Evaluating vibroacoustic sensor performance and vibration attenuation: implications for soil biodiversity sampling

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Abstract

Earth's biodiversity is undergoing substantial changes in response to anthropogenic stressors, creating a need for efficient methods of assessing biodiversity, particularly in soil ecosystems where sampling remains challenging. Soil vibroacoustics - the use of substrate-borne vibrations or sounds to quantify or detect below-ground biological activity – offers a potentially rapid and scalable approach to sampling soil fauna, but several methodological gaps remain. There is currently a lack of standardisation across studies. For example, few studies have compared sensor performance, evaluated sampling procedures, or quantified how soil conditions influence attenuation in field settings. We assessed the performance of three sensors in dry-season tropical soils: an Aquarian H1a hydrophone ('Hydrophone'), a JrF C-Series Pro contact microphone ('JrF'), and a JrF sensor attached to a metal waveguide ('Waveguide'). To test attenuation, sensors were positioned at varying distances from a buried speaker that emitted impulse tones (short broadband signals). The Waveguide approach was not suitable for dry, compacted soil because insertion caused structural damage to the waveguide. Recorded amplitudes did not differ significantly between sensors, but the Hydrophone exhibited a significantly higher signal-to-noise ratio (how clearly signals can be detected above unwanted background noise), whereas the JrF recorded significantly higher maximum frequencies in sandy soil. These differences may influence the detection of low amplitude vibrations from soil faunal activity. Soil type, compaction, moisture, temperature, and tree cover had minimal effects on attenuation and frequency loss. Further methodological refinement across different soil systems and geographical regions is vital for progressing soil vibroacoustic research.

Keywords: “ecotremology”, “soil-borne vibrations”, “biotremology”, “bioacoustics”, “passive monitoring”

1. Introduction

Earth's ecosystems are degrading rapidly due to anthropogenic stressors such as climate change, habitat transformation, and pollution. Anthropogenic impacts on biodiversity have been studied extensively in aboveground terrestrial systems, yet comparatively few studies have focused on soil ecosystems (Cameron et al., 2018; Guerra et al., 2020). Despite this, soils are vital to global biodiversity and ecosystem functioning, with an estimated 59% of all Earth's species living in the soil (Anthony et al., 2023). Therefore, improving our understanding of below ground biodiversity and their associated ecosystem functions, which underpin human livelihoods, is essential (Bardgett & van der Putten, 2014; Lavelle et al., 2006).

Large-scale and long-term biodiversity assessments require effective sampling methods, yet monitoring soil biodiversity remains challenging due to the labour-intensive and time-consuming extraction and identification required by traditional methods (e.g., soil coring, sieving, and hand-sorting; Edwards, 1991; van Klink et al., 2022). In recent years, there has been considerable development in alternative methods such as eDNA (Sahu et al., 2023; Y. Zhang et al., 2025) and passive acoustic monitoring (PAM) – the use of sounds to monitor species, environments and behaviours (Sugai et al., 2019).

Animals above and below the soil generate mechanical waves or substrate-borne sounds/vibrations (for consistency, we use the term 'vibration' throughout the manuscript), that can be detected using acoustic and vibrational sensors (Hill & Wessel, 2016), providing a potential means of detecting and quantifying below-ground biological activity. Soil vibroacoustics is a new term (Robinson et al., *in prep.*), yet research in this area dates back to the 1990s (Palestrini et al., 1990; Mankin, 1998) and early 2000s (Brandhorst-Hubbard et al., 2001; Zhang et al., 2003), with the field growing considerably in recent years. Vibroacoustic monitoring offers benefits compared with traditional methods of sampling soil biodiversity; it is less destructive and invasive, while also allowing for high temporal resolution – making it easier to capture both diel and seasonal patterns in activity (Metcalf et al., 2024; Robinson et al., 2024). Soil vibroacoustic research can therefore support long-term conservation and restoration projects by providing a rapid and efficient method of assessing biodiversity and ecosystem condition. However, there have only been a handful of ecologically linked vibroacoustic studies in this substrate thus far, and considerably more methodological research is required to develop a robust method of sampling biodiversity.

Several key knowledge gaps remain in soil vibroacoustics (Taylor et al., 2026), including the lack of standardised methods and vibroacoustic libraries (e.g., Mankin, 2024), alongside challenges in developing and applying appropriate analytical techniques. Crucially, little is known about how vibroacoustic sensors perform under different soil conditions. Mankin et al. (2000) compared an accelerometer and electret microphone for detecting subterranean insects, while Mankin et al. (2010) described acoustic and vibrational approaches for monitoring soil fauna; however, neither systematically quantified sensor performance across different soil conditions. Researchers have used a variety of sensors, with those in the early 2000s tending to use accelerometers (Mankin et al., 2000, 2001), geophones (Mankin & Benshemesh, 2006), or electret microphones (Mankin et al., 2000, 2007). Recently, piezoelectric sensors or contact microphones have been used for ecological monitoring (Farina & Mullet, 2025; Robinson et al., 2023). The absence of standardised recording approaches may limit comparability and reproducibility, while differences in sensor sensitivity, frequency response, and soil coupling could influence the detection and quantification of soil fauna. Direct comparisons of sensor performance are therefore urgently needed to inform standardised monitoring approaches.

Many soil-dwelling taxa actively or incidentally produce low-frequency vibrations, typically below 5000 Hz (Görres & Chesmore, 2019; Rauth & Vinson, 2006). For example, Japanese rhinoceros beetle (*Trypoxylus dichotomus*) pupae produce vibrations below 500 Hz (Kojima et al., 2012), whilst some ant and termite species stridulate between 1000 – 5000 Hz (Casacci et al., 2013; Hager & Kirchner, 2013). However, the distance over which current sensors can reliably detect these low-frequency soil-borne vibrations across different soil conditions remains poorly understood.

Determining the detection radius of each vibroacoustic sensor is important for defining the effective sampling volume, understanding species-specific bias, and assessing sampling completeness in diversity studies. The detection radius can be estimated by quantifying changes in amplitude over distance and determining the maximum range at which the vibration remains detectable by a sensor (Conrad et al., 2024). For example, Mankin et al. (2000) recorded insects in laboratory and field conditions and could identify insects with almost 100% reliability at <30 cm away in the laboratory, whilst reliability dropped to ~75% in the field due to environmental background noise.

