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AUDIO EQUALIZATION OF DIFFERENT SOUNDSCAPE RECORDERS IS NECESSARY TO PERFORM A CORRECT ANALYSIS

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ABSTRACT

Passive acoustic monitoring (PAM) is widely used by soundscape and bioacoustics researchers. Nowadays, there is a large number of instruments available to record environmental sound, with different characteristics and costs. Given this availability, using all the devices on hand, even from different manufacturers, can be tempting since it allows to expand the area of study with less costs. Unfortunately, due to their diverse frequency response, this procedure introduces biases in a comparative analysis of the recordings (e.g., the computation of acoustic parameters and indices, and the following elaborations). For these reasons, equalization of audio recording is fundamental to ensure proper analysis. Therefore, in this study, we evaluated the effects of the equalization on the data acquired by two soundscape recorder typologies (Song-Meter-Micro and Soundscape-Explorer-Terrestrial). The evaluation was carried out by computing the eco-acoustic indices. The equalization was performed in a laboratory: the soundscape recorders and a class 1 sound level meter (able to produce a .WAV file) were exposed to a white noise source. The equalization curve was calculated in MATLAB environment with a successful response. As a second step, its effect on the eco-acoustic indices was evaluated by applying it to audio recordings from a park in Milan (Italy).

Keywords: *soundscape, equalization, eco-acoustic indices, recorder.*

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1. INTRODUCTION

Soundscape studies using passive acoustic monitoring (PAM) have rapidly increased in the last decades [1] and this growing interest has stimulated the development of various autonomous recorders [2]. These devices have different characteristics (i.e., sampling rate, sensitivity) designed to monitor a particular taxon or to record in a specific environment, and can be used in various survey designs.

Among the soundscape studies, monitoring campaigns can sometimes be carried out using arrays of sensors operating in tandem or widely spaced over a large area on a regular grid [2,3]. The majority of these studies use static sensors, placing one or three devices in the field while only a slight minority employs more than ten recorders [3]. Using a high number of recorders made by the same company can be challenging due to their cost. Thus, it can be tempting to use all the available sensors regardless of the manufacturers to cover a larger area reducing the costs. The main drawback of this procedure is the generation of biases in the following data elaboration due to the unevenness of the recorders' characteristics (i.e., sensitivity, frequency response, dynamic range and bandwidth limits). In fact, when exposed to the same soundscape, different typologies of recorders will mostly produce audio files with diverse amplitude values. These differences can be also present when using recorders of the same typology given the high uncertainty of their sensitivity.

Previous studies faced this problem [4,5]. In one of them, the authors developed a procedure to obtain calibrated sound pressure levels from audio recorders between 0.025 - 6.3 kHz [4]. Their study is highly useful because a calibration procedure of the soundscape recorders allows comparing spectrograms and levels from different recorders. Following this path, three procedures to calibrate

.wav file are implemented in an R and MATLAB script [5]. These techniques have various degrees of accuracy; the best one allows calibrating the recording using a known frequency level as a reference value. Unfortunately, the different sensitivity curves of the instruments (which are not flat) don't allow a perfect calibration and thus a calibration test in the laboratory is necessary. Generally speaking, if digital audio recorders were calibrated in certified laboratories, as in the case of sound level meters, it will be possible to speed up soundscape studies and develop standardized guidelines to protect soundscape and biodiversity, as suggested by [6].
In this study, we propose a protocol for the equalization of the data acquired by two soundscape recorder typologies: Song-Meter-Micro (SMM) and Soundscape Explorer Terrestrial (SET). It will help to overcome the biases introduced by employing different sensors when monitoring the soundscape of an area, and thus allow comparison and further analysis. To achieve this goal, an equalization curve was generated between 0.2-20 kHz for each device by exposing the two recorders to a reference signal (which theoretically is a white noise) emitted by a loudspeaker in a laboratory while using a class 1 sound level meter as a reference.

2. MATERIALS AND METHODS

2.1 Theoretical concepts

2.1.1 Microphone sensitivity

Microphone sensitivity indicates the mic efficiency in transducing the input acoustic pressure into an electrical signal. The input acoustic pressure is equal to 94 dB (which corresponds to 1 Pa). The output electric signal is measured in mV or dBV (decibels relative to 1 Volt, calculated as 20*log10(V/V0)). Thus, mic sensitivity is expressed as dB relative to 1 V when it is subjected to a pressure of 1 Pa.

