2022; Chen et al., 2022b; Hong et al., 2019a). The sub-indicators, temporal variability of sounds (TVS) and vocal activities of organisms (VAO), are employed for evaluation. TVS is commonly assessed by fluctuation strength or $L_{10\text{-}90}$ (Aletta and Kang, 2018; Hong and Jeon, 2017; Jeon et al., 2012), which captures the general perception of sound capacity to vary in levels and frequencies. We deduced the fluctuation potential values of included sounds from Yang and Kang (2013), Hong and Jeon (2017), and Jeon et al. (2018). VAO is dependent on the acoustic signals generated by animal communities, reflecting habitat specificity and vegetation structures (Bormpoudakis et al., 2013). It can be measured using the Landscape Shape Index (LSI) and Edge Density (ED) of green spaces. These landscape indices are commonly employed to explore the relationships between soundscape dynamics and landscape configuration (Barbaro et al., 2022; Liu et al., 2014a, 2014b).

2.2. Data sources and preparation

2.2.1. Case study area

We selected Springe municipality, Lower Saxony, Germany, as our study area to test the NSQ model. Springe boasts various ecosystem types, including green spaces, farmlands, and meandering streams, supporting plentiful habitats for bird species (Fig. 2). It is located

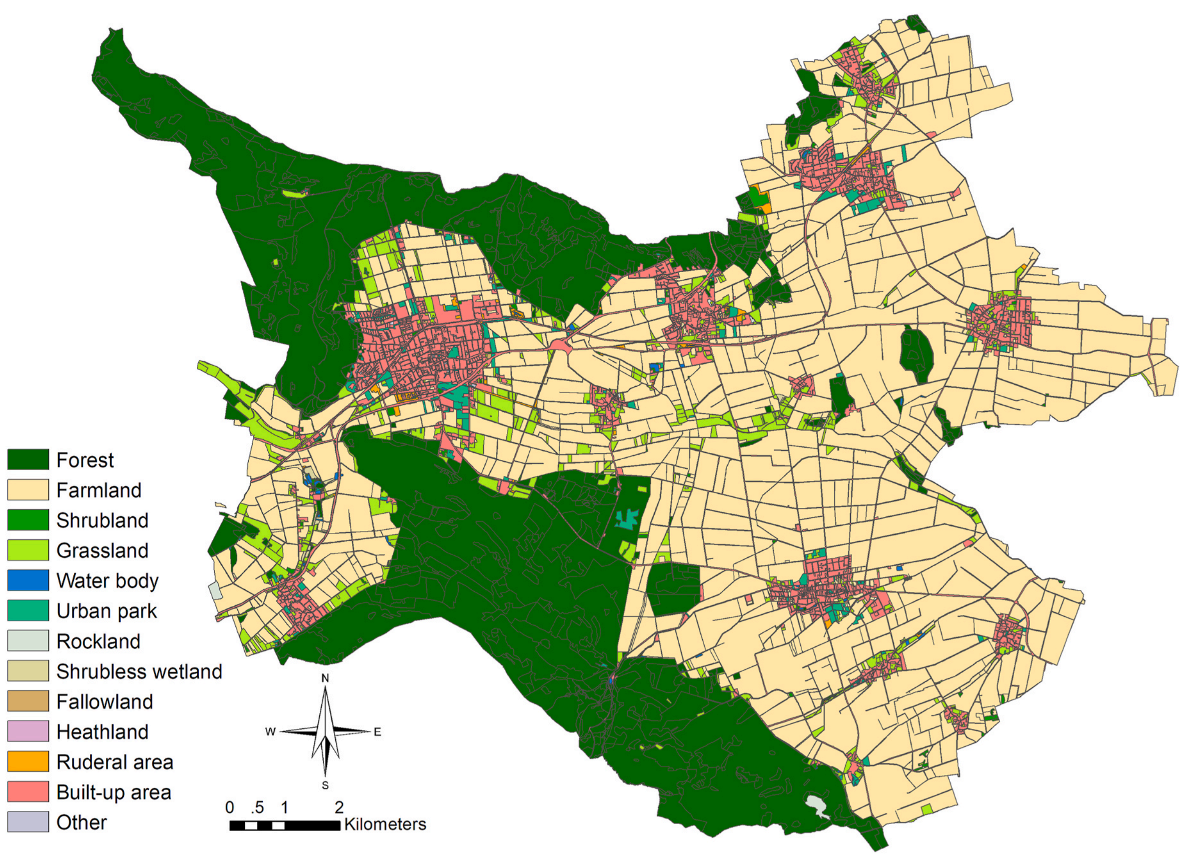

Fig. 2. Land cover types in Springe municipality.

southwest of the Hannover region and covers approximately 16,000 ha with a population of about 30,000. The municipality features a portion of the Deister Hills as an urban forest, attracting visitors and tourists for visits and recreational activities.

2.2.2. Data processing

2.2.2.1. Analyzed biotopes. The biotope map of Springe plays a crucial role in locating the natural sound sources. It is the polygon data extracted from a biotope mapping effort of the Hannover Region by the environment department of the local authority of Hannover (Landeshauptstadt Hannover, 2017). The biotope map of Springe encompasses over 6600 patches representing more than 120 detailed habitat types. In this test, we extracted the green and blue spaces and agricultural landscapes for spatial analysis, including the six main land cover types: forests, grasslands, shrublands, urban parks, water bodies, and farmland.

2.2.2.2. Distribution of songbird species. The model evaluates bird-related indicators based on the data of songbird species (i.e., Passerine) commonly existing in the ecosystems. Theoretically, Lower Saxony hosts 91 typical songbird species, as indicated by the "Atlas der Brutvögel in Niedersachsen und Bremen 2005–2008" (Krüger et al., 2014). These 91 species constitute the potential species database for the region. In our case study, we mapped 70 songbird species observed in Springe municipality, accounting for 76.92% of the database. This deliberate selection serves as a practical test of the model, integrating the considerations of both potential and actual data. The songbird species data are sourced from the lastest report of the asscociation "Naturschutzbund Deutschland (NABU)" - Avifaunistischer Bericht 2015–2017 (https://www.nabu-springe.de/projekte-und-schwerpunkte/springer-vogelwelt/).