Detection distance can be mediated by species-specific vibration amplitudes or frequencies, which determine vibration transmission. For instance, a study assessing the attenuation of sound in stored grain found that the degree of attenuation (the decrease in amplitude of a wave travelling through a medium) tripled from 0.02 dB cm^{-1} at 500 Hz to 0.06 dB cm^{-1} at 3 kHz (Hickling & Wei, 1995), indicating that species which produce high frequency vibrations may be harder to detect at distance due to more rapid attenuation. Detection distance is also affected by the levels of background noise relative to the target signal, typically quantified as the signal-to-noise ratio (SNR). Sensor-specific characteristics, such as intrinsic sensor noise or sensitivity to the lower frequency range, can influence the magnitude of background noise detected. SNR presents a particular challenge in soil vibroacoustic research, as background noise – often below 500 Hz – overlaps with the frequency range of many target vibrations. Therefore, a sensor with a low SNR (i.e., higher levels of background noise proportionate to the signal) will likely reduce detectability of particular species within recordings. Consequently, evaluating the SNR of different sensors is critical for assessing their suitability for ecological field studies.

Physical soil conditions can influence attenuation and, consequently, the effective detection radius of each sensor, as demonstrated by laboratory studies examining the effects of soil type, compaction, and moisture content on vibroacoustic waves. Sabatier et al. (1990) found that sand had the highest attenuation (i.e., greatest loss of wave energy) when compacted and dry, while clay and loess soil had substantially higher attenuation when compacted and wet. Oelze et al. (2002) discovered that attenuation was generally lower in more loosely compacted and drier soils, with variations in each soil type, whilst Lo et al. (2007) found that increasing water saturation produced a non-linear response in attenuation, with signal loss being greatest at intermediate moisture levels in most soils.

Although relatively few studies have directly examined the influence of soil temperature on vibroacoustic attenuation, temperature-dependent effects on vibrational waves have been demonstrated in other solid and sedimentary materials (Ye et al., 2024; Zou et al., 2015). For example, Zou et al. (2015) simulated how temperature influences attenuation in seafloor sand sediments and found that, at low frequencies, attenuation increases with temperature. While the geophysical studies are useful for understanding how different physical conditions may impact the detection range of soil fauna, these studies use measurements from simulations or controlled conditions in lab-based conditions and do not account for the heterogeneity of soils (e.g., rocks, roots, burrowing). Therefore, translating these results into a realistic ecological context remains a necessity.

Here, we compare the performance of three different sensor setups in seasonally dry tropical soils. Specifically, we focus on: (1) Differences in the amplitude and frequency response, and signal-to-noise ratio (SNR) of vibroacoustic sensors across two soil types (sand, clay); (2) The influence of physical conditions (soil type, compaction, moisture content, temperature, tree cover (as a proxy for presence of roots)) on attenuation and frequency loss. We predicted that: (1) The vibroacoustic sensors will differ in their effectiveness at detecting soil-borne vibrations, owing to differences in sensor design, frequency response, and coupling to the soil matrix, and (2) Physical conditions will have soil-type-specific impacts on attenuation and frequency loss.

Our study therefore assesses the performance of sensors and quantifies the influence of physical conditions on attenuation, with implications for determining a suitable ecological soil sensor for drier, warmer habitats and discovering potential biases involved with recording in different soils.

2. Methods

2.1. Study area

Sampling was conducted in the savanna grasslands of Laikipia County and Meru County in the central highlands of Kenya (located at 0.11 – 0.34° latitude and 37.07 – 37.53° longitude). We collected data in three conservancies situated either side of the Laikipia-Meru boundary: Lewa Wildlife Conservancy, Borana Conservancy, and Lolldaiga Conservancy. The elevation of this region is between 1400-2400 m. Average annual rainfall is typically between 400-600 mm (Giesen et al., 2017; Shaw et al., 2002) with considerable interannual variation.

Soil type varies across the study site. Lewa Wildlife Conservancy and Borana Conservancy are dominated by black cotton soil. These Vertisol soils are composed of an average of 50% clay (predominantly montmorillonite) and 24% sand (Young et al., 1998), and are high in humus, phosphorus, and ammonia. Black cotton soils (hereafter, 'clay soil') experience deep cracking during the dry season and high soil erosion rates during the wet season due to the shrink and swell properties of montmorillonite. Lolldaiga Conservancy is dominated by red soil. The red soils are Nitisol soils which average 74% sand and 24% clay content (Augustine, 2003) and are rich in iron and aluminium oxides. Red soils (hereafter 'sandy soil') experience less interannual variation in structure (less cracking) than black cotton soils, owing to lower montmorillonite content.

2.2. Field data collection

We assessed the ability of our sensors to detect vibrations at twenty-one 50 × 50 m study plots (11 in sandy soil and 10 in clay soil) during the dry season in central Kenya (June–August 2024), when sites were accessible, which is consistent with the timing of most ecological surveys in the region. For sandy soil, we collected data from five plots with low tree cover (<25% tree cover) and six plots with high tree cover (>25% tree cover), while clay soil comprised five plots in each category. Sites were therefore broadly balanced between areas with low and high tree cover due to the potential impacts of tree roots.

2.2.1. Vibroacoustic recordings

We collected recordings at three sampling points in each plot, yielding a total of 63 different sampling points (three per plot x 21 plots) across the study.

At each sampling point we compared three sensor setups: an Aquarian H1a hydrophone (sensitivity of -185 dB re 1V for a sound pressure of 1 µPa, with a frequency range from 1 Hz to 100 kHz; www.aquarianaudio.com/h1a-hydrophone.html; hereafter referred to as 'Hydrophone', but owing to the direct contact with the soil this sensor is effectively operating as a contact microphone); a JrF C-Series Pro contact microphone (no formally published sensitivity or frequency response specifications; www.jezrileyfrench.co.uk/contact-microphones; hereafter referred to as 'JrF'); and a JrF sensor attached to a metal waveguide (2 mm diameter, 15 mm length solid copper rod; hereafter referred to as 'Waveguide').