2.1.2 Graphic representation of the mic sensitivity

Microphone sensitivity may not be linear alongside the spectrum. For this reason, a mic frequency response or a mic sensitivity curve helps to visualize the changes in the output dB values on all frequencies. In particular, a frequency response graph scales the sensitivity values to obtain 0 dB at the reference frequency of 1 kHz, while a sensitivity curve displays absolute values.

2.2 Acoustic devices

During this study, three sensors were used:

- An LD-831C (831) of the Larson Davis. It is a sound level meter and it was used as a reference. It is equipped with a class A microphone, calibrated in a certified laboratory, with a sensitivity of -26.19 dBV relative to l Pa at 251.2 Hz. It has a flat response on all frequencies in the field 0-20 kHz. This level meter is able to produce a .wav file.
- A Song Meter Micro (SMM) of the Wildlife Acoustic. It is a programmable economic passive acoustic recorder. The sensitivity of the whole signal transmission chain (i.e., microphone, gain and analogue-to-digital converter) is 2 dBV ± 4 dBV relative to 1 Pa at 1 kHz Full-Scale, measured using a gain of +18 dB. The sensitivity curve is not linear on the spectrum (Fig. 1). Its output files are .wav.
- A Soundscape Explorer Terrestrial (SET) of the Lunilettronik. It is a soundscape recorder equipped with two microphones (with a sampling rate of 48 and 192 kHz respectively), and environmental sensors (for humidity, temperature, light and atmospheric pressure). The microphone has a sensitivity of -28 dBV ± 3 dBV relative to l Pa at 1 kHz; its frequency response is almost flat up to 6 kHz (Fig. 2). Its output files are .wav.

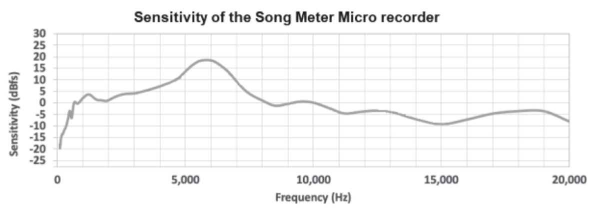

Figure 1. SMM sensitivity curve.

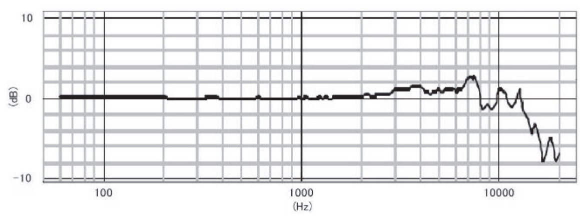

Figure 2. SET frequency response.

2.3 Acoustic measurements

2.3.1 Laboratory measurements (white noise)

To develop a protocol for the equalization of files from different devices, a series of recordings were performed by exposing them to “white” noise. Using the level meter as a reference, an equalization curve was calculated in MATLAB to correct the SMM and SET recordings.
The “white” noise measurements were done by placing, one after the other, the two soundscape recorders and the level meter at 30 cm from a loudspeaker (V12FREE, Proel), with the microphone facing the sound source and vertically centred in the middle of the woofer (Fig. 3). The loudspeaker has a frequency response ranging from 50 Hz to 20 kHz. It can generate a maximum SPL of 123 dB with an angular coverage of 90° horizontally and 60° vertically. The recordings were performed using a sampling rate of 48 kHz and a gain of 0 dB.

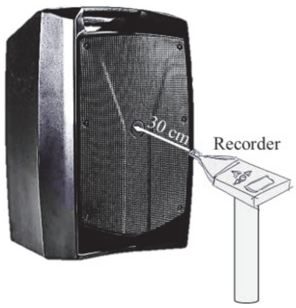

Figure 3. Scheme of the "white" noise measurements in the laboratory.

2.3.2 Field measurements (soundscape)

To test the equalization protocol, a short monitoring campaign was performed in a “pocket” park (Vivaio-Bicocca) belonging to the University Campus on 23rd November 2022. The SMM and SET were placed next to each other in the middle of the park, at the same height (50 cm) and with the microphones oriented in the same direction. The campaign was conducted using a sampling rate of 48 kHz and a gain of +18 dB; it was programmed to acquire 10 simultaneous recordings for each instrument, 30 seconds long.