We considered the spatial distribution of songbird species from habitat location and population. Our approach was inspired by a multisource sound model but advanced in the methodology (Aumond et al., 2018). In Europe, the 70 songbird species typically live in one or more of the habitats of coniferous forests, deciduous forests, mixed forests, farmlands, and water bodies. To compute the bird population, we factor in the territory sizes of each songbird species and the total areas of their habitats. A territory represents a defended area within the home range of songbirds where they generally live (Pitelka, 1959), and different species can use the territories independently or overlappingly (Finch, 1989). A study has shown that the mass of bird species can indicate their territory size (Schoener, 1968). We thereby performed the calculation of each bird population as follows:

$$TS_i = 0.1072 m_i^{1.12}$$

$$P_i = TA_j / TS_i$$

where TS_i is the territory size (ac) of bird species i, m_i denotes the average mass (g) of bird species i, P_i represents the population of bird species i, and TA_j stands the total area (ac) of the land cover type j. We hypothesize that 10% of the population of each bird species generates sounds simultaneously in the model (Aumond et al., 2018). The distribution for each of the 70 songbird species was created automatically using the tools we designed in Model Builder in ArcGIS 10.7. These tools can initially compute bird populations by considering average mass and habitat areas, and subsequently allocate point data randomly to match the bird populations to their respective habitat types. Data on habitat types and mass of the songbird species were obtained from an online database, BirdLife INTERNATIONAL (https://www.birdlife.org/) (for details, see Table S1, Supplementary data).

2.2.2.3. Creating soundtopes. The "soundtope", serving as the spatial unit for sounds, represents the propagation and perception range of each sound source. Table 1 displays an overview of the category of natural sounds within the study area. To create the soundtope maps of these sounds, we employed a distance-based method akin to the approach used for Quiet Area (Votsi et al., 2012). We set a 250 m buffer for each sound source in the sub-category to define their soundtopes (Aumond et al., 2018). Data on land cover types and songbird species distributions were used to determine the spatial locations of sound sources. The soundscape compositions generated by overlapping the main category soundtopes are shown in Table 2.

2.2.2.4. Calculating metrics. The metrics computation involved several knowledge domains and encompassed much information from data sources, methods, and tools. Table 3 provides further indications and details.

2.2.3. Mapping and spatial analysis

Prior to aggregation, the (sub-) indicators and metrics undergo normalization on a scale between 0 and 100. This normalization process can address the scale discrepancies of the utilized data. The aggregation process uses the spatial analyst tool "Weighted Sum" according to the weights proposed in Fig. 1. Results are visualized as maps that show spatial values across the study area. Furthermore, we calculated the proportional distribution of relative values (0–100) and the mean values for Calmness, Vibrancy, and NSQ at both landscape and soundscape levels. To generate the former, the standardized floating-point values underwent rounding to integers, followed by using the "Zonal Statistics" tool to extract these values. Notably, the model is indicative, showing relative values spatially on a cardinal scale, and the results exhibit where quality is higher or lower compared to other areas within the assessed area. All processes and analyses were conducted in ArcGIS 10.7.

3. Case study results

The mapping results reveal that Calmness and Vibrancy exhibit similar overall spatial variable patterns (Fig. 3a and b). NSQ values are relatively high in green spaces with complex and diverse structures (Fig. 3c). The distribution curves of Calmness and Vibrancy significantly differ (Fig. 3d), and the former is comparably uniform. The high shares and peaks of Calmness, Vibrancy, and NSQ all occur in the relative value range of 19–36. This implies that larger areas in the study area score relatively low, while high values only occur in a few locations. The differencing analysis of the Calmness and Vibrancy maps illustrates that a soundscape can be perceived as either relative-calm or relative-vibrant in the study area (Fig. 3e). The relative-calm perception is prevalent within the interior of forests and farmlands. The relative-vibrant perception tends to emerge along the perimeters of landscape patches characterized by complicated shapes, especially those near built-up areas.

The maps were further analyzed based on the six land cover types (Fig. 4). Results show that the relative values of Calmness, Vibrancy, and NSQ with high proportions are similar across land cover types, but the distribution patterns of the proportions show significant differences. High shares of the comparably high relative values are chiefly in forests, grasslands, and shrublands, while urban parks obtain high shares of moderate values in Calmness and NSQ. The mean value of Calmness is the highest in forests at 53.98. The highest mean value of Vibrancy of 70.99 occurs in grasslands, whereas the lowest, at 42.13, is found in farmlands. Remarkably high mean values of NSQ are found in green spaces, particularly grasslands, with a peak value of 61.66, followed by

Table 1
Natural sound category in the study area.

Main category	Sub-category
Bird sounds	Sounds from one of the 70 passerine bird species (Table S1)
Vegetation sounds	Sounds of coniferous forests, deciduous forests, mixed forests, grasslands, and shrublands
Water sounds	Sounds of streams, ponds, and still water

Table 2
Soundscape compositions in the study area.

Soundscape composition	Abbreviation
Bird sounds	BS
Bird and vegetation sounds	BVS
Bird and water sounds	BWS
Bird, vegetation, and water sounds	BVWS
Vegetation sounds	VGS
Water sounds	WS
Vegetation and water sounds	VWS

shrublands and forests, with 60.84 and 55.97, respectively.

As depicted in Fig. 5, the proportional distributions of relative values of Calmness, Vibrancy, and NSQ across soundscape compositions exhibit similar patterns. All soundscape compositions cover a relatively narrow range of Calmness values, except for BVS and BVWS. BVS attains the highest mean value of Calmness (49.65), while BS registers a relatively lower mean value of 22.29. The most considerable mean value of Vibrancy is observed in BVWS at 61.45, followed by BVS as the second-highest value. BVWS and BVS demonstrate the highest and second-highest mean values of NSQ, mirroring the trend of mean values observed in Vibrancy.

