Asia-Pacific Journal of Science and Technology :Volume :25 .Issue :04 .Article ID :.APST-25-04-10. Research Article

APST

Asia-Pacific Journal of Science and Technology

https//:www.tci-thaijo.org/index.php/APST/index

Published by the Research and Graduate Studies,
Khon Kaen University, Thailand

Sound ecology indicators applied to urban parks: a preliminary study

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Received 6 June 2020
Revised 3 September 2020
Accepted 8 October 2020

Abstract

In soundscape ecology, different acoustic indices have been developed to describe the acoustic environment, mainly in natural areas. Avian species are among the sources of natural sounds that positively influence the human perception of a natural environment. However, the acoustic environment is rather complex due to the contemporary presence of different sources, leading to the difficult task of discriminating these sources in audio data. This task is even more essential in medium-large urban parks, as they are often exposed to road traffic noise produced by surrounding roads and to anthropogenic sounds due to people using the park for different purposes. Such non-natural sounds can deteriorate the perceived soundscape quality of the park and, therefore, reduce its potential restorative function. The aim of this preliminary study is to evaluate the potential of sound ecology indicators for discriminating the different types of sounds present in medium-large urban parks. For this purpose, two environmental settings were considered: a large urban park surrounded by busy roads and a shrub-dominated area, the latter of which was used as a reference site for natural areas. The two sonic environments were characterized by the presence of different anthropogenic noises, especially in the urban park, and sounds from avian species. Sound ecology indicators, or their combinations, could help identify the urban park areas with higher biophonic activities and, therefore, the areas that offer greater relief and restorative value. Such information can be helpful for improving the use of parks by directing users towards areas with features more conducive to their enjoyment and consistent with their expectations.

Keywords: Sound ecology indicators, Urban parks, Sound source discrimination

1. Introduction

The increasing intrusion of human activities into ecosystems during recent decades has produced highly fragmented natural environments [1], causing the endangerment and depletion of many species [2]. Regarding the acoustic environment, the introduction of the "soundscape" concept [3] gave great attention to its perception in a specific context and, therefore, highlighted the relationships between individuals, activities, and locations. Thus, soundscapes have undergone further development as noise regulators, and many studies have shown a strong relationship between soundscapes and public nuisances [4] as well as the perception of living environments [5]. The use of soundscapes is extremely interesting when applied to urban parks, as these areas have a vital role in offering persons close contact with nature and its restorative properties [6-9]. Unfortunately, the presence of noisy areas, such as roads, industrial parks, and other areas that often surround urban parks, represents a serious hindrance. The presence of quiet areas is also correlated with the size of parks, due to the effect of distance in reducing traffic noise intrusion from surrounding roads, and the presence of natural biodiversity [10].

European Directive 2002/49/EC for the assessment and management of environmental noise [11] prompted the promotion of the conservation and improvement of environmental quality in urban parks. For this reason, the number of studies applying the soundscape approach to evaluate the acoustic environment in urban green spaces is increasing in the literature [6,12-17]. For example, a study found that exposure to road traffic noise below 50 dB(A) during the daytime can be characterized as a good soundscape [6]; others showed that an improvement in the quality of a green area soundscape can be achieved by masking anthropogenic sounds by natural sounds, such as those produced by running water [18,19]. This means that the presence of natural sounds in city parks is extremely important in shaping soundscapes, as many studies have reported that annoyance is also influenced by the presence of sounds not belonging to a specific environment [20,21].

The sounds that might be present in an environment are, usually, distinguished as biophony (non-human biological sounds), geophony (sounds from water and wind), and anthrophony (human-produced noises) [22,23]. Avian species are among the sources of natural sounds that positively influence the perception of a natural environment. Soundscape ecology, defined as the science of sound in the landscape [24], is an emerging research field that develops methodologies and acoustic indices focused on discriminating different types of sound sources and enabling analysis of the acoustic environment. However, the acoustic environment is rather complex due to the contemporary presence of different noise sources, leading to the difficult task of discriminating them in audio data. Due to these multifactorial characteristics, evaluations based on a single index describing a specific feature may be insufficient and misleading.