2.4 Equalization procedure and data analysis

File equalization (Fig. 4) was carried out in MATLAB environment. It consisted in comparing the acoustic data of the sound level meter with the SMM and SET and obtaining an equalization function for each soundscape recorder.
The equalization function was obtained according to the following relation:

$$Eq_{curve} = \frac{PSD_{ref}}{PSD_{test}} \tag{1}$$

Eqn. (1) defines the equalization function as the ratio between the Power Spectral Density (PSD) of the reference instrument (831) and the Power Spectral Density (PSD) of the test instrument (SMM and SET). The PSD shows the average power of the signal over frequency bins.
After this step, the curve was adapted to be used, on the raw recording data, by a rational transfer function to equalize the recordings without the PSD calculus (Fig. 4). The equalized audio file was saved in .wav format.

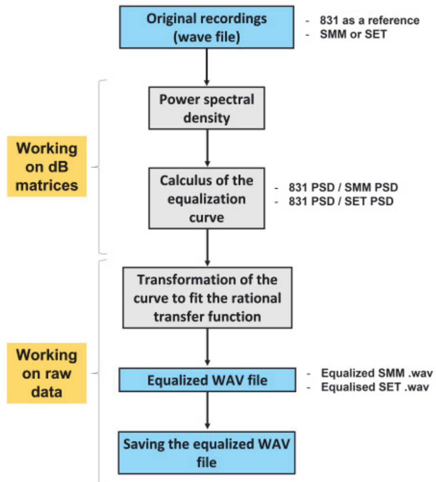

Figure 4. Scheme regarding the equalization protocol.

The curve was implemented in the frequency range of 0.2-24 kHz; the lower limit was set to avoid signal distortion while the upper limit was linked to the sampling rate of the recordings (48 kHz).
After the calculation of the curves, the equalization was performed on the audio files recorded in the park.
To assess the equalization process, the following analyses were carried out on the park recordings:

- computation of the root-mean-square deviation (RMS) of the amplitude (2);

$$RMS_{AMP} = \sqrt{\frac{1}{n_f} \cdot \sum_{i=f_{min}}^{f_{max}} (Amp_{ref}(f_i) - Amp_{test}(f_i))^2} \tag{2}$$

- implementation of the eco-acoustic indices (ACI, ADI, AEI, BI, NDSI, H, DSC, ZCR) using an FFT of 1024 points [7, 8];
- computation of the percentage error on eco-acoustic indices (3).

$$\%err_{index} = \frac{Index_{ref} - Index_{test}}{Index_{ref}} \quad (3)$$

3. RESULTS AND DISCUSSION

3.1 Laboratory measurements ("white" noise)

3.1.1 Song Meter Micro versus LD-831C

In this section, the spectrograms (Fig. 5) and the mean frequency spectrum (Fig. 6) of the "white" noise measurements done with the LD-831C and SMM are reported. In a second step, a quantitative comparison was conducted between original and equalized recordings, by calculating the RMS deviation of the amplitude between 0.5-12 kHz (Tab. 1) and the percentage error on eco-acoustic indices (Tab. 2).

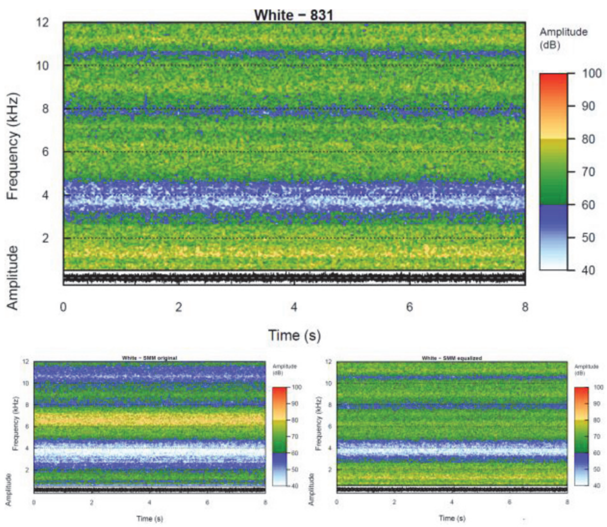

Figure 5. Spectrograms of "white" noise recordings by 831 (top), SMM original (bottom left) and SMM equalized (bottom right).

