Ecological Indicators 158 (2024) 111566

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Listening to tropical forest soils

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ARTICLE INFO

Keywords:
Ecoacoustics
Soil ecology
Soundscapes
Bioacoustics
Soil macrofauna
Tropical forests

ABSTRACT

Acoustic monitoring has proven to be an effective tool for monitoring biotic soundscapes in the marine, terrestrial, and aquatic realms. Recently it has been suggested that it could also be an effective method for monitoring soil soundscapes, but has been used in very few studies, primarily in temperate and polar regions.

We present the first study of soil soundscapes using passive acoustic monitoring in tropical forests, using a novel analytical pipeline allowing for the use of in-situ recording of soundscapes with minimal soil disturbance. We found significant differences in acoustic index values between burnt and unburnt forests and the first indications of a diel cycle in soil soundscapes.

These promising results and methodological advances highlight the potential of passive acoustic monitoring for large-scale and long-term monitoring of soil biodiversity. We use the results to discuss research priorities, including relating soil biophony to community structure and ecosystem function, and the use of appropriate hardware and analytical techniques.

1. Introduction

Acoustic monitoring has allowed the field of ecoacoustics to reveal new information on a range of soniferous communities in above-ground terrestrial and aquatic habitats (Desjonquères et al., 2020, Sueuer et al., 2014, Sugai et al., 2019). In particular, it has proven effective at showing that soundscapes vary significantly across landscapes and habitat types at large spatial scales (Mitchell et al., 2021, Metcalf et al., 2021, Bradfer-Lawrence et al., Eldridge et al., Do Nascimento et al., 2020), and in revealing temporal dynamics such as diel and seasonal variation in a range of habitats from tropical forests to coral reefs (Garcia Oliveira et al., 2021, Bertucci et al., 2016, Farina et al., 2023).

Passive acoustic monitoring - long-duration recording without human presence, has recently been suggested as a tool for studying soil soundscapes (Maeder et al., 2019). Despite being apparently well-suited to the task, ecoacoustic analytical techniques have rarely been used to monitor soundscape dynamics below the ground. Few studies have used soundscapes to compare soil biodiversity in different locations (Keen et al., 2022, Maeder et al., 2019, Maeder et al., 2022; Robinson et al., 2023), all of which used different methodologies and equipment, and have all been conducted in temperate and polar regions. We are unaware of any studies from the tropics. Monitoring changes in soil health and biodiversity is of particular importance in tropical forests, as these are amongst the most biodiverse habitats in the world, and amongst the most threatened by human impact (Barlow et al., 2018). Anthropological impacts such as forest disturbance have already been shown to negatively impact soil fauna (Franco et al., 2019), although the temporal and spatial dimensions of such impacts are poorly understood.

As soil soundscape assessment is a novel application of ecoacoustics in the tropics, it is first necessary to make basic assessments of the capacity to differentiate soundscapes from different habitats and the time of day, prior to application at large spatial and temporal scales. Here we

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https://doi.org/10.1016/j.ecolind.2024.111566
Received 17 October 2023; Received in revised form 21 November 2023; Accepted 6 January 2024
Available online 13 January 2024

develop a novel pipeline for processing acoustic data to assess soil soundscapes in tropical rainforests. We test the method's suitability by comparing soundscapes from burnt and unburnt forests, and by assessing biophonic activity patterns across the diel cycle. This application is particularly pertinent as forest disturbance, such as edge effects, selective logging, wildfire, and increasing drought frequency (Lapola et al., 2023) is pervasive across Amazonia, and understanding their impacts is considered a conservation priority.

We assess the suitability of acoustic monitoring as a tool for monitoring soil in the tropics. First, we evaluate the composition of soil soundscapes, testing whether soil soundscapes are predominantly generated in the soil (e.g. aren't spill over sounds from the air). Second, we investigate the spatio-temporal dynamics of soil soundscapes by testing the sensitivity of soil soundscapes to forest disturbance and by assessing if the soundscapes exhibit diel periodicity.

2. Methods

2.1. Data collection

We collected two soil acoustic datasets in three municipalities: Santarém, Belterra and Mojuí dos Campos, in the state of Pará, (eastern Brazilian Amazon latitude ~ − 3.046, longitude − 54.947 WGS 84), from long-running forest degradation monitoring sites (Gardner et al., 2013). The region has a hot and humid climate with a marked dry spell between August and November, and annual average temperatures of 25 °C, 86 % mean relative humidity and a mean 1920 mm of rain (Berenguer et al., 2018). In general, soils are rich in clay and nutrient poor (Silver et al., 2000). All recordings were made in *terra firme* forests - i.e. those not seasonally flooded.

To test whether soil recordings are sensitive to forest disturbance, we sampled ten sites in total, seven sites (hereafter 'spatial dataset') unaffected by fire and three sites in which the forest has been burnt during the prolonged drought associated with the El Niño events of 2015/2016 (Withey et al., 2018). The plots have been chosen as they are used in ongoing studies on the impacts of fire and drought in the region (see Berenguer et al, 2021 for further details on fire impact in the region). Frequent monitoring has shown that fire impacts remain the dominant forest disturbance impact at the burnt plots, whilst the unburned plots have not subsequently burned. The long temporal duration of fire impacts is to be expected in humid tropical forests which have no evolutionary experience of fire and matches empirical data on stem dynamics (Silva et al., 2018). All sites were separated by a minimum distance of 2 km. Data were collected between 21 November and 6 December 2022. This period is the onset of the rainy season when soil biotic activity is likely at its highest (Levings and Windsor, 1985) - although we avoided recording during periods of rain.