Fig. 6 indicates that except for BVS and BVWS, the remaining five soundscape compositions display similar differences in Calmness, Vibrancy, and NSQ across the land covers. Both BVS and BVWS trends across land covers are identical between Vibrancy and NSQ but diverge from Calmness, particularly in grasslands. Across the different land covers, the scores for Calmness, Vibrancy, and NSQ in BVS and BVWS are predominantly "medium" and "slightly high", whereas those in BS and VS are categorized mainly as "slightly low". All soundscape compositions are present in urban parks and farmlands, whereas forests only contain three soundscape compositions. The statistical analysis reveals that the soundscape compositions in forests exhibit the highest scores for Calmness, Vibrancy, and NSQ. However, if the soundscape compositions are absent in forests, the highest scores for Calmness, Vibrancy, and NSQ are achieved in urban parks.

4. Discussion

In this study, we developed an indicator-based model for spatially assessing and quantifying NSQ and then examined it in Springe municipality, Germany. The natural soundscape is widely acknowledged as positive, which led us to utilize the Calmness-Vibrancy components to characterize NSQ. This model employs several indicators and metrics to spatially evaluate and visualize these components. We performed spatial statistical analyses of the mapping results from landscape and soundscape perspectives.

4.1. Assessment results of the study area

Our results show significant spatial disparities in the relative values of NSQ across the study area. The maps of Calmness and Vibrancy present similar spatial trends. This spatial similarity is associated with the modeling logic, because the spatial unit "soundtope" for these two

Table 3
Detailed description of calculated metrics.

Calculated metric	Data source	Process description	Applied tool
Spectral Centroid (SC)	1	The SC values were calculated and normalized by importing all audio files of songbird species into Python 3.10. This process utilizes the packages "os", "librosa", "numpy", and "scikit-learn". Finally, all the birdsongs were assigned separately to the five ranks (Fig. 1 and Table S1) according to their normalized SC values, and then scored to the corresponding soundtopes.	Python 3.10; ArcGIS 10.7
Terrain Ruggedness Index (TRI)	2	TRI values were calculated for each grid cell based on the DEM data of Springe, using the method proposed by Riley et al. (1999) and adapted by Stojilković (2022). The "Focal Statistics" and "Raster Calculator" tools were utilized to calculate TRI in this process.	ArcGIS 10.7
Normalized Difference Vegetation Index (NDVI)	3	The Sentinel-2 level-2A images (2017–2018) of the study area were imported as a whole into the Google Earth Engine (GEE) JavaScript-based code editor environment (Gorelick et al., 2017). The NDVI values were calculated for each image element. Finally, a time series NDVI image collection was generated with a 10 m resolution.	GEE JavaScript API
Quiet Area (QA)	4	QAs were scored by the "Laermbereiche" data that present noisy areas spatially (Fig. 1). Generation of the data follows the maximum impact distance of noise in the German DIN standard (Reuter, 2013).	ArcGIS 10.7
Euclidean distance to sound sources	5, 6	The distances to each sub-category sound source (Table 1) were calculated by "Euclidean Distance" with a maximum of 250 m and then aggregated using "Weighted Sum".	ArcGIS 10.7
Percentage of green spaces and water bodies	5	The data of green spaces and water bodies of Springe were extracted from the biotope map, and then their area percentages were calculated.	ArcGIS 10.7
Variety of sound sources	7	The variety was calculated by counting aggregated soundtopes of sub-category sounds (Table 1). Specifically, the bird sounds in this calculation were classified into five main types according to the ranks of SC values (Fig. 1 and Table S1).	ArcGIS 10.7
Population density of songbirds	6	Population density using the "Kernel density" tool based on the distribution points of songbird species.	ArcGIS 10.7
Rating of water types, rating of foliage vegetation, fluctuation potential of sounds	7, 8	All the ratings were deduced from the empirical evidence in the reviewed literature and then assigned to the corresponding soundtopes.	ArcGIS 10.7
PD, LPI, CONHESION, SHDI, SHEI, LSI, ED	5	All the landscape metrics were calculated at the landscape level by the moving window technique, a method considered a useful proxy for human perception (Chen et al., 2022b; Hermes et al., 2018; Roser, 2011). We set the radius at 250 m and created 250 m buffers for the input data to minimize the boundary effects (Modica et al., 2012).	ArcGIS 10.7; Fragstats 4.2

1: Audio files of the 70 songbird species, Xeno-canto Wildlife Sound Library (http://xeno-canto.org).
2: Digital Elevation Model (DEM), Open Maps for Europe (https://www.mapsforeurope.org/).
3: Sentinel-2 level-2A images less than 10% cloudiness, Sentinel missions (https://sentinel.esa.int/web/sentinel/home).
4: Data of "Laermbereiche", Hannover government (Landeshauptstadt Hannover, 2017).
5: Biotope map, Hannover government (Landeshauptstadt Hannover, 2017).
6: Distribution of potential songbird species; for details, see Section 3.2.1.2.
7: Soundtope map; for details, see Section 3.2.1.3.
8: Empirical evidence (Aletta and Kang, 2018; Galbrun and Ali, 2013; Hong et al., 2019c; Hong and Jeon, 2017; Jaszczak et al., 2021b; Jeon et al., 2018; Rådsten-Ekman et al., 2013; van Renterghem, 2019; Yang and Kang, 2013).

components was generated based on habitat types. Afterward, the soundtopes were used to determine the scope of spatial value assignment in the assessment process. In addition, previous studies based on user-dependent evaluations also observed similar spatial patterns between Pleasantness and Eventfulness (Chen et al., 2022b; Hong and Jeon, 2017). These findings can indirectly reflect that our evaluation criteria and results are in line with the public's perceptions and preferences for natural soundscape characteristics. This is because numerous studies have shown a positive correlation between soundscape calmness and pleasantness, as well as between soundscape vibrancy and eventfulness (Aletta et al., 2016; Aletta and Kang, 2018; Davies et al., 2009, 2013). Besides, the spatial distribution of the soundscape perceived as relative-calm or -vibrant is also consistent with previous studies (Aletta and Kang, 2018; Hedblom et al., 2017).