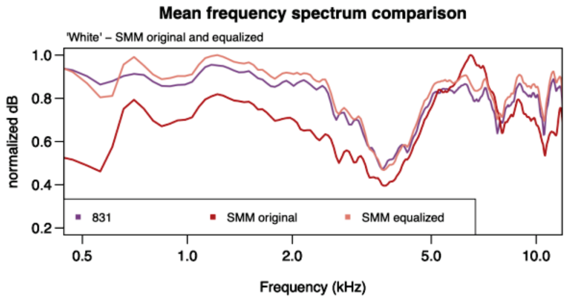

Figure 6. Mean frequency spectrum of "white" noise recordings by 831 (orchid), used as reference, SMM original (red) and equalized (pink).

Table 1. RSM amplitude deviation of "white" noise recorded by the SMM.

831 vs SMM	RMS amplitude deviation (dB)
original wave	12.5
equalized wave	3.6

Table 2. Percentage error on the eco-acoustic indices; comparing the .wav file of 831 vs SMM original (left column) and equalized (right column).

831 vs SMM		Original wave	Equalized wave
% error	ACI	0.1	-0.5
	ADI	0.3	0.2
	AEI	-393.3	-194.5
	BI	-10.9	-14.0
	NDSI	-126.7	1.9
	H	7.6	0.2
	DSC	-28.0	-1.1
	ZCR	-10.1	-8.8

In Fig. 5, it is possible to notice an elevated amplitude difference along the spectrum between the 831 and SMM measures. The highest difference is visible between 6-7 kHz, where SMM presents a peak due to its higher sensitivity, as shown in Fig. 1. After the equalization process, the SMM recording seems to be more similar to the 831 one; in Fig. 6 it is possible to notice the smoothing of the 6 kHz peak, which is actually not flattened but the intensities of the remaining frequencies are increased.
The improvement is confirmed by Tab. 1, which shows that the root-square-mean deviation of the amplitude drop of about 10 dB.

Regarding the eco-acoustic indices' calculation, Tab. 2 shows a decrease in the percentage error after the equalization for all parameters, except for ACI which increases slightly.

3.1.2 Soundscape Explorer Terrestrial versus LD-831C

The same protocol applied to the SMM was replicated on the SET measure. An equalization curve was created using white noise measurements and applied to the soundscape data.

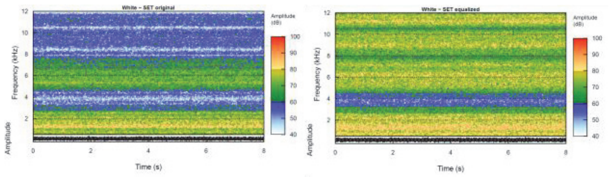

Figure 7. Spectrograms of "white" noise recordings by SET original (bottom left) and SET equalized (bottom right).

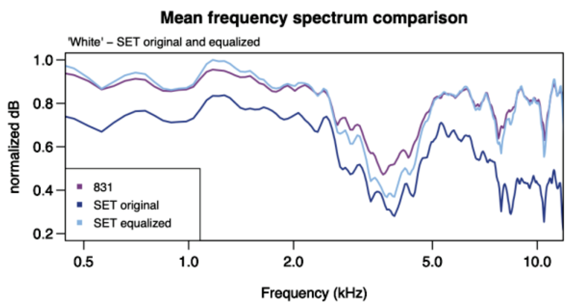

Figure 8. Mean frequency spectrum of "white" noise recordings by 831 (orchid) used as a reference, SET original (blue) and equalized (cyan).

Table 3. RSM amplitude deviation of "white" noise recorded by the SET.

831 vs SET	RMS amplitude deviation (dB)
original wave	32.8
equalized wave	3.6

Table 4. Percentage error on the eco-acoustic indices; comparing the .wav file of 831 vs SET original (left column) and equalized (right column).

