



Soundecology indicators applied to urban soundscapes

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ABSTRACT

In remote ecological monitoring studies the characteristics of the soundscape is one of the key aspects in the assessment of the ecological environment. In order to characterize these natural soundscapes different acoustic indices are currently under study: the bioacoustic index, the acoustic complexity index, the acoustic diversity index, the acoustic evenness index and the normalized difference soundscape index. These indices reflect in part the nature of the different sounds present in the soundscape. As an example the acoustic complexity index is known to correlate with the number of bird vocalizations in the environment, while it is insensitive to airplane noise. In general, the indicators could reveal the balance between biophony, geophony, and anthrophony in the natural soundscape. Starting from urban sound recordings the different acoustic indices are calculated. In this way the resulting temporal character of the acoustic indices is obtained and can be related to the activity level in the biophony, geophony or anthrophony of the urban environment. The results show that soundecology concepts can be applied for soundscapes more strongly governed by noise.

Keywords: Natural sources of sound, soundscapes; I-INCE Classification of Subjects Numbers: 22, 56.3

1. INTRODUCTION

A soundscape can be seen as the collection of environmental sounds, the sonic environment, and its perception by a person or a society. It originates from the presence and activity of different sound emitters present in a landscape. As such, it contains a wealth of information since it reflects the nature and the behaviour of the sound emitters. A soundscape shows a remarkable importance with respect to the perception of sounds by humans. Due to the complexity of sounds on the temporal and spectral scales, the characterization and classification of soundscapes is difficult (1).

In studies with main focus on noise abatement, the characterization of soundscapes is made using calibrated acoustical equipment, spectrally weighted with respect to human hearing system. Continuous use of this type of equipment results in time and intensity information of the present soundscape. This type of information can be used for, amongst others, urban area planning purposes. An example is given in (2) where the redevelopment of an urban industrial site into an area with dwellings and an urban park is studied. The strengthening of the natural component in the design of new urban areas is of key importance since this natural component is important for well being, mental restoration, and may stimulate the use of the area for activities involving physical activity (which in turn has health benefits) (3).

Another approach in the characterization of soundscapes focusses on the complexity of the sounds present, as they emanate from the different types of sound emitters. These emitters can be biological resulting in biophonic sounds, or can be of mechanical nature resulting in anthrophonic sounds, or can be of geophysical origin (water, wind). This type of study is of importance in ecology and has led to the development of different soundecology indicators (e.g. bioacoustic index, acoustic complexity index, acoustic diversity index, acoustic evenness index, normalized difference soundscape index and total entropy). These indices have proven their use in the study of the diversity in different ecosystems (4). In order to monitor permanently different ecological habitats the emerging sounds can easily be collected with wireless recorders and massive audio datasets become available. The processing of

these data puts new challenges on the use of these indicators.

In this study a preliminary assessment of the use of these soundecology indicators for urban areas with a natural character is presented. The considered areas are residential areas with dwellings combined with gardens and limited agricultural terrains.

The paper is structured as follows. After this introduction, the different soundecological indicators are described, and the details of the collected recordings and the processing method are given. Concerning the results, the temporal behaviour of the indicators is discussed. In addition the indicators are demonstrated for atomic anthrophonic sounds typical in urban areas, and the correlation between the different indicators is demonstrated.

2. METHOD

2.1 Soundecology indicators

For use in habitat characterization different acoustic indexes can be calculated (5). Since the current main use of these indexes lies in ecological studies, they can be depicted as soundecology indicators. Following different approaches they give an indication of the spectral or time variation of the underlying sound emitters of the soundscape. The most important of these indicators are:

Acoustic Complexity Index (ACI):

This index focusses on the intensity variations in the signals and calculates the absolute intensity difference between succeeding time frames for a specific frequency bin. These values are summed over all the timeframes and all the frequency bins in the frequency range in a time cluster (typically 5s). These results are summed over all the time clusters in the signal and normalized with respect to the signal duration (6). The index was created to estimate the number of bird vocalizations (biophonic content) and is based on the strong time variability of intensities typical in birdsong. Environmental noise from passing cars or airplane transit have rather slow intensity variation, and as such are not or only partly reflected in the index.