Combining the results depicted in Fig. 3a, b, 3c, and Fig. 4, we found that Calmness, Vibrancy, and NSQ basically had higher relative values in green spaces. In comparison, their lower relative values predominantly manifest in farmland. In our case, farmland habitats demonstrate reduced bird species and vegetation types and densities compared to forest habitats (Table S1). This diminished biodiversity causes a decrease in exposure opportunities and the emotional value of birdsongs and vegetation sounds, thereby significantly reducing the value of Calmness. Additionally, the homogeneous shapes and monotonous structures of farmland patches lead to a reduction in diversity and complexity at the landscape level. These features likely limit the species richness and the possibility of acoustic communication among animal communities (Bormpoudakis et al., 2013), resulting in lower sound diversity and variability and thus yielding lower Vibrancy values. Consequently, it is reasonable to exhibit that NSQ in farmland experiences a decline compared to green spaces. Prior studies have similar findings that farmland landscapes may have relatively low biodiversity and landscape diversity (Gabel et al., 2016; Massaloux et al., 2020). Interestingly, agricultural areas were also observed to have low LAQ values (Hermes et al., 2018; Kalinauskas et al., 2021).

The result maps showcase that Calmness and Vibrancy may reach relatively high values at the same location (Fig. 3a and b). However, this does not mean that the soundscape here is perceived as calm and vibrant simultaneously, because these results cannot be interpreted wholly in the same way as those evaluated by user-dependent subjectivist approaches. In our methodology, Calmness and Vibrancy serve as intrinsic characteristics that determine NSQ, and therefore, the evaluation results represent the capacity of natural soundscape features and quality provided by ecosystems, but not necessarily the extent to which these natural soundscapes are present or perceived currently (Chen et al., 2022a). Based on this model, planners can measure the NSQ capacity in the region from a global perspective, by utilizing habitat or land cover type data directly, rather than paying attention to or constantly measuring the soundscape features with moment-to-moment changes, which are of very limited significance in terms of contributing to the planning purpose and the measure development.

The results in Fig. 5 indicate that NSQ scores of sound combinations are higher than those of individual sound types, except for bird and water sounds, and vegetation and water sounds, which have lower relative mean values than water sounds. The maps of the proportional distribution of relative values exhibit that the high-share relative values of bird or vegetation sounds are lower than those of water sounds, thus pulling down the mean relative values of the sound combinations. This is because the soundtope of individual bird sound was mainly found in the species' sparsely distributed farmland areas. Also, the soundtope of single vegetation sounds generally came from grassland and shrubland and was rated relatively low compared to the forest areas. Apart from these exceptional cases, the results reveal that diverse soundscapes have higher values than individual sound types in general, which mirrors the findings of previous studies (Deng et al., 2020; Herranz-Pascual et al., 2019). We also observed that the values of Calmness, Vibrancy, and NSQ for the same soundscape compositions were higher in forests and in urban parks than in other land cover types (Fig. 6), aligning with the observations of existing studies (Jaszczak et al., 2021a; Liu et al., 2019). This also echoes that the quality of the same soundscapes may vary in different contexts (Hong et al., 2020a). These similarities are evident that the differential patterns of our results conform to human perceptions and preferences, supporting their validity in considering the public interests in the planning process.

The geo-visualization of relative values allows planners to compare NSQ region to region. These comparisons yield useful insights for protecting landscape assets, environmental management, and sustainable landscape development (Kempa and Lovett, 2019; Xu et al., 2020a). The possible application involves but is not limited to soundscape monitoring, scenario simulation, and assessments of the planned project impacts on natural soundscapes. For instance, areas possessing natural soundscapes with high values can be identified to support and balance the decisions regarding tourism development. Additionally, the model can offer data on the spatial pattern of NSQ for the DPSIR modeling framework (Albert et al., 2016b). In this context, the evaluation results can be understood as an independent state of the natural soundscape and a supplement for the landscape state. The model facilitates the evaluation of both the current state and the states in different periods, including past and future, using available data. This allows planners to pinpoint the impacts stemming from the execution of planning projects on soundscapes.

4.2. Potentials and uncertainties of the methodology

The developed methodology meets landscape planning requirements and offers an indicator-based model that echoes indicator selection principles outlined in the research objectives. Building on the groundwork of Chen et al. (2022a), our model further expands and filters pre-validated indicators and metrics successfully applied in various contexts and scales. Similar workflows have effectively been used in assessing LAQ and other offered CES (Hermes et al., 2018; Thiele et al., 2020), allowing for complementing such works with our model for NSQ. Therefore, we argue that the current theoretical foundation and examined findings are sufficient to endorse the validity of the modeling indicators and evaluation criteria. Although the current weight setting refers to existing scientific research, it does not mean it is perfect and unchangeable. Notably, the model still leaves opportunities for future adjustments to adapt to evolving societal developments and shifting public perceptions. Such adaptability and generalization capabilities are a distinctive feature and an advantage of our straightforward model, ensuring it retains a user-friendly nature, allowing for easy adjustments and enhancements for environmental planning and management purposes. Moreover, the approach is implemented in GIS-based models, enabling users to evaluate NSQ spatially. The model was executed on a computer with an Intel(R) Core(TM) i7-6700 CPU @ 3.40 GHz and 16.0 GB RAM. These configurations are easily accessible for planning departments and even non-governmental organizations. We are confident it can also run efficiently on the Apple computer with an Apple M series processor.

