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Soundscape Design in an Urban Natural Park

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Abstract: Urban natural parks represent a remarkable concept that evokes the coexistence of human habitation with a wild environment, and the associated interactions between human and natural territories. In this context, urban noise infringes upon the natural soundscape, leading to various consequences for both realms. This study seeks to characterize the impact of anthropic noise levels on biodiversity in the urban natural Văcărești Park (Bucharest, Romania), utilizing on-site measurements and software simulation techniques. The study seeks to develop a method for evaluating integrative strategies to mitigate the impact of traffic noise on wildlife in an urban wild park, without addressing the specific effects of noise on the perception and communication of individual species. By calibrating field measurements with laboratory results, a more reliable data set will be used to identify areas where the biophonic environment is impacted by anthropogenic noise. Since human-generated noise in an urban natural park predominantly originates from road traffic and industrial sites, managing traffic noise and its propagation pathways could substantially improve the park's soundscape. Additionally, this study will apply software simulations for noise reduction strategies, such as vegetation planting and earthen embankments, to obtain suitable solutions and propose plausible and effective actions to authorities for improving the biophonic environment. This research could also serve as the basis for long-term monitoring, allowing for the assessment of the evolution and impact of implemented measures over time.

Keywords: soundscape; urban natural park; bioacoustics; sound map

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1. Introduction

Acoustic monitoring of avian species and fauna is mandatory for conserving their habitat and diversity inside an urban park, which comes with more challenges than a wild area. Sounds that arise from such a mixed environment have opened research fields such as ecoacoustics [1] and new terms such as biophonics (non-human sounds produced by living organisms), anthropophonics (humans related sounds), technophonics (technologically generated sounds, like traffic noises), and geophonics (natural sounds, like wind or water sounds) [2].

An Urban Natural Park, as defined by Category V IUCN (International Union for Conservation of Nature), is a place that requires conservation, development, or logistic support from an ecosystem point of view [3], besides protection, leading to the necessity of applying sustainable administrative planning. As such, the planning, defining, and sustaining a proper soundscape [4] is an important action for maintaining an ecosystem. The soundscape of an ecosystem constitutes a dynamic auditory space influenced by diverse biological and environmental factors, including migrations, breeding periods, and seasonal variations. Consequently, it is advisable for such studies to encompass the sensitive periods during which the biophonic environment is particularly complex, characterized by numerous overlapping communicative signals from various species like it is during the spring or autumn.

Văcărești Natural Park, located in the south-east of the metropolitan Bucharest area (Romania), exemplifies a significant instance of urban biodiversity, situated within a densely populated metropolitan area. Therefore, it serves as an appropriate subject of study for the proposed research objectives. Văcărești Natural Park was established by a government decision in 2016 [5]; it is located 5 km away from Bucharest city center and has a surface area of 183 ha [6]. The park is the biggest compact green space in Bucharest and is composed of a mixture of water areas and zones with vegetation specific to wetlands. From a bio-habitats point of view, Danubian communities (*Lemna minor*, *Lemna trisulca*, *Spirodella polyrhiza*, *Wolffia arrhizal*, *Typha angustifolia*, *Typha latifolia*), and anthropic species (*Polygonum aviculare*, *Lolium perenne*, *Sclerochloa dura*, *Plantago major*, *Agropyron repens*, *Arctium lappa*, *Artemisia annua*, *Ballota nigra*) were identified. Willow species predominate among the trees, with *Salix alba*, *Sallix fragilis* (wicker), *Salix cinerea*, and poplar (*Populus* sp.), willow (*Elaeagnus angustifolia*), but also exotic species such as ash (*Chinese vinegar*) or paradise tree (*Ailanthus altissima*), American ash (*Fraxinus pennsylvanica*) and Siberian elm (*Ulmus pumilla*), or common fruit species such as *Prunus cerasifera*, white mulberry (*Morus alba*) and walnut (*Juglans regia*). So far, 600 species have been identified, including 180 bird species, most of which are protected at a national and international level (according with Văcărești National Park Foundation), including: summer swans (*Cygnus olor*), white-cheeked grebes (*Chlidonias hybrida*), tits (*Cyanistes caeruleus*), ducks (*Anas Penelope*), herons (*Ixobrychus minutus*), cormorants (*Phalacrocorax carbo*), egrets (*Egretta garzetta*), herons (*Circus aeruginosus*), seagulls (*Larus cachinnans*), etc. [7]. Additionally, reptiles, like the European water turtle (*Emys orbicularis*), lizard (*Lacerta viridis*), field lizard (*Lacerta agilis*), house snake (*Natrix natrix*), water snake (*Natrix tessellata*), and mammals like the field mouse (*Microtus arvalis*), dwarf squirrel (*Sorex minutus*), bison (*Ondatra zibethica*), weasel (*Mustela nivalis*), fox (*Vulpes vulpes*), otter (*Lutra lutra*) and bats [8] have been found.

Văcărești Natural Park, in contrast to other natural parks, is relatively newly established. Before its designation as a natural park, the area consisted of a mix of swampy and agricultural zones, hosting avian and faunal species typical of peri-urban areas. Before 1988, the area currently encompassing Văcărești Natural Park represented the southeastern periphery of Bucharest. This region was unpaved, featuring scattered residences and extensive gardens, linked by a modest network of streets, some of which remain to this day. During 1988–1989, hydrotechnical works were undertaken to create a lake (Figure 1).

Figure 1. Hydrotechnical works—Văcărești Lake 1989 [source: ASOCIAȚIA PARCUL NATURAL VĂCĂREȘTI].

However, due to design flaws that resulted in frequent water infiltrations, the initial project was abandoned. Consequently, the area reverted to a wild state, becoming overgrown with vegetation and subsequently attracting various species of birds, animals, and reptiles. This transformation led to the development of a mixed bio-habitat with only sporadic human presence. The Guardian newspaper mentioned in an article, “how nature turned a failed communist plan into Bucharest’s unique urban park” [9].

Following the government's decision to protect it [10], an aquatic ecosystem was formed in the area with swamps, waterholes, reeds, willow groves, poplar nests, and reed curtains bordering the lake, all of which constitute the habitat of birds, which come to nest and breed, many species of reptiles, insects, and amphibians and even small mammals, completing an entire ecosystem (Figure 2).

Figure 2. Văcărești Natural Park—images taken with DJI Drone [source: ASOCIAȚIA PARCUL NATURAL VĂCĂREȘTI].

Each year, new species arrive without human intervention, initially surviving and subsequently acclimating to the environment. Although human access to the protected area is limited to walking, surrounding noise penetrates the natural park almost unimpeded, compelling birds to tolerate and adapt to it. The initial embankment, constructed for water accumulation, has remained and now serves as a protective barrier between the city and the wild area within. In contrast to other urban natural parks, which have undergone extensive and ongoing reforestation and environmental redevelopment interventions, Văcărești Natural Park has developed naturally, without human intervention in the existing fauna or flora. This natural development has led to high biodiversity, making it a unique place (Figure 3).

Figure 3. Biodiversity in Văcărești Natural Park.

Currently, being nearly surrounded by the metropolis, the entire bio-habitat is impacted to some extent by continuous anthropogenic noise; however, among all the species residing in the park, birds are the most affected. City noise significantly impacts the bio-habitat within an urban natural park in several ways. Many species rely on sound for communication, especially birds, frogs, and insects; city noise can mask these sounds, making it difficult for animals to find mates, defend territories, and alert others to danger [11]. Constant exposure to loud noises can cause chronic stress in wildlife, leading to changes in behavior. Animals may become more vigilant, reducing time spent on essential activities like foraging and caring for their young. This stress can also impact their reproductive success and overall health [12].

Some species may choose to avoid areas with high noise levels altogether, leading to a decrease in biodiversity. Species sensitive to noise pollution might relocate to quieter areas, disrupting the ecosystem's balance [13]. Noise can interfere with the ability of predators to hunt and prey to evade capture. For example, birds of prey rely on hearing to locate their targets, and small mammals use sound to detect approaching predators [14]. Over time, noise pollution can lead to shifts in species composition. Species that can tolerate or adapt to high noise levels may thrive, while others may decline or disappear. This can lead to a less diverse and more homogenous ecosystem [15]. Indirectly, noise pollution can also affect plant life. Many plants rely on animals for pollination and seed dispersal. If noise drives these animals away or alters their behavior, it can impact plant reproduction and growth [16]. Overall, city noise disrupts the natural processes and interactions within an urban natural park, leading to potential long-term ecological consequences.

This study aims to evaluate the impact of anthropophony, particularly from traffic and industrial sources, on a confined wild area where numerous wildlife species strive to survive and thrive. Additionally, various physical intervention methods for the park area will be assessed for their ability to maintain an appropriate internal soundscape, and the results could be a reference for authorities' intervention. An integrative strategy for evaluating the impact of traffic noise on wildlife in an urban wild park will be applied, without specifically addressing how noise affects the perception and communication of individual species.

