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BIOACUSTICS OF ECOSYSTEMS: INSIGHTS FROM MULTI-COMPONENT OBSERVING STATIONS IN ITALY AND MOZAMBIQUE

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ABSTRACT

Human activities impact the environment, prompting science to help create policies for responsible use of natural resources. Environmental sustainability, biodiversity, and ecology are interconnected and crucial for healthy ecosystems. This means we need to study the ecosystems as a whole, not just as an integration of individual parts.

Sound is present in all environments and can help us understand the relationship between biodiversity and environmental conditions. Scientists usually study sounds in the air, focusing on how living organisms behave in different situations. However, the biosphere includes air, soil, and water, each requiring different methods based on available technology.

We investigated the potential of an instrumental set-up to simultaneously record sounds in air, soil, and water in two ecosystems: mangroves in Mozambique and a humid forest in Italy. Preliminary results allowed to identify common traits and differences between the different components, and suggest we should move beyond traditional methods that only analyze frequencies or acoustic indicators.

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1. INTRODUCTION: WHY

Environmental sustainability, biodiversity, and ecology are interrelated foundations crucial for the well-being of ecosystems and the overall health of our planet. Safeguarding biodiversity, which refers to the variety of life on Earth, has received large attention as a key to contribute in the functioning of ecosystems. Every species has in fact a specific role in maintaining the equilibrium of the system, ranging from pollination to soil regeneration. Ecology, the study of interactions between organisms and their environments, helps us understand how ecosystems operate and how human activities impact on it. The integrity of ecosystems relies therefore on a rich tapestry of biodiversity [1] and the interrelationships between organisms and physical conditions [2-4]. Disrupting ecosystems through deforestation, habitat destruction, and the spread of invasive species endangers biodiversity and weakens ecological resilience. Protecting biodiversity is not just about saving individual species but preserving the intricate web of life that sustains ecosystems and the services they provide, such as air, water, soil, and food. In this context, it is essential to incorporate the monitoring of all the different components of biosphere to gain insights into the functioning of ecosystems. However, in many cases, these processes are technically complex, time-consuming, and challenging when needed for feeding models and simulations.

Since biological resources, natural events and human activities are pervading the acoustic field, we focused on monitoring the soundscape of the different components of the environment and look for emergent properties.

We investigated the potential of an instrumental set-up to simultaneously record sounds in air, soil, and water in two ecosystems: mangroves in Mozambique and a humid forest in Italy. Preliminary results allowed to identify common traits and differences between the different components, and suggest we should move beyond traditional methods that only analyze frequencies or acoustic indicators.

2. METHODOLOGY: WHERE, WHAT AND HOW

2.1 Locations

An instrumental set-up to monitor simultaneously the soundscapes in air, soil, and water has been developed and installed in Italy and in Mozambique.

One observing station was positioned in the Regional Park of Migliarino, San Rossore, Massaciuccoli, central Italy, 4 m above sea level (43°43'18.2"N, 10°17'4.8"E). The Park extends on a coastal alluvial plan, characterized by a coastal dune system [5]. In this environment, superficial aquifers are present, and the study area was selected within a coastal oak forest dominated by Quercus ilex L., typical of the Mediterranean forest ecotype of the Regional Park. The access to the Park is limited and very few cars can enter every day.
Data were acquired from March 2024 to July 2024.

Another station was installed in the island of Inhaca, in Mozambique, in two different locations (26°2'49.2”S, 32°54'3.6"E, and 26°3'8.22"S, 32°53'53.56"E). Both locations are characterized by the presence of mangroves and are included in a reserve area in Inhaca, where human activities are limited to few passages by foot, and they can be considered as pristine environments.
Data were acquired for two weeks during a summer school of the ManGrowth project held in October 2024 [6].

2.2 Instrumentation

A system consisting of four acoustic sensors were used and positioned accordingly to the geomorphology of the environments we selected for the observations.
The signals were amplified using the four channels of a Zoom P4 Podtrack, and the respective gains were adjusted to maintain the mean signals within the available dynamic range. Simultaneous recordings at 16 bit and 44100 Hz sampling frequency were saved as successive files of 3h 22m 53s duration each.
The overall system, excluding the sensors and the power supply, has a weight less than 1 Kg and dimensions of less than 20x20x20 cm3.