In this case study exploration, our model considers the uncertainty between observed birds in the study area and potential bird species across the broader region. The Springe possesses an accessible and robust dataset on songbird species, and the potential songbird species data of Lower Saxony is also publicly available online. The evaluated bird species in this study represent 76.92% of the potential species database. This further bolsters the substantive nature of our research, allowing the users to juxtapose the uncertainty levels between the appearing and potential songbird species. However, in other case studies, the availability of local bird observation data could pose challenges, as such data may not always be ready. Despite this, our case-study exploration still demonstrates the evaluation feasibility for the users who only have access to the upper-scale regional dataset instead of the local measurement results. The developed model is able to provide

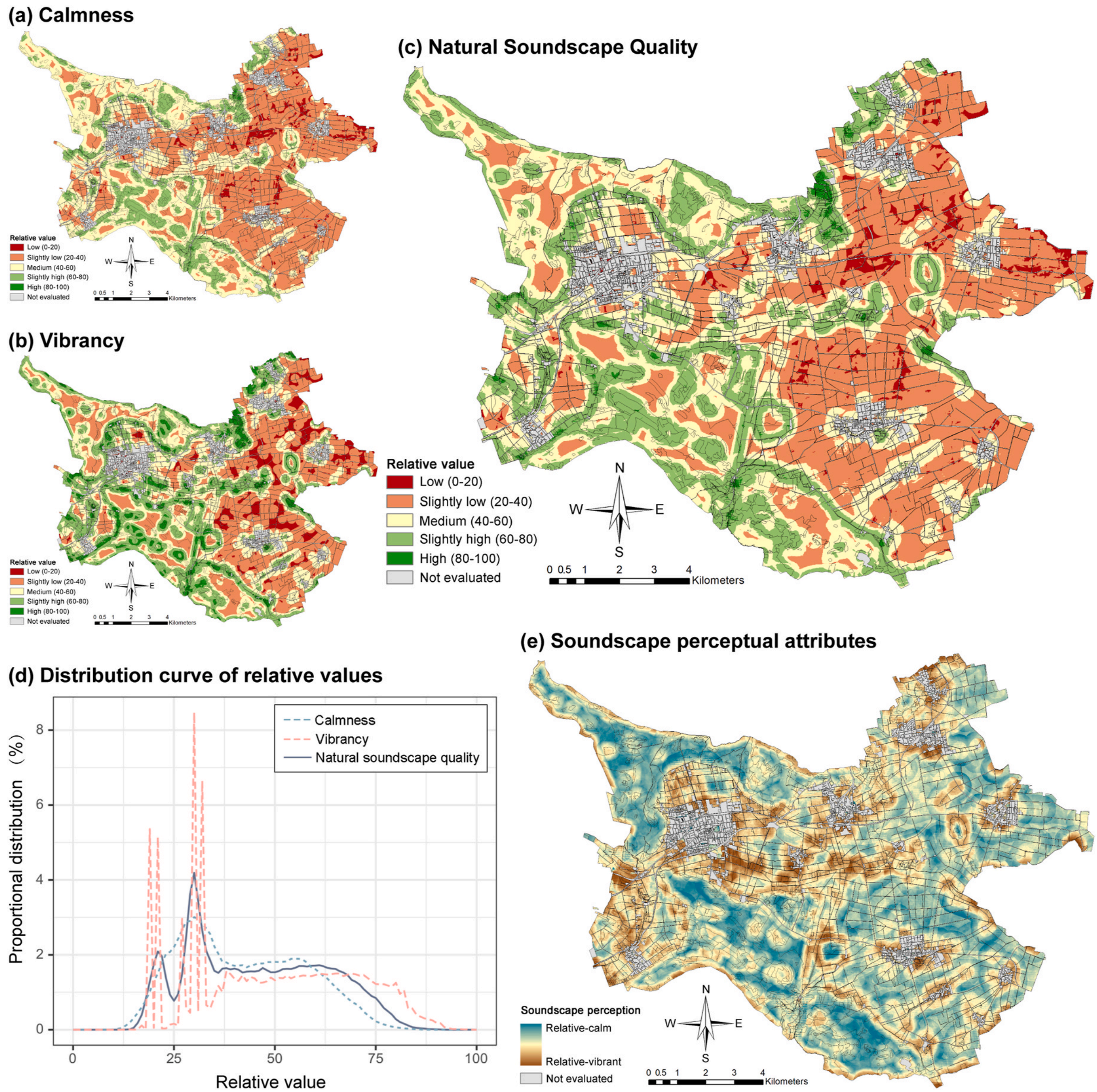

Fig. 3. Overview of mapping results: (a) mapped Calmness; (b) mapped Vibrancy; (c) mapped natural soundscape quality; (d) distribution curves of relative values; and (e) map of soundscape perceptual attributes.

meaningful results under uncertainties, which can be further explored by carrying out actual measurements at lower scales and comparing them with the model results. With such comparisons, users can discern the extent of divergence between the appearing and potential songbird species, and better identify the NSQ magnitude in ecosystem potential and actual utilization.

Users are welcome to use more diverse data sources and formats to feed the indicator-based model. The primary purpose of this study is to propose a methodology with assessment criteria for NSQ. Therefore, the data used in the exploration is not the only form that can reflect the indicators and metrics, but serves as a practical application to present and examine the executability of this developed methodology better. Suppose the user holds other types of datasets that correspond to the various indicators in the model, indeed, they can also be used to input and execute the model program. It would also be interesting that inputting different data types might generate different model results, and this difference is also worthy of further exploration. In this sense, the robustness and accuracy of model results may be affected by the quality of input data instead of data availability, but this causal relationship is inevitable in data-driven analysis (Batini et al., 2009). Nonetheless, users can still employ such data to generate valuable information of NSQ by using our model. This is also a reflection of the applicability, practicality, and replicability of this model as a tool in the environmental planning and management processes. Such adaptive and transferrable examples have been shown by Kalinauskas et al. (2021). They mapped and assessed LAQ in Lithuania using different data sources by adapting the LAQ assessment approach applied initially in Germany (Hermes et al., 2018).