The study also investigates the attenuation of traffic and industrial noise through the use of various types of vegetation and terrain configurations within urban parks, utilizing both software simulations and measured data. Specifically, it will focus on the effectiveness of peripheral vegetation layers, without additional afforestation in an already established wild area, in mitigating anthropophonic and technophonic noise impacts on the associated bio-habitat. Furthermore, the influence of terrain configuration in the peripheral zone surrounding the park on the internal soundscape will be examined by simulating three scenarios of earthen embankment: no embankment, embankment with afforestation, and embankment with acoustic panels. Bendtsen has proposed a few noise screening variants of the embankment, such as an earth embankment and a supported earth embankment with vegetation [17], but has not conducted a comprehensive study on noise impact on a certain area. Through our study, the vegetation on embankments will also be assessed.

This study aims to develop a fast and cost-effective method for evaluating soundscapes and search options for noise reduction strategies with applications in urban wild parks. Such methods can be employed by local authorities to mitigate the effects of traffic and industrial noise on avian and faunal habitats within protected urban parks. By utilizing advanced simulation techniques and empirical data, this study will provide a comprehensive framework for assessing noise levels and identifying effective noise mitigation measures. The approach will include the analysis of various vegetation types and terrain configurations to determine their efficacy in attenuating noise. The goal is to offer practical, evidence-based solutions that can be readily applied by municipal planners and environmental managers to enhance the acoustic environment of urban natural parks, thereby promoting healthier and more sustainable habitats for wildlife. This methodology not only addresses immediate noise reduction needs but also provides a scalable model for long-term environmental monitoring and improvement.

2. Materials and Methods

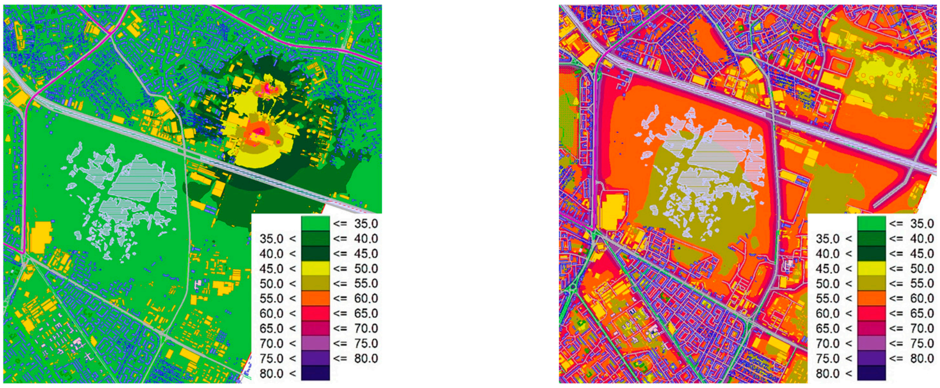
In ecoacoustics (which involves analyzing the acoustic signals produced by various organisms, natural processes, and human activities within a given ecosystem), sounds are used to gather data about the populations and habitats of fauna inside an area, using passive acoustic investigations [18], which are methods of sound monitoring without human interference with avian and fauna. In contrast to a wild natural park, an urban park, despite its protected status, contends with considerable challenges related to noises originating from surrounding urban areas. These technophonic and anthropophonics noises exert significant impacts on the habitats and breeding behaviors of wild birds and animals, which heavily depend on sound for communication, orientation, and territorial behavior [19].

A soundscape represents a complex mixture of audible elements overlapping from diverse sources, which collectively define a distinct environment within a specific dynamic temporal and spatial context. It comprises natural sounds such as the rustling of leaves in the wind, flowing water, and animal vocalizations, alongside anthropogenic noise sources such as traffic, industrial activities, and human voices. These elements collectively shape the soundscape, imparting it with a unique identity characterized by distinct auditory features. Conceptually, a soundscape can be defined as a sound map overlaid onto a specific geographic area, serving as a repository of acoustic information within which the corresponding biological life thrives. The perception of a wild-associated soundscape within an urban park evokes an innate human response, offering psychological and cognitive restoration with associated positive effects [20], but it is not perceived the same by the birds or insects. Several tree species distributed throughout the park exert significant influence on the local wildlife and, consequently, the soundscape. The combination of different vegetation and water zones, in an aleatory distribution, contributes to attracting different species, each with their own habitual characteristics. Also, the density and height of vegetation has a major influence, especially on avian species' distribution and density [21]. Therefore, even though different components of the biosphere are being treated separately, each contributes to varying degrees to the creation and maintenance of a soundscape that eventually achieves equilibrium over time.

Technophonic and anthropophonic sounds envelop the wild area, penetrating its boundaries and exerting both negative and positive influences. Statistical measures such as *LAeq*, *Lden*, *Ln*, *L10*, and *LAmax* typically describe the perceived noise in urban environments and serve as indicators of pollution with significant implications for human health [22]. According to European Directive 2002/49/EC, for assessment and management of environmental noise, each agglomeration must perform noise maps every 5 years.

Figure 4 presents the noise map (*Lden*) generated by traffic and nearby industrial facilities (the data are part of the Bucharest noise map for 2021, and the data are available on https://hartiacustice.pmb.ro/page/hstrat, accessed on 12 August 2024). One can observe that the simulated noise levels in certain areas within the park, particularly near the roads, exceed the 55 dBA threshold criteria necessary for maintaining conditions suitable for avian vocalization with minimal noise masking effects. It is also observed that industrial noise has a lower impact within the park, although sporadic increases in industrial noise were noted during field measurements. The primary source of this industrial noise is an electrothermal center that operates predominantly during the winter, resulting in a low probability of interference with avian activities, as most birds are migrating during this period.

Assessing the exact influence and magnitude of this complex blend of quasi-static and transient background noises on biodiversity immersed within it remains challenging. There are many acoustic metrics that are based on passive acoustic monitoring, and which give ecological indices that could be used for evaluating the soundscape, mostly within the context of having a negative influence on fauna [23]. Thus, Sueur et al., 2014 [23]. divided bioacoustics indices into two classes, α indices as within the group parameters, and β indices as between the group's parameters. Such indices evaluate from the acoustic point of view the amplitude, evenness, richness, or heterogeneity of the signal and, consequently, the properties of the soundscape. These indices are used as statistically deduced indicators of information encoded in a soundscape. The information conveyed within a natural soundscape is inherently complex, owing to the multitude of species acting as both emitters and receivers that must decode it in real-time. Unlike straightforward information transmission, where a transmitter communicates with a receiver through a medium affected by varying degrees of noise, in a complex soundscape environment, multiple transmitters overlap information, further complicating the already noisy propagation pathways. Consequently, one or more receivers must adeptly detect and decode the information amidst this intricate acoustic milieu.



(**a**) (**b**)

Figure 4. Traffic noise map: (**a**) industrial noise map; and (**b**) *Lden* [dBA] (source: Bucharest City Hall strategic map).

In a natural environment, the main transmission route of information is through sounds, where transmitters rarely see each other with the receivers and the environment becomes a chaotic chorus with inter-species and intra-species overlapping α within the group indices, based on amplitude or intensity characteristics of a signal, or the complexity of the signal in terms of time, frequency, or amplitude by the difference of frequency magnitudes between the bands. Besides these, some indices are taking into consideration bio-, geo-, or anthropo-phonics of the signal [24]. A mixed soundscape with biophonic and anthropophonics sources was investigated by Benocci et al., 2021 [25] using statistically dependent eco-acoustic indices with the scope of discriminating the habitats in Parco Nord of Milan. A widened array of acoustic indices was used by Lawrence et al., 2021 [26] to characterize an acoustic environment in an urban mixed area in Buchum, Germany. A series of bioacoustics indices were introduced as soundscape indicators. The Acoustic Complexity Index ACI [27] is a quantitative measure used to assess the variability and complexity of the environmental soundscapes which was introduced as an indicator for biodiversity monitoring, and provides insights into ecosystem health and species diversity. The Acoustic Diversity Index ADI [28] is derived by calculating the Shannon entropy of the distribution of acoustic energy among frequency bands, and its higher values indicate a more even energy distribution among the bands. Acoustic Evenness AEve [28], which measures the evenness of the distribution of acoustic energy across different frequency bands within a soundscape, is used to assess the balance of sounds in an environment, where a more balanced or "even" distribution of acoustic signals across frequencies indicates a more ecologically stable or healthy environment. The bioacoustics index BI [29] is used to assess the intensity and richness of biological sounds in a given environment and is particularly effective in distinguishing areas with high biological activity from those with lower biological presence or areas dominated by non-biological or anthropogenic sounds. Acoustic entropy H [30] is a measure used to assess the complexity and diversity of soundscapes by quantifying the distribution of acoustic energy across different frequencies and periods and is mostly applied to evaluate how evenly sound energy is distributed in an environment, providing insights into ecosystem health, biodiversity, and the presence of noise, mostly anthropic. The temporal entropy index [30] is used to evaluate the temporal structure of acoustic events, such as animal vocalizations or other natural sounds, over time and provides insights into the temporal dynamics of ecosystems, including daily or seasonal patterns of acoustic activity. Acoustic Richness AR [31] is a measure used to quantify the diversity and abundance of acoustic signals within a soundscape, focusing on the variety and intensity of sounds produced by different sources, where higher values indicate a greater variety of sounds. The Normalized Difference Soundscape Index NDSI is used to quantify the balance between biological and anthropogenic sounds in a given environment [32]. All these indices are used to characterize the soundscape. Acoustic descriptors of this nature are highly scientifically specialized and challenging to implement effectively in the design of soundscapes, where a comprehensive and integrative evaluation method would be more suitable.