831 vs SET		Original wave	Equalized wave
% error	ACI	0.20	-0.02
	ADI	0.5	0.1
	AEI	-654.9	-18.6
	BI	-4.3	5.6
	NDSI	95.9	2.6
	H	10.6	0.3
	DSC	54.5	1.3
	ZCR	60.4	-4.2

In Fig. 7, the SET original spectrogram differs from the one of the sound level meter (Fig. 5), especially in the high frequencies above 8 kHz. As it can be seen in Fig. 2, the SET does not present an anomalous peak in the frequency response like SMM, and its response is more linear under 3 kHz. Moreover, in Fig. 7 and Fig. 8, it is possible to notice that the equalized SET recording is very similar to the 831s. In fact, in Tab. 3, the root-square-mean deviation of the amplitude between the level meter and the SET drop of about 30 dB, due to the greater RMS deviation of 831-SET than 831-SMM. Finally, the percentage error on the calculation of eco-acoustic indices (Tab. 4) benefits from the equalization except for BI, which increases, in absolute value, by 1 percentage point.

Comparing the RMS values and percentage error between the SMM and SET analysis (Tab. 1-4), it is possible to assert that:

- the overall audio file amplitude, referenced to the 831, is equal after the process (RSM = 3.6 dB for both instruments);
- the percentage error is reduced, especially for the SET, probably due to its flatter sensitivity than SMM which helps the software transformation (Fig. 1, 2).

3.2 Field measurements (soundscape)

3.2.1 Analysis of a single recording through spectrograms and amplitude deviation

In this section, we examined a single audio file as a model for the application of the equalization protocol. This audio file, recorded at 12:07 a.m. at the Vivaio-Bicocca, contains traffic noise, human speech and the alarm call of a Eurasian wren (*Troglodytes troglodytes*). As stated by the protocol, the spectra of the recording and the mean frequency spectrum were produced (Fig. 9 and Fig. 10 respectively).

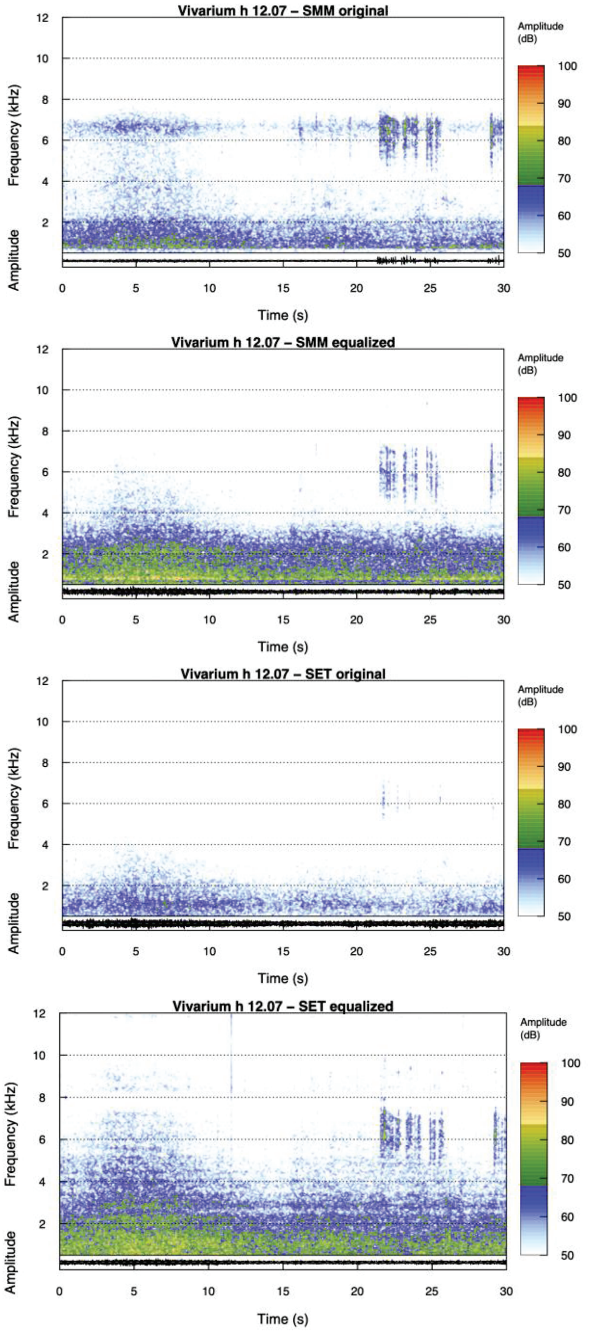

Figure 9. Spectrograms of the vivarium recording at 12:07 a.m. From top to bottom the spectrograms belong to the SMM (original and equalized) and to the SET (original and equalized).

