Hums in the humus: Opportunities and challenges for soil ecoacoustics

Alex F. Taylor[1*], Martin F. Breed[1,2*], Carlos Abrahams[3], Amy Annells[1], Tom Bradfer-Lawrence[4], Timothy Cavagnaro[1], Carolyn-Monika Görres[5], Martin M. Gossner[6,7], Craig Liddicoat[1,2], Simon Linke[18], Oliver C. Metcalf[9,10], Louise Roberts[11], Louise Vang Sørensen[12], Xin Sun[13,14], Jonathan H. Timperley[15], Jake M. Robinson[1,2*]

[1]College of Science and Engineering, Flinders University, Bedford Park, SA 5042, Australia

[2]The Aerobiome Innovation and Research Hub, Flinders University, Bedford Park, SA 5042, Australia

[3]School of Animal, Rural and Environmental Sciences, Nottingham Trent University, Nottingham, NG25 0QF UK

[4]Centre for Conservation Science, Royal Society for the Protection of Birds, Edinburgh, H12 9DH, UK

[5]Department of Applied Ecology, Hochschule Geisenheim University, Von-Lade-Str. 1, 65366 Geisenheim, Germany

[6]Forest Entomology, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, 8903 Birmensdorf, Switzerland

[7]Department of Environmental Systems Science, Institute of Terrestrial Ecosystems, ETH Zurich, 8092 Zurich, Switzerland

[8]CSIRO Environment, Dutton Park, 4104, QLD, Australia

[9]Lancaster Environment Centre, Lancaster University, LA1 4YQ, UK

[10]Department of Natural Sciences, Manchester Metropolitan University, M1 5GD, UK

[11]Department of Earth, Ocean and Ecological Sciences, School of Environmental Sciences, University of Liverpool, Liverpool, L69 3GP, UK

[12]Department of Ecology, Environment and Geoscience, Umeå University, 901 87, Sweden

[13]State Key Laboratory of Regional and Urban Ecology, Ningbo Observation and Research Station, Fujian Key Laboratory of Watershed Ecology, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, China

[14]University of Chinese Academy of Sciences, Beijing, 100040, China

Correspondence: alex.taylor@flinders.edu.au; jake.robinson@flinders.edu.au; martin.breed@flinders.edu.au

Keywords: Bioacoustics; Biotremology; Ecoacoustics; Soil ecoacoustics

ORCIDs:

AFT: 0009-0005-1858-3907

MFB: 0000-0001-7810-9696

CA: 0000-0003-0301-5585

AA: 0009-0004-9678-2760

TBL: 0000-0001-6045-4360

TC: 0000-0002-9922-5677

CMG: 0000-0001-7166-1947

MMG: 0000-0003-1516-6364

CL: 0000-0002-4812-7524

SL: 0000-0002-1797-3947

OCM: 0000-0003-3441-2591

LR: 0000-0002-5066-2024

LVS: 0009-0001-4431-2693

JHT: 0009-0002-1115-3670

XS: 0000-0002-3988-7847

JMR: 0000-0001-8108-3271

Abstract | Soil ecoacoustics is an emerging field and suite of tools that use sound and vibration to detect belowground biological activity. It offers a minimally invasive way to assess soil communities and ecosystem processes. Across biomes, we found that soil ecoacoustics is being used to detect organisms, quantify animal behaviour, monitor soil health and assess restoration interventions. Our review shows that ecoacoustic metrics reflect changes in soil fauna activity, disturbance impacts and recovery trajectories. However, major challenges remain, including inconsistent terminology, limited understanding of sound propagation across soil types, difficulty separating biotic from abiotic signals and a lack of standardised methods. We propose foundational standard operating procedures and identify how soil ecoacoustics could be integrated into global biodiversity monitoring frameworks.

The importance of soils

Soils are the foundation of terrestrial life. They are conglomerates of both abiotic (non-living) and biotic (living) components that form complex, dynamic ecosystems. An estimated 59%->99.9% of Earth's species live in soil systems[1,2]. We view soils as systems because they are integrated assemblages of physical, chemical and biological entities that interact dynamically across scales. Despite the importance of soils in our biosphere, 75% of the world's soils are affected by degradation—a figure projected to rise to 90% by 2050 if deforestation, pollution, overgrazing, urbanisation and other harmful practices continue[3-5].

Belowground organisms play a critical role in functions such as biogeochemical cycling, ecosystem productivity, and climate regulation (e.g., fungi and bacteria mediate carbon sequestration and greenhouse gas fluxes; soil fauna such as earthworms and arthropods influence soil structure and decomposition dynamics), while supporting 97% of our calories[6-8]. Understanding soil biodiversity is therefore vital because it underpins global food security, carbon storage and climate change resilience. However, despite its ecological significance, soil biodiversity remains comparatively understudied as it is challenging to study and monitor, particularly *in situ*[9-11]. Reliable methods to detect and monitor soil life are urgently needed to guide conservation, restoration and sustainable land-use decisions.