From the soundscape design and governmental or local intervention point of view, the sound pressure level parameter (*SPL*) would be the easiest approach for measurements and simulations in assessing the noise impact in an area like an urban park. This approach is considered in the present article and detailed steps will be presented.

Soundscape design is a process of evaluation and implementation of the perceived restoration or annoyance from the human point of view [33], but in a study like this one, this should be considered in parallel with bio-habitat life. Tian et al., 2023 [34] studied a few strategies for optimization of the soundscape of an urban park based on landscape elements and soundscape human perception. Sun et al., 2023 [35] have studied how the soundwalk path in an urban park affects the soundscape, but, for a wild urban park, soundscape design should be combined with the needs of the bio-habitat. Xu et al., 2024 [36] have studied how spatial-temporal soundscape mapping helps with the management and planning of a protected area. Benocci et al., 2022 [37] also made a mapping of the acoustic environment in an urban park in Milan showing the influence of anthropic noise on the biophonic environment, but without making any proposal for soundscape improvement. As a possible consequence, Van Renterghem, 2024 [38] proposed a soundscape augmentation using fountains for masking the traffic noise in a soundscape of an urban park, although this solution is a human-oriented one. Urban wild areas, which maintain constant interaction with human environments, are perceived as therapeutic soundscapes and have been studied by Cheesbrough et al., 2019 [39], thus authorities must also consider this aspect when adopting related solutions.

One of the critical considerations in assessing perceived sound within background noise is the masking effect, which varies in its impact across different species. Noise within the 2–4 kHz spectral range of a bird's vocalizations and enhanced hearing sensitivity significantly mask communication signals more than noises found outside this frequency range. There are studies [40] on the masking effect on birds which have resulted in an overarching noise level guideline of approximately 60 A-weighted decibels (dBA) for continuous noise, but several improvements have occurred since the introduction of this criterion, and a 55 dBA was found to be more realistic [41]. This level will also be considered in this study as a reference level.

Regarding the frequency band on which the birds' vocalizations are produced, Clark et al., 2023 [42] found, by using recordings of 54 common bird species and CNN methods, that it is within the range of 2–11 kHz. The anthropogenic noise effect on birds was studied by Hao et al., 2024 [43] who found that bird vocalization frequencies in urban areas are significantly higher than those in quite zones. Also, their study appreciates that anthropogenic noise is typically lower than 4 kHz and mostly in the 0–1 kHz range. Tolentino et al., 2018 [44] found that the dominant frequency of songs for common bird species is higher in a noisy environment with $0.2+/-0.4$ kHz compared to a quiet area.

Using sound pressure level (*SPL*) measurements in a study is not a comprehensive and definitive method for evaluating a soundscape in an urban park from a bioacoustics perspective. Although overall *SPL* is a straightforward energetic parameter for describing acoustic aspects in a complex and mixed urban-park environment, it falls short of capturing the full acoustic impact on wildlife. In the vicinity and at the boundaries of the natural park, overall SPL is employed as the primary noise descriptor. To understand how the frequency distribution of mixed sources affects the acoustic perceptions of avian and fauna habitats, the sound spectrum of surrounding traffic and industrial sources will be evaluated. By examining the overlap between the traffic and industrial sound spectra and the noise perception curves of birds and animals in this bio-habitat, the study seeks to gain a perspective on how avian perception and communication are influenced through the masking and frequency content of anthropic noise.

It will be considered that anthropogenic noise is dominant in the frequency range of up to 1 kHz and in the 1–10 kHz range for avian sounds. High-frequency noise produced by insects, and which is dominant during some night hours, will not be taken into consideration. The overall sound pressure level, which contains both anthropic and biological noise, is considered to be in the range of 13–20,000 Hz.

2.1. Method for Noise Control in Natural Parks

Considering that the noise maps commissioned by city authorities are not suitable for assessing the impact of noise on biodiversity, but rather only on human communities, there is a clear need to develop a fast method for evaluating the impact of noise on biodiversity, which constitutes a preliminary step towards implementing measures to reduce noise and improve the living conditions and biodiversity in an urban natural park. The objective is to create a soundscape map of the park, overlaid with the urban noise layer, and to develop a fast method for assessing the impact of human-induced noise on the natural biophonic environment.

The study proposes a mixed-method approach that integrates software simulation that computes the noise map within the park, resulting from noise generated by surrounding traffic, supplemented with measured data collected from a network of acoustic sensors strategically placed at multiple locations within the park. The recorded data is used to refine the simulation results, enabling the creation of a virtual sound map that closely approximates the actual acoustic environment. Subsequently, three solutions with noise abatement scenarios (no embankment, perimetral embankment with forestation, and embankment with acoustic panels near the roads) are simulated as part of soundscape design.

For Văcărești Natural Park, specifically, concerning its proximity to traffic noise sources, it includes high-traffic roads located very close to two sides of the park, a major boulevard approximately 300 m away, and a "quiet" side primarily bordered by residential buildings with minimal nearby traffic. Additionally, a large industrial facility, comprising a significant thermoelectric center and a data center, is situated relatively close to the park, although these sources were not included in the software simulation because of their temporary low operation during the hot season when the recordings were performed. Consequently, the park's terrain encompasses various scenarios for evaluating the impact of traffic noise on biological habitats concerning the distance from noise sources. As already mentioned, a traffic or noise map, as commissioned by authorities, presents the distribution of noise, and as a consequence, emphasizes the noisiest zones, but the evaluation is only from the point of view of human perception. Therefore, the noise reduction methods employed by authorities are focused on the impact on human communities, not on biodiversity, which involves the coexistence of a multitude of species within a confined area.

An overall evaluation method includes several actions, as follows:

- Evaluation of noise levels distribution in the park resulting from on-site measurements and then calibrating the input data for the noise map simulation;
- Identification of possible hot spots in the noise measurements/simulation which might affect the bio-habitat areas;
- Evaluation of noise level distribution inside the park on different scenarios of noise reduction using afforestation and embankments;
- Identification of possible correlations between the surrounding afforestation and embankment levels of the parks and inner soundscape, as a starting point for future measures made by the authorities.

2.2. Noise Measurement Instrumentation

For field data acquisition, 10 AudioMoth full-spectrum acoustic loggers, Open Acoustic Devices, Berlin, Germany, capable of recording at sample rates up to 384 kHz, with incorporated MEMS microphones, were deployed at points of interest within the park.

These locations were chosen to encompass well-known avian nesting zones and probable animal routes. The AudioMoth is a small, low-power, and highly versatile acoustic monitoring device designed for environmental and ecological research, particularly for monitoring wildlife and environmental sounds. It records audio as uncompressed WAV files, which are stored on a microSD card, and can be programmed to record at specific times, on certain days, or in response to environmental triggers, offering high flexibility for various configurations. Figure 5 presents an image of the data-logger with a 3D-printed protective cage for weather protection and a tree placement example. The protective cage has been designed with a small opening with a diameter of 10 mm in front of the onboard microphone. To avoid the risk of short-circuiting due to water, an acoustic and hydrophobic transparent material was mounted into this opening.

(**a**) (**b**) (**c**)

Figure 5. Data-logger components and mounting solution: (**a**) Audiomoth acoustic logger; (**b**) 3D-printed insulation box; and (**c**) acoustic logger placed on a tree.

Before the on-site measurement campaign, a series of noise tests were conducted in an anechoic chamber to determine the spectral differences in frequency and amplitude between the AudioMoth data loggers and Class 1 precision noise measurement equipment.

Considering that the AudioMoth is not a professional instrument and is housed in a 3D printed box with an unknown acoustic response, which could act as a sound filter, the data loggers were compared with a Class 1 dB sound level meter in an anechoic chamber to assess their acoustic sensitivity and frequency response. Background noise and controlled generated noise levels were recorded simultaneously using both the AudioMoth and the noise measurement equipment. The recorded signals from both measuring systems were then processed using band filters for comparison and future noise corrections. The AudioMoth data logger was first tested in an anechoic chamber for evaluation of its response and sensitivity, and then compared with a professional Class 1 noise measurement equipment and data acquisition system. For these tests a DEWEsoft Sirius, Trbovlje, Slovenia data acquisition module was used, which is a DualCoreADC® system that utilizes a pair of 24-bit ADCs per channel, providing a dynamic range of 160 dB across both time and frequency domains, along with a signal-to-noise ratio of 130 dB. It supports sample rates of up to 200 kS/s per channel and includes integrated anti-aliasing filtering, ensuring precise measurements with over 70 kHz of bandwidth free from aliasing effects. For capturing acoustic sound pressure signals, an 8 ½″ 40AE microphone manufactured by G.R.A.S., Hotle, Denmark, was employed, which is a high-precision condenser microphone, designed by IEC 61094-4 standard [45], capable of measuring sound pressure levels from 3.15 Hz to 20 kHz, peaking at 148 dB, mounted on a GRAS ½-inch Preamplifier Type 26CA. To ensure precise calibration of the entire measurement setup, a Sound Calibrator Type 42AB, also manufactured by G.R.A.S., was utilized. This calibrator generates a sound pressure level of 114 dB (re. 20 μPa) $\pm$ 0.2 dB at 1 kHz, meeting the standards of IEC 942 (1988) Class 1 calibration. The anechoic chamber used for these tests has been designed and constructed following the specifications outlined in ISO 3745. Its volume measures 1200 m^3, with dimensions of 15 $\times$ 10 $\times$ 8 m, and the absorption coefficient of the chamber walls is 99% within the frequency range from 150 Hz to 20,000 Hz. The background noise falls within the Cz 25 noise curve. The recorded data obtained from the Class 1 microphone are processed with DewesoftX (version SP10) [46] software to get the spectrum and finally obtain the values for comparison with those recorded on the loggers. The noise signals recorded in WAV format on AudioMoth loggers are imported and processed with dBFA (version 4.9) [47] software. The technique for processing of the raw data from the WAV files consists of applying the 1/3 octave band filters and getting the A-weighted spectrum in time with an averaging time interval of 60 s, with the frequency domain set between 13–20,000 Hz. The resulting set of spectra were further processed by using a spreadsheet software where a spectral correction was applied, after which the overall levels for morning and evening periods were computed. The spectral correction was obtained based on the tests presented below.