The aim of this preliminary study is to evaluate the potential of sound ecology indicators to discriminate the different types of sounds present in medium-large urban parks. These indicators have already been applied in urban contexts with interesting results [25]. The description of this study is structured as follows. Section 2 reports the experimental protocol for the field recordings as well as the analyses and computation of the six indices examined. In particular, two environmental settings were considered: a large urban park surrounded by busy roads and a shrub-dominated area, the latter of which was used as a reference for natural areas. The two sonic environments were characterized by the presence of different anthropogenic noises, especially in the urban park, and sounds from avian species. Section 3 describes the results obtained, confirming that sound ecology indices can be used to identify acoustics related to distinct activities, for example, activities that occur at dawn (bird vocalizations) and at night (nocturnal animals) or those occurring in different environments. Section 4 addresses how sound ecology indicators, or their combination, could help identify areas within urban parks that have higher biophonic activities and, therefore, offer potentially greater relief and restorative value. Such information can be used to improve the use of the park by directing users towards areas with features more conducive to their enjoyment and consistent with their expectations.

2. Materials and methods

The studied area is a large peri-urban park in northern Milan (Italy), characterized by wooded land rich in biodiversity and exposed to different sources and degrees of anthropogenic disturbances, such as road traffic noise and artificial light. The sound recordings analysed in this study were taken in May, early in the morning (7:00 a.m.), when the singing activity of birds is at its peak, making it is easy to detect their presence and to study their singing dynamics in natural light conditions.

A Soundscape Explorer Terrestrial (SET) recorder unit was used for this analysis. This device is a sound and meteorological data recorder for terrestrial environments, providing real-time acoustic complexity index (ACI) computation. It is equipped with two microphones, an electronic control board, a full set of meteorological sensors (for recording pressure, temperature, relative humidity, and ambient light) and a rechargeable lithium battery pack, all contained in a waterproof plastic case. One of the two microphones of the recorder targets low frequencies and acquires data in the sonic range (up to 24 kHz), and the other microphone targets high frequencies and acquires data in the sonic and ultrasonic ranges.

The recording period and frequency can be written and stored on an SD card according to a predefined schedule. Figure 1a shows the position of the SET recorder inside the park, located near the Bruzzano cemetery, in a suburban context. The land coverage in this area is quite green, with widespread presence of roads (ranging from local roads within green areas to main arterial roads), activities and residential areas. The recording analysed in this study was taken at site 1 (denoted as “UP” hereinafter), where the SET recorder was mounted on a tree at a height of five metres, as shown in Figure 1b. The recorder position is approximately 90 m from a peri-urban arterial road with continuous road traffic noise emission; more specifically, the daily mean traffic flow is approximately 22000/24000 vehicles, while the traffic flow during sound recordings is approximately 1500 vehicles per h; the estimated mean traffic speed is approximately 50-60 km/h, with very rare congested flow events.

The reference site was located in a natural shrub-dominated area, denoted as “NB” hereinafter, and the recordings were taken early in the morning in May.

In both environments, the recordings were made when there was no rain and wind speeds were less than 5 m/s.

(A) (B)

Figure 1 (A) Location in the park selected for sound recording (site 1) from Google Earth; (B) the installation of the recording instrument.

2.1 Analysis and index computation

The analysis and computation of the sound ecology indices were performed in the "R" environment, version 3.5.1 [26]. In particular, Fast Fourier Transform (FFT) was computed by the function *spectro* available in the R package "seewave" [27], with frequency boundaries of 100 Hz and 24 kHz and computation based on 1024 points. This setting corresponds to a frequency bin of FR = 46.875 Hz and, therefore, a time resolution TR = 1/FR = 0.0213 s. All the indices presented in this paper were computed using the R package "soundecology" [28], except the dynamic spectral centroid (DSC), for which a script run in the R environment was specifically developed.

Some of the indices are the result of the application of the concept of soundscape ecology, which tends to differentiate between the relative contributions of biophony, geophony and anthrophony. A simplified approach consists of splitting the spectral components into two main intervals:

(1) The frequency region between 0.1-0.2 and 2 kHz, corresponding to mechanical sources (anthrophony); and

(2) The frequency region between 2 and 8 kHz, corresponding to the frequencies of animal activity (biophony).