Normalized Difference Soundscape Index (NDSI):

This index is calculated using specific spectral regions in the normalized power spectral density (PSD) of the signal. A first spectral region is between 1000 and 2000 Hz, where mechanical sounds are more prevalent. The sum of the power in this frequency bin over the time span of the signal is calculated as the α -value. Another frequency range is between 2000 and 11000 Hz, where biophonic sounds are more prevalent. This frequency range is divided into 1 kHz frequency bins, for which the summation over the time span of the signal of the power in these frequency bins is calculated. The maximum value of these summations yields the β -value. The NDSI is calculated as $NDSI = (\beta - \alpha) / (\beta + \alpha)$, and results in a value between -1 and +1. A value of +1 indicates the presence of only biophonic sounds, a value of -1 indicates the presence of only anthrophonic sounds (7). The spectral limits of the biophonic and anthrophonic regions are important parameters in the calculation of this index. Due to the wide diversity in animal vocalizations, examples where a negative NDSI is obtained, can be found.

Bioacoustic Index (BIO):

The bioacoustic index was introduced by Boelman et al. (8) and is calculated from the presence of spectral power above a threshold in the frequency range from 2000 to 8000 Hz to reflect biophonic activity.

Acoustic Diversity Index (ADI):

The ADI from Villanueva-Rivera et al. (9) is calculated by dividing the spectral range of the spectrogram into frequency bins (default 1 kHz steps) and taking the proportion of the signal energy in each bin above a threshold (default -50 dBFS). The ADI is the result of the Shannon index applied to these bins.

Acoustic Evenness Index (AEI):

This index is related to the ADI: the obtained distribution of the different frequency bins is now indexed used the Gini index (9). The index is in the range from 0 to 1.

Entropy:

The total entropy is calculated as the product of the spectral entropy and the temporal entropy of the signal (10). The spectral entropy is calculated from the frequency mean spectrum of time frames in the signal. The temporal entropy is calculated from the Hilbert amplitude envelope of the signal.

2.2 Data

A first area under study (site A) is in the Ghent (Belgium) agglomeration. The area is characterized as a residential area with a mix of detached single-unit housings and semi-detached dwellings, gardens and local roads with sparse low speed traffic governed by a 50 km/hr speed limit. The area makes the switch to an agricultural (rural) area (with mixed grasslands and fields) and is in this way located at the outer side of the urban-rural gradient. In the rural landscape a railway is present, resulting in transit sounds of trains which are more or less in a line of sight of the recorder, at a distance of 375 m.

A second area under study (site B) is a similar location in the Ronse (Belgium) agglomeration and consists of a residential area with limited agricultural terrains (grassland). The main differences are the absence of a railway, the presence of a small roundabout close to the measurement point, and the denser use of the local roads, due to the presence of a hospital in the neighborhood.

As both measurement sites are at the outer side of the urban-rural gradient, a combination of anthroponic and biophonic sounds can be expected.

The sounds originated from these urban areas were recorded during time spans of more than 24hrs using a Tascam DR60D recorder and an omni-directional Sennheiser ME62 microphone with windshield. In this way, mono audio (wav) files of 16 bit samples, recorded at 44.1 kpsps were obtained. In total more than 150 hrs of data was recorded during consecutive days of convenient recording conditions with no or limited rainfall and moderate wind velocities. These recordings took place in spring 2016, when bird vocalizations were strongly present. From these recordings 24 hr parts were studied in detail. These 24 hr parts, representing almost $4 \cdot 10^9$ samples, are considered to represent the characteristics of the soundscape.

The different soundecology indicators were calculated using the R statistical computing environment (11) with the soundecology package (12) and seewave-R (13). The results were calculated with the default parameters and time steps of 10 minutes with 50 % overlap. The listed ACI-values refer to the values for a reference time span of 1 min.

3. RESULTS

3.1 Temporal behaviour

The temporal behaviour of the soundecology indicators follows a diurnal pattern which is shown in figure 1. The pattern shows a pronounced peak in all the indicators around sunrise. This pattern was present in all the daily tracks of the recordings, and at the 2 different sites. A smaller peak in most of the indicators is present around sunset. This peak can be pronounced (as in the case of the NDSI or BIO indicator), or can be absent (as in the case of the ACI indicator). The peaks are negative in case of the AEI indicator, positive in case of the other indicators.

During night the levels of the indicators show strong short time variation, but remain in principle at a certain constant or slowly varying level. The same principal behaviour of the indicators can be seen during the day. Apart from this tendency, additional peaks (of limited duration) can also be present in the recordings.