Recordings were made at each point for 30 min between 09:20 and 14:00 (for logistical reasons, with a minimum buffer of 3 min at the start and end of each recording to avoid including footsteps or other anthropogenic sounds associated with researcher presence. Recordings were made using a Zoom H5n recorder with JrF C-series Pro Piezo contact microphones and XLR impedance adapters in both the left and right channels. The input levels were set to the maximum (10). We chose to use contact microphones as they are most sensitive to sounds transferred through contact with solid material, therefore reducing the sensitivity to above-ground sounds that may obscure the soil soundscape pattern. Microphones were placed at the furthest distance apart the cables would allow, approximately 4 m, and a slot was created with a knife so that the microphones would sit in the soil/clay layer, with the top of the microphone disc in contact with the hummus layer (see SOM Appendix 1 for video of standard deployment). This method of microphone deployment thus only caused a minimal amount of soil disturbance, ensuring that recordings were likely to be as unimpacted by the experimental setup as possible.

To test whether soundscapes exhibit temporal periodicity (hereafter "temporal" dataset), we sampled three new sites within the study region located a minimum of 100 m apart. Recording was conducted using the equipment set-up described above for 24 h on 7 December 2022 at Site 1, for 48 h starting on 8 December 2022 at Site 2 and 24 h on 12 December 2022 at Site 3.

2.2. Analysis

We split all recordings from both datasets into 1 min files. We tested whether the recordings contained biophony with a qualitative analysis conducted by viewing a proportion of the spatial dataset in Raven Pro (ver 1.6; Center for Conservation Bioacoustics, 2019). We compared the recordings to data from the Sounding Soil repository (Maeder et al., 2019; https://www.soundingsoil.ch/en/listen/) to qualitatively assess the presence of biophony. It was clear that the vast majority of sound was at frequencies < 500 Hz. Consequently, we used a macro in Audacity (ver 2.3.3; Audacity team, 2021) to shift the pitch upwards by 900%, such that sounds in the original data at 1 kHz were now at 10 kHz. In the text hereafter, we refer to the frequencies at their original values. To remove prominent non-biophonic noise from the recordings (most likely microphone self-noise), we applied an adaptive level equalisation algorithm (Towsey, 2013) using the remove_background_along_axis function in the scikit-maad package (ver 1.3.12.; Ulloa et al., 2021) in Python (Van Rossum & Drake, 2009).

To provide a statistical summary of the soundscape we calculated a suite of acoustic indices. Given the general paucity of information on the dynamics of soil biophony, we selected six acoustic indices that reflect a range of soundscape patterns; the Acoustic Complexity Index (ACI, Pieretti et al., 2011), the Bioacoustic Index (BI, Boelman et al., 2008), the number of spectral events per second (EVNspCount, Towsey et al., 2013, QUT, 2023), an adjusted version of the Normalized-Difference Sound Index (NDSI, Kasten et al., 2012), the proportion of the spectrogram covered by regions of interest (ROIcover, Ulloa et al., 2021) and Frequency Entropy (Hf, Sueur et al., 2008) - see Table 1 for our expectation of their responses to increased biotic soil activity.

Table 1
Acoustic indices used in this study, and our expectations of the way index values would be reflected in soil soundscapes.

Index	Expectation
Acoustic Complexity Index (ACI) (Pieretti et al., 2011)	Increasing values in unburnt soils with an increase in biophony. One of a pair of heuristic indices (with BI) intended here to directly reflect biophony.
Bioacoustic Index (BI) (Boelman et al., 2008)	Increasing values with an increase in biophony. One of a pair of heuristic indices (with ACI) intended here to directly reflect biophony.
Spectral Events (EVNspCount) (Towsey et al., 2013, QUT, 2023)	Increasing values in unburnt soils with an increase in biophony. One of a pair of indices (with ROIcover) intended here as a metric of general acoustic activity levels.
Normalized-Difference Sound Index (NDSI) (Kasten et al., 2012)	Values are expected to be lower in unburnt forest as we expect biophony to be spread over a greater range of frequencies and not solely clustered at very low frequencies. One of a pair of indices (with Hf) intended here as a metric of the distribution of sound across frequency.
Regions of Interest (ROIcover) (Ulloa et al., 2021)	Increasing values in unburnt soils with an increase in biophony. One of a pair of indices with EVNspCount intended here as a metric of general acoustic activity levels.
Frequency Entropy (Hf) Sueur et al., (2008)	Values are expected to be higher in unburnt forest as we expect biophony to be spread over a greater range of frequencies and not dominated by a single species at one frequency. One of a pair of indices (with NDSI) intended here as a metric of the distribution of sound across frequency.

We calculated each of the acoustic indices with a maximum frequency of 500 Hz, as the majority of acoustic energy was below this. The other parameters for each index were; Acoustic Complexity Index (ACI) at default settings using the 'soundecology' method; the Bioacoustic Index (BI) had a minimum frequency of 10 Hz and up to the maximum of each bandwidth using the 'soundecology' method; the number of spectral events per second (EVNspCount), with a 6-db threshold and a minimum duration of 0.2 s; Normalized-Difference Soundscape Index (NDSI), with the lower frequency band set at 0 to 150 and Hz and upper frequency band set at 150 Hz to 500 Hz; and the proportion of the spectrogram covered by regions of interest (ROIcover), with the default amplitude settings, a max xy ratio of 10, a mask 1 parameter of 6 and a mask 2 parameter of 0.2. Finally, we calculated Temporal Entropy (Hf) using the default settings and with compatibility set to the 'seewave' package. Full details of these settings can be found in Ulloa et al (2021).

To assess the sensitivity of acoustic index values to the frequency parameters and denoising techniques selected, we tested the impact of two different noise removal techniques and three different frequency bands to calculate the indices, the results of which are available in SOM Appendix 1. All acoustic index values were scaled between zero and one prior to analysis.