Despite the JrF sensor not having formally published specifications, it was selected due to its broad frequency response and use in previous ecological studies (Farina & Mullet, 2025; Metcalf et al., 2024; Robinson et al., 2023).

Each of the three sensors was attached to an AudioMoth 1.2.0 (www.openacousticdevices.info/audiomoth) using Aquarian PA1 hydrophone buffer amplifiers (www.aquarianaudio.com/pa1.html) to ensure impedance matching (the similarity between the sensors and recording system that maximises energy transfer), signal amplification, and preservation of the sensors' full frequency response (Fig. S1). In this study, the AudioMoths act only as a miniature recording device; once equipped with an external sensor, the AudioMoth's built-in microphone is bypassed. We soldered a 3.5 mm jack onto the circuit board of the AudioMoths to attach the buffer amplifiers (see Open Acoustic Devices (2024)).

We placed the sampling points in a triangle, each 10 m from the plot centre at bearings 0°, 135°, and 225° (and sampling points spaced 20 m apart from each other; Fig. 1a). At each sampling point, we dug a central hole 20 cm deep into the soil into which we inserted a speaker. We used a Minirig Mini 2 (https://minirigs.co.uk/speakers/bluetooth-minirig-mini-2) as the speaker, featuring a 52 mm driver and an integrated 15 W RMS amplifier, with a nominal frequency response of 65 – 16,000 Hz. Audio signals were delivered via Bluetooth connection, and the speaker's compact size (84 x 53 mm; 312 g) allowed for consistent positioning across sampling points. The speaker was wrapped in plastic at the beginning of each new field day to prevent ingress of water and soil particulates (Fig. S2). We ensured that the wall of the hole

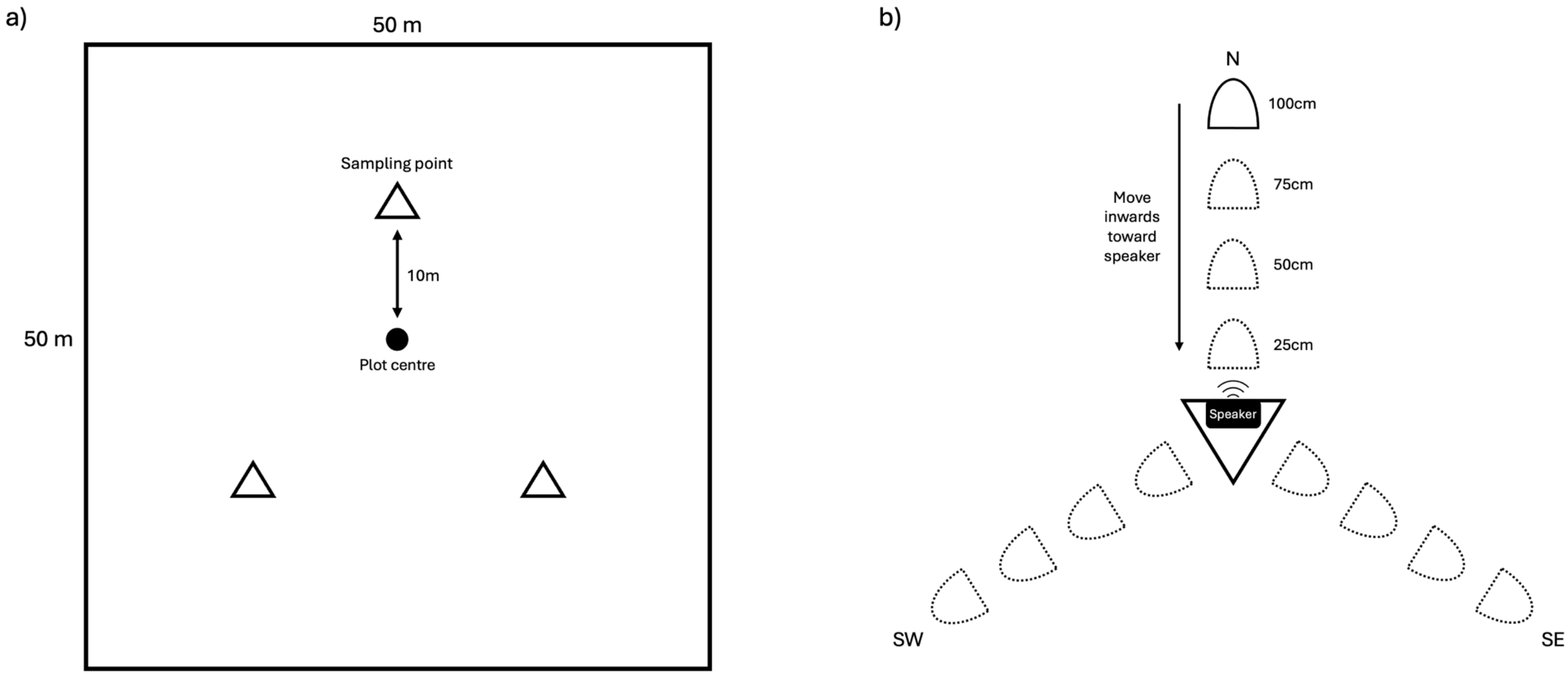


Figure 1 Example study plot (a) and sampling points (b) for the experiment. In (a), each triangle represents a sampling point. The sampling points are positioned in a triangle, each 10m away from the plot centre. In (b), the semi-circles represent the holes where we placed the sensors. The flat surface facing the speaker is where the sensors were situated alongside each other (and in contact with the wall of the hole). The semi-circle with the solid line shows where we began the experiment on each branch, moving inwards at 25cm intervals (semi-circles with dashed lines) toward the speaker.

facing the direction of North was flat before placing the speaker in the soil against the hole wall, to maximise the contact between the speaker and the soil. Because the speaker was in direct contact with the soil, it acted as a source of substrate-borne vibrations, replicating the type of signals targeted by vibroacoustic sensors during field surveys. We added the displaced soil back on top and compressed the reinstalled soil three times using similar force to standardise compaction.