A Bruel & Kjaer 4204 Reference Sound Source was used to generate 100 Hz to 20 kHz pink noise, with a power output of 91 dB re 1 pW (A-weighted, 50 Hz line frequency). DEWEsoft and AudioMoth equipment were set to a 50 kHz and 48 kHz acquisition rate, respectively, thus allowing a frequency analysis up to 20 kHz. Figure 6 presents the sensitivity testing set-up for data logger comparison and calibration between a Class 1 sound level meter and an AudioMoth data logger.

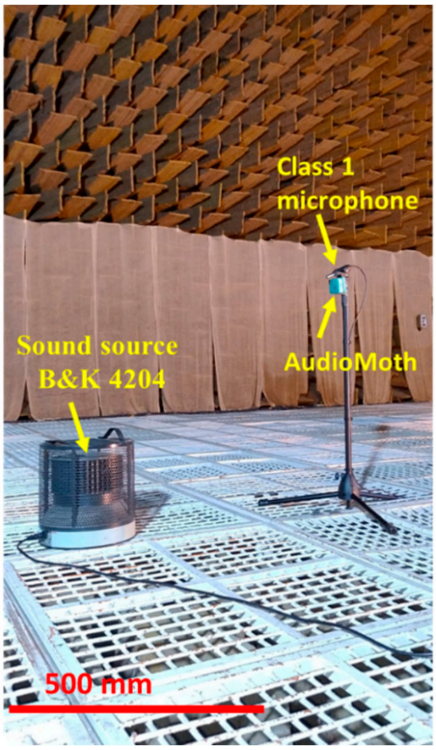


Figure 6. Sensitivity tests in anechoic chamber.

The experiment involved positioning the acoustic source at a distance of 1 m from the microphones, which were situated at a height of 1.2 m above the floor grid. The tests were conducted to ensure that the noise waves impinged perpendicularly on both devices used.

The raw noise signals were processed by applying an FFT function in the frequency domain with a spectral resolution of 24.4 Hz, Hanning windowing, and an overlap of 50% between the data blocks. The comparative spectral analysis, conducted using AudioMoth data loggers in conjunction with a Class 1 microphone (40AE-G.R.A.S. microphone with DEWEsoft data acquisition module), as presented in Figure 7, aims to determine the correction values to be applied to all the following recorded data. The results indicate that there is minimal variability in amplitude across frequencies between data loggers, as evidenced by the calculated standard deviation and illustrated in Figure 8. This suggests that applying a uniform correction to the recording results for all stations is feasible and reliable.

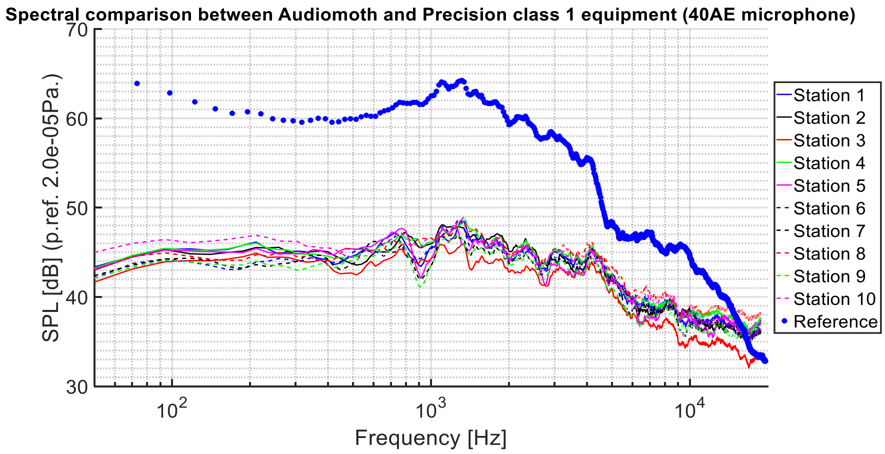


Figure 7. Spectral comparison of AudioMoth loggers vs. Class 1 microphone.

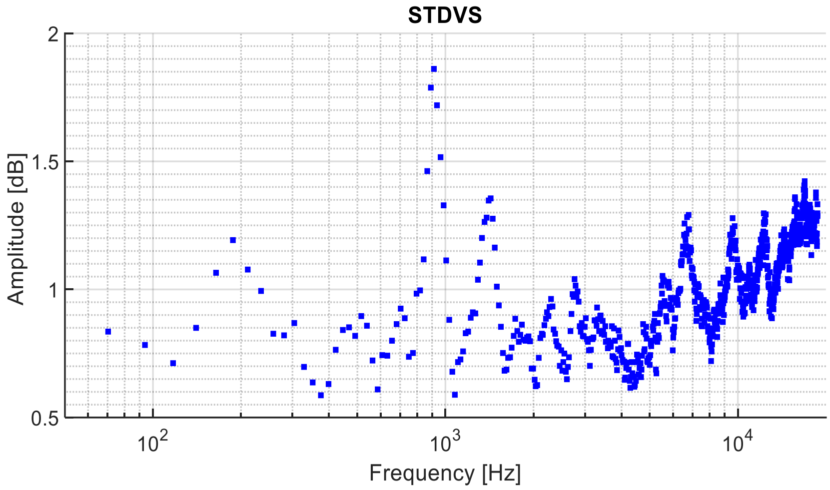


Figure 8. The standard deviation of spectral amplitudes between AudioMoth data loggers.

2.3. Site Measurements and Signal Processing

For covering more areas inside the park with 10 pcs. of loggers available (Figure 9), the measurement process was divided into three days, with each day monitored for a 24-h session (one of these loggers was not properly functioning on the field and it was excluded from the analysis). On the first day, the area with the densest vegetation and nesting zones was covered. On the second day, the sensors were placed primarily along the visitors' pathways. On the final day, the sensors were positioned around the park's perimeter, on the embankment, to directly record intruding noise from traffic, industrial sources, and other human-generated activities. The noise measurements inside and perimetral to the park were done for calibrating and adjusting the noise mapping with real data.

Figure 9 presents locations of the measurement locations inside the Văcărești Urban Wild Park and at the border of it, as well as the primary and secondary roads considered as noise sources in simulations.

The measurement points codification, as presented in Figure 9, represents the day number from 1 to 3 (D1,2,3), the station number from 1 to 9 (S1. . .S9), and the point ID from 1 to 20.

A differentiated filtration of the recorded signals was considered after the normalized difference soundscape index *(NDSI)* calculation. In the context of biological and anthropogenic mixture noise, the study evaluates the combined acoustic environments where natural sounds from biological sources (such as bird vocalizations) coexist with human-made noises (like traffic, industrial activities, or urban infrastructure). For obtaining the

NDSI, with values ranging from −1 to 1, the recorded signal will be computed to quantify the energy present in each band, and the following formula was used:

$$NDSI = \frac{L_{bio} - L_{anth}}{L_{bio} + L_{anth}} \quad (1)$$

where L_{bio} is the sum of the *SPL* values for the corresponding bins to biophonic specter and L_{anth} is the sum of the *SPL* values for the corresponding bins to anthrophony. Values closer to 1 indicate a soundscape dominated by biological sounds and values closer to −1 indicate a soundscape dominated by anthropogenic sounds.

Figure 9. Measurement points placement inside Văcărești Urban Wild Park.

A filtering delimitation will be used in the following ranges for a better interpretation of different noise sources: 13–3000 Hz for anthropic sounds and 3000–10,000 Hz for biological sounds on perimetral measurements; 13–1000 Hz for anthropic sounds and 1000–10,000 Hz for biological sounds measured in the central area of the park; and 13–1250 Hz for anthropic sounds and 1250–10,000 Hz for biological sounds on measurements in radial areas inside the park. In Figure 10 is presented an example of the spectrum for one-hour recording and its correspondent *NDSI* over the recorded time (station no. 8, third day, evening). A predominance of negative values could be interpreted as a prevalence of anthropic noise over the biological one.