2.2.1. Assessing soil soundscape composition

Firstly, we tested the independence of the right and left channels from each recording. This had two purposes. Firstly, we wanted to assess if each channel could be used as a nested data point in further analysis – previous studies have suggested a recording radius 30 cm for Piezo contact microphones in soil, albeit using different equipment (Maeder et al., 2019). Additionally, as our microphones were placed close to the surface, we wanted to ensure we were not recording airborne sounds such as birdsong, insect stridulation, and human noise. Sound attenuates slowly in air compared to soil (Oelze et al., 2002), so most airborne sounds should be able easily travel the 4 m gap between microphones, and be recorded on both channels, resulting in highly correlated index scores between the channels. However, if the index scores from both channels are independent, then this suggests that soundscape is predominantly composed of sounds generated and conducted in the soil that do not carry the distance between the microphones.

To address the question of independence, we first conducted qualitative analysis by creating long-duration spectrograms of the 24 hr period from Site 1 of the temporal dataset (Fig S2.1), showing the first 10 s of each minute over the 24 hr period. Secondly, we undertook a quantitative analysis using the spatial dataset. We calculated the Spearman's Rank correlation between the index values from the left and right channels of each site (same-site correlations) using the cor function in R. Next we calculated the pairwise correlation of the left channel of a site with the left channel from each remaining site, and did the same for the right channels (cross-site correlations). We used a generalised linear mixed effect model to compare the same-site correlations with the cross-site correlations to see if index values were more strongly correlated if they came from the left and right channels of the same site. We used the glmmTMB R package with the correlation coefficient as the dependent variable and a two-level independent variable of same-site and cross-site correlation, with acoustic index as a random factor and a beta family distribution using a logit link. Due to the beta family distribution, to make the correlation coefficients fit between the 0–1 scale, we added 0.00001 to the two values that had a correlation coefficient of 0.

Whilst independence of the recording channels is a strong indication that the soundscape is predominantly generated in the soil, it does not necessarily prove a biophonic (faunal or floral) origin of the sound – it could equally come from geophony such as water movement. Quantitatively proving biophonic origin of sounds in soundscapes is difficult given there are no acoustic traits that are definitive of biophony and few, if any, sound repositories exist for Amazonian soil macrofauna to make comparisons with. Consequently, we opted to qualitatively assess the recordings, listening to them whilst reviewing spectrograms, and comparing the sounds heard to the few sound repositories available for European soil macrofauna (Maeder et al., 2019; https://www.soundingsoil.ch/en/listen/, Royal Entomological Society (n.d.), 2023). We have made the entire audio dataset available on Dryad so that readers can also listen to it. It was possible to eliminate the possibility of anthropophony as recordists sat quietly a minimum of 50 m away during the recordings, with all transects located a minimum of 140 m away from the nearest possible vehicle access – with no passing vehicles or other human sounds heard by the team during any of the recordings.

2.3. Spatial and temporal variation in soil soundscapes

We compared the scores from unburnt and burnt sites using a generalised linear mixed model for each index. We hypothesised that soil biotic activity would decline with disturbance, represented by lower ACI, BI, EVNspCount, Hf and ROI cover and higher NDSI values in burnt forest. We used the glmmTMB R package (ver 1.1.5, Brooks et al., 2017, R Core Team, 2022) using the same structure for each model, with the acoustic index as the dependent variable, the burnt/unburnt forest class as a two-level independent variable, and recording location and recording channel as a nested random factor with a beta family distribution using a logit link. The beta distribution has been used for analysing acoustic indices previously (Bradfer-Lawrence et al., 2020). As values range from 0 to 1 in the beta distribution it is well suited to normalised data and has no prior expectations related to the distribution within that range, so can handle heteroskedastic and asymmetrical data (Ferrari and Cribari-Neto, 2004).

Finally, to assess temporal periodicity in soil soundscapes, we looked for the presence of a diel cycle in soil acoustic activity. Using the temporal dataset, we computed indices in the same manner as above. We used hierarchical general additive models following Pedersen et al., (2019) to assess temporal patterns in the index values. Again, we retained the same model structure for each model, with index value as the dependent variable, a smooth term for time as an independent variable with a cyclic cubic regression spline and six basis dimensions, and a factorial smooth of recording channel by recording site with a random effect spline. We used a beta family distribution with logit link and restricted maximum likelihood estimation for the smoothing parameters.

3. Results

3.1. Assessing soil soundscape composition

A qualitative assessment of long-duration spectrograms of the 24 hr period from Site 1 of the temporal dataset (Fig. 1), showed some similarity in trends between channels, but in general there is limited direct correspondence between individual sound events, indicating a high degree of independence between the channels. It is also worth noting that in the raw recordings, the footsteps of departing and returning researchers were audible on both channels in the discarded portions at the start and end of all recordings, suggesting that louder sounds do carry between the channels.

In the quantitative analysis, we found that correlation between the index values from the left and right channel recordings at the same site was low (Fig. 2) - ACI had the highest mean correlation of 0.26 ± 0.24 (SD) and NDSI had the lowest 0.11 ± 0.04. Overall, there was no significant difference ($p = 0.903$) in the correlation coefficients for same-site correlation as there was for crossed-site correlation. Such low correlations imply that there is minimal overlap in sound events in soil soundscapes over even very short distances (approximately 5 m) implying a high level of local spatial variation.

Qualitative assessment of the sound recordings suggested that differentiation between geophony, such as sounds of water filtration through the soil, and biophony such as faunal and floral sounds was not straightforward. In some cases, clear patterns that appeared consistent