We dug a 15 cm deep and 10 cm wide hole at 100 cm distance from the speaker in the exact direction the speaker was facing, ensuring that the wall of the hole closest to the speaker was at 100 cm (Fig. 1b). We also flattened the wall of this hole facing the speaker, to maintain close soil/sensor contact and to place the sensors equidistantly from the speaker. We positioned the Hydrophone and JrF sensors in the hole alongside each other and 15 cm deep. We placed the sensors in close contact with the flat wall of the hole and compressed the displaced soil on top using the same method as described above. Sampling with the Waveguide involved inserting it directly into undisturbed soil adjacent to the excavation containing the Hydrophone and JrF. AudioMoths were switched to DEFAULT mode (continuous recording in .WAV format, 48 kHz sample rate, medium gain). We played three repetitions of a broadband impulse tone from the speaker at a fixed volume setting. The broadband impulse tone comprises a high-amplitude transient onset followed by an exponential decay lasting ~300 ms. Spectral energy at onset extended from 0 – 22 kHz, with higher frequency components decaying more rapidly than lower frequencies over time (see Fig. S3 for spectrogram). We then switched the AudioMoths to OFF, to attain individual sound files for each distance, equating to approximately 30 second per recording. We repeated the above process at three more distances: 75 cm, 50 cm, and 25 cm away from the speaker (the whole line of holes is hereafter known as a 'branch'). Each sampling point had a triplet of branches at bearings 0º, 135º, and 225º (Fig. 1b). We did not record during windy or rainy conditions, as this would have introduced background noise in our frequency range of interest.

2.2.2. Soil conditions

We measured soil compaction, moisture content, and temperature owing to their potential impact on attenuation in substrates (Lo et al., 2007; Oelze et al., 2002; Sabatier et al., 1990).

Soil compaction was calculated using a pocket penetrometer (Mousavi et al., 2021; Yasun et al., 2020). We pressed the pocket penetrometer into the soil at three random locations between each hole until insertion reached the manufacturer-specified depth indicator (6 mm). Therefore, we attained 108 values of soil compaction per plot (3 per hole x 4 holes x 3 branches x 3 sampling points). The pocket penetrometer gives values between 0 and 4.5 kg cm^{-2}. The compaction measurements were taken before temperature and moisture content as these methods may have affected the structure of the soil.

We used a UBIBOT soil temperature sensor (www.ubibot.com/products/soil-temperature-humidity-probe) to measure soil temperature. We pushed the three probes of the sensor 5 cm into the soil at one random location at each sampling point. We took one reading per sampling point as the soil temperature sensor takes at least 20 minutes for accurate measurements. Therefore, we obtained three temperature values per plot.

We used a HH2 moisture meter (www.delta-t.co.uk/product/hh2) to quantify soil moisture content. We pushed the two probes of the moisture meter 5 cm into the soil at three random locations between each hole. Therefore, we attained 108 values of moisture content per plot.

2.3. Data extraction

We used RavenPro 1.6.5 (K. Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology., 2024) to view and measure our recordings. We calculated spectrograms using the following parameters: a Hann window with 75% overlap, a Discrete Fourier Transform (DFT) size of 4096 (frequency grid spacing = 11.72 Hz), a window size of 256, and a contrast setting of 75%.

We used the measurement tool to select the three broadband impulse tones (per recording) on the spectrogram. For each impulse, a 12,000-sample temporal window was selected from the onset, and the frequency bounds were adjusted to include the highest frequency at which energy was visibly present in the spectrogram. We also selected 12,000 samples from an adjacent section of the recording without impulse activity to represent ambient conditions (‘noise’) for signal-to-noise ratio (SNR) calculations. The upper frequency bound of each noise selection was matched to that of the corresponding impulse tone selection, ensuring that signal and noise measurements were extracted over identical spectral ranges. Therefore, we measured three impulse tones and three areas of background noise in each recording. See supplementary materials (Fig. S4) for further information on this process.

We extracted the values of peak amplitude (a measure of the highest recorded amplitude within the selection; here provided in RavenPro relative units U), maximum frequency (highest frequency recorded in hertz, i.e., the upper boundary of the selection), and in-band power (total spectral power within the selection, measured in decibels) from each selection. Terminology was adapted from RavenPro for clarity (e.g., 'peak amplitude' in this study is defined as 'maximum amplitude' in RavenPro, and 'maximum frequency' in this study as 'high frequency' from RavenPro). The signal-to-noise ratio (SNR) was calculated by subtracting noise in-band power (dB) from signal in-band power (dB).

We initially aimed to measure impulse tones from all recording distances. However, the impulse tones at 75 cm and 100 cm were not consistently detectable above background conditions. Due to this low SNR and therefore limited analytical reliability, the impulse tone measurements from these distances were excluded from further analyses, and our analyses focused on 25 cm and 50 cm distances only. For the remaining 25 cm and 50 cm distance data, we also excluded observations with an SNR below our threshold of 6 dB to minimise measurement errors derived from weak or noise-dominated signals.

We quantified attenuation from peak amplitude by comparing mean peak amplitudes measured at 25 cm and 50 cm from the speaker. Attenuation captures relative changes in signal strength across distance and is therefore more directly linked to soil transmission properties than raw peak amplitude measurements. An attenuation coefficient (α) was calculated assuming exponential decay of peak amplitude with distance:

$$A(d) = A_0 e^{-\alpha d}$$

where *A(d)* is the peak amplitude at distance *d*. We rearranged this equation to calculate α using peak amplitude measurements at 25 cm and 50 cm:

$$\alpha = \frac{\ln A_{25} - \ln A_{50}}{50 - 25}$$

We quantified loss of high-frequency content (hereafter referred to as 'frequency loss') during signal transmission using the change in maximum frequency between recording distances. Frequency loss complements the attenuation coefficient by quantifying the reduction in high-frequency components during propagation. Frequency loss was calculated as the absolute difference between 25 cm and 50 cm from the speaker (frequency loss = maximum frequency at 25cm – maximum frequency at 50 cm). Higher values therefore indicate a greater reduction in high-frequency components of the impulse during transmission through the soil.