Some of our evaluation results can be deviated but unavoidable from those using user-based soundscape methods like interviews or questionnaires (ISO, 2018). This phenomenon can be expounded in two aspects. On the one hand, the differences lie in the type of captured preferences. The indicators and criteria of our model follow the general public's soundscape preferences, whereas the evaluations using user-based methods only observe the participants' responses immediately. Furthermore, variations are evident in the explanation of the results. Our results imply relative values for the whole assessed area, representing the ecosystem's capability for providing soundscape quality. In contrast, common soundscape studies typically reflect absolute values of individuals' perceptions of the moment at specific sampling

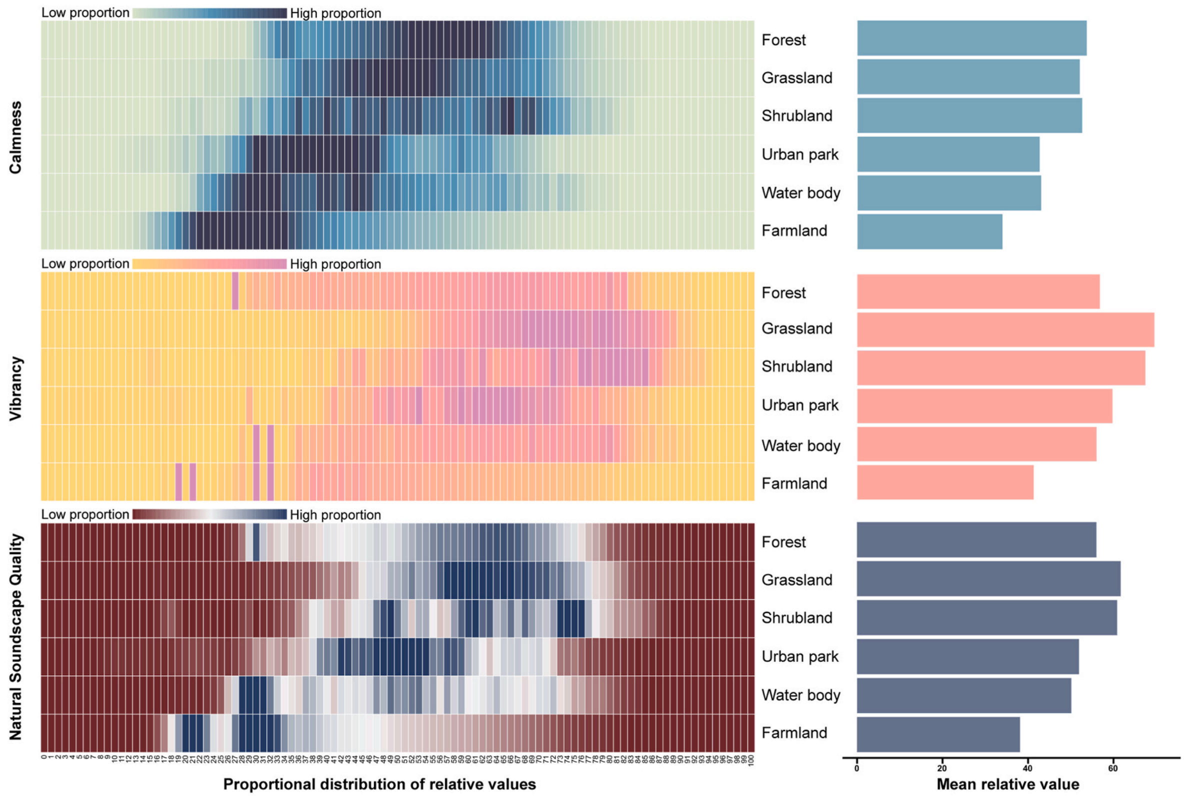

Fig. 4. Proportional distribution of relative values and mean relative values across the land cover types.

sites. These discrepancies are also why the developed approach is more suitable for communication and discussion among decision-makers and stakeholders in the planning process.

We are convinced that the developed methodological approach holds the potential to be applied on larger scales. Naturally, more empirical research is imperative to determine how to adapt and utilize the information supplied by the model in the actual policy-making for different scales. Applying the same model across multiple scales and levels is extraordinarily intricate and gives rise to several inevitable challenges. Consequently, the practical adaptation of the model is crucial and may necessitate alterations in metrics and data suitability. Nevertheless, our study still provides an easy-to-follow framework and approach for addressing the oversight of positive soundscapes in landscape character assessments on a relatively large scale. The mapping results can provide a holistic understanding of the spatial attributes of the supralocal natural soundscape. The evaluative framework and model empower landscape planners to identify iconic and valuable natural soundscapes. Besides, they can also contribute to advancing the state of knowledge on the aims and methods of landscape character assessments.

Furthermore, we argue that the proposed methodology can be applied in principle to the planning systems in most countries, and help decision-makers, researchers, and the public better understand the significance and role of soundscape issues through the methodology. Despite this, regardless of the planning system in which country the methodology is applied, it should be adapted to the quality and availability of data in the particular context, as we have discussed in this section. In our discussion, landscape planning is actually considered a term to denote all types of environmental planning concerned with addressing environmental resources and services. However, planning systems and contexts in different countries are influenced by many underlying factors, such as legal, economic, political, cultural, demographic, and environmental conditions (Haaren et al., 2019). For instance, Germany, Japan, and the United Kingdom are countries with limited spatial resources and high population densities, and therefore have developed mandatory systems of spatial planning. The United States gets relatively little pressure from lands and does not have a planning system at the federal level, but there are some regions, such as Oregon, where legal-based growth boundaries have been established through early planning measures. China, on the other hand, is currently engaged in territory spatial planning oriented toward rational allocation of environmental resources. Its abundant national land resources are often concentrated in specific densely populated areas, leading to a competitive relationship among different types of land uses with regard to natural resource utilization. All these illustrate how political and socio-economic factors have shaped the characteristics of planning systems across countries, and therefore, there is no "one size fits all" approach. The foundational conditions and planning systems across countries can be regarded as starting points for diverse landscape planning. In addition, attention should be paid to differences in the evaluation criteria and public preferences derived from different legal and political systems. Accordingly, we also suggest that the adoption of relevant legal standards, where applicable, may lead to a better basis for NSQ evaluation in the planning system and, thus, to the legitimacy of the results.