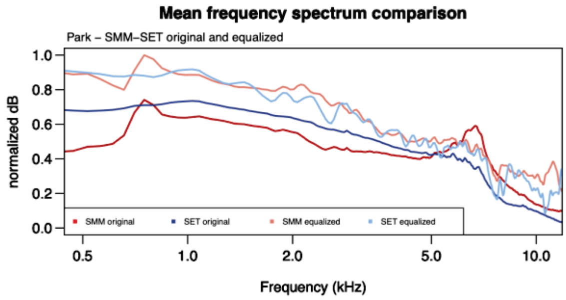

Figure 10. Mean frequency spectrum of the vivarium recording at 12:07 a.m. Darker colors represent SMM and SET original audio while lighter ones represent the equalized audio.

The RMS deviation of the amplitude between 0.5-12 kHz was calculated to carry out a quantitative comparison between original and equalized recordings at the vivarium (Tab. 5, 6).

Table 5. RSM amplitude deviation of the vivarium recording at 12:07 a.m.; comparison inter-devices.

	RMS amplitude deviation (dB)
Original: SMM vs SET	23.4
Equalized: SMM vs SET	3.7

Table 6. RSM amplitude deviation of the vivarium recording at 12:07 a.m.; comparison intra-devices.

	RMS amplitude deviation (dB)
SMM: original vs equalized wave	13.2
SET: original vs equalized wave	34.9

The spectrograms of Fig. 9 show the remarkable difference between the original recordings of SMM and SET. The greatest contrast is noticeable at 6 kHz, where the traffic and the Eurasian wren call were almost not recorded by the SET, while it seems to be amplified by the SMM due to its frequency response (Fig. 1). The high unevenness of the SMM and SET is also evident in their mean frequency spectrum (Fig. 10) and in Tab. 5 where a 23 dB gap is underlined. On the other hand, the equalized audios are certainly more similar, with an exception around 4 kHz where the SET presents higher levels. This overall difference is estimated in 4 dB of RMS amplitude deviation (Tab. 5). This slight shift may be linked to the laboratory conditions (it is not an anechoic nor semi-anechoic chamber) and to the “white” noise used to calculate the equalization curves. In fact, a flatter signal may increase the accuracy of the audio correction. In any case, the improvement is noticeable as shown in Tab. 5 and 6 by the RMS values.

3.2.2 Analysis on the whole campaign using eco-acoustic indices

As a final method to assess the improvement of the equalization procedure, time series trends of the eco-acoustic indices were elaborated on the park campaign recordings.