2.4. Data analysis

We conducted all statistical analyses using R version 4.5.2 (R Core Team, 2025) within RStudio version 2026.01.0 (Posit team, 2026). We used the *tidyverse* range of packages (Wickham et al., 2019) for data wrangling, exploration, and visualisation. We used *lme4* (Bates et al., 2015) for fitting linear mixed-effects models using Guassian error distributions.

2.4.1. Comparison of sensors

Three measurements were used to quantify sensor performance: peak amplitude (the maximum recorded amplitude of the impulse tone), maximum frequency (the highest frequency component detected within the impulse), and signal-to-noise ratio (SNR; the ratio of the impulse signal amplitude to background noise levels, indicating detection clarity). For each of these measurements, used as response variables in analyses, we calculated the mean of the three impulse tones per sensor recording at each distance from the speaker.

We fitted separate mixed-effects models for each response variable (peak amplitude, maximum frequency, and SNR). Peak amplitude and maximum frequency were log-transformed using a log(1+x) transformation to improve normality and homogeneity of model residuals. Our models included sensor and soil type as categorical fixed effects, along with their interaction. We did this to test the overall difference between the sensors across both soil types, but also to test how each sensor performed within each soil type. We included site as a random intercept effect in all models to account for repeated measurements within study plots. Our models therefore took the form: acoustic measurement ~ sensor * soil type + (1|site).

Model assumptions were assessed using the *DHARMa* package (Hartig, 2016). We checked for patterns in the simulation-based residual diagnostics, including tests of residual uniformity and overdispersion. We used analysis of variance (ANOVA) on the fitted models to evaluate the significance of fixed effects. Where significant effects were detected, we conducted post hoc pairwise comparisons using the *emmeans* package (Lenth & Piaskowski, 2017), applying Tukey adjustments for multiple comparisons. Estimated marginal means were used to compare sensor performance within each soil type.

2.4.2. Influence of physical conditions

To assess the influence of physical conditions on attenuation and frequency loss, analyses were conducted using recordings from the JrF sensor only. This reduced dataset size, minimised variation associated with differences in sensor sensitivity and noise characteristics, and reduced the likelihood of detecting statistically significant effects with limited biological relevance due to the large sample size. The JrF sensor was selected because of its common use in soil vibroacoustic research (Farina & Mullet, 2025; Metcalf et al., 2024; Robinson et al., 2023). We used soil type, compaction, moisture content, temperature, and tree cover as our measures of physical conditions. Prior to analysis, we calculated soil compaction and moisture content values at 50 cm from the speaker by averaging the 25 cm and 50 cm values, to represent the mean soil conditions along the transmission path between the speaker and the sensors. We also centred and scaled (z-scores) all continuous variables (compaction, moisture content, temperature) prior to analysis to facilitate model convergence and comparability of effect sizes. Collinearity among predictors was assessed using variance inflation factors (VIF), with values > 3 considered indicative of potential concern.

We fitted separate linear models for each response variable (attenuation coefficient (α) and frequency loss). Both models included soil type, tree cover, and scaled environmental predictors (compaction, moisture, and temperature), as well as interaction terms between soil type and each continuous predictor to test for soil-type-specific effects. An additional interaction between compaction and moisture was included to account for their potential combined influence on the transmission of vibrations. We analysed attenuation coefficient using linear mixed-effects models, and site was included as a random intercept to account for non-independence of observations within sampling sites. In contrast, frequency loss was analysed using standard linear models, as inclusion of a random effect for site was not supported by exploratory analyses. We validated and tested the significance of our models using the same methods as described above.

3. Results

Although the primary aim of this study was to compare the performance of three sensors, field conditions constrained deployment of the Waveguide setup. Despite being widely used in temperate soils, the tropical savanna soils during the dry season in Kenya were highly compacted, which prevented insertion of the copper waveguide without causing damage to the waveguide (which would, in turn, affect sensor performance). Consequently, this type of waveguide setup was deemed unsuitable for dry and hard tropical soils, and analyses focus on the Hydrophone and JrF sensors only.

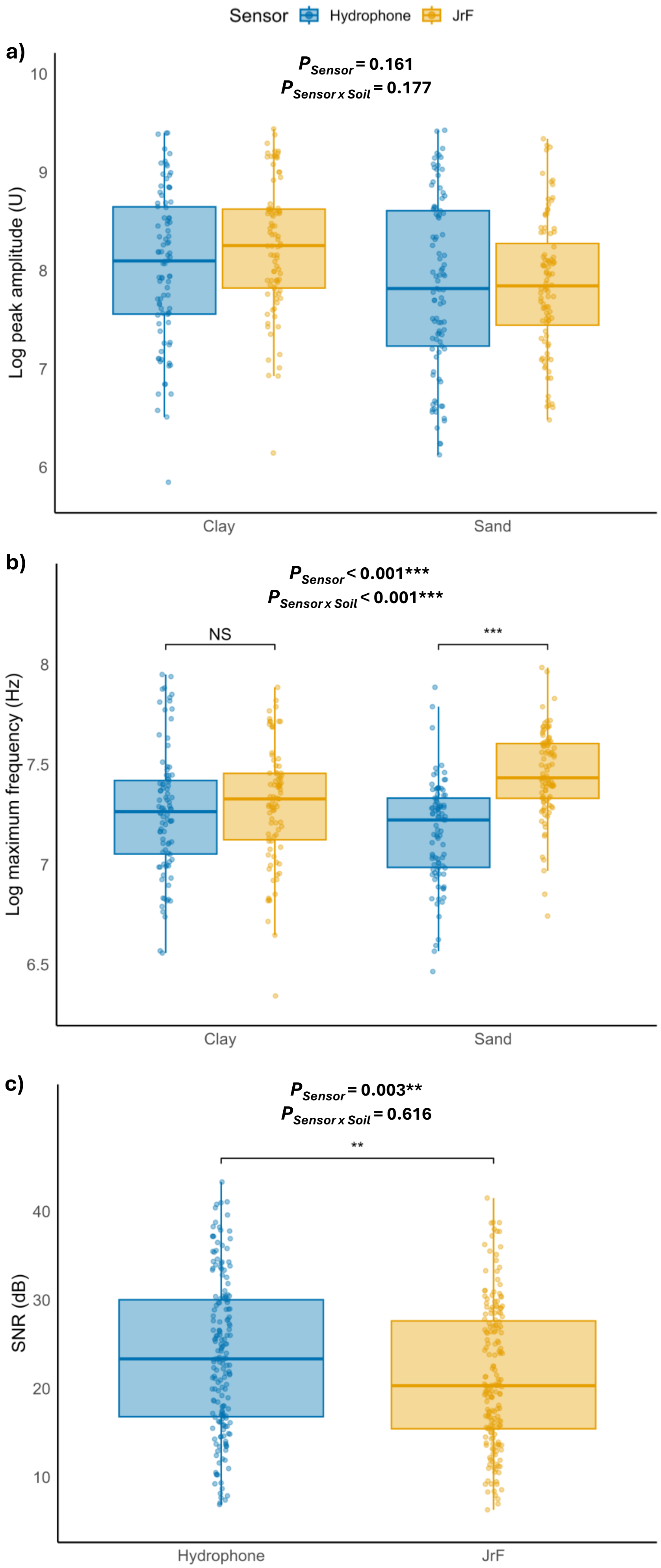
We analysed a total of 350 recordings (Hydrophone, n = 177; JrF, n = 173; approximately 2 hours of total recording time). We removed a total of 105 (4.8%) impulse tone measurements, as they were below our SNR threshold of 6 dB. This comprised 3.9% (n = 43) Hydrophone measurements, and 5.8% (n = 62) JrF measurements. By distance, 1.2% (n = 13) of excluded measurements were collected at 25 cm and 8.6% (n = 92) at 50 cm from the speaker.