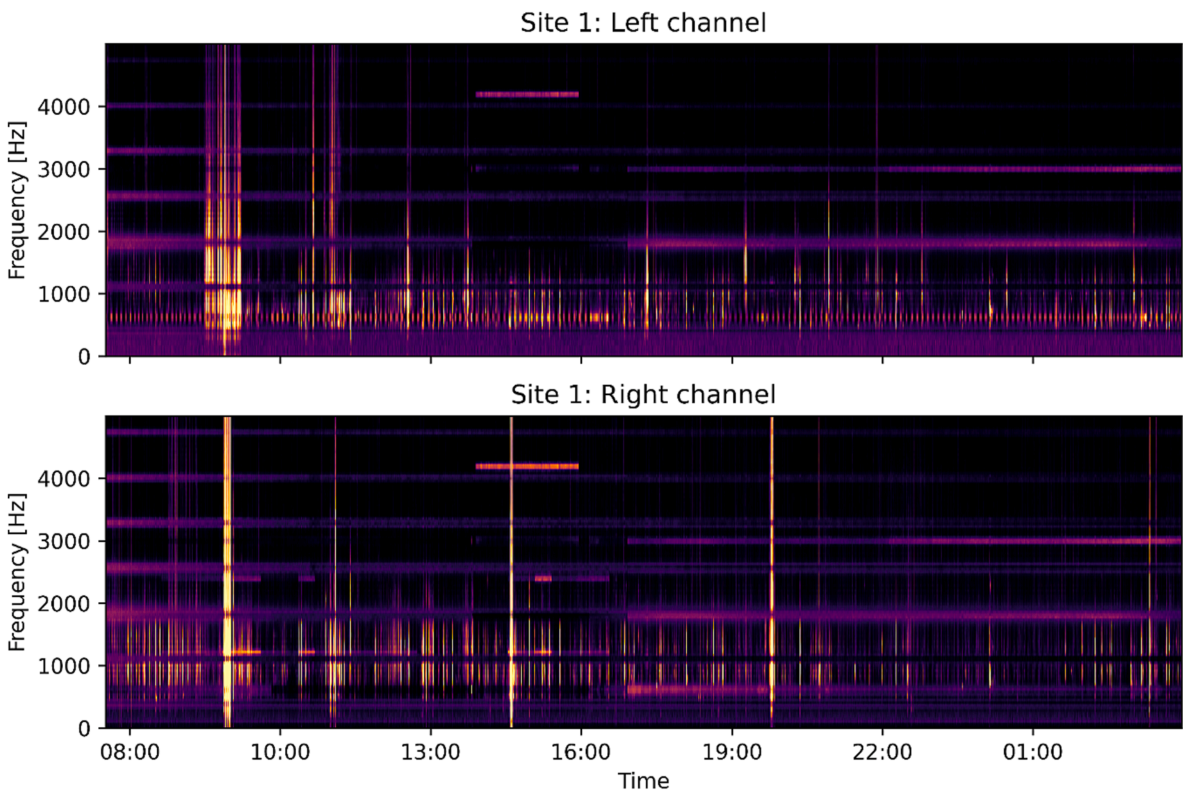

Fig. 1. Long duration spectrograms of the 24 hr period from Site 1 of the temporal dataset, comparing the left channel (top) with the right channel (bottom). Spectrograms produced in Python using the scikit-maad package and are pitch-shifted by 900%.

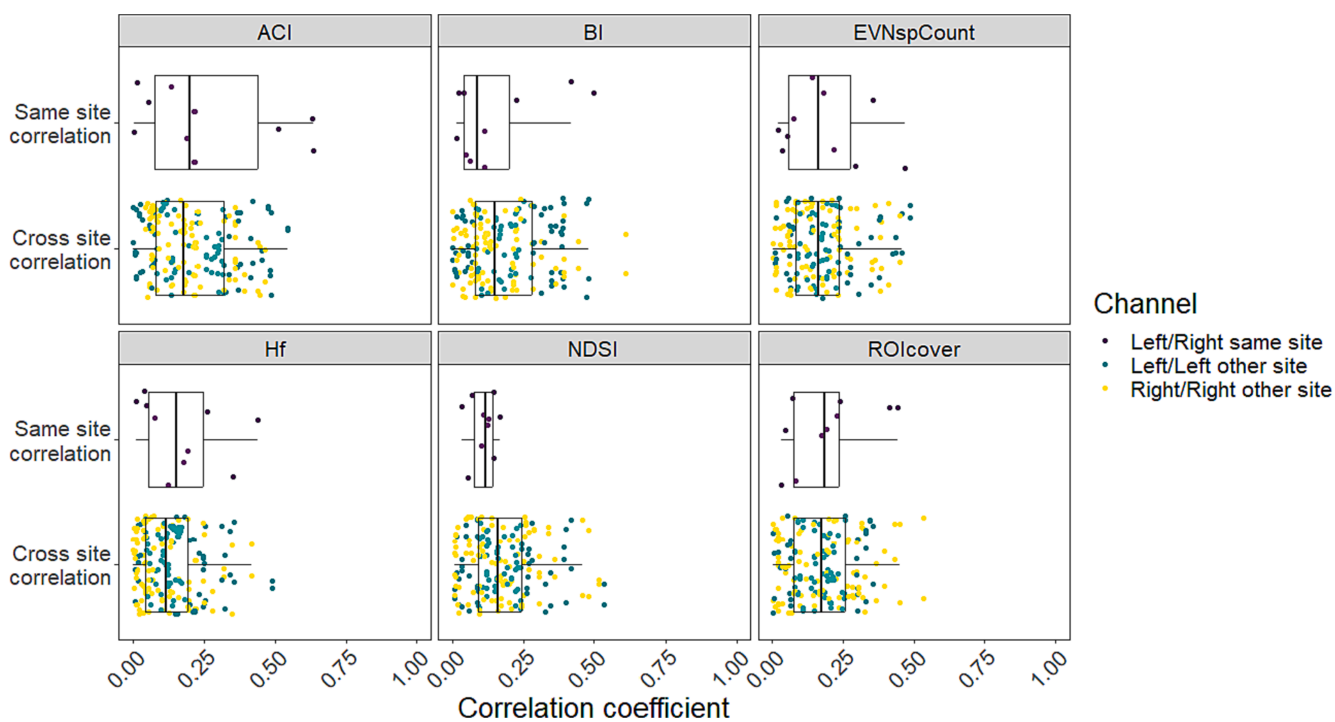

Fig. 2. Spearman's rank correlation coefficient values comparing correlation of acoustic index values derived from both channels at the same site (Same site correlation), with correlation values from the corresponding channels at other sites (Cross site correlation). Overall, correlation was low, and same site correlations were not significantly larger than cross site correlations, indicating a high degree of independence between channels from the same site and potentially a high level of local soundscape variation between sites.