Geophonies, i.e., natural noises such as rain and wind, tend to spread over the whole spectrum but concentrate at lower frequencies [29]. The abovementioned ranges may be slightly artificial, as animals may produce sounds below 2 kHz and above 8 kHz, especially in tropical habitats.

2.1.1 Dynamic spectral centroid (DSC)

The dynamic spectral centroid is based on the concept of the gravity centre of a spectrum reported in [30,31] and represents a measure of the spectral content or timbre of the soundscape [31-33]. It is calculated according to the following formula for the spectral centroid (SC) [34]:

$$SC = \frac{\int_0^{dt} f p^2(f) df}{\int_0^{dt} p^2(f) df} \quad [\text{Hz}] \qquad (1)$$

where f is the frequency and $p(f)$ is the corresponding sound pressure; the latter value is squared because it has positive (air compression) and negative (air rarefaction) values. To obtain the dynamic spectral centroid (DSC), the entire sound clip was divided into equal time units with a duration (dt) of 100 ms, and for each of these units, the SC was computed. The DSC combines both spectral and temporal analysis to reveal the composition of sound events and background sounds.

2.1.2 Acoustic complexity index (ACI)

The acoustic complexity index [35] was derived to provide a direct quantification of the singing activity of birds by processing the sound spectrogram, divided into temporal steps and frequency bins, of the recording. In its original formulation, the ACI measures the absolute difference of two subsequent intensities, $d_k=|I_k-I_{(k+1)}|$, in temporal step j and within a single frequency bin, with the latter determined by the number of points employed to compute the FFT. In this study, the frequency range was from 100 Hz to 24 kHz.

Adding all the dk in the first temporal step (j) of the recording, we obtain [36]:

$$D = \sum_{k=1}^{n} d_k \text{ with } j = \sum_{k=1}^{n} \Delta t_k \text{ and } n \text{ the number of } \Delta t_k \text{ in } j \quad (2)$$

To compare recordings from different settings, D is normalized by dividing by the sum of the intensity values obtained in j:

$$ACI = \frac{D}{\sum_{k=1}^{n} I_k} \quad (3)$$

This index estimates the number of bird vocalizations (biophonic content) and is based on the strong time modulation of intensities typical in birdsongs. Environmental noise due to cars passing by or airplanes flying over has rather slow intensity variation and, therefore, has no or only partial contribution to the index.

2.1.3 Acoustic diversity index (ADI)

The acoustic diversity index (ADI) [24,37] is calculated by dividing the spectrogram into bins and taking the relative signal in each bin above a threshold. The ADI is the result of applying the Shannon index, H, [38-40] to these bins. Higher values of this index should be interpreted as evenness among the signals. The Shannon index is described as:

$$H = -\sum_{i=1}^{S} p_i log(p_i) \quad (4)$$

where p_i is the proportion of signals belonging to the i^{th} bin in the spectrogram and S is the number of different types of signals in the dataset of interest. For example, the species richness of a dataset is the number of different species in the corresponding species list. Then, H quantifies the uncertainty in predicting the species identity of an individual that is taken at random from the dataset.

2.1.4 Acoustic evenness index (AEI)

The AEI is calculated by dividing the spectrogram into bins and considering the relative signal in each bin above a threshold. The AEI is the result of applying the Gini index to these bins [41]. The ADI and AEI have been shown to efficiently distinguish, for example, between diurnal bird vocalizations and nocturnal animals' activities or between different environments. This index provides complementary information to the ADI.

2.1.5 Bioacoustic index (BI)

The bioacoustic index is calculated as the "area under each curve including all frequency bands associated with the dB value that was greater than the minimum dB value for each curve. The area values are thus a function of both the sound level and the number of frequency bands used by the avifauna" [42]. Thus, it is a measure of avian abundance. A distinction that is usually made in biodiversity assessment regards the intra-group and extra-group diversity, with a group being the result of an aggregation of units, such as a site, an environment or a time period [43]. Both intra- and extra-group diversities are calculated from a list of attributes or objects defining the sample. Intra-group diversity indices are mainly linked to the number of objects and their relative richness in a specific sample, whereas extra-group diversity is meant to estimate similarity or dissimilarity between a list of attributes or objects [44]. Typically, these attributes refer to animal species, but this approach can also be applied to the fields of morphology or ecology [45].