Fig. 11 shows the time trends of the eight eco-acoustic

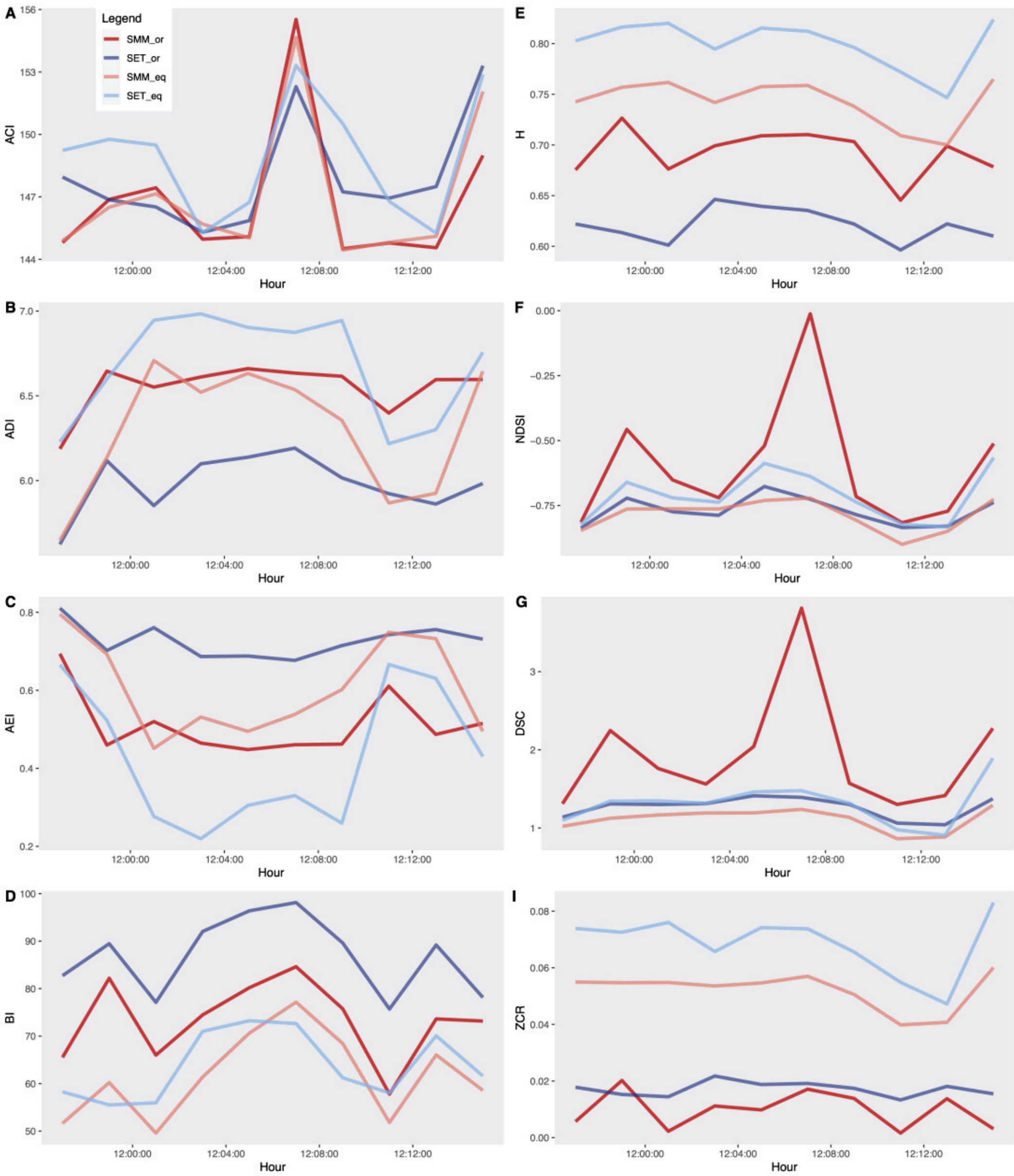

Figure 11. Time trends of the eco-acoustic indices.

indices implemented. While interpreting the graphs, it is important to keep in mind the effects of the equalization on the mean frequency spectrum (Fig. 6, 8), which flattens the 6 kHz peak of the SMM and increases the low-frequency bands in both SMM and SET.

ACI's trends do not seem to gain a relevant benefit from the equalization process; this may be due to its calculation process, which compares adjacent temporal and spectral bins. ADI and H measure the intensity evenness of a recording, both in time and frequency; thus, SMM's trend is flattened while SET's is increased. On the contrary, since AEI indicates the unevenness of a recording, its values decrease for both instruments but the curves' separations remain constant. BI and NDSI show an overall improvement in the trends and values caused by the frequency limit requested in their calculation; the biases, which are known in the literature [9, 10], are reduced after the equalization process. SMM's NDSI and DSC benefit from the equalization, especially when birds' vocalizations around 6 kHz are present (at 12:07 a.m.). Finally, ZCR's values increase after the process due to the higher traffic and background noise levels which were underestimated in the original recordings due to the poor microphone sensitivity at those frequencies.

4. CONCLUSIONS

To correctly characterize the soundscape of an area, the use of calibrated soundscape recorders is fundamental. Unfortunately, nowadays there is still scarce information and concern regarding this matter in soundscape and eco-acoustic studies.

In this paper, we explained how the equalization was carried out in a laboratory and in MATLAB. The preliminary results on the amplitude and eco-acoustic indices differences show that an uncareful use of diverse instrument typologies can cause interpretation biases and errors while monitoring the soundscape of an area. These biases must be limited and a calibration procedure in a laboratory is necessary if the research community wants to define guidelines and limits to properly monitor and protect soundscape and ecosystems and habitat biodiversity.

Future steps to improve the equalization procedure involve real white noise measurements in an anechoic or semi-anechoic chamber with different distances from the sensors and longer simultaneous field measurements. Finally, the effect of the eco-acoustic indices will be evaluated by comparing a wide area soundscape spatial map before and after the equalization process.

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