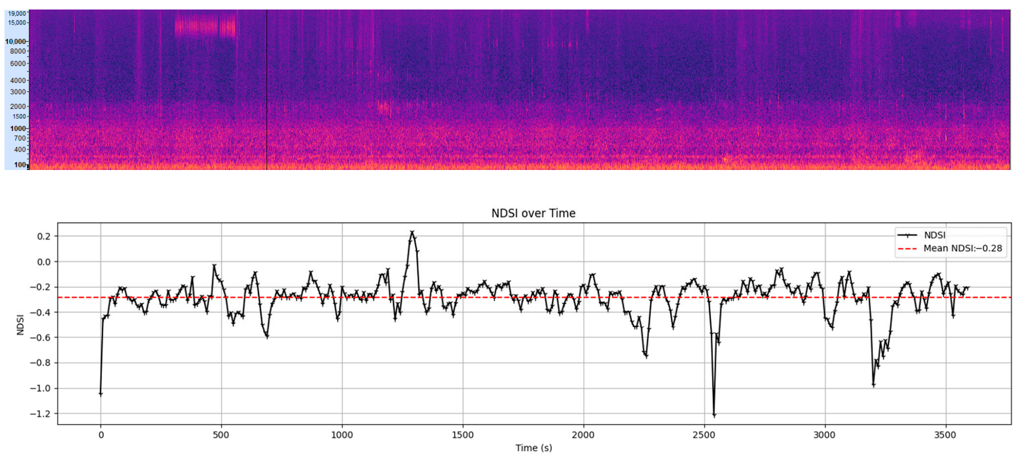


Figure 10. Spectrogram for one-hour measurement (**top**); NDSI over time for one-hour measurement (**bottom**).

For temporal references, the periods from 6:00 to 10:00 AM and 4:00 to 7:00 PM will be considered, as these times correspond to peak traffic noise, which coincides with the main vocalization hours of birds. Table 1 presents the NDSI values calculated on morning and evening period for each station.

Table 1. Mean NDSI.

Mean NDSI						
	Day 1		**Day 2**		**Day 3**	
Station	**Evening**	**Morninig**	**Evening**	**Morninig**	**Evening**	**Morninig**
S1	0.54	0.61	0.59	0.61	0.02	−0.11
S2	0.29	0.15	−0.21	−0.18	−0.35	−0.82
S3	0.55	0.61	0.59	0.61	−0.22	−0.08
S4	0.13	0.12	0.21	0.35	−0.28	−0.22
S5	−0.24	−0.23	−0.33	−0.21	−0.34	−0.16
S6	0.21	0.11	0.34	0.34	0.14	0.12
S7	−0.11	−0.17	0.23	0.27	−0.15	−0.21
S8	0.42	0.39	0.35	0.28	−0.11	−0.15
S9	0.14	0.25	0.21	0.11	−0.33	−0.32

The numerical modeling of the study area was conducted using IMMI (version 2021) [48] noise mapping software, which adheres to the requirements of Directive 2002/49/EC by employing the calculation method from ISO 9613-2. For outdoor scenarios, IMMI supports two methods for calculating sound reflections: the mirror source method and the ray tracing method. The mirror source method becomes highly time-consuming with higher orders of reflections (second-, third-, or fourth-order) when combined with numerous reflecting surfaces. IMMI initially analyzes the desired reflection order and the number of reflectors to determine the appropriate method. For simple projects involving first-order reflections, the mirror source method is used, whereas for higher orders of reflection, the ray tracing method is employed. In this study, second-order reflection was adopted using the ray tracing method. The ray tracing method involves substituting the sound wave with a ray, which is a straight line emitted by the noise source, carrying sound energy that is specularly reflected by the walls, with energy reduction according to the reflection coefficients. The prediction software requires various input data, including land surfaces with their acoustic characteristics, the shape and heights of buildings, and noise power levels of the noise sources. Geospatial vector data of residential or industrial buildings in the analyzed area were modeled with the QGIS software and MapFlow extension. Additionally, the numerical model requires data on humidity and temperature to compute sound wave propagation through the air. Based on the yearly average climate of Romania, a relative humidity of 70% and a temperature of 21 °C were incorporated into the numerical model.

Three scenarios were adopted to simulate potential noise reduction strategies and evaluate the effectiveness of various landscape design methods in reducing noise within the park. The first scenario consists of flat land with the current afforestation conditions situated between the traffic zones and the park. In the second scenario, a 10-m-high earth embankment was modeled according to the actual situation in the field, with the current afforestation conditions, presenting the actual situation. In the third scenario, afforestation with spruce and fir vegetation was considered on the exterior slope of the embankment.

Figure 11 presents the maps with streets modeled as linear noise sources, for which an acoustic power level was defined and calibrated based on the measured values at the upper boundary of the embankment. The calibration procedure involved adding or reducing the number of vehicles (both light and heavy) or increasing or decreasing the running speed until the simulated noise values matched the measured ones.

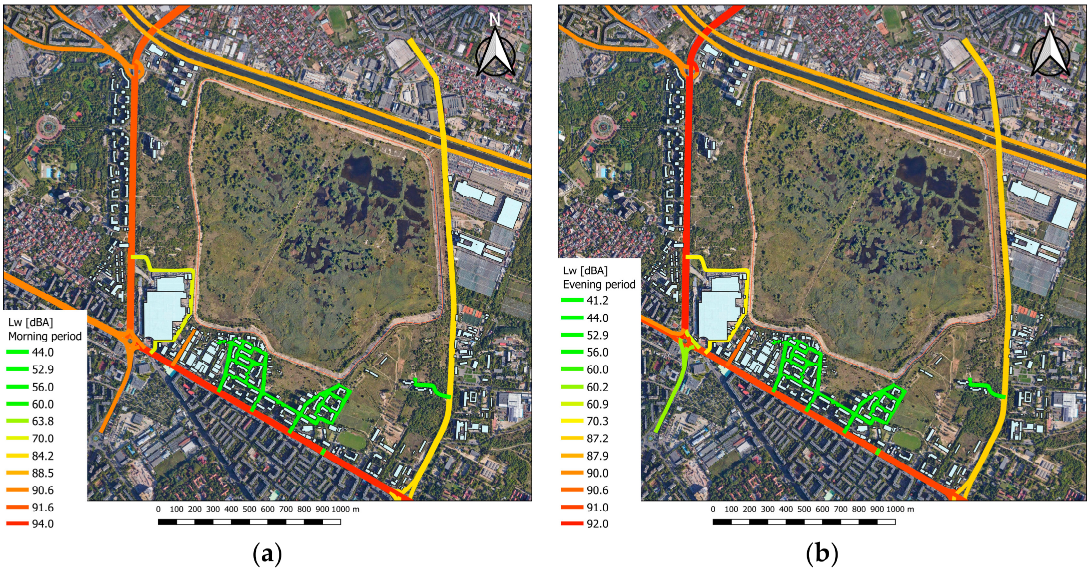


Figure 11. Streets as linear noise sources–Sound power level [dBA] ((**a**) morning; (**b**) evening).

Thematic layers can significantly influence noise propagation in simulation software mapping by affecting how sound travels through and interacts with different elements of the environment. Different types of vegetation and terrain configurations can act as barriers to or absorbers of sound waves. For example, dense forests or thick vegetation can attenuate noise by absorbing sound energy, whereas open fields or hard surfaces like concrete can reflect sound and increase propagation.

Vegetation plays a primary role in sound propagation within an environment, benefiting all species for purposes such as communication, breeding, concealment, and hunting [49]. A detailed vegetation mapping was done by the Văcărești National Park Foundation, as presented in Figure 12. Such a map, with its acoustic characteristics (excess attenuation), will be overlaid and used in software simulations to obtain the noise mappings. The height of the vegetation areas was determined using a DJI 3Pro drone. During these activities, a drone was used to capture images from hard-to-access areas, which are noisy and could disturb wildlife. However, using an aerial drone is essential for creating a detailed topographic map of Lake Văcărești, providing precise data necessary for acoustic studies. The previously used SRTM images, with a 30-m resolution, lack the detail needed for accurate contour analysis. The drone enables the collection of high-resolution topographic data, allowing precise three-dimensional modeling of the terrain and vegetation, which is crucial for understanding sound propagation. To minimize disturbance to the park's birdlife, especially in Văcărești Park, a low-noise drone is recommended, ensuring data collection without affecting the natural behavior of sensitive species.

For Scenario 3, the thematic vegetation layer was integrated into all peripheral areas around the park, incorporating spruce and fir type vegetation modeled at a height of 10 m (Figure 13). The existing vegetation exceeding 16 m in height was retained in the simulation.

Thematic layers with correspondent surface materials (e.g., earth, grass, water) can affect noise propagation by influencing sound reflection and absorption. Hard acoustic surfaces like water tend to reflect sound waves, while softer surfaces like grass or earth can absorb sound to varying degrees. Terrain elevation and contour layers play a crucial role in noise propagation. Valleys and slopes can alter the path of sound waves, causing them to diffract, reflect, or concentrate in specific areas depending on the topographical features. Layers depicting urban features such as roads and industrial zones can emit significant noise sources. These features can introduce continuous noise patterns that propagate differently based on their proximity to sensitive areas like parks or residential zones. Thematic layers indicating wind patterns and atmospheric conditions (e.g., temperature, humidity) can influence noise propagation by affecting sound speed and direction. In simulation software mapping, as IMMI (Version 2021) is used for this study, these thematic layers are integrated to model and predict how noise propagates across a geographic area. Adjustment of these layers can be simulated in scenarios to evaluate the effectiveness of noise mitigation strategies, such as adding vegetation barriers, in reducing noise exposure in sensitive habitats or residential areas. The numerical model incorporates environmental data such as humidity and temperature to simulate sound wave propagation in the atmosphere.