Tuning into soil sounds and vibrations

One underexplored approach for better understanding soils is to ‘listen’ to them. Soils are dynamic environments in which organisms generate and respond to sounds and substrate-borne vibrations. Many soil-dwelling taxa, including earthworms, beetle larvae, termites, and ants, generate sounds and substrate-borne vibrations through movement, feeding and/or communication[12-15]. Even plant roots generate vibrations as they grow and interact with soil particles. These biological signals are interspersed with abiotic (non-living) sounds from processes such as water movement and shifting soil aggregates. By identifying and interpreting these sound and vibrational cues, researchers can obtain minimally invasive insights into organism presence, behaviour and ecology.

Soil ecoacoustics (see Glossary) could help overcome the soil biodiversity detection and monitoring challenge, e.g., through its technological capacities, such as passive acoustic monitoring (PAM). Although ‘soil biodiversity’ encompasses a vast array of organisms, including many microbes that do not generate detectable sounds, soil ecoacoustics is particularly suited to monitoring soniferous or vibration-producing groups. These taxa and activities produce detectable acoustic signals, making them the most relevant to this emerging field.

Soil **ecoacoustics** encompasses a suite of approaches to study soil **soundscapes** in order to assess and understand ecological processes and biological activity[11,16]. It draws on the disciplines of **bioacoustics**, **biotremology**, soil physics, and zoology. Indeed, soil ecoacoustics integrates abiotic soil physics, biotic community dynamics and technological capacities to detect and monitor belowground life[11,17,18]. This opens new opportunities to answer key ecological questions: How does soil biodiversity respond to disturbance and recovery? Can acoustic activity be used as a proxy for ecosystem functioning? And might soil soundscapes serve as early warning indicators of degradation or restoration success?

Feedback loops—such as soil degradation affecting biodiversity, and biodiversity loss altering soil function—can be traced acoustically, potentially creating opportunities for minimally invasive and cost-effective ecological soil monitoring[12,19]. For example, degraded soils often support reduced invertebrate abundance and diversity, which appears to be somewhat reflected in lower acoustic activity/complexity[12,19]. Conversely, and more speculatively, disturbances such as soil compaction or drying may amplify abiotic sounds (e.g., cracking, shifts in soil aggregates) while suppressing biological signals; however, this remains to be studied. Monitoring these acoustic shifts could therefore provide minimally invasive indicators of soil degradation and recovery.

There are outstanding challenges to overcome before soil ecoacoustics can be reliably and widely implemented. These include:

- understanding how key soil characteristics (e.g., composition, texture, porosity, compaction, moisture) influence signal **propagation**;
- distinguishing biotic from abiotic signals;
- developing standardised methodologies for data collection, processing and interpretation.
- terminology issues;

Here, we synthesise current knowledge and identify key ecological, technical, and analytical challenges in this emerging field. Moreover, we outline the foundations of a global experimental network supported by standard operating procedures (SOPs) to encourage methodological consistency and cross-site comparability. Additionally, we highlight the potential to democratise soil ecoacoustics through open science, citizen participation, and integration into global biodiversity monitoring frameworks.

Soil sound and substrate-borne vibration terminology

The terminology used in acoustic-related biological disciplines is still evolving, and several overlapping terms have been proposed in the literature. A *soundscape* generally refers to the total acoustic environment in a given place and time, encompassing both biotic and abiotic sources. The term *sonoscape* is sometimes used synonymously, though less widely adopted[20]. *Sonosphere*[21] is employed more broadly to describe the domain of acoustic phenomena, while *sonotope* refers to a discrete spatial unit within an acoustic landscape, analogous to an ecological biotope[22].

In soils, various mechanical waves propagate between soil particles and through the air and water spaces between particles. These mechanical waves are acoustic (sound waves; compressional waves travelling in the same direction as the propagation) and substrate-borne (e.g., waves travelling in the boundary between soil-air, non-compressional waves oscillating with perpendicular motion)[12]. The physical properties of soil—such as texture, porosity, compaction, and moisture—constrain the transmission of sound, while enhancing or attenuating vibratory signals.

Fauna living in and on soil generate substrate-borne vibrations through locomotion, feeding, and communication[23]. The study of how organisms produce, transmit and receive vibrations through a substrate falls under the discipline of 'biotremology'. This is a sibling discipline to bioacoustics, with vibrational communication thought to have evolved long before acoustic[16,24]. Importantly, since most below-ground dwelling organisms lack pressure-sensing receivers and organs, substrate-borne communication and sensing is their primary mode of communication[24]. That means that in soils, the term 'bioacoustics', which has traditionally focused on the *sounds* of individual species (e.g., air-borne or water-borne, detectable by pressure-sensing organs)—is arguably less applicable to the animals themselves. However, soil studies predominantly sense below-ground signals using pressure-sensing devices (acoustic), and thus, 'acoustics' remains dominant.