2.3 Positioning

One microphone (model Maono model PM 320), protected from atmospheric agents such as rain and wind, was positioned above the ground at approximately +60 cm in Italy, while hanging at approximately +120 cm on a mangrove branch in Mozambique.
Three other sensors (hydrophones Aquarian model H2a) were positioned.
In Italy, one hydrophone was at -15 cm depth from the ground level, and other two hydrophones, aligned vertically, at -15 cm and -80 cm respectively and both at a distance of approximately 13m from the first hydrophone. The hydrophone at -80 cm was immersed in the aquifer.
In Mozambique, one hydrophone was hanged on a mangrove’s root, and at a height that allowed the sensor to be in air or in water accordingly to the tide cycle, another hydrophone was buried in the soil, that in our case was mainly in the mud, the last hydrophone was a few meters apart from the other two, ad always in the water. The first location was on a flat area, while the second close to a river.

In Fig. 1 and Fig. 2, the three different locations and positioning of the sensors are shown.
We will refer at signals from the four different positions of the sensors in the three locations as specified in Table 1.

Table 1. The four different positions of the sensors in the three locations. Colours refer to sensors in Fig.1.

REFERENCE NAMES	Location	Position
HUMFOR_AIR	Humid forest, IT	AIR
HUMFOR_SOIL1	Humid forest, IT	-15 cm
HUMFOR_SOIL_2	Humid forest, IT	-15 cm
HUMFOR_AQUIFER	Humid forest, IT	-80 cm
MANFLAT_AIR	Mangroves, MZ	AIR
MANFLAT_BRANCH	Mangroves, MZ	Branch
MANFLAT_SOIL	Mangroves, MZ	Mud
MANFLAT_WATER	Mangroves, MZ	Water
MANRIVER_AIR	Mangroves, MZ	AIR
MANRIVER_BRANCH	Mangroves, MZ	Branch
MANRIVER_SOIL	Mangroves, MZ	Mud
MANRIVER_WATER	Mangroves, MZ	Water

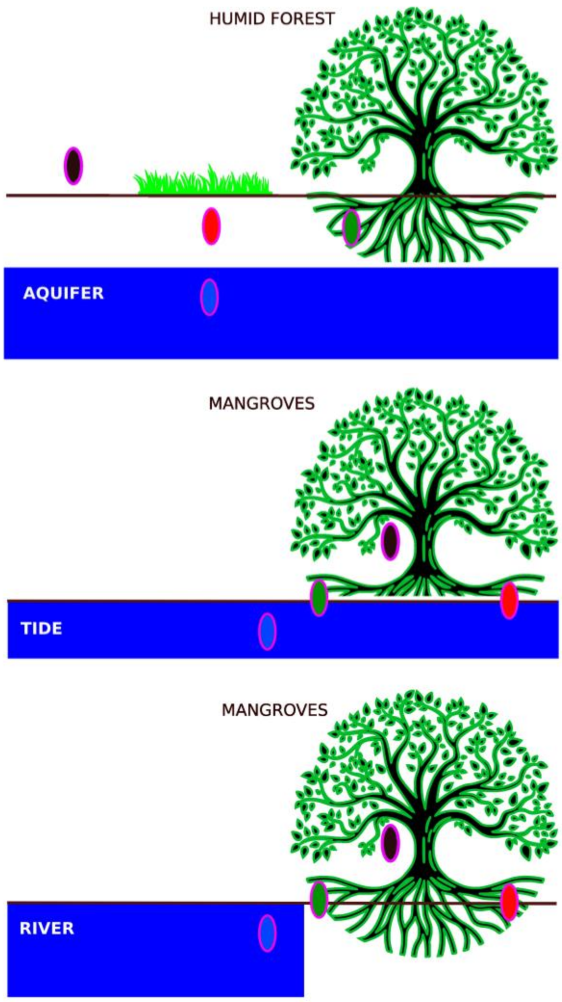

Figure 1. A schematic representation of the three locations (from upper to lower panels) and the four different positions of the sensors (colours refers to the positions described in Table 1).