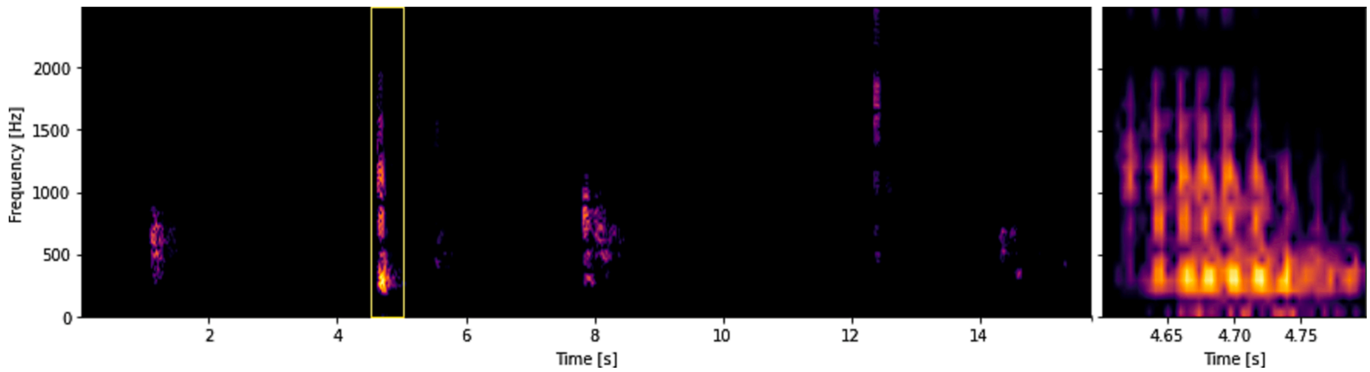

Fig. 3. A pitch-shifted 15 s recording taken from the temporal dataset at Site 1 on 7 December 2022 at 06:35, showing an apparent alternating signalling between stridulating fauna. The stridulations at just after 1 s and 8 s are similar volume so likely emitted by the same animal, whilst the stridulation at 4.7 s (shown in close-up in the right-hand panel) is louder and presumably closer. The event just after 12 s is at a higher frequency and may be from a different individual or species. Sound file manually edited in Adobe Audition to remove noise and highlight biophony, spectrograms produced in Python using the scikit-maad package.

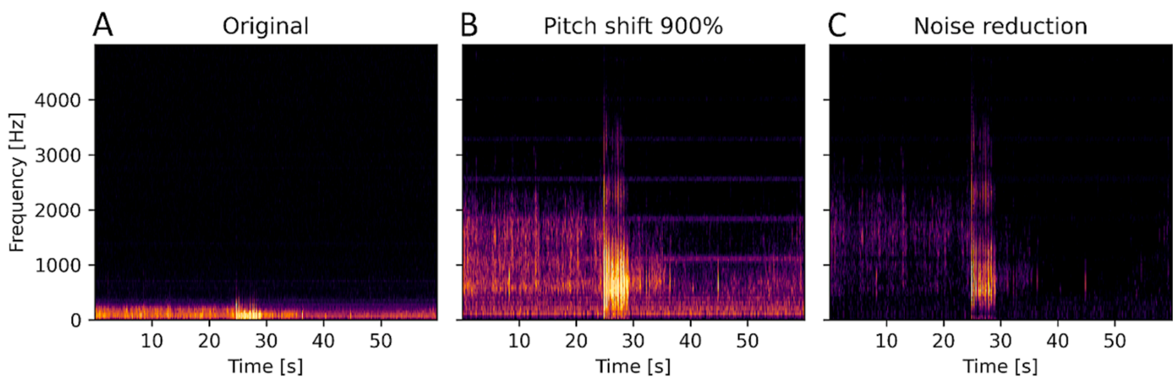

Fig. 4. *Spectrograms of one minute of audio recording from a burnt forest site on 21 November 2022 at 09:47 in its untransformed state (A), after applying a 900 % pitch-shift transformation in Audacity (B) and following denoising (C). The sound event at approximately 25 s appears to be biophonic in origin.* Spectrograms produced in Python using the scikit-maad package.

with biophony in soil soundscapes from other regions were observed such as apparently alternating stridulations (Fig. 3) and knocking and scratching noises (Fig. 4). An example recording with this alternating signalling is available on Dryad (https://doi.org/10.5061/dryad.05qfttf7t), alongside the full spatial dataset for anyone wishing to listen to recordings. However, in many cases it was not possible to definitively assign sounds to a source and this remains a key research priority in this nascent field.

However, inspection of spectrograms across the human audible frequency ranges (e.g. 0–20 kHz, Purves et al., 2001) often used to assess above-ground soundscape recordings were not very useful, as acoustic energy was concentrated at low frequencies. When listening to the recordings at their original frequencies it was difficult to distinguish biophony from microphone self-noise and environmental sound, suggesting that a degree of sound processing was required. The pitch-shifting process in Audacity enhanced the clarity of these sounds (Fig. 4).

3.2. Spatial and temporal variation in soil soundscapes

We found support for our hypothesis that soil soundscapes vary between burnt and unburnt forest with significant differences ($p = < 0.05$) in the values of BI and EVNspCount in burnt and unburnt forest (Fig. 5). However, these indices responded differently to disturbance than anticipated, with increased values in burnt forest (mean BI in burnt forest 0.31 ± 0.12 (SD), unburnt forest 0.21 ± 0.10 (SD); mean EVNspCount in burnt forest 0.12 ± 0.13 (SD); unburnt forest 0.07 ± 0.10(SD)). ACI, Hf, NDSI, and ROIcover were not significant.