3.1. Comparison of sensors

We found no significant difference in recorded peak amplitude of the impulse between sensors ($F = 1.97$, $P = 0.161$), and there was no significant interaction between sensor and soil type (F = 1.83, P = 0.177), indicating that sensor performance was consistent across soil types (Fig. 3a). Although soil type had a significant effect on peak amplitude (F = 5.49, P = 0.030), this is not considered further here, as the attenuation coefficient provides a more appropriate metric for comparing physical conditions.

Analysis of maximum frequency of the impulse revealed a significant interaction between sensor and soil type (F = 24.4, P < 0.001), suggesting that the frequency-detection capabilities of the sensors varied between soil types (Fig. 3b). Post-hoc analyses indicated that the JrF sensor recorded over 1.34 times higher geometric mean maximum frequency (i.e., detected higher frequencies) than the Hydrophone sensor in sandy soil (P < 0.001), whereas no significant differences were observed in clay soil (P = 0.409).

We found significant differences in SNR between sensors (F = 8.81, P = 0.003), with no significant interaction between sensor and soil type (F = 0.25, P = 0.616), indicating that the difference between the sensors was consistent between soil types (Fig. 3c). Across both soil types, the arithmetic mean SNR for the Hydrophone was over 1.11 times higher than the JrF sensor, indicating that the Hydrophone recordings generally contained clearer vibrations that were more distinguishable from the sensor noise floor and environmental noise.


Sensor Hydrophone JrF
a)
P Sensor = 0.161
P Sensor x Soil = 0.177
Log peak amplitude (U)
10
9
8
7
6
Clay
Sand
b)
P Sensor < 0.001***
P Sensor x Soil < 0.001***
NS
***
Log maximum frequency (Hz)
8
7.5
7
6.5
Clay
Sand
c)
P Sensor = 0.003**
P Sensor x Soil = 0.616
**
SNR (dB)
40
30
20
10
Hydrophone
JrF

400

Figure 3 Differences in recorded peak amplitude (a), maximum frequency (b), and SNR (c) between the Hydrophone and JrF sensors. For panels (a) and (b), soil type is shown on the x-axis, visualising sensor differences within each soil. For panel (c), data are pooled across soil types and sensor is shown on the x-axis, highlighting the overall effect of sensor on SNR and reflecting the absence of a significant sensor × soil type interaction. For all plots, the effects of sensor and the sensor and soil type interaction are shown above in text (***$P < 0.001$, **$P < 0.01$, *$P < 0.05$). The boxplots show median (horizontal crossbar) and interquartile ranges, with individual data points overlaid. For peak amplitude and maximum frequency, the datapoints are log-transformed, as this is consistent with the analytical approach for both variables.

3.2. Influence of physical conditions

Soil conditions varied across sites, with compaction ranging from 0.4 – 4.5 kg cm^{-2} (median = 2.9 kg cm^{-2}) and temperature from 18.1 – 38.7 °C (median = 30.1 °C). Soil moisture ranged from 0 – 22.1 % (median = 3.2 %), with approximately 62% of measurements occurring under very dry conditions (< 5% moisture).

We found no significant effects of soil type, compaction, moisture content, temperature, or tree cover on the attenuation coefficient ($P > 0.05$ for all; Table S1). Additionally, no significant interactions were detected between soil type and soil conditions, nor between compaction and moisture content ($P > 0.05$ for all; Table S1).

Although the attenuation coefficient (α) did not differ with our environmental variables, mean peak amplitude (± 95% CI) declined from 3,899 U (3,506 – 4,293 U) at 25 cm to 1,878 U (1,642 – 2,114 U) at 50 cm across all conditions (Figure S5). This represents 52% reduction in amplitude between the two distances, suggesting high levels of attenuation.

We found no significant effects of soil type, compaction, moisture content, temperature, or tree cover on frequency loss ($P > 0.05$ for all; Table S2). We did, however, find a significant interaction between compaction and moisture ($t = 2.170$, $P = 0.031$), suggesting that the effect of compaction on frequency loss varied with soil moisture conditions (Fig. 5). Model predictions indicated that moist compacted soils attenuate higher frequencies more than drier compacted soils (Fig. 5). We found no significant interactions between soil type and our soil conditions ($P > 0.05$ for all; Table S1). The emitted impulse contained frequencies up to 22,000 Hz, whereas mean maximum recorded frequency was 1,652 Hz at 25 cm and 981 Hz at 50 cm, indicating substantial attenuation of higher frequencies over this relatively short distance (Fig. S6).