2.1.6 Normalized difference soundscape index (NDSI)

The normalized difference soundscape index (NDSI) is the ratio between human-generated (anthrophony) and biological (biophony) acoustic components and is used to evaluate the disturbance on a landscape [46]. Computing the normalized difference as $(b-a)/(b+a)$, where (a) and (b) refer to the anthrophony and biophony components, it is possible to calculate their relative levels of energy, thus allowing us to estimate the relative levels of biophony through a soundscape index. NDSI ranges between -1 and 1, with the low and high bounding values representing the predominance of human-generated and biophonic sounds, respectively. Previous works showed how this index was applied to investigate a soundscape in a North American lacustrine forest habitat

[47] and to study the spatial and temporal patterns of soundscape characteristics in an urban-belt landscape by independently analysing anthrophonic and biological levels of energy, as reported in [37].

In this study, the NDSI was calculated using the contributions of anthrophony, as the frequency band between 0.1 and 2 kHz, and biophony, as the frequency band between 2 and 11 kHz. The time evolution of the NDSI was calculated with a resolution of 1 s.

3. Results and discussion

The two sound recordings mainly differ in the presence (urban park, site UP) or absence (natural shrubs, site NB) of anthrophony.

Figure 2 shows the mean squared sound pressure ($<p^2>$) as a function of the frequency, with the mean value calculated over the entire recording length, namely, 1 minute for both recordings. In the first plot (Figure 2a), background road traffic noise was present, with birds singing starting at 13 s (before this time, there are very faint chirps). The second plot is dominated by birds singing during the whole sampling interval. The value of $<p^2>$ was calculated starting from the FFT matrix. Figure 2a (left panel) shows the mean energetic content in the first recording, where two small peaks appear corresponding to the biophonic contributions centred at 3000 and 3500 Hz. The energetic content is shifted towards the low frequencies (i.e., below 1000 Hz) generated by road traffic noise. On the other hand, the biophonic recording in the pristine environment presents two major peaks at 3250 and 7000 Hz with a full width at half maximum (FWHM) of approximately 1500 ($FWHM_1$) and 1000 Hz ($FWHM_2$), respectively, as shown in Figure 2b (right panel).

This is also confirmed by the spectrogram obtained for the two recordings and reported in Figure 3, showing that the spectrum is concentrated in the low frequency range for the urban park (UP) recording, with relatively faint biophonic sounds in the 2-4 kHz range (Figure 3a), whereas the spectrum of the natural bush (NB) recording is concentrated in two main regions: 2-4 kHz and 6-8 kHz.

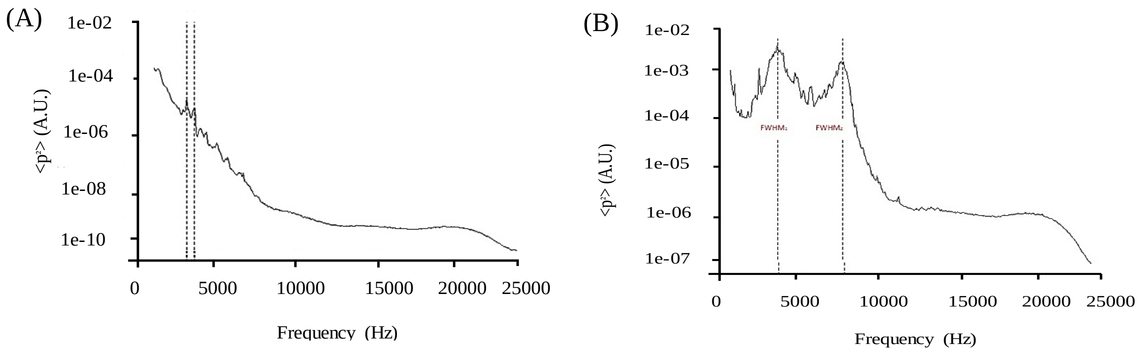

Figure 2 (A) Urban park (UP) recording: mean squared sound pressure $<p^2>$ as a function of frequency; the two peaks (dashed lines) correspond to 3000 and 3500 Hz. (B) Natural bush (NB) recording; the two main peaks (dashed lines) correspond to 3250 and 7500 Hz with FWHM of approximately 1500 ($FWHM_1$) and 1000 Hz ($FWHM_2$). The frequency ranges between 100 Hz and 24 kHz in both cases.