The developed user-independent approach is accessible to policy-makers and non-specialists. It can serve as a planning instrument for the monitoring and scenario simulation of natural soundscapes, thus analyzing changes in the provision of natural resources (Albert et al., 2016b). The evaluation results are presented through visualized maps with relative values, enabling users to discern changes in the soundscape states by comparing the disparities between the maps. Such change identification offers a vital basis for relevant authorities to amend the inappropriate aspects of the policy promptly (Tscherning et al., 2012). Our differentiated methodology and findings introduce a fresh perspective on integrating soundscape assessments to fill in the gaps within existing landscape planning, and contribute to informed land use decision-making. Also, they help address the knowledge gap of ES in positive soundscapes, promoting the development of existing CES assessments, with a particular emphasis on landscape aesthetics.

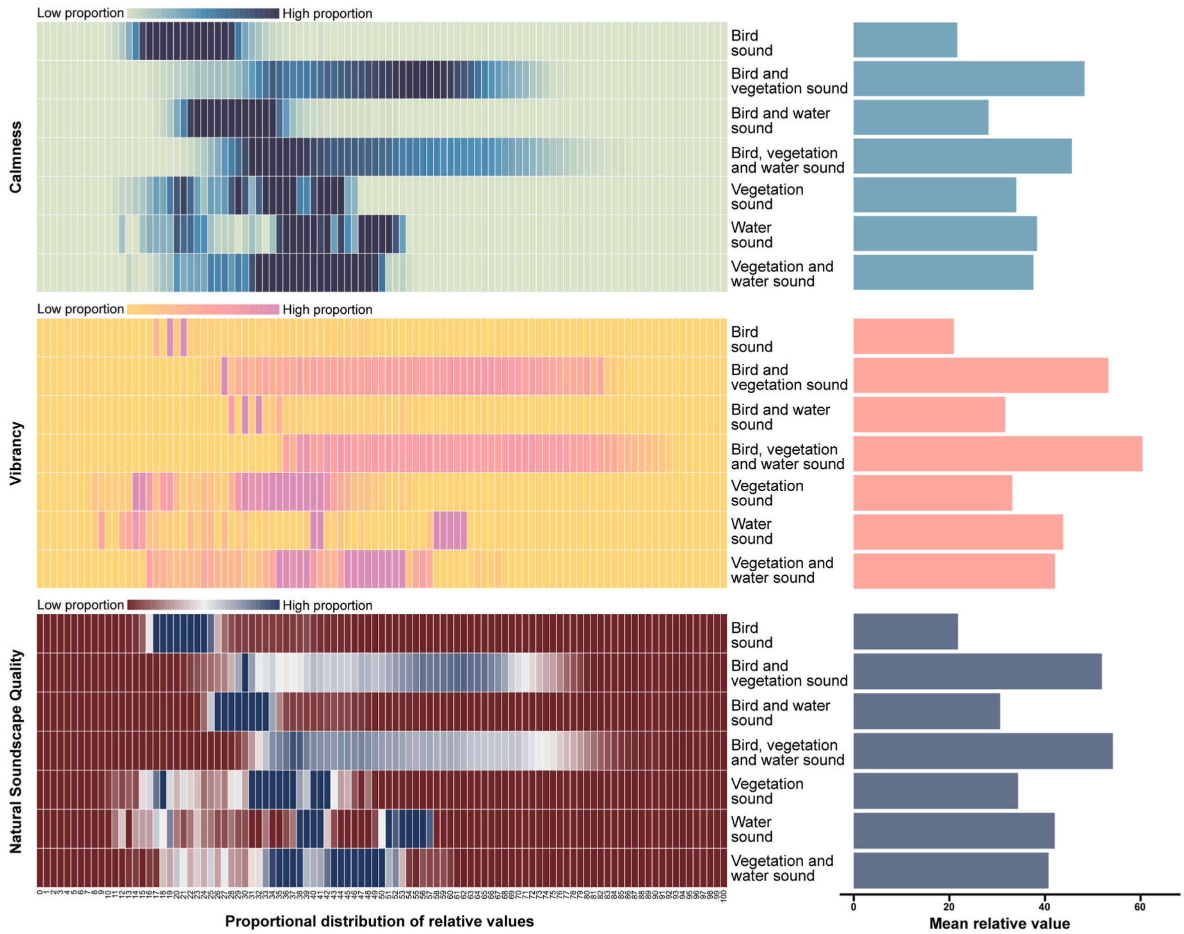

Fig. 5. Proportional distribution of relative values and mean relative values across the soundscape compositions.

4.3. Limitations and prospects

This study has some limitations that could be further improved in the following studies. Initially, the model focused exclusively on bird, water, and vegetation sounds in the case study. In subsequent studies, the spatial model could accommodate broader natural sound sources if substantial knowledge and evidence exist. Furthermore, our approach employed the unified value to represent the propagation range of each sound source. We encourage future studies to differentiate the average sound propagation ranges according to different sound types (Embleton, 1996). Lastly, the bird species data utilized in this study are validated within European regions. Should the model be applied beyond Europe, expanding the bird species information would be imperative. This is because the potential disparities in songbird species and their typical habitats vary across continents, climate, and food resources (Devictor et al., 2012).

We look forward to incorporating the NSQ index into landscape aesthetics assessments in the following research. The added-value of such integration can be identified by comparing the deviations in the results of the integrated assessments with those of the original ones. Such comparisons also provide a new perspective for exploring the relationship between landscape features and soundscape quality. The index can provide opportunities for exploring the interrelationships between the supply and demand of natural soundscapes, such as comparisons between the high NSQ provision areas and regional demands for natural soundscapes, and the identification of regions with under-supplied natural soundscapes (Albert et al., 2016a). The impact of pressures (e.g., traffic or wind-turbine noise) on the state of NSQ can also be explored, which could be further employed to build a projecting model for future NSQ states based on DPSIR framework. In addition, we also encourage more studies measuring and collecting data of sound sources monthly or seasonally, such as varied leaf density and bird courtship (vocalization) periods, to support temporal NSQ mapping. Future studies using subjectivist evaluations can also serve as data validation and updating for the NSQ model, thereby improving the generalization performance of the model. The designed GIS tools and Python codes are always accessible upon request, ensuring the reproducibility and portability of the model and indicators.