Analysis of temporal periodicity demonstrated variation in the values of ACI, BI, and EVNspCount and ROIcover (Fig. 6), with peaks between 08:00 and 12:00, and lows between 23:00 and 02:00, providing strong evidence for diel cycles in soil acoustic activity. Hf showed an inverse trend, with low values just before 08:00 and high values around midnight, whilst NDSI showed two peaks, one at around 04:00 and the second at 16:00, with lows at around 10:00 and 20:00.

4. Discussion

4.1. Assessing soil soundscape composition

Through establishing the independence of the recording channels, we have demonstrated that the dominant soundscape being recorded with our microphones was not conducted through the air. There is strong evidence from other regions that soil fauna contribute strongly to the below-ground soundscape (e.g. Keen et al., 2022), and we found that the tropical soundscapes recorded here had considerable similarities in the type and quality of the sounds that are found in known soil fauna sonifications (e.g. Maeder et al., 2019). However, as with other studies conducted in Europe (Maeder et al., 2019, 2021), it is not easy to differentiate between geophonic noises and biophony, or between faunal and plant biophony given that roots can be a major source of sound emission (Gagliano et al., 2012, Lacoste et al., 2018). Nevertheless, it has been argued that geophony can form an integral part of a soundscape and can be just as unique to an environment as the biophony (Bradfer-Lawrence et al., 2019).

It is, however, impossible to comprehensively rule out that animals moving on the surface may be contributing to an unknown extent.

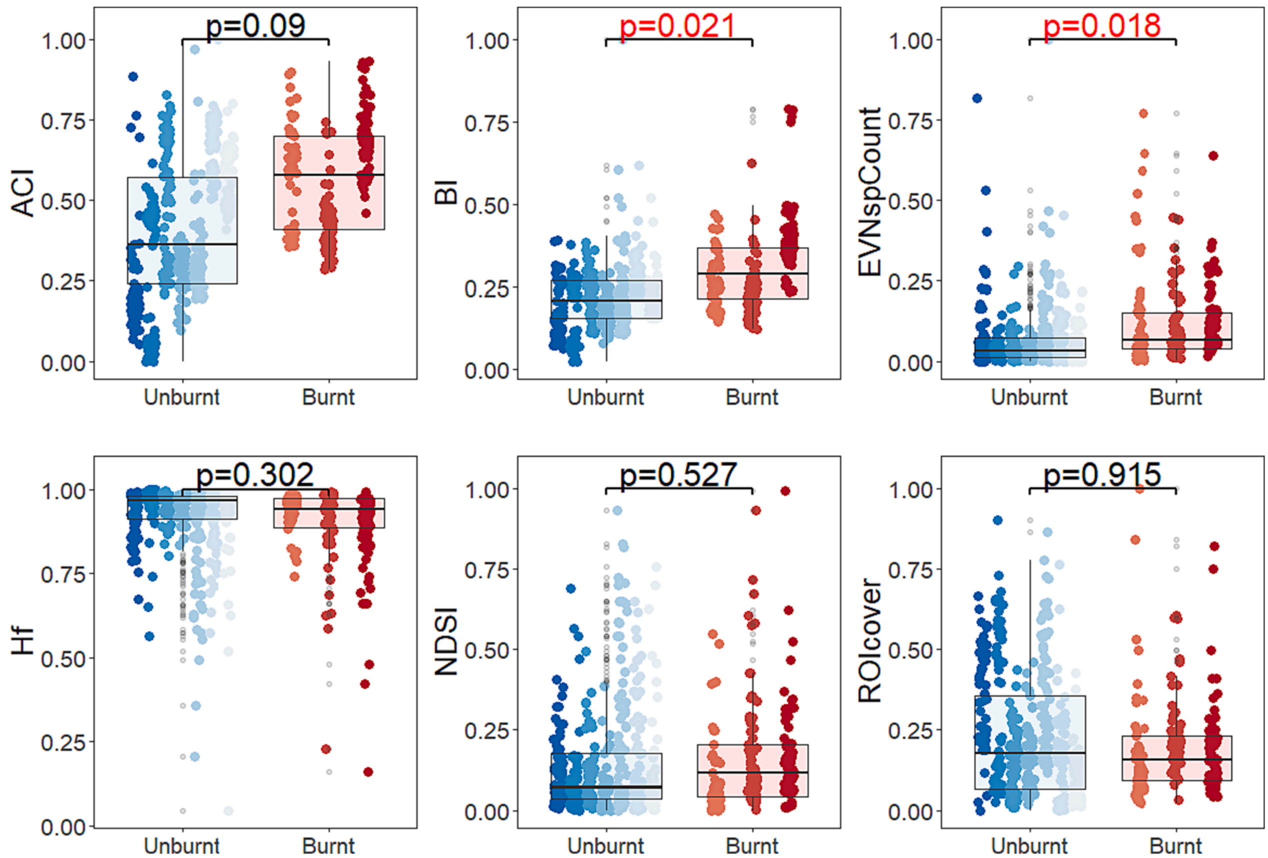

Fig. 5. Boxplots of the acoustic index values for six acoustic indices between burnt and unburnt forest. Points are jittered by recording site. Significance values are derived from generalised linear mixed models with red text indicating $p < 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