2.4 Data analysis

Signals were analyzed via Fast Fourier Transform, using first the software *Audacity* for a preliminary check of frequencies and main traits. Timeseries, power spectra and further analysis were obtained with *IDL* software package. Additional elaboration of the signals to compute the acoustic indexes was performed using different software packages (soundecology [7-8], *warblerR* [9], *tunerR* [10] *seewave* [11]).

Figure 2. The observing stations in the three locations (from top to bottom, respectively: the humid forest in the Park of San Rossore, the first and second stations in Inhaca).

3. RESULTS

What immediately emerged from the analysis is that the dynamics of the soundscape in Inhaca MANRIVER is much richer than MANFLAT and richer than in the Park of San Rossore. Some samples are shown in Figures from 3 to 8.

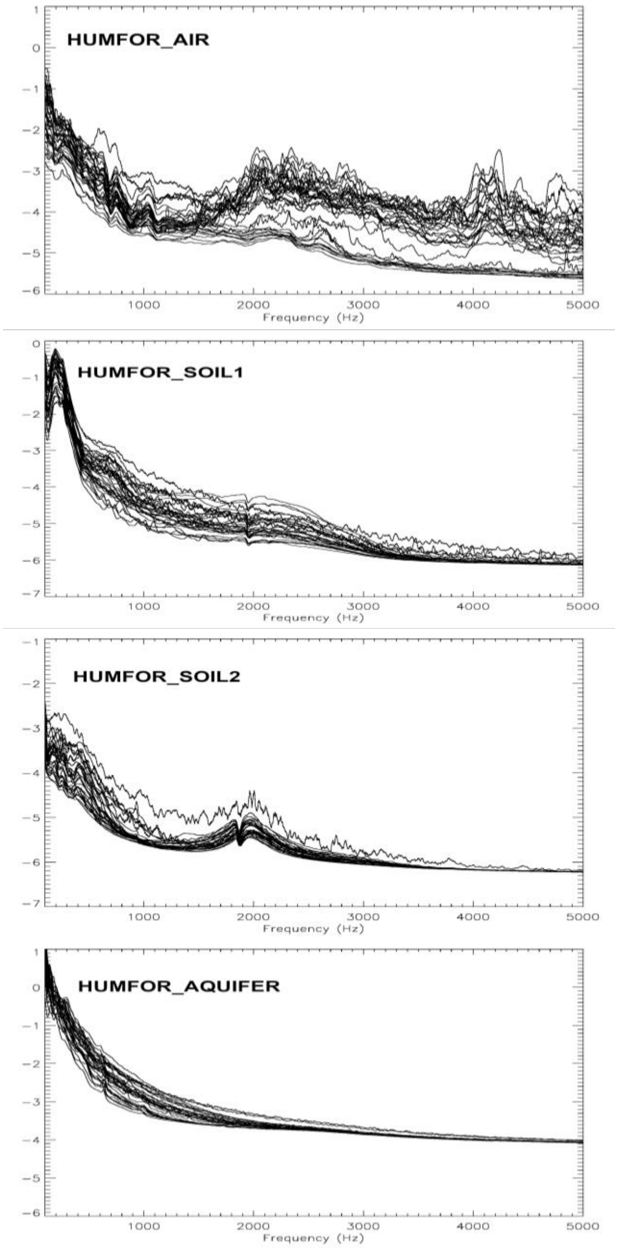

Figure 3. The log in base 10 of the power spectra (centred between 1 and 5 kHz to better show the details) of the signals from HUMFOR_AIR,HUMFOR_SOIL1,HUMFOR_SOIL2,HUMFOR_AQUIFER (from top to bottom panels respectively). Each curve corresponds to a power spectrum of a set of 43 files of 3h 22m 23s duration, starting from 24 May 2024. On y-axis arbitrary units.