Considering biophonic sounds it is known that in general, bird species during their breeding season give rise to peak vocalizations near sunrise, the dawn chorus (14). The sunrise peaks present in the indicators, together with the identification of these sounds, gives evidence for this.

During the day birdsound activity is at a lower level, but can be persistent along the day for some specific birds species (e.g. House Sparrow, *Passer Domesticus*). Apart from residential birds with their vocal activity in use to occupy and defend a convenient breeding site, migrating birds pass over the measuring site. In many cases, their calls are recorded and account for additional biophonic sounds.

Considering anthroponic sounds they originate from the different types of human activities in the neighbourhood of the measuring sites. This ranges from daily traffic sounds, to sounds related to construction or gardening work in the residential areas, and to sounds from farming activities in the agricultural terrains. The intensity of these activities generally follows a daily, weekly and seasonal pattern, related to the specific social organization in the society at the given site. In general these anthroponic activities lower the NDSI indicator. Taking into account the positive influence on the NDSI value of biophonic activity during the day, it will give a higher NDSI value during the day than during the night. This systematic behaviour is in general present in the diurnal patterns recorded.

As a quantitative indication of this observation the midday and midnight 1 hr values of the ACI and the NDSI are respectively 1865 (36.7), 1807 (3.87) and -0.26 (0.48), -0.73 (0.13) for site A, and 1827 (22.38), 1798 (7.34) and -0.21 (0.08), -0.56 (0.07) for site B (standard deviation between parenthesis).

Both biophonic and anthropogenic activity are dependent upon the meteorological conditions. While this is an important influence, the limited dataset of the present study covers only small differences in meteorological conditions.

In a landscape configuration study 24 hr time-of-day acoustic indices were investigated in fragmented Australian forest landscapes by Fuller et al. (15). The patterns of the ACI and BIO indicators correspond with the current (urban) observations. The other indicators (NDSI, ADI, ACI and entropy) show a different behaviour with respect to their mean night and day levels. As stated, the dominant presence of night activity of Orthoptera in Australian forests could account for this. In the present urban study, no insect sounds were recorded.