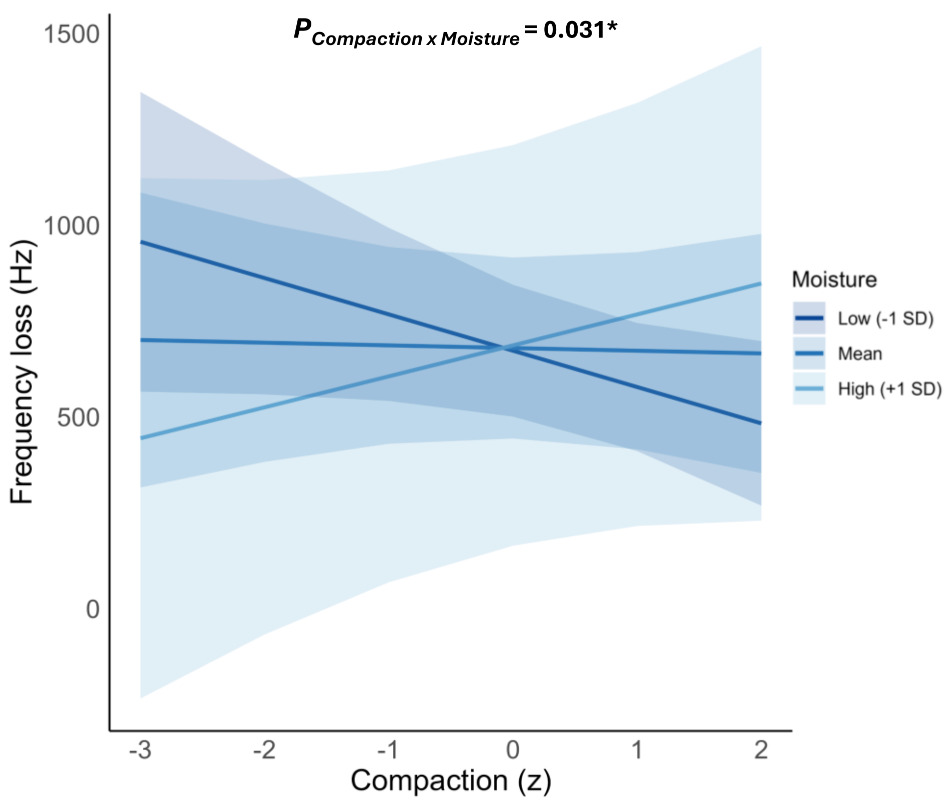


Figure 5 The relationship between soil compaction and frequency loss (Hz) changes depending on soil moisture content. In wetter soils, increasing compaction is associated with a greater loss of high-frequency components of the impulse than in drier soils. Lines show model-predicted relationships at low (−1 SD), mean, and high (+1 SD) moisture levels, with shaded areas representing 95% confidence intervals. Compaction is standardised (z-score; mean = 0), with negative and positive values indicating below- and above-average compaction, respectively. Higher frequency loss values indicate greater reductions in frequency. The effect the compaction and moisture content interaction is shown above in text (****P* < 0.001, ***P* < 0.01, **P* < 0.05).

4. Discussion

To our knowledge, this is the first quantitative field-based study that directly evaluates and compares the performance of vibroacoustic sensors in a soil substrate, building on prior comparisons of vibroacoustic sensors (Mankin et al., 2000; Mankin et al., 2010). We found that recorded amplitudes of our impulse tone (0 – 22 kHz) did not differ significantly between the Hydrophone and JrF, but key sensor specifications such as SNR and frequency sensitivity did significantly differ between sensors. We found minimal effects of physical conditions on both the attenuation and frequency loss of our recorded impulse.

4.1. Comparison of sensors

A key aim of this study is to aid methodological development of vibroacoustic research in seasonally dry tropical soils. Although we set out to test the waveguide approach, and despite its widespread use in temperate systems (e.g., Maeder et al., 2022; Robinson et al., 2023), it could not be used at our site because the soils were dry and compacted. This result highlights the importance of evaluating sensor effectiveness under local soil conditions before undertaking ecological surveys. However, we only trialled a thin (2 mm diameter) copper waveguide in this study – more robust waveguides may be able to effectively penetrate dry and compacted soils but would require hammering into the soil and could cause vibrational stress to below-ground fauna.

Sensor performance differed depending on the variable considered. Despite finding no difference in the recorded amplitude, signal-to-noise ratio (SNR) differed between both sensors. The higher SNR for the Hydrophone may be due to lower intrinsic sensor noise, differences in physical coupling (the degree of contact and signal transfer between the sensors and surrounding soil matrix), and/or a reduced sensitivity to the lower frequency range where background noise is concentrated (< 500 Hz) compared with the JrF sensor. Soil invertebrates can produce low amplitude and low frequency vibrations (Kojima et al., 2012; Rauth & Vinson, 2006). For example, a study found that fire ants (*Solenopsis invicta* Buren) stridulate between 200 – 600 Hz (Rauth & Vinson, 2006). A higher SNR (i.e., lower levels of background noise proportionate to the signal) will therefore likely increase the ability to detect and classify low amplitude vibrations from soil fauna (Mankin et al., 1998; Mankin et al., 2000), especially in the lower frequency range where background noise dominates. Soil fauna also generate low-frequency passive vibrations through activities such as feeding, movement, or burrowing (Lacoste et al., 2018). As passive vibrations could potentially provide useful taxonomic, functional, or behavioural data, it important that a sensor is able to accurately detect these vibrations above the noise floor. However, we note that the effect size between our sensors was relatively small for this difference in SNR (approximately 10% higher in the Hydrophone), indicating that the observed difference in SNR is unlikely to translate into substantial differences in the detection of soil faunal activity.