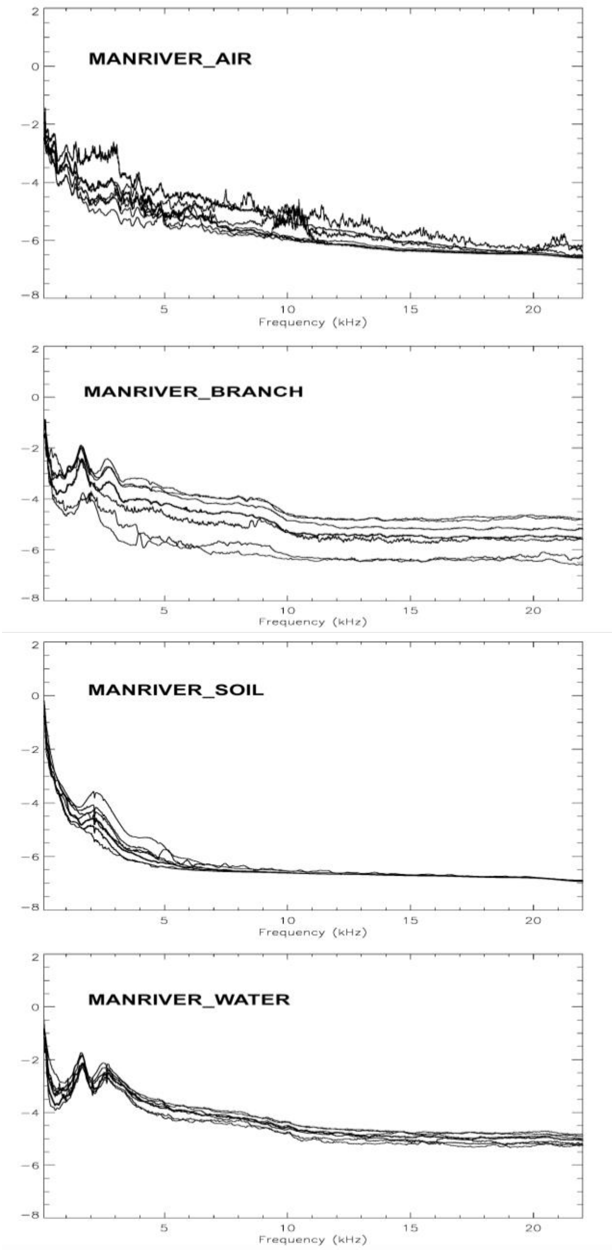

Figure 4. The log in base 10 of the power spectra (up to the Nyquist Frequency) of the signals from MANRIVER_AIR,MANRIVER_BRNCH,MANRIVER_SOIL,MANRIVER_WATER (from top to bottom panels respectively). Each curve corresponds to a power spectrum of a set of 7 files of 3h22m23s duration, starting from 6 Oct 2024. On y-axis arbitrary units.

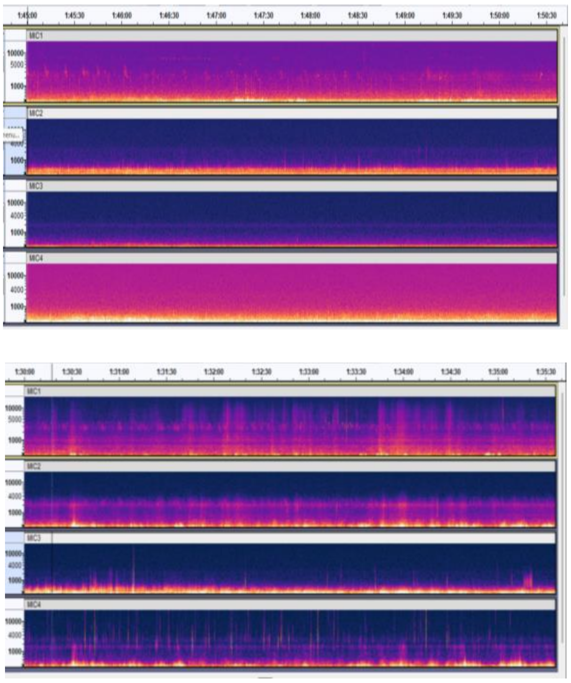

Figure 5. Examples of traits of power spectra for the 4 sensors in Park of San Rossore (upper panel) and in Inhaca (bottom panel). Panels show a 5-min zoom of the power spectra of a 3h22m23s run. On y-axis, frequencies in Hz. White and reddish colours refer to more powerful signals.