5. Conclusions

This study debuts a user-independent methodology for assessing NSQ, applied in a municipality on a supralocal scale. The relative-calm soundscape is concentrated inside forests and farmlands, while relative-vibrant soundscape is mainly associated with complex edges where different land cover types intersect. The indicative values highlight that green spaces display high NSQ scores while farmlands score lower. Soundscape compositions present higher NSQ scores than individual sound types. Besides, the same soundscape compositions attain higher NSQ values in forests or urban parks. These results align with the conclusions drawn in prior studies that employed user-dependent subjective approaches. However, our user-independent approach is applicable in GIS-models, ensuring transferability and reproducibility, with comparable results across evaluated areas. The approach conceptualizes NSQ as a capacity provided by ecosystems, a crucial member of LAQ assessment under the ES paradigm. These underscore the greater applicability of our model in planning processes compared to the subjectivist methods. Consequently, our methodology can equip planners with

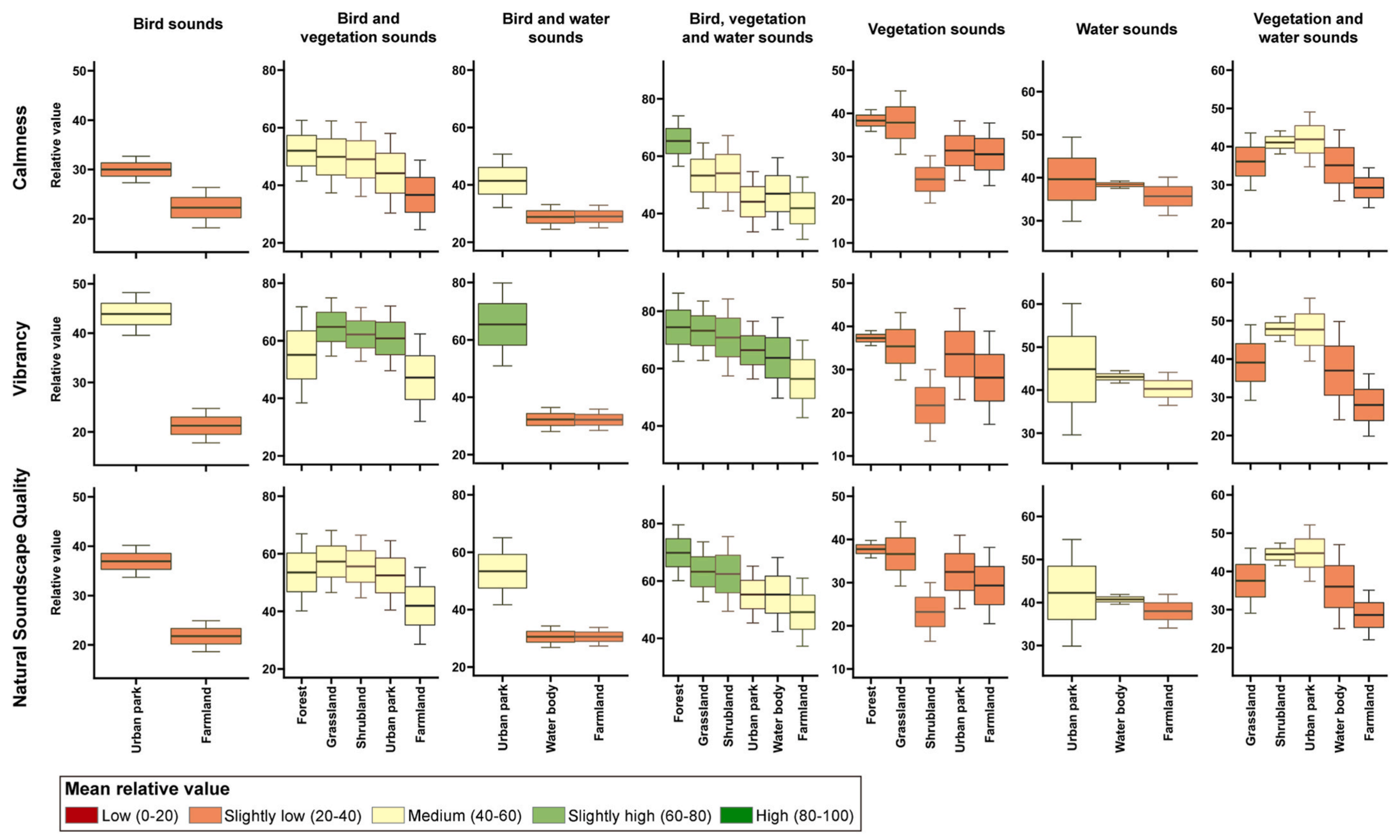

Fig. 6. Relative values of each soundscape composition in different land cover types.

feasible tools and additional opportunities to incorporate natural soundscape evaluations into landscape planning. The land-use conditions and needs are changing in different countries due to experiencing environmental challenges. Emphasizing the value of nature for human and socio-economic development, it is imperative not to neglect the analysis and assessment of ecosystem status and capacity. This forms the basis for a constructive dialogue with decision-makers and the public. We understand planning no longer as a static stack of paper, but as a dynamic database of geographic information, characteristics, and criteria that can be adapted to new situations and reflect uncertainties, thus serving as a bridge between science and policy. As such, we are confident that this study can bring theoretical and practical added-value to landscape sustainability, environmental management, and decision-making in different contexts.

CRediT authorship contribution statement

Zhu Chen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Johannes Hermes:** Conceptualization, Methodology, Validation, Writing – review & editing. **Christina von Haaren:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120422.

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