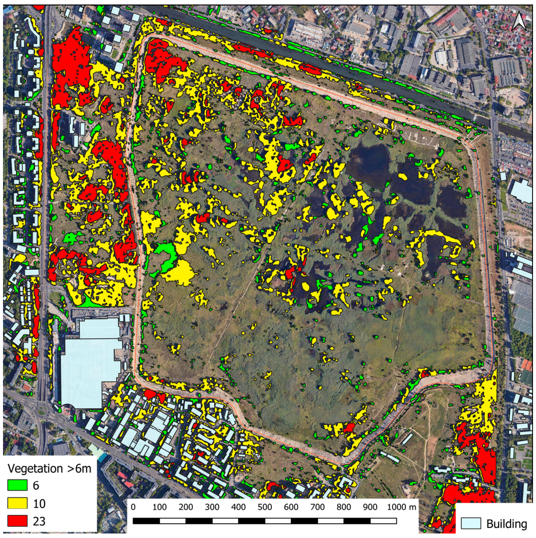


Figure 12. Vegetation layer–vegetation heights [m].

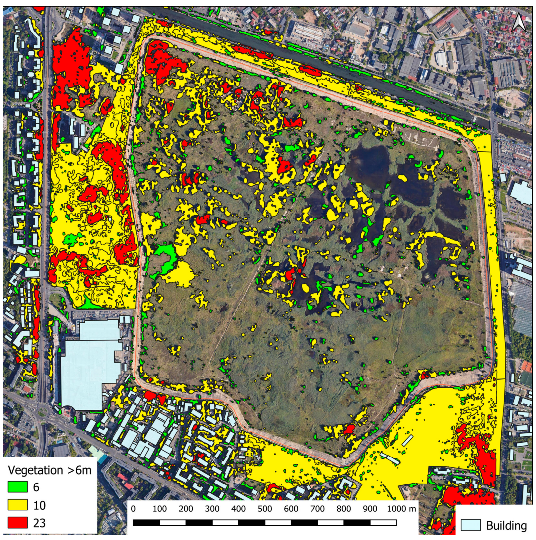
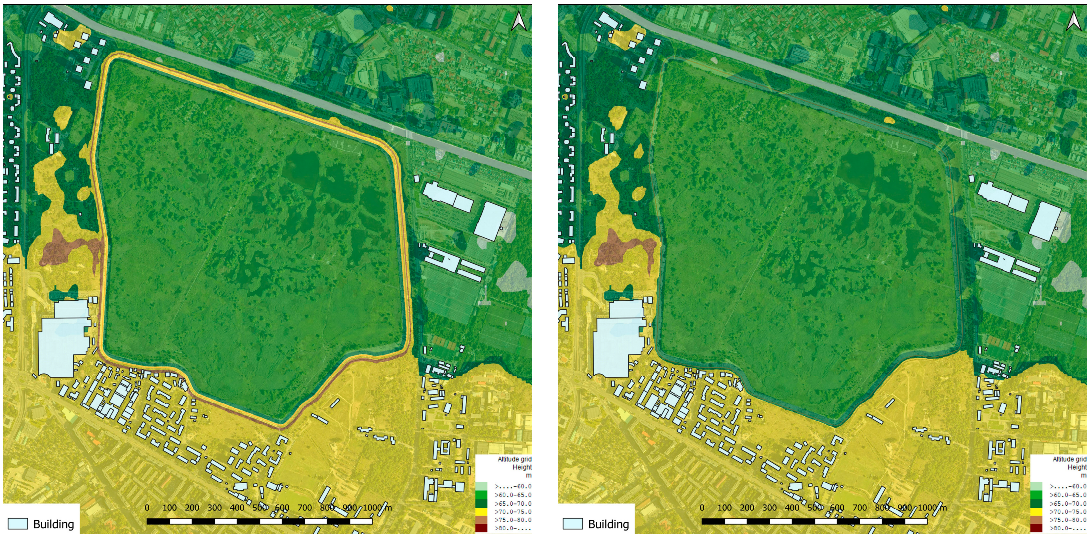


Figure 13. Vegetation thematic layer Scenario 3.

QGIS software 3.18.2 [50], formerly Quantum GIS, is a free and open-source geographic information system software application widely used for viewing, editing, analyzing, and mapping spatial data. In QGIS, layers such as vegetation are often represented with specific attributes, in this case height information. This height data is derived from Mapflow, a plugin of QGIS that processes orthophotographs (orthophoto imagery) to extract detailed geographic data, allowing accurate measurements and analyses of features like vegetation height. After QGIS processing to the vegetation layer, an additional attribute is added with sound absorption where the values are taken from reference [51].

Based on the contour lines and altitude points, the height regime calculated within IMMI for acoustic propagation considers acoustic screening and divergence. IMMI calculates how these barriers influence the spread of sound from noise sources to specific receivers (such as sensitive habitats) and calculates the divergence of sound waves based on factors like distance and environmental conditions, which affect how loud or attenuated the sound will be at different points in the modeled area.

Contour lines, or elevation contours, represent lines on a map connecting points of equal elevation above a reference datum (such as sea level). These contour lines are generated with open-source plugins like SRTM Downloader from QGIS which were corrected by using accurate elevation data sourced from Google's database. Inside the park the terrain level is constant with the height which varies with a maximum of 1 m compared to the water table level or with the Dâmbovița River situated in the north part of the park. The water table level is situated at 64 m above sea level. In Figure 14 the altitude maps for each scenario weres computed in IMMI software using the contour lines generated in QGIS software.



(**a**) (**b**)

Figure 14. Altitude regime considered in simulations, with ((**a**) Embankment around the park (**b**) no) and without embankment (**b**).

In the southern part, the streets have an elevation of 80 m above sea level, while in the northern part is at 65 m, the same level as inside the park, so the traffic noise has a different propagation path, depending on the incidence zone. The embankment has an effect only on the lower zone from the northern part of the park, where direct sound propagation is restricted by the embankment elevation.

Residential and commercial buildings, as well as others with height attributes, are considered, along with streets where the number of cars and heavy vehicles during morning and evening periods, and their corresponding speeds at different times of day, have been defined. Vegetation acts as a natural sound absorber, with its effectiveness influenced by a variety of factors including species, density, arrangement, and environmental conditions. Integrating vegetation into urban planning and noise mitigation strategies can provide significant acoustic and ecological benefits. Vegetation can absorb, reflect, and scatter sound waves, leading to noise reduction and improved sound quality.

Harris, 1996 [52] introduces the term, "excess attenuation of sound propagation due to spherical divergence," without taking into account scattering or other factors. DeLoach, 1975 [53] extended the research in by also taking into account other influential factors like refraction, altitude, ground attenuation, effects of dust and fog, and turbulences. They used dB/100 m as a unit for excess sound attenuation, representing the additional reduction in sound intensity beyond what is expected from the basic spreading of sound waves as they travel through a medium. Excess sound attenuation was studied by Aylor, 1972 [51] for corn (*Zea mays*), pine (*Pinus resinosa*), hemlock (*Tsuga canadensis*), hardwood brush (*Vacciniumc orymbosum*, *Clethra alnifolia*, *Rhododendron nudiflorum*, *Acer rubrum*, *Alnus rugosa*) and different soils. In beech and ash tree forests, Martens, 1981 [54] observed that excess attenuation was at least 10 dB/100 m when the receiver was at the same height as the source (1.2 m), and at least 5 dB/100 m when the receiver was at 3.9 m, with even higher attenuation in the 1/3-octave bands. For spruce–fir forests, he found that the excess attenuation was at least 10 dB/100 m with the receiver at 1.2 m, and 7 dB/100 m with the receiver at 3.9 m. Depending on the nature of the ground, if it is soft or hard, its reflections interfere with incident sound, causing either attenuation or amplification [55]. Regarding the noise abatement properties of a vegetation belt on a 44% slope, Karbaiei et al., 2015 [56] conducted a study demonstrating that a mixed surface of conifers and broadleaves results in a 40 dB attenuation over a 100-m vegetation belt. Such an extensive vegetation zone cannot be implemented in narrow areas specific to urban zones. The effort to standardize noise calculation algorithms in Europe was achieved with ISO 17534-3 [57] and ISO 9613-2 [58], standards also used by IMMI prediction software in this study. The sound absorption of vegetation is calculated by IMMI software by defining an area that causes a flat rate of attenuation due to vegetation when sound propagates through.

In the present study, it was used for the common reed (*Phragmites australis*), with an attenuation value of 5 dB/100 m for weeping willow (*Salix* spp.), Ailanthus altissima and Prunus spp., a value of 7 dB/100 m for common walnut (*Juglans regia*), spruce and fir 10 dB/100 m at 1.2 m high. A 3 dB/100 m was applied for excess attenuation for steppe herbs areas. The ground effect, as applied by ISO 9613, employs a frequency-dependent algorithm to calculate, which largely varies with frequency. This method considers the reflection properties of the ground between the sound source and receiver and is defined by the parameter G (G = 0: hard reflecting ground or water surface; G = 1: porous, absorbing ground).