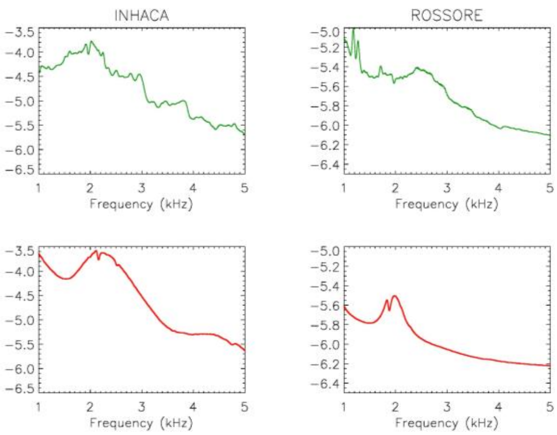

Figure 6. The log in base 10 of the power spectra (centred between 1 and 5 kHz) of the signals from MANRIVER_BRANCH and MANRIVER_SOIL (on the left, in green and red respectively), HUMFOR_SOIL1 and HUMFOR_SOIL2 (on the right, in green and red respectively), for a 3h22m23s temporal window. On y-axis arbitrary units.

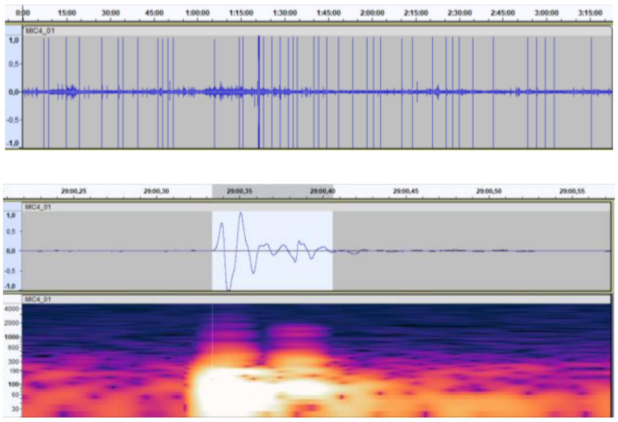

Figure 7. Examples of impulsive signals (i.e. spikes) detected in the aquifer in Park of San Rossore on 19th March 2024. Upper panel: a 3h22m23s run. Bottom panel: a zoom on one of the impulses with the associated power spectrum (on y-axis, frequencies in Hz). The impulses are not periodically occurring, show always the same signature, and last approximately 0.07s.

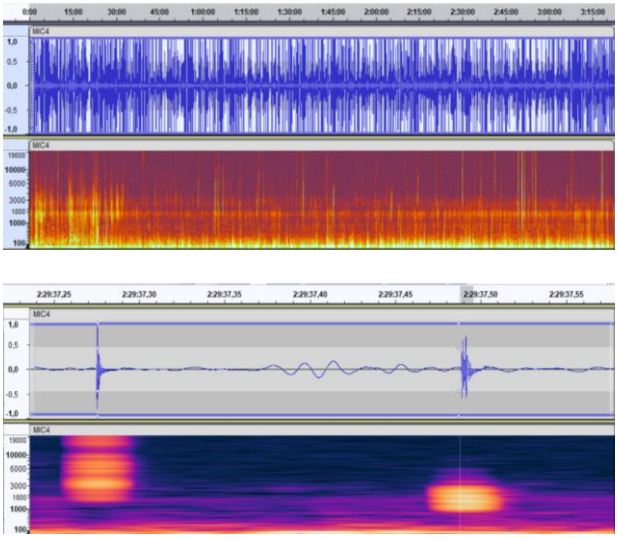

Figure 8. Examples of impulsive signals (i.e. spikes) detected in the river in Inhaca on 6th October 2024. Upper panel: a 3h22m23s run with the associated power spectrum (on y-axis, frequencies in Hz). Bottom panel: a zoom on a couple of successive impulses with the associated power spectrum (on y-axis, frequencies in Hz). The impulses are not periodically occurring, show different signatures with durations between 0.02 and 0.08s.