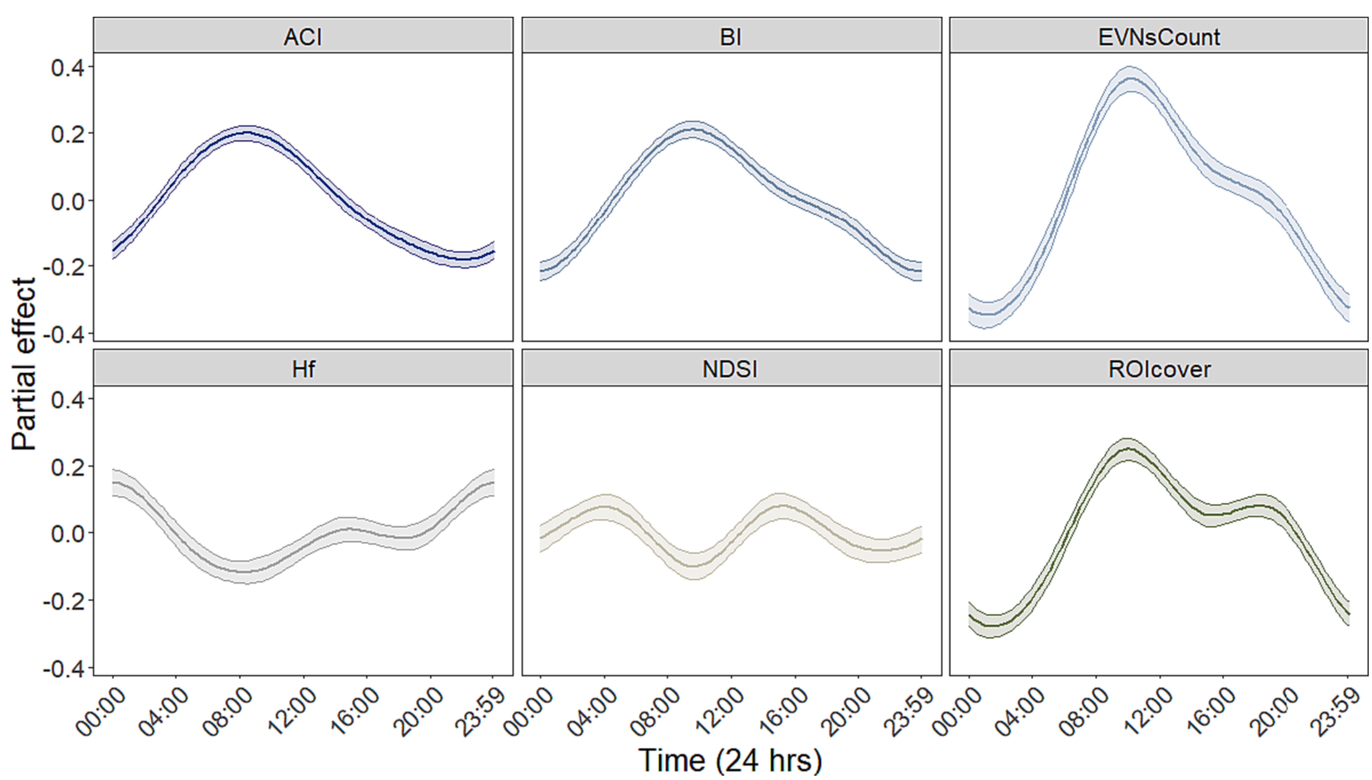

Fig. 6. The effect of time of day on six acoustic indices.

Whilst it would be desirable to further investigate this possibility, ideally in an ex-situ environment or with a paired microphone above the ground, it is also possible to consider surface sounds that permeate the soil part of the soil soundscapes, especially in studies wishing to understand the undersoil acoustic environment. This fits with the concept of a 'sonotone', an acoustic boundary similar to an ecotone, with different but permeable soundscapes on either side of the divide (Farina et al., 2021). It may be that, as with ecotones in ecology, sonotones provide a rich avenue for future research for ecoacoustics.

We did identify a range of apparently biotic sounds but assigning them to any taxonomic group is currently not possible as there are very few, if any, reference sounds available for tropical soil fauna. Creating a reference library of soil biotic sound should be a research priority for this ecoacoustic field and would greatly facilitate understanding the composition of the soil soundscape, although it may be quite some time, if ever, before soil taxa can be inventoried as effectively as birds with PAM recordings. Rather, soil biophony may be best utilised to generate community level metrics, perhaps indicative of macrofaunal biomass or representative of ecosystem functions, such as bioturbation rates.

Studying soil fauna is challenging; existing methods are labour intensive, time consuming, often invasive, and require specialist taxonomic knowledge (Geisen et al., 2019). Soil faunas are also highly diverse and functionally important (Bardgett et al., 2014), playing important roles in nutrient cycling, carbon sequestration and soil structure (Briones, 2014; Lavelle et al., 2006). Therefore whilst there may remain significant analytical challenges in linking soil soundscapes to soil biodiversity metrics, the potential benefits are any potential considerable given the significant gaps in the soil ecology literature. Soil faunal knowledge is particularly lacking for studies covering large spatial extents and temporal dynamics (Guerra et al., 2020) - areas passive acoustic monitoring may be particularly well-suited to resolving.

With regards to methodological considerations, we were able to effectively record soil soundscapes in-situ using contact microphones placed directly into the soil, in contrast to other studies which have used ex-situ soil samples (Robinson et al., 2023) or microphones above the ground with waveguides (probes) to carry the sound from the soil (Maeder et al., 2019). However, at this stage we are unable to say which approach is likely to be optimal. At such an early phase of soil soundscape research, it is likely that embracing and testing a plurality of approaches is beneficial to the field.

Equally, from an analytical standpoint we found that the soil soundscape is dominated by much lower frequencies than those aboveground, meaning that some form of pre-processing of the sound is probably beneficial to use standard ecoacoustic analysis techniques such as indices that are designed for higher or broader frequencies. In this case, we chose to use pitch-shifting and denoising techniques. We believe that as the vast majority of trends and significant differences were insensitive to denoising method and the frequency band selected for analysis (SOM 1), it is highly likely that the differences in index values are reflective of true soundscape differences rather than sampling artefacts. Still, there are a range of alternatives that may be as effective, such as customising the acoustic index calculations for lower frequencies and using more expensive equipment that can record with less recorder self-noise, or using lower gain settings and better pre-amplifiers. The low frequencies and high attenuation rates of sound in soil also have consequences for sampling design, and it would be beneficial to undertake experiments to look at the spatial heterogeneity of soundscapes at different scales. This could potentially follow the 'sonotope' sampling designs set out by Farina et al (2023) in order to better understand the spatio-temporal dynamics.