3. Results

The data loggers were placed in various locations in order to cover the most representative habitats, i.e., those which contain dense vegetation and water zones, and are most habituated by birds, animals and insects.

Figure 15 presents the noise values obtained for the scenario where the embankment is not present, providing a clear understanding of how the absence of such a physical barrier influences noise distribution across the park. The data reveal that the main noise sources are concentrated in the northeast part of the park, an area likely exposed to the highest levels of traffic activity from adjacent roads. This region experiences significant noise pollution, particularly during the evening period when traffic intensity increases, leading to noise levels that are approximately 3 dB higher compared to other times of the day. This increase highlights the sensitivity of the park environment to fluctuations in traffic volume, especially during peak hours.

Within the park, the area surrounding the lake is particularly affected, with noise levels exceeding 57 dBA. This is a critical observation, as this region is characterized by a high density of birds, suggesting that the elevated noise levels could have adverse effects on local wildlife. The presence of such significant noise in a biologically sensitive area underscores the importance of implementing effective noise mitigation strategies to preserve natural habitats.

In contrast, the southern part of the park experiences a lower impact from traffic noise. This reduction is attributed to two main factors: the presence of buildings that act as a physical screen, and the greater distance between the street and park boundary. The combined effect of these elements creates a buffer zone that helps to attenuate the noise before it reaches the interior of the park, thereby preserving the silence of this area.

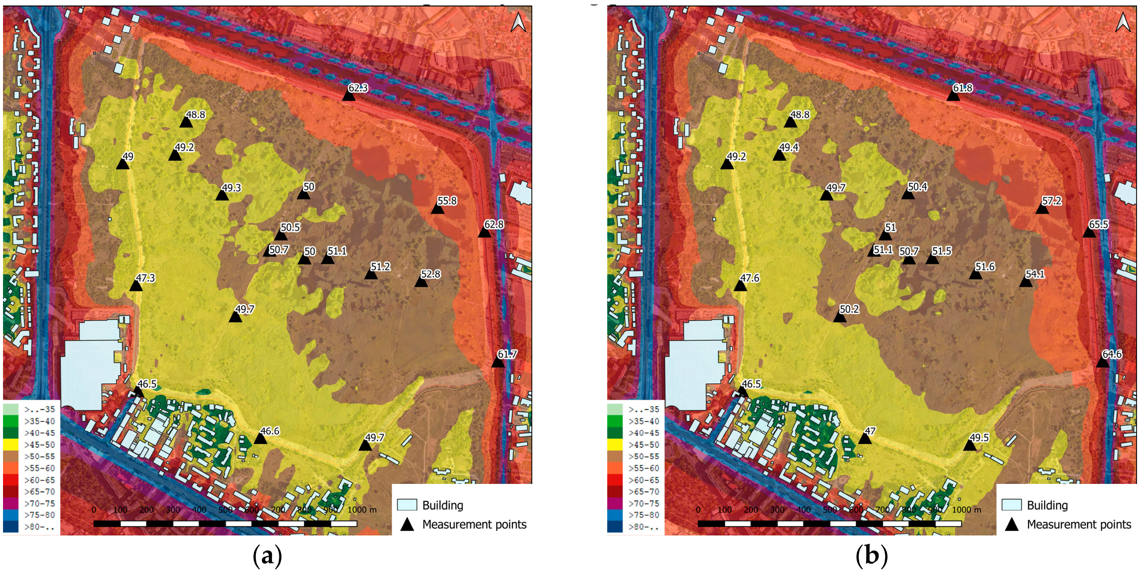


Figure 15. Traffic noise map Scenario 1—the actual situation with afforestation and no embankment: (**a**) morning, and (**b**) evening.

The western part of the park benefits from a unique terrain profile, where a mound of earth, with a maximum height of 10 m, serves as a natural sound barrier between the main boulevard and the park. This topographical feature plays a crucial role in reducing noise levels, and its effectiveness is further enhanced by the relatively dense vegetation in this region. The vegetation not only screens the noise but also absorbs sound waves, contributing to a quieter environment. The combination of these natural barriers creates a significant noise reduction, making the western section of the park one of the quieter areas. The noise levels resulting from the simulation are presented numerically at the same positions where actual noise measurements were conducted. This approach provides a comprehensive comparison between the simulated and real-world data, offering valuable insights into the effectiveness of current landscape features in noise mitigation.

Figure 16 presents the actual situation in the park, where both the afforestation and the embankment are in place. The figure provides a comparative analysis of the measured and simulated noise values, with numerical data presented to highlight the differences and similarities. Upon examination, it is evident that the simulated noise values at the park's borders closely align with the measured ones, indicating that the simulation accurately captures the noise levels in these peripheral areas. This suggests that the embankment, along with the existing vegetation, effectively screens noise from external sources, particularly from surrounding traffic.

However, inside the park, the comparison reveals that, at most measurement points, the actual noise levels are higher than those predicted by the simulation. This discrepancy can be attributed to several factors not accounted for in the simulation. A significant factor is the noise generated by the park's wildlife, including birds, which are particularly abundant in some areas. These natural sources of noise were not included in the simulation model, leading to an underestimation of the actual noise levels in these regions.

Interestingly, there are three specific locations (D1_S7_P6, D2_S2_P9, D1_S4_P4) where the simulation predicts higher noise levels than those recorded in the field. This anomaly can be explained by the presence of thick trees at these stations, which were not fully accounted for in the simulation. These trees likely provide additional noise screening, reducing the actual noise levels more than the simulation anticipated. Furthermore, the dense vegetation in these areas, which plays a significant role in sound attenuation, could not be accurately modeled in the simulation, leading to discrepancies between the predicted and observed data.

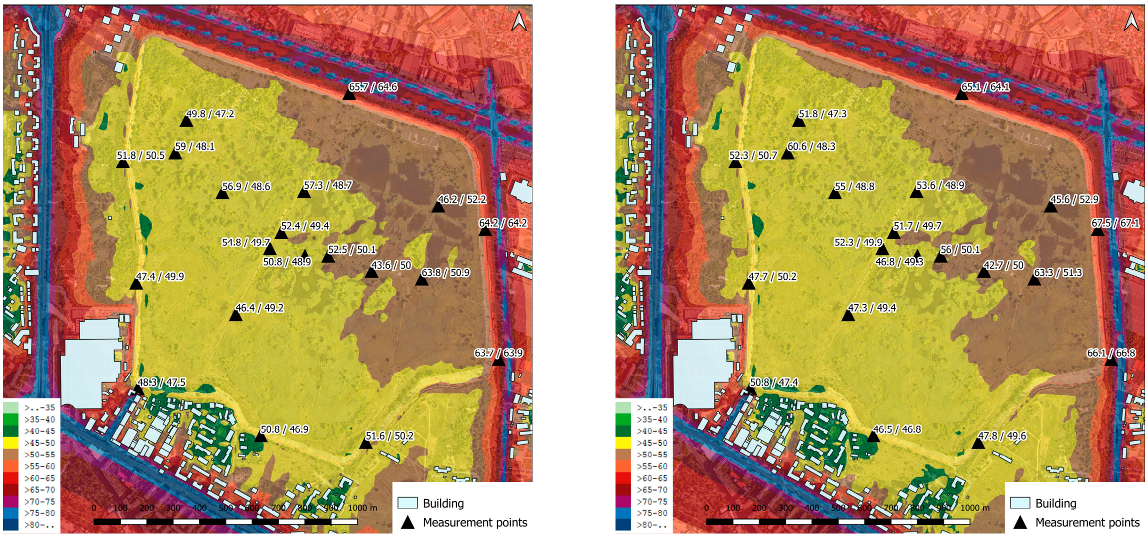


Figure 16. Traffic noise map Scenario 2—the actual situation with afforestation and embankment: (**a**) morning, and (**b**) evening (measured values/simulated values).

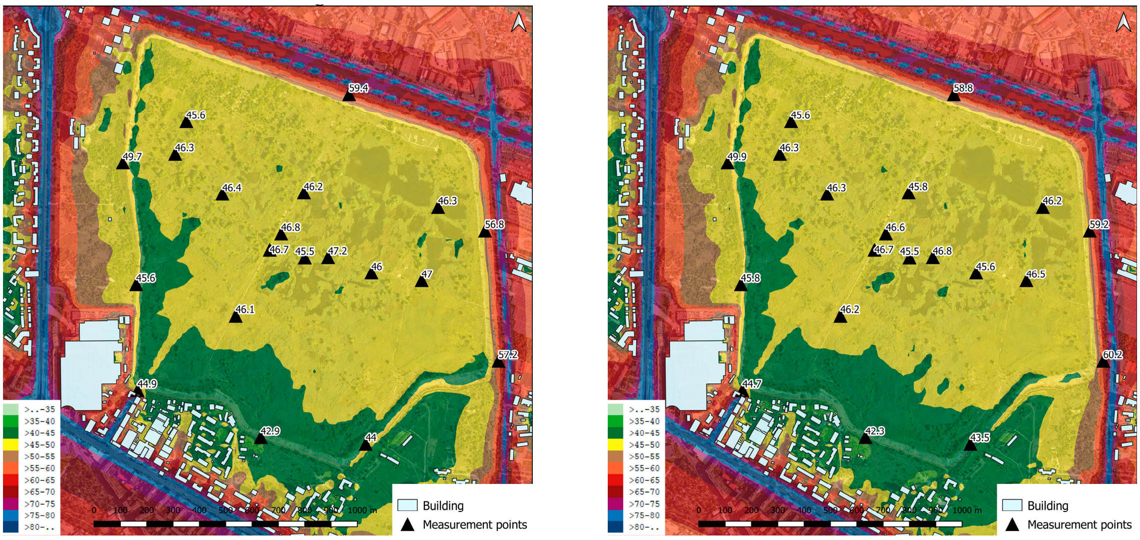
When compared to Scenario 1, the presence of the embankment shows a marked impact on noise propagation, particularly in the northeast part of the park. In this region, a significant reduction in noise levels, with a drop of almost 5 dBA, is observed. This reduction is primarily due to the embankment's role in screening noise from external sources, effectively acting as a barrier that limits noise transmission into the park. This is a crucial finding, as it demonstrates the embankment's effectiveness in mitigating noise pollution, especially in areas most exposed to traffic noise.