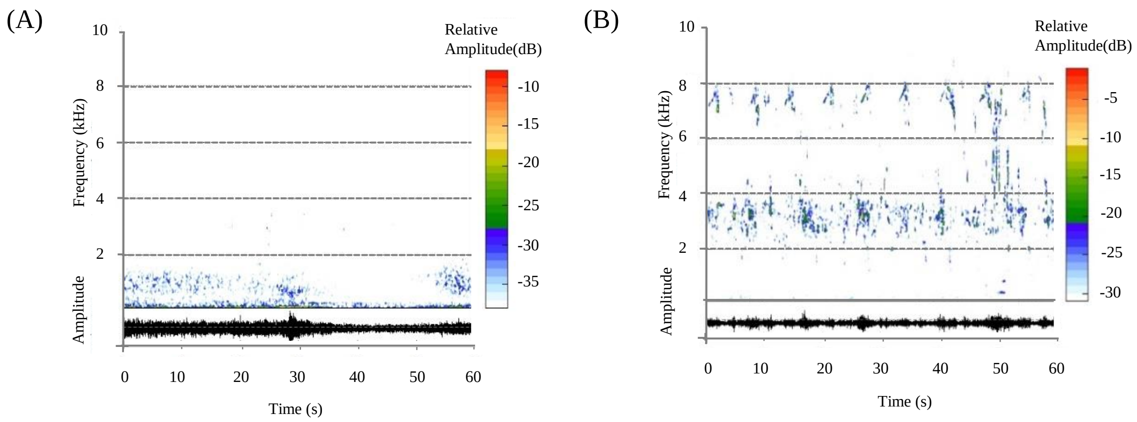

Figure 3 Spectrogram for the two recordings: (A) UP; (B) NB. The frequency range shown is between 100 Hz and 10 kHz. The lower part of the figure shows the sound pressure (p).

Figure 4 shows the time history of $<p^2>$ for the UP (left panel, a) and NB (right panel, b) recordings. In this case, the mean value is calculated over the entire range of frequencies considered (100-24 kHz). The time resolution is provided by the initial choice of 1024 points for the FFT calculation (0.0213 s). The left panel shows quite uniform fluctuations typical of distant road traffic noise, with a more prominent peak corresponding to a noisy pass-by at approximately 30 s. The reduction in the sound pressure between 35 and 55 s is due to a temporary reduction in vehicles passing by. The right panel shows stronger fluctuations of biophonic sounds, typical of an environment with high biophonic activity and low background noise. The dashed line represents the median value, drawn as a guide for visual inspection.

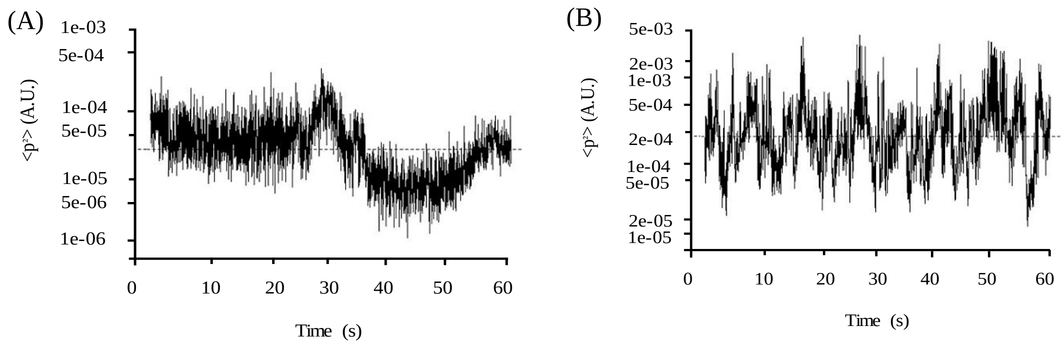

Figure 4 Time history of $<p^2>$ for both the UP (left panel, A) and NB (right panel, B) recordings. The dashed line represents the median value, drawn as a guide for visual inspection.