4. DISCUSSION AND CONCLUSIONS

Investigation of soundscapes in air relies on an historical large experience in the recognition of acoustic sources. Signatures of natural sources (e.g. rain, thunders, earthquakes), biological (mainly birds) and anthropogenic ones (e.g. cars, aircrafts) have been catalogued and many tools are available. It is not the aim of this paper to list the species that have been identified. As an example for one of our locations, some reports are available for the identification of birds In Inhaca [12].
Many acoustic indexes have been proposed for the extraction of information from the data, and their values have to be interpreted accordingly to the benefits and limitations that each of them can provide [13-14].

Despite of the large experience in acoustics in air, the identification of signals to the respective sources is a real challenge in soils and water.
In fact, when an acoustic signal is difficult to be clearly recognized in the spectrum, the experience as humans embedded in soundscapes in air facilitates the recognition via listening directly the sound. In soils and water this is very rare.
Acoustic studies in various terrains have traditionally focused on investigating movements within the Earth's mantle or rock layers. Beyond seismic applications, acoustic measurements served to monitor changes in soil characteristics, as well as capture sounds related to flowing water, cracks, and other indicators of physical conditions or habitats for flora and fauna. Generally, the methodologies to observe the biosphere within soils are not fully developed, and only a few examples have been documented. Our understanding of soil soundscapes at higher frequencies than those typically measured by geophones (20–20,000 Hz) remains limited, likely due to the increased attenuation of sound. In fact, soil structures strongly attenuate acoustic wave propagation above 2 kHz [15].
Few examples of acoustic studies of biodiversity in soils reported, mainly in forests [13,16]. Acoustic traits were associated with abiotic parameters and soil communities, Diurnal and seasonal trends were observed. Additional experiments in laboratory have been implemented to associate soundscapes and biotic sources in soils [17]. All the mentioned observations used sampling frequencies below 50kHz.
Some progress has been made in studying soundscapes within aquatic environments, particularly in marine ecosystems. The Wenz curves [18] still serve as the primary framework for understanding marine soundscapes, outlining the key characteristics of the spectral distribution of acoustic sources. However, most studies focus on the effects of maritime traffic at low frequencies, and many biological sources remain difficult to identify, with the exceptions of mammals' vocalism and fish chorus. Innovative approaches have been proposed for understanding the links between acoustic sources and processes that govern the equilibrium of the marine ecosystems [19-20].

For these reasons, when approaching the soundscape of ecosystems as a whole, we need to reflect on the limitations of the used instrumentation and the previous knowledge that can suggest any interpretation.

We installed acoustic observing stations in different ecosystems, and we took advantage of the high sensitivity of hydrophones installed in humid or aquatic media.
The system has already proven its potential to monitor the different components of the biosphere in a mangrove ecosystem in a remote island in Mozmbique [6].
Now we compared the data acquired also in a humid forest in a Reserve Area in Italy.
We focused on the main traits, commonalities and differences between the soundscapes, looking at clues for the identification of signatures of the ecosystems as a whole, that when signals are acquired simultaneously in air, soil and water.

Having in mind that is not the aim of this paper to describe in detail the identification of the signatures of the acoustic sources, we summarize the main results as follows.
Commonalities: the signals from the soil and vegetation show clear acoustic signatures at frequencies between 1 and 4 kHz. The power spectra show a characteristic "bell" shape with details that are slightly different between the stations, suggesting that they refer to a distribution of contributing acoustic sources (see Fig. 6).
Differences: the locations are very different in terms of ecosystems, with the African one characterized by a richness of biodiversity and the influence of tides. The aquifer in Italy is poor of living organisms, in contrast with the river in Africa. In terms of acoustic noise, the Italian ecosystem, despite embedded in a reserve area, is largely impacted at low frequencies by the aircraft passages that are detected in all the components, while the human impacts in Inhaca have not been detected and can therefore be considered a true pristine environment for acoustic monitoring.
Impulsive events in the aquatic media have been recorded in both locations: they are both aperiodic but their nature is very different.