In contrast, in other parts of the park, the noise levels remain relatively unchanged compared to Scenario 1. This can be attributed to the diffraction phenomenon, where sound waves bend around obstacles like the embankment. As a result, while the embankment significantly reduces noise in certain areas, its impact is less pronounced in others where sound diffraction allows noise to spread. Nonetheless, the overall effect of the embankment, combined with the existing vegetation, contributes to a noticeable improvement in the park's soundscape, making it a quieter environment for visitors and wildlife alike.

Figure 17 presents the results of Scenario 3, which explores the impact of incorporating dense vegetation around the park. The results demonstrate the significant effectiveness of this natural barrier in mitigating noise pollution within the park. The dense vegetation acts as a sound barrier, leading to a substantial reduction in noise levels across all measurement points within the park, with recorded values consistently around 46 dBA. This uniformity in noise reduction suggests that the vegetation effectively screens sound energy, thereby creating a quieter and more serene environment throughout the park. Additionally, the dense foliage plays a crucial role in absorbing noise, further contributing to the significant reduction in sound levels.

Moreover, the analysis of the points situated at the park's border reveals an impressive noise reduction of nearly 6 dB. This reduction is particularly noteworthy because a decrease of 6 dB represents a significant improvement in ambient noise levels. The effectiveness of vegetation in reducing noise highlights the potential of using natural elements as sustainable solutions for urban noise management.

These findings are further supported by the data presented in Table 2, which provides a comprehensive comparison of simulated noise levels at various measurement points for each scenario. The table illustrates the relative performance of different noise mitigation strategies, with Scenario 3 showing the most pronounced reduction in noise levels. This suggests that strategic planting of dense vegetation could be a key component in urban planning, particularly in areas where noise pollution is a concern.



(**a**) (**b**)

Figure 17. Traffic noise map Scenario 3—afforestation with spruce and fir vegetation and embankment: (**a**) morning, and (**b**) evening.

Table 2. Noise values at each point for each scenario and averaged on all points [dBA].

	Point	**Morning**			**Evening**		
		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
inside park	D1_S1_P1	49.2	48.1	46.3	49.4	48.3	46.3
	D1_S2_P2	50.7	49.7	46.7	51.1	49.9	46.7
	D1_S3_P3	52.8	50.9	47.0	54.1	51.3	46.5
	D1_S4_P4	55.8	52.2	46.3	57.2	52.9	46.2
	D1_S6_P5	48.8	47.2	45.6	48.8	47.3	45.6
	D1_S7_P6	49.7	49.2	46.1	50.2	49.4	46.2
	D1_S8_P7	49.3	48.6	46.4	49.7	48.8	46.3
	D1_S9_P8	51.1	50.1	47.2	51.5	50.1	46.8
	D2_S2_P9	51.2	50.0	46.0	51.6	50.0	45.6
	D2_S6_P10	50.0	48.7	46.2	50.4	48.9	45.8
	D2_S8_P11	50.5	49.4	46.8	51.0	49.7	46.6
	D2_S9_P12	50.0	48.9	45.5	50.7	49.3	45.5
	Avg. inside park	51.2	49.6	46.4	52.0	49.9	46.2
park border	D3_S1_P13	46.5	47.5	44.9	46.5	47.4	44.7
	D3_S2_P14	61.7	63.9	57.2	64.6	66.8	60.2
	D3_S3_P15	49.0	50.5	49.7	49.2	50.7	49.9
	D3_S4_P16	62.8	64.2	56.8	65.5	67.1	59.2
	D1,2,3_S5_P17	62.3	64.6	59.4	61.8	64.1	58.8
	D3_S6_P18	46.6	46.9	42.9	47.0	46.8	42.3
	D3_S8_P19	47.3	49.9	45.6	47.6	50.2	45.8
	D3_S9_P20	49.7	50.2	44.0	49.5	49.6	43.5
	Avg. park border	58.3	60.2	54.1	60.2	62.1	55.5

4. Discussion

To gain a comprehensive understanding of the noise reduction strategies within the park across the different scenarios, average noise levels were calculated both inside the park and at its border. The results highlight the effectiveness of specific landscape design methods in managing noise pollution in natural reserves. The introduction of an embankment (Scenario 2) shows a modest yet noticeable noise reduction inside the park, with a decrease of 1.6 dB in the morning and 1.1 dB in the evening. This suggests that embankments can serve as a basic noise mitigation strategy, providing some relief from external noise sources.

However, the addition of afforestation, specifically with spruce and fir vegetation, significantly enhances noise reduction efforts. In Scenario 3, this combination leads to a substantial noise reduction of 4.8 dB in the morning and 5.8 dB in the evening compared to Scenario 1. This demonstrates the critical role of dense vegetation in absorbing and screening noise, making it an essential strategy in the design of natural reserves aimed at preserving tranquility and protecting wildlife from noise pollution.

At the park's border, the results show that the embankment alone can slightly increase noise levels by 1.9 dB due to sound reflections. Yet, when combined with afforestation, there is a marked reduction in noise by 4.2 dB in the morning and 4.7 dB in the evening compared to Scenario 1. This outcome underscores the importance of integrating natural barriers, such as vegetation, with structural features like embankments to effectively manage noise levels both within and around natural areas.

These findings suggest that a holistic approach, combining structural elements like embankments with strategic afforestation, is most effective in managing noise in natural reserves. Such strategies not only reduce noise pollution but also preserve the natural soundscape, which is vital for the well-being of both wildlife and visitors. The results of this study, particularly those from the third scenario, provide valuable insights that authorities can use to implement effective noise reduction techniques and protect natural areas. By applying these findings, authorities can enhance conservation efforts and ensure a quieter, more sustainable environment in urban wildlife reserves.

5. Conclusions

This study highlights the significant impact of anthropogenic noise on the biodiversity of Văcărești Park, an urban natural park in Bucharest, Romania. By combining on-site measurements with software simulations and laboratory calibration, the research aims to develop a fast and cost-effective method for assessing anthropic noise impact on the biophonic environment of a wild urban park. This approach addresses the shortcomings of existing noise maps, which primarily focus on human communities rather than biodiversity. The intended goal of creating a holistic and integrative evaluation method for reducing the impact of traffic noise on wildlife in urban wild parks has been achieved. The proposed strategies, such as planting vegetation and constructing earthen embankments, were thoroughly tested through software simulations, demonstrating their effectiveness in noise reduction. Specifically, the spruce and fir afforestation on the 10-m embankment was shown to maintain noise levels inside the park's biosphere below 55 dB, a threshold beneficial for bird communication and reduced sound masking, outperforming simple afforestation without an embankment. The outcomes of this research validate the proposed method and confirm its utility in guiding the implementation of measures aimed at enhancing biodiversity conditions. Moreover, this study lays a solid foundation for long-term monitoring and on-site evaluation of these interventions, ensuring that the intended environmental benefits are realized and maintained over time.

This study highlights the significant impact of anthropogenic noise on the biodiversity of Văcărești Park, an urban natural park in Bucharest, Romania. By combining on-site measurements with software simulations and laboratory calibration, the research aims to develop a fast and cost-effective method for assessing anthropic noise impact on the biophonic environment of a wild urban park. This approach addresses the shortcomings of

existing noise maps, which primarily focus on human communities rather than biodiversity. The study aims to provide an evaluation method for holistic, integrative approaches to reducing the impact of traffic noise on wildlife in an urban wild park, without delving into the specific impacts of noise on the perception and communication of individual species. From this point of view, the study reached its goal, offering a mixed method which combines numerical simulations with on-file measurements for obtaining a fast evaluation of anthropic noise impact on the wild soundscape. The study underscores the importance of managing traffic noise and its propagation pathways to improve the park's soundscape. Proposed strategies include planting vegetation and constructing earthen embankments, which were tested through software simulations to identify effective solutions for noise reduction. A spruce and fir afforestation on the 10 m embankment ensures a noise level inside the park's biosphere less than 55 dB, taken as reference for good bird communication and less sound masking, compared to simple afforestation without embankment. The outcomes of this research will guide the implementation of measures to enhance biodiversity conditions and serve as a foundation for long-term monitoring and on-site evaluation of these interventions.

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