We found significant differences in maximum detected frequency, driven by the JrF sensor consistently detecting the higher frequencies of the impulse tone better than the Hydrophone in sandy soil. Despite the broadcast impulse tone containing frequencies up to 22,000 Hz, frequencies detected after propagation through the soil were largely restricted to below 2,500 Hz, indicating strong attenuation of higher-frequency components. However, the frequencies retained after propagation still fall within the range of vibrations produced by soil invertebrates (Mankin & Benshemesh, 2006; Stroud et al., 2025). For example, the ant *Myrmica scabrinodis* stridulates at approximately 1450 Hz (Casacci et al., 2013), two species of scarab beetle larvae (*Melolontha melolontha*, *M. hippocastani*) stridulate between 1700 – 3000 Hz (Görres & Chesmore, 2019), and termite species (*Macrotermes natalensis*, *Odontotermes* spp.) stridulate between 1000 – 5000 Hz (Hager & Kirchner, 2013). Therefore, greater sensitivity to higher frequencies may improve the detection and classification of soil fauna producing high-frequency vibrations, suggesting that frequency response characteristics are an important consideration alongside SNR when evaluating sensors for soil biodiversity sampling. However, the observed difference in maximum detectable frequency between sensors was dependent on soil type, highlighting the importance of physical parameters on vibration detection. Both sensors also showed high levels of variation in recorded amplitude and maximum frequency of the impulse, suggesting potential variation in physical coupling to the soil which can influence detection of vibrations. As the effects of physical coupling were not quantified in this study, further research is needed to determine the extent to which this may influence detection and classification of soil fauna activity.

4.2. Influence of physical conditions

Our studied physical conditions had minimal impacts on attenuation or frequency loss. These results contrast previous studies which have found effects of soil type, compaction, and moisture content on attenuation (Lo et al., 2007; Oelze et al., 2002; Sabatier et al., 1990). Firstly, the lack of differences across our physical conditions may reflect the restricted range of soil moisture in tropical soils during seasonal dry periods, with over 60% of our measurements falling between 0–5% moisture content. Where a broader range of soil conditions occurs, variation in vibrational attenuation may be more pronounced. Secondly, the cited geophysical studies were conducted in laboratory conditions where the heterogenous nature of the substrate could be controlled, whereas, in our field study, there would have been additional factors that could have affected attenuation, such as rock abundance, variation in pore size distribution and soil particle shape, or faunal activity (e.g., burrows), which were not explicitly accounted for. Thirdly, we measured soil moisture content and temperature at 5 cm depth due to equipment limitations, which may not fully represent conditions at our 15 cm recording depth. We also used plot-level tree cover as a proxy for root presence in the soil rather than directly quantifying local root density around each sampling point, which may also limit the interpretation of these results. We did find a significant interaction between compaction and moisture content when analysing frequency loss in both soil types combined. Our results suggest that moist compacted soils attenuate higher frequencies more than drier compacted soils. This effect is likely due to changes in soil structure and particle coupling, which in turn influence the attenuation of higher frequencies (Oelze et al., 2002).

We also found an approximate 50% reduction in mean amplitude between 25 cm and 50 cm from the speaker, indicating rapid attenuation over short distances. This is further supported by the recordings collected at the 75 cm and 100 cm distances from the speaker, in which the measured impulse tones consistently fell below our SNR threshold, preventing reliable detection of the impulse. This high level of attenuation is consistent with previous soil studies which suggest that the effective detection range of sensors is highly localised, especially for species which produce higher frequency vibrations. For example, Mankin et al. (1998) found that insects were detectable within approximately 20 cm of the sensor, whilst Maeder et al.

(2022) estimated an effective detection radius of 30 – 100 cm. These findings suggest that soil vibroacoustic monitoring is inherently localised, with effective detection distances likely to remain relatively short under most physical conditions.

5. Implications

Our results suggest there is a trade-off between the two sensors in SNR and frequency detection. The Hydrophone detected clearer signals above the noise floor across both soil types, whereas the JrF sensor showed greater sensitivity to higher frequencies in sandy soils. However, owing to the relatively small differences in performance and the substantial disparity in cost (currently [2026] the Hydrophone is more than three times the cost of the JrF), the JrF sensor appears to be a suitable and cost-effective option for ecological monitoring projects. This is particularly relevant in studies where multiple sensors are deployed across habitats and budget constraints are a key limitation. In contrast, the Hydrophone may be more appropriate for smaller-scale studies (e.g., behavioural experiments), where fewer sensors are required and its higher unit cost may be justified by the improved signal clarity. However, the extent to which these differences translate to detection of biological vibrations in field conditions remains to be determined.

Whilst we have quantified the performance of different sensors and the influence of physical conditions on attenuation in dry tropical soils, how these patterns vary across other soil types remains unknown. Our results demonstrate that sensor choice may influence vibroacoustic data and should therefore be carefully considered when designing studies or interpreting differences among datasets. We therefore stress the need for further methodological standardisation within the field of soil vibroacoustics. For example, there have been few soil vibroacoustic studies conducted in the tropics, and therefore it is vital to test the effectiveness of sensors in a more diverse range of soil types. For instance, in softer soils where the Waveguide approach is viable, it is important to evaluate how this approach performs relative to Hydrophone and JrF sensors.

However, methodological standardisation is not solely limited to considerations of sensors and an understanding of how physical conditions affect attenuation. For example, owing to the high level of attenuation in soil, researchers need to determine the appropriate number of recording areas per sampling site to ensure that representative data are obtained. In addition, the optimal recording schedule should be established to best capture soil fauna activity, including key factors such as time of day recorded and sampling duration (i.e., number of hours or days the sensors are deployed). It is also vital that more research is conducted on describing both active (e.g., stridulations) and passive (e.g., movement) vibrations produced by soil fauna. Expanding vibroacoustic libraries of soil fauna (Mankin, 2024) is a key step towards improving understanding of species-specific biases in detection range and developing more accurate classification (e.g., machine learning) and data processing methods (e.g., acoustic indices) within recordings for reliably quantifying biodiversity.

6. Conclusions

Our results suggest that sensor choice may be more influential than physical conditions for the detection of soil fauna in seasonally dry tropical soils. However, these findings are specific to our study system and may not translate to other soil types or habitats. We recommend further research comparing sensor performance, particularly assessing how physical conditions and sensor-soil coupling influence vibrational transmission across different geographical regions.

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