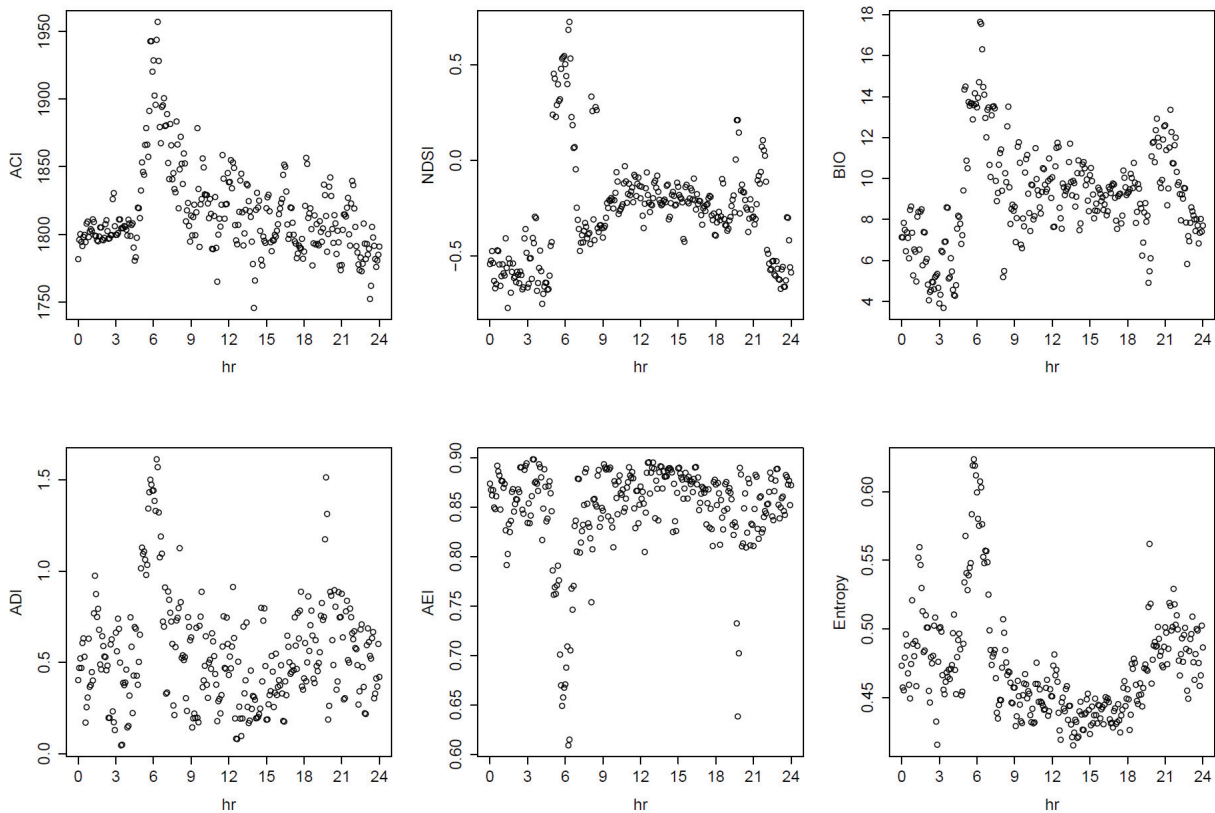


Figure 1 – Diurnal behaviour of the ecological indicators measured at site B (5 May 2016, sunrise at 6h12, sunset at 21h13).

3.2 Acoustic identification study

As the site recordings shown were made during spring a large part of the recorded sounds originates from human activity typical for this period in combination with intense vocal activity of animals. In order to study the different sound emitters with respect to their soundecology indicators different fragments in the recordings were isolated after identification and processed separately. An overview of the resulting indicators for a representative list of emitters, as measured from both sites, is given in Table 1.

As stated the NDSI indicator can be used for distinction of biophonic (positive values) or anthropogenic (negative values) nature of the recorded sounds. The listed values of the recordings in

table 1 indicate this general behaviour. However as already mentioned this is not always the case (7). For certain biophonic sounds the NDSI indicator gives the wrong detection of an anthropogenic origin (e.g. oyster catcher); for certain anthropogenic sounds the NDSI indicator gives the wrong detection of a biophonic sound (e.g. hedge trimmer, moped, ploughing tractor).

Table 1 – Soundecology indicators of specific isolated sound fragments

Sound	ACI	NDSI	BIO	ADI	AEI	Entropy
helicopter	2043	-0.65	13.41	0.92	0.80	0.47
propeller airplane	1892	-0.62	10.27	0.92	0.80	0.50
car 1	1846	-0.28	9.58	0.66	0.84	0.41
car 2	1747	-0.62	7.03	0.78	0.82	0.45
car 3	1763	-0.31	9.07	0.75	0.83	0.44
car 4	1541	-0.72	5.74	0.95	0.78	0.50
moped	1796	0.29	5.34	2.15	0.30	0.73
truck	1760	-0.06	8.94	0.63	0.85	0.45
tractor crane	1812	-0.27	5.64	1.42	0.69	0.59
tractor (ploughing)	1991	0.13	11.06	1.02	0.78	0.40
lawnmower	1923	-0.05	7.37	1.64	0.61	0.58
hedge trimmer	2001	0.30	7.01	2.26	0.15	0.83
church bells	1785	-0.84	10.61	0.97	0.78	0.52
train (passengers)	1819	-0.92	15.49	1.19	0.74	0.57
train (goods)	1777	-0.76	13.39	0.77	0.82	0.52
train + blackbird	1992	-0.82	9.37	1.17	0.74	0.61
blackbird	2058	0.74	9.24	1.71	0.58	0.63
blackbird + house sparrow	1903	0.73	14.19	1.47	0.67	0.60
oyster catcher	1886	-0.18	11.64	1.25	0.73	0.55
rain (plants)	1961	0.04	7.11	0.04	0.90	0.39

In urban areas sources from human activity combine with the sounds of communicating animals. It is often the case that these sounds occur simultaneously. Such occurrences are not reliably detected using the NDSI indicator. This can be seen in the values related to the (singing) blackbird. The fragment of a (singing) blackbird in combination with a house sparrow gives an NDSI value comparable to the value of an isolated blackbird. On the other hand the fragment of a (singing) blackbird in combination with a train gives a strong negative value (anthropogenic), indicating the anthropogenic sound is dominant in this case.