The DSC values are reported in Figure 5a: the spectral centroid shows quite low values in the urban park (UP, DSC median value = 330 Hz), whereas in the pristine environment (NB), the biophonies predominate (DSC median value = 3.52 kHz), as also shown in the density plot on the right-hand side of Figure 5a. The urban park recording shows a main SC peak centred at 270 Hz and a small peak at 500 Hz, most likely due to surrounding road traffic noise. The recording from the natural bush site shows two main peaks at higher frequencies and with larger bandwidths, which accounts for the amplitude of sound modulation.

The values obtained for the ACI metric in the frequency domain are reported in Figure 6 for the urban park (UP, left panel, a) and the natural bush (NB, right panel, b). Different peaks are present: in the UP recording, the main mid-frequency peaks at 2.9 kHz and 3.45 kHz represent the biophonic signature of the active species, and the low frequency peak is most likely due to road traffic sources, whereas in the NB, a more complex pattern is observed due to the presence of a variety of biophonic signatures in the mid-frequency range. The temporal analysis of the ACI metric over the recording period (1 minute) is shown in Figure 5b, where the temporal step considered is $j = 0.1$ s. The median values are approximately 230 and 236 for the UP and NB sites, respectively. The density plot shows two peaks, corresponding to the median values. For the NB site, the ACI value is higher as a consequence of the higher biophonic modulation and the absence of road traffic noise, the frequency modulation of which is rather low.

The different values of richness can also be observed in Figure 5c, by looking at the amplitude of the ADI index modulation. Indeed, both the median and the interquartile range (IQR) are higher for the natural bush location (median = 6.19 and IQR = 0.35) than for the urban park location (median = 5.99 and IQR = 0.23). In the density plot, the peak of the UP distribution corresponds to the median value, whereas the NB presents a bimodal distribution, with maxima at 6.15 and 6.45.

The AEI provides complementary information to the ADI, as shown by comparing Figures 5c and 5d. Higher median evenness values were found for the urban park site (AEI = 0.63 and IQR = 0.09), and a greater modulation was found for the natural bush site (AEI = 0.56 and IQR = 0.16). In the density plot, the peak of the distribution for the urban park site corresponds to the median value, whereas the distribution of the natural bush site is bimodal, with maxima at 0.57 and 0.42.

The temporal analysis of the BI is reported in Figure 5e. The dashed lines represent the medians (73.24 and 71.7 for the UP and NB sites, respectively). This analysis was performed by setting the temporal step at 0.1 s (as for the previous analysis) and the frequency range between 2 and 10 kHz to exclude the contribution of road traffic noise. By including the low frequencies in the analysis, the BI values for the urban park increase. However, the IQR is higher for the natural bush site (16.1) than for the urban park site (13.2); thus, there is higher variability associated with the major abundance of both sound levels and the number of frequency bands. Increasing the temporal step from 0.1 to 0.5 s, the BI median value for the natural bush site (median value = 64.7, IQR = 15.7) increases relative to that for the urban park site (median value = 62.2, IQR = 9.9).

The NDSI results are shown in Figure 5f. The dashed lines represent the medians (-0.97 and 0.85 for the UP and NB sites, respectively). The urban park presents an abundance of anthropic sounds, with peaks revealing the presence of biophonic activity overlapping anthropic activity. On the other hand, the natural bush site is dominated by biophonic sounds. In this case, the presence of valleys may represent either the overlapping of anthropic signals or a reduction in biophonic signals. In the density plot, the maxima of the distributions are well separated, with median values of -0.98 and 0.88 for the UP and NB sites, respectively.

To compare the two groups of sound ecology indicators obtained from the urban park and the natural bush sites, a Wilcoxon signed-rank test was computed to determine whether the two groups were selected from populations having the same distributions. This test is applied when the distribution of the difference between two samples' means cannot be assumed to be normally distributed and, in this sense, it can be used as an alternative to a paired Student's t-test. The null hypothesis is that the variables of the two samples are from identical populations. In cases in which the p-value is less than the 0.05 significance level, the null hypothesis is rejected. The results of the Wilcoxon signed-rank test, reported in Table 1, indicate that only the BI does not satisfy the null hypothesis and, therefore, cannot be used to discriminate between the two very different environmental settings of the UP and NB sites. In contrast, the other indices show quite clearly the different richness in anthrophony and avian activity.