4.2. Spatial and temporal variation in soil soundscapes

We were able to distinguish between soil soundscapes from burnt and unburnt forests using acoustic indices. This capacity to discriminate between habitats by soundscape is in keeping with above-ground ecoacoustic analysis (Bradfer-Lawrence et al., 2019, Do Nascimento et al., 2020, Metcalf et al., 2021). Although the trend in index values was the inverse to that hypothesised, we should be cautious in ascribing this to an increase in biodiversity in burnt forest.

Studies on soil fauna in burnt forests have shown reduction in diversity and abundance in soil organisms (Zaitsev et al., 2016), although there are very few studies globally and particularly in Amazonia (Franco et al., 2019). A study in northern Amazonia showed fire caused declines in both species richness and abundance of dung beetles, leading to a reduction in larger beetles and dominance of small-bodied species (Andrade et al., 2014). A plausible explanation for our results could be post-fire dominance of a single species that is more prone to making sound, or alternatively the competitive release of one or two generalist or fire-resilient species and subsequent increase in abundance causing the increase in BI and EVNspCount values we found. A third explanation is that fewer or the same number of individuals may be present, but fire may alter the structural or chemical composition of the soil so that the rate of sound attenuation alters, leading to a different recording radius in burned forests. Resolving the underlying ecological or acoustic reasons for the significant differences in soundscapes is likely to be a valuable direction for future research.

Generally, however, it is very difficult to infer direct biodiversity change from acoustic index values, and it is not clear how effective acoustic indices are as proxies for traditional biodiversity metrics. There are a large number of studies linking above-ground acoustic indices to biodiversity metrics such as species richness, diversity, or abundance, but none of the acoustic indices have a clear and consistent relationship with these metrics (Alcocer et al., 2022), even for well-studied taxa like birds. This is particularly the case in soundscapes such as these that seem to be predominantly composed of incidental sounds generated through movement, rather than communicative sound, somewhat undermining the theoretical underpinnings of many of the heuristic indices based in the acoustic niche hypothesis (Sueur 2008).

Whilst attempting to link soil soundscapes directly to diversity metrics is obviously desirable, and linking acoustic indices from soil soundscapes to more traditional measures of soil diversity such as those derived from pit-traps should still be considered a research priority - it may be better to link soundscapes to acoustic morphotypes or 'operational sound units' (Luypaert et al., 2022), or to soil functioning such as bioturbation. This may be especially true for soil functions associated with a few abundant species, especially if they produce sound or the functional processes themselves produce sound.

We believe our study is also the first acoustic evidence for diel cycles in soil fauna in the tropics, and there is very limited research on the topic using any method. Our findings support similar results from Switzerland (Maeder et al., 2022), showing strong daytime peaks in acoustic activity. Interestingly the Swiss study finds peaks in ACI values after midday, in line with maximum surface temperature. In contrast, our results show ACI peaking just before 09:00, well before the average surface temperature peaks at our study site (13:00 during the survey period, calculated using the weathermetrics package in R (Anderson et al., 2013), which may be due to the different ecosystems and macroclimates. Previous studies have shown roughly similar peaks in soil insect activity using direct measurements such as trapping (Williams, 1959), but studies into the diel cycle or circadian rhythms of soil fauna are rare. Further research is required to explore whether this diel cycle is universal amongst soil fauna or, as seems more likely, there are multiple trends, as in birds where some species avoid vocalising at the peak of the dawn chorus (Metcalf et al., 2021), and our method was only sensitive enough to detect the dominant pattern.

4.3. Summary

We show that passive acoustic monitoring can facilitate research into important and understudied aspects of soil biodiversity (Guerra et al., 2020) and in regions of high conservation value. Substantially more research is required to refine ecoacoustics as a tool for monitoring soil fauna. Still, given the early stage of development of the method, our results demonstrate the potential value of passive acoustic monitoring for soil research in the tropics, producing novel insights into soil biotic activity within just a few months of data collection.

CRediT authorship contribution statement

Oliver C. Metcalf: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft. **Fabricio Baccaro:** Conceptualization, Investigation, Validation, Writing – review & editing. **Jos Barlow:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. **Erika Berenguer:** Data curation, Funding acquisition, Investigation, Project administration, Resources, Writing – review & editing. **Tom Bradfer-Lawrence:** Formal analysis, Methodology, Visualization, Writing – review & editing. **Alexander C. Lees:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The spatial dataset is available at (https://doi.org/10.5061/dryad.05qfttf7t and the temporal dataset is available on request.

Acknowledgements

We would like to thank the RAS field and laboratory assistants: Marcos Oliveira, Gilson Oliveira, Renílson Freitas, and Josué Jesus de Oliveira for their hard work and assistance, without whom this would not be possible. We are also grateful to Joice Ferreira for logistical field support in Brazil.

Fieldwork in Brazil and/or later analysis was supported by research grants PELD-RAS (CNPq, Brazil/CAPES, Brazil/PELD, Brazil 441659/2016-0), the BNP Paribas Foundation, France, Climate and Biodiversity Initiative (Project Bioclimate), and the NERC Rainfauna project NE/X015262/1.

Authorship statement.

No AI generative writing tools have been used in the production of this paper.

All authors made substantial contributions. Oliver Metcalf, Jos Barlow, Alexander Lees, Fabricio Baccaro and Tom Bradfer-Lawrence made substantial contributions to conception and design. Oliver Metcalf, Erika Berenguer, Liana Chessini Rossi and Érica Marinho do Vale contributed to the acquisition of data. All authors contributed to analysis and interpretation of data, and drafting the article. All authors had final approval of the version to be published, agree to be accountable for the aspects of the work that they conducted and ensuring that questions related to the accuracy or integrity of any part of their work are appropriately investigated and resolved.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.111566.

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