In urban areas sounds of cars are prominent. The noise they emit strongly depends upon different parameters (car type, type of tires, speed, acceleration, ...). As a result a strong variation of soundecology indicator values is seen for the different car fragments as listed in table 1.

Sounds from geophonic origin (water, wind) are almost absent in the recordings. This is due to the difficulties in recording the acoustical environment in case of conditions with strong rainfall or high wind speed. A single detection and identification was made during light rainfall, the resulting NDSI value is almost zero.

3.3 Correlation

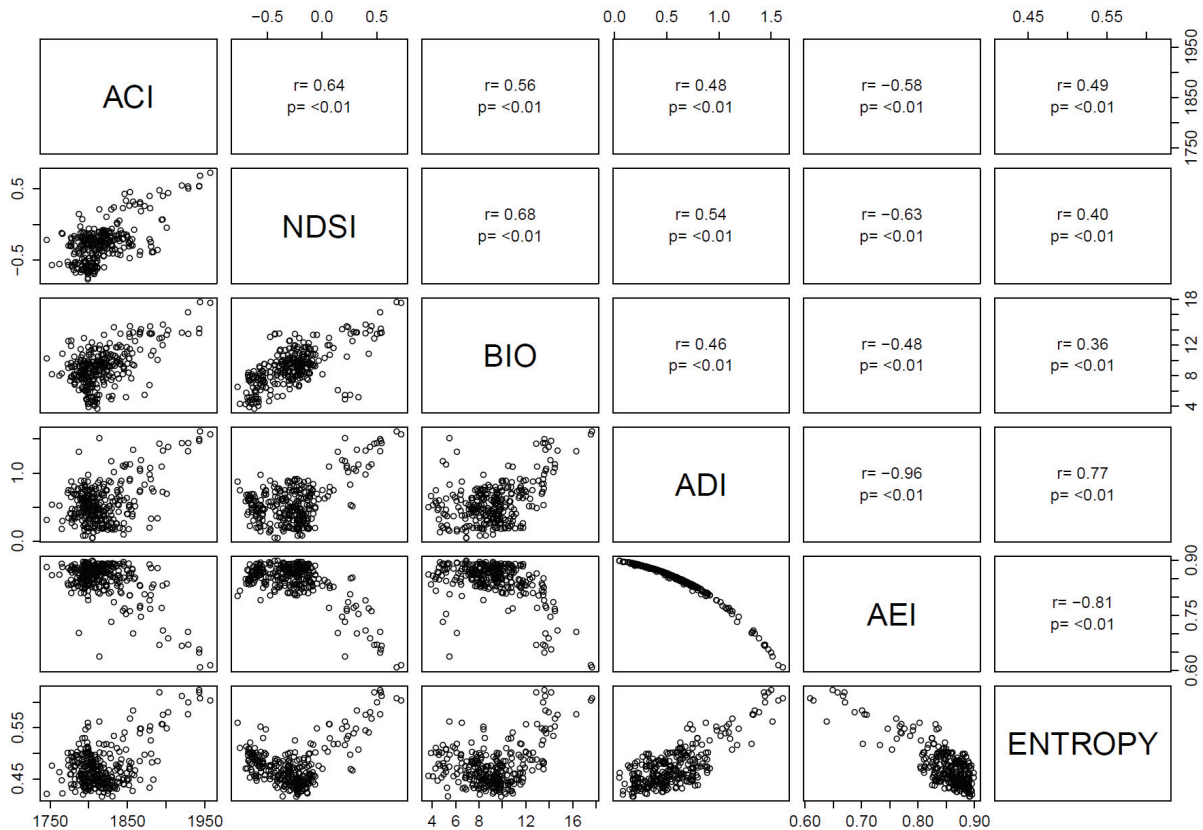


Figure 2 – Matrix correlation plot of the 24 hr indicator data as recorded on 5 May 2016 at site B.

As the different ecological indicators show a similar temporal pattern (fig. 1) an evaluation of their correlation is made. In this respect a plot of the correlation between the different ecological indicators from the 24 hr data from site B (fig. 1) is given in figure 2. These resulting correlations are typical for all the recordings. The resulting corresponding r-values (correlation coefficients) and p-levels are shown.

Strong correlation exists between the Entropy, AEI and ADI indicators. As the ADI and AEI originate from the same underlying data, and differ only in index calculation, a strong correlation between them exists.

Moderate correlation exists between BIO and NDSI indicators.