Table 1 Results of the Wilcoxon signed-rank test of the sound ecology indicators for the two sites shown in Figure 5.

Index	*P*-value
SC	2.2e-16
ACI	2.2e-16
ADI	2.2e-16
AEI	2.2e-16
BI	0.4461
NDSI	1.671e-11

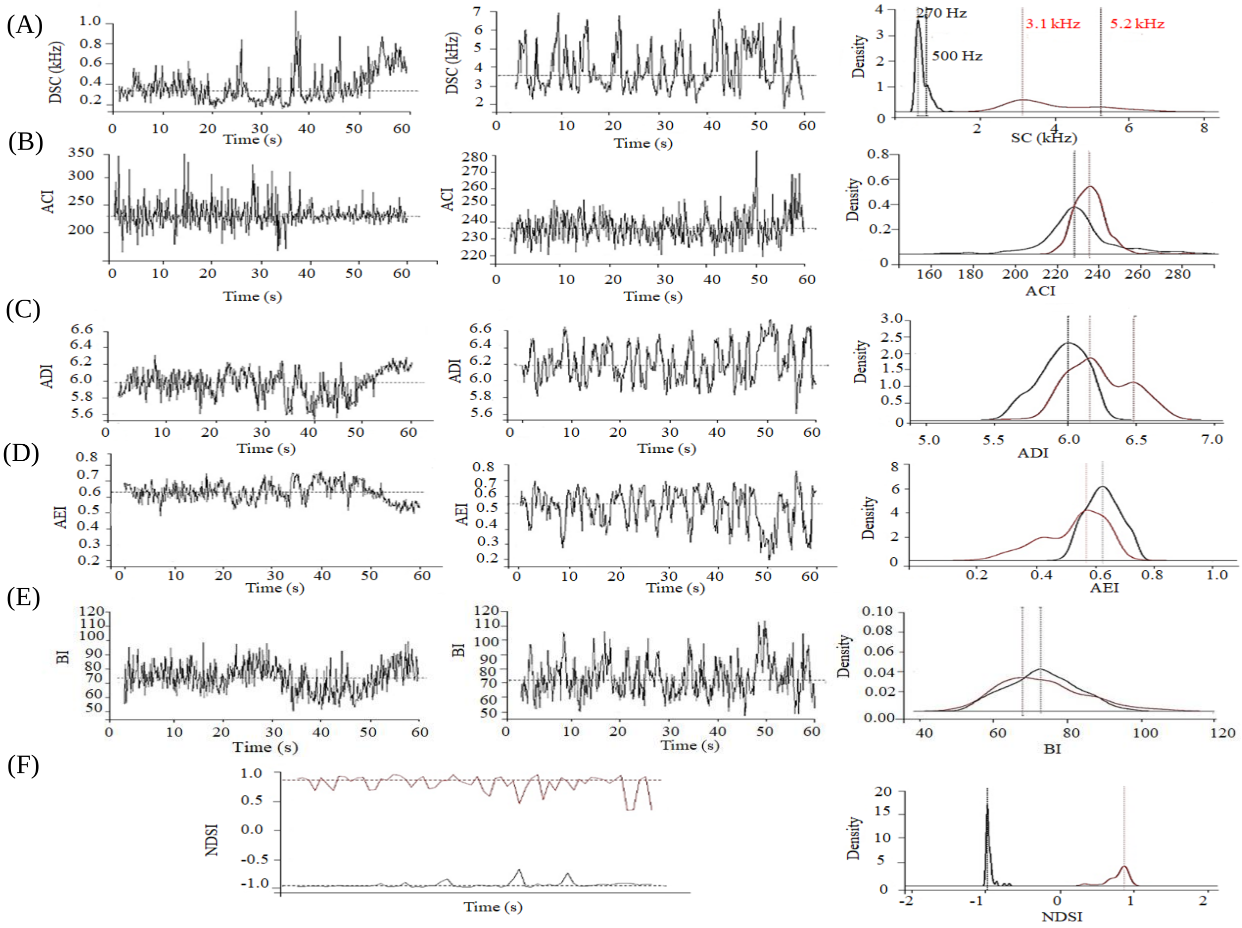

Figure 5 Temporal analysis of the sound ecology indicators in the two environmental settings (A-F); Urban park (UP) = black line and Natural bush (NB) = red line.