Those in the aquifer shows a constant temporal profile, while those in the river not. We suggest that those in the aquifer are related to the relaxation of energy associated to the physical properties of the system, while those in the river are associated to the crustaceous and crabs.

In this context, we proceed to a comparison of the information extracted via acoustic indexes and other indicators produced by algorithms that were built ad-hoc to extract different information. Power spectra of 0.27s time intervals have been computed and, at different frequencies, powers above 10 standard deviations were selected and identified as events. The number of spikes has been averaged over a 5 min interval and named EVENTS.

We report the temporal behaviour of classical acoustic indexes and one indicator (EVENTS) in Fig. 9 and 10.

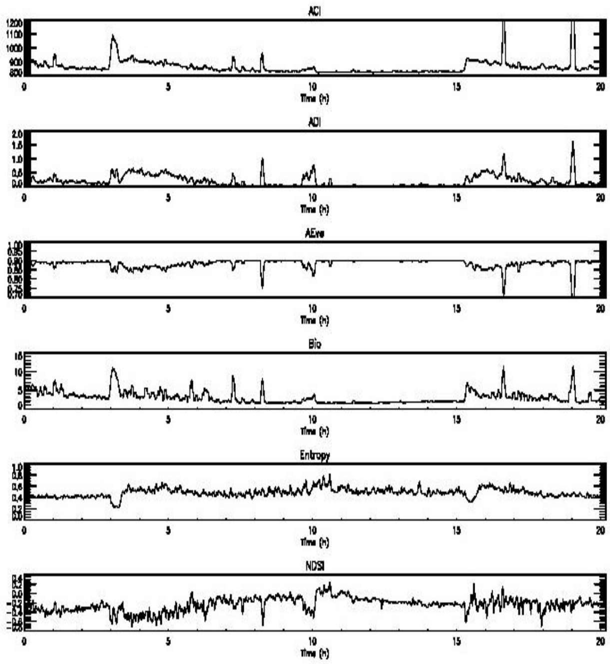

Figure 9. The values of different acoustic indexes (from top to bottom: ACI, ADI, AEve, Bio, Entropy and NDSI) computed for MANRIVER_WATER on 1st Oct 2024.

To conclude, we showed that the soundscape at frequencies between 1 and 4 kHz *in soils* from different ecosystems can be a useful tool to describe the characteristics of biotic sources and their health.

We also showed that the information on biodiversity usually extracted via acoustic indexes can be misleading, as already referred [21] when applied to soils and aquatic environments, suggesting to look at different data analysis for a better understanding of the interconnected components of the ecosystems.

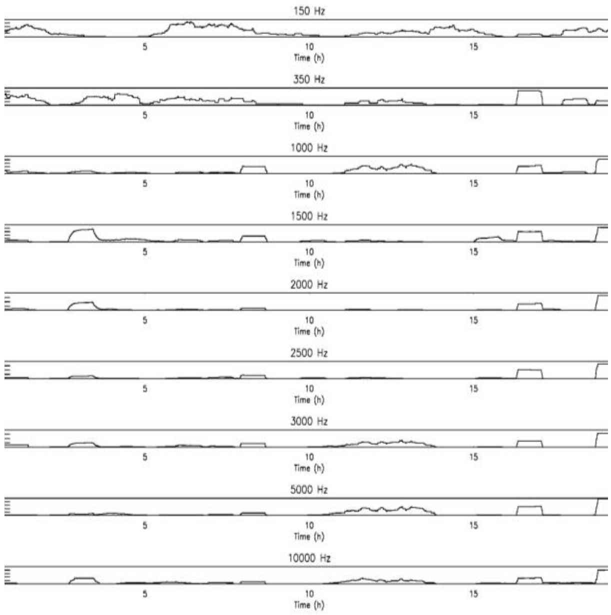

Figure 10. The values of the indicator named EVENTS (see text) at different frequencies (MANRIVER_WATER on 1st Oct 2024). Temporal coincidences at many different frequencies suggest impulsive events. Different time cycles are shown, preliminarily associated to biological sources and/or physical processes. On y-values are arbitrary units, aiming to show time cycles.

5. ACKNOWLEDGMENTS

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