The correlation between the different indicators, suggests that data reduction is possible, enabling less processing power for soundscape characterization. This is confirmed in a principal component analysis (PCA) of the 24 hr recordings at both sites. In both cases 2 components describe more than 75 % of the cumulative proportion of variance in the data (78 % for site A, 83 % for site B). The data is shown in figure 3 as a two-dimensional indicator space defined by the first two principal components (PC). The direction of the variability of the main soundecology indicators is shown as red arrows in the plots. The ADI, AEI and entropy indicators behave in a large part as the main principal component in the recordings at both sites. These indices seem to be related indicators of the temporal diversity in the recordings. The additional ecology indicators (NDSI, ACI, BIO) seem to describe in part the remaining variability in the data. Their main focus could lie in the spectral variation in the recordings.

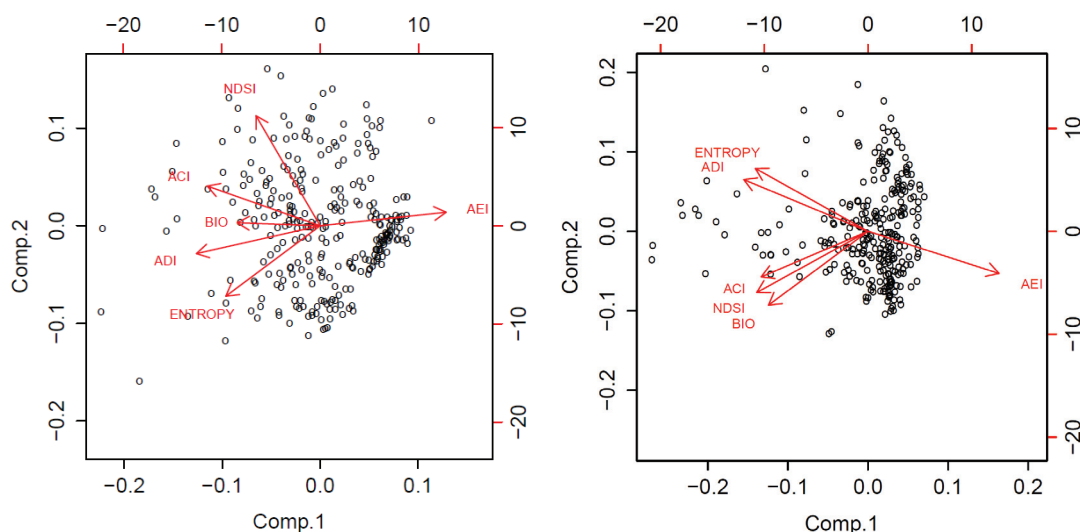


Figure 3 – PCA plots for the 24 hr indicator data as recorded on 13 April 2016 at site A (left) and on 5 May 2016 at site B (right).

4. CONCLUSIONS

Using continuous recordings at urban sites with a strong natural aspect an evaluation of different soundecology indicators is made. These indicators are currently in use for the characterization of habitats. The analysis shows that temporal behaviour of the indicators can be used to estimate bird activity, especially at morning dawn. In this way they can be used to evaluate the green content of an area and it is expected they can give an quality indication for (future) green cities.

From the current data set, it is shown that only 2 principal components can account for more than 75 % of the variance in the recordings.

As in urban areas many sources of sound emitters are present, different examples of atomic sounds of biophonic and anthrophonic nature are given with their ecological indicators. Separation of the sounds in biophonic and anthrophonic origin can be made, but fails in case of simultaneous biophonic and anthrophonic sounds.

The active sound emitters at the study areas are mainly of biophonic and anthrophonic origin. For urban areas different human vocalisations are expected to be strongly present at specific places. In the current dataset only very limited human vocalisations are present.

In order to use the indicators to address human restoration, health effects, ... of natural soundscapes in cities, it is needed to account for the sounds that people will pay attention to during daily activities. In case of sounds that occur together, one of these may be more likely to receive attention due to its saliency. This is not incorporated in the indicators and such studies need a combination with computational models of auditory attention.

While the indicators show promising characteristics for use in urban soundscape characterization, further research is needed, especially concerning the aspects of their long and short time behaviour, concerning site comparison and concerning meteorological conditions. In order to study their influence on the characteristics of the different ecological indicators larger datasets, including detailed additional information is needed.

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