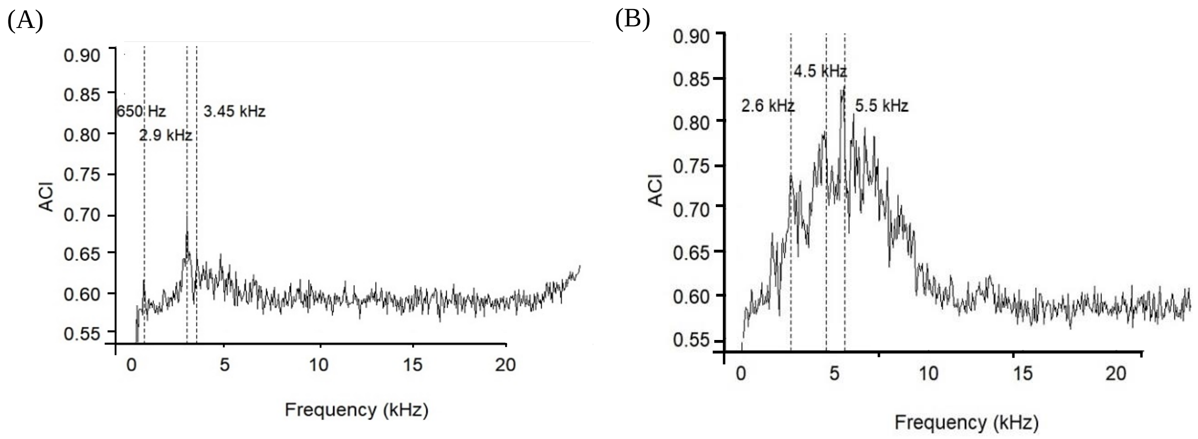

Figure 6 Frequency analysis of ACI for the recordings from both the urban park (UP, left panel, A) and natural bush (NB, right panel, B) sites.

The DSC presents a very different temporal pattern for the two environments (Figure 5A). Indeed, for the NB environment, the modulations show longer durations (partly due to the specific avian species) than those observed for the UP site. This higher "pulse" width is also observed in the ADI (Figure 5C) and the AEI (Figure 5D) and, partially, the BI (Figure 5E). Thus, the dynamic study or temporal evolution of each index can also help identify differences among differently populated environments. This is especially effective in cases in which one wants to characterize dawn choruses and nocturnal activities (within the same environment) but less effective in cases in which different habitats are considered. Indices with a strong spectral fingerprint seem to better describe the complexity of natural soundscapes.

4. Conclusion

In this preliminary study, we evaluated the potential of sound ecology indicators to discriminate the different types of sounds present in two environmental settings: a large urban park in Milan, Italy, surrounded by busy roads and a shrub-dominated area, the latter of which was used as reference site for natural areas.

The analysis was aimed at comparing the sensitivity of these indicators applied to the two sonic environments characterized by the presence of different anthropogenic noises, especially in the urban park, and sounds from avian species. The results confirmed the capability of the considered indices to discriminate between the two different habitats, though with different sensitivities. In particular, the differences in the BI calculated for the two environments were not statistically significant. Additionally, the ratios between the median values of the ACI, ADI and AEI are close to being equal. This means that other characteristics should be taken into account, such as the dynamic evolution of the indices and, for the ACI, the frequency analysis, which actually provides very interesting information on sound modulation. In contrast, the DC and NDSI ratios are rather sensitive to changes in the sound/noise composition and, therefore, could be considered for a rapid evaluation of the sound quality in an urban park. The results obtained, despite being very preliminary, are encouraging even though deeper insights are needed to assess the robustness of the findings. In particular, a longer duration of the analysed recordings (or a wider distribution across the day) can strengthen the results regarding the significance of the indicators. Therefore, more recordings will be taken and studied. Investigations extended to different environments will also be helpful for supporting the results obtained herein. Sound ecology indicators, or their combination, could help identify areas within urban parks that have relatively high biophonic activities and, therefore, potentially offer greater relief and restorative value. Such information can be used to improve the use of parks by directing users towards areas with features more conducive to their enjoyment and consistent with their expectations.

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