Recent studies in acoustic ecology have used the term 'ecoacoustics', which refers to the "theoretical and applied discipline that studies sound along a broad range of spatial and temporal scales to tackle biodiversity and other ecological questions"[25]. Ecoacoustics focuses on sounds as signals to infer ecological information. Historically, ecoacousticians have primarily focused on terrestrial and aquatic systems, analysing air- and water-borne sounds from birds, mammals, invertebrates, fish, and amphibians, as well as abiotic and anthropogenic sounds[26,27]. A more recent term, 'ecotremology', presents the biotremological equivalent of ‘ecoacoustics’, expanding this scope to investigate how substrate-borne vibrations can inform our understanding of ecological processes, such as trophic interactions or habitat use[28].

The term *sonopedon* has been proposed to capture the acoustic properties of a soil profile[29], paralleling the concept of a *pedon* in soil science, and *sonotone* has been used to describe temporally bounded acoustic conditions[22]. While some of these terms are experimental or niche, clarifying their usage helps avoid confusion, and we adopt soil soundscape here as the most consistent and accessible framing.

By the very nature of the soil substrate, the developing field of soil ecoacoustics encompasses sounds and substrate-borne signals and cues emitted by soil fauna (e.g., through locomotion, stridulation), as well as geophonic and anthropogenic sounds and vibrations propagating through or on the surface of soil[11]. This systems-based approach seeks to interpret belowground ecological function and biodiversity through vibroacoustic signals. Recognising this overlap is important for soil ecoacoustics: it highlights that the signals we detect may represent either direct vibratory emissions or their conversion into sound, and that interpretation must account for the soil matrix as both a filter and an amplifier of belowground processes.

Researchers working in soil systems should be aware of these overlapping terminologies. While we adopt the term ‘soil ecoacoustics’ in this paper, we acknowledge that ecoacoustics and ecotremology may increasingly converge in soils, as do bioacoustics and biotremology. Clearer etymological distinctions and shared frameworks will help to ensure that relevant studies are not overlooked and that researchers avoid inadvertently reinventing conceptual tools.

Soil ecoacoustics processes and challenges

Realising the potential of soil ecoacoustics necessitates (a) a broader understanding of the processes and tools involved, and (b) overcoming a series of challenges that influence the transmission and interpretation of biotic signals in the soil system. Here, we outline these processes and challenges, including the complex nature of sound and vibration sources, understanding how soil physical properties affect sound and vibration transmission, the variability of sound production from different sources, along with spatio-temporal, hardware and analytical challenges.

Source of the soil soundscape

At the core of soil ecoacoustics are the biological and physical processes that generate sound and substrate-borne vibrations. Key biological sources include locomotion, feeding, communication, and mating by soil fauna, as well as plant root growth and plant water transport[11,24,30]. Abiotic sources include geophysical processes such as water movement and soil particle displacement[31]. Microbial activity is largely inaudible in isolation, but we speculate that it may contribute indirectly through effects on soil aggregation and invertebrate behaviour.

These diverse sources produce mechanical energy, often modulated by anatomical structures of organisms and their interaction with soil particles. This energy propagates as acoustic waves through the soil matrix, where it is further shaped by soil physical properties such as texture, porosity, and moisture[32]. Vibrational sensors such as contact microphones, geophones, or accelerometers convert these waveforms into electrical signals for analysis. The complexity and overlap of these sources currently make it difficult to separate biological from abiotic contributions, as signals can be perceived as either sound or vibration depending on the sensor used.

Soil physical properties

Sound and vibration transmission in soil is governed by soil factors such as texture (i.e., sand/loam/clay fractions), porosity (i.e., the proportion of air spaces), temperature, compaction, moisture content, organic matter and rhizosphere structure[32]. These influence **acoustic impedance** and **attenuation**, determining how sound propagates and decays with distance. For example, increasing water potential (suction pressure) in dry soils, higher bulk densities and decreased porosity with compaction are associated with greater contact between soil particles and increased speed of wave transmission. Moreover, dry and saturated soils behave quite differently, as air-borne waves in the former are replaced by water-borne waves in the latter[32,33]. The heterogeneity of soil structure—including the presence of roots, stones and macropores[34]—likely creates **anisotropic environments** that influence the transmission direction and frequencies of mechanical waves.

In terrestrial and aquatic systems, acoustic propagation has been investigated. Sound propagation distances vary widely depending on medium, frequency, and environmental context. In marine environments, the density of water often allows sound to travel long distances[35], while in terrestrial and freshwater systems, attenuation is heavily influenced by substrate, vegetation, water movement, and background noise—leading to variable propagation distances depending on local conditions[36]. Rules of thumb for detection ranges[37,38] are therefore of limited generality and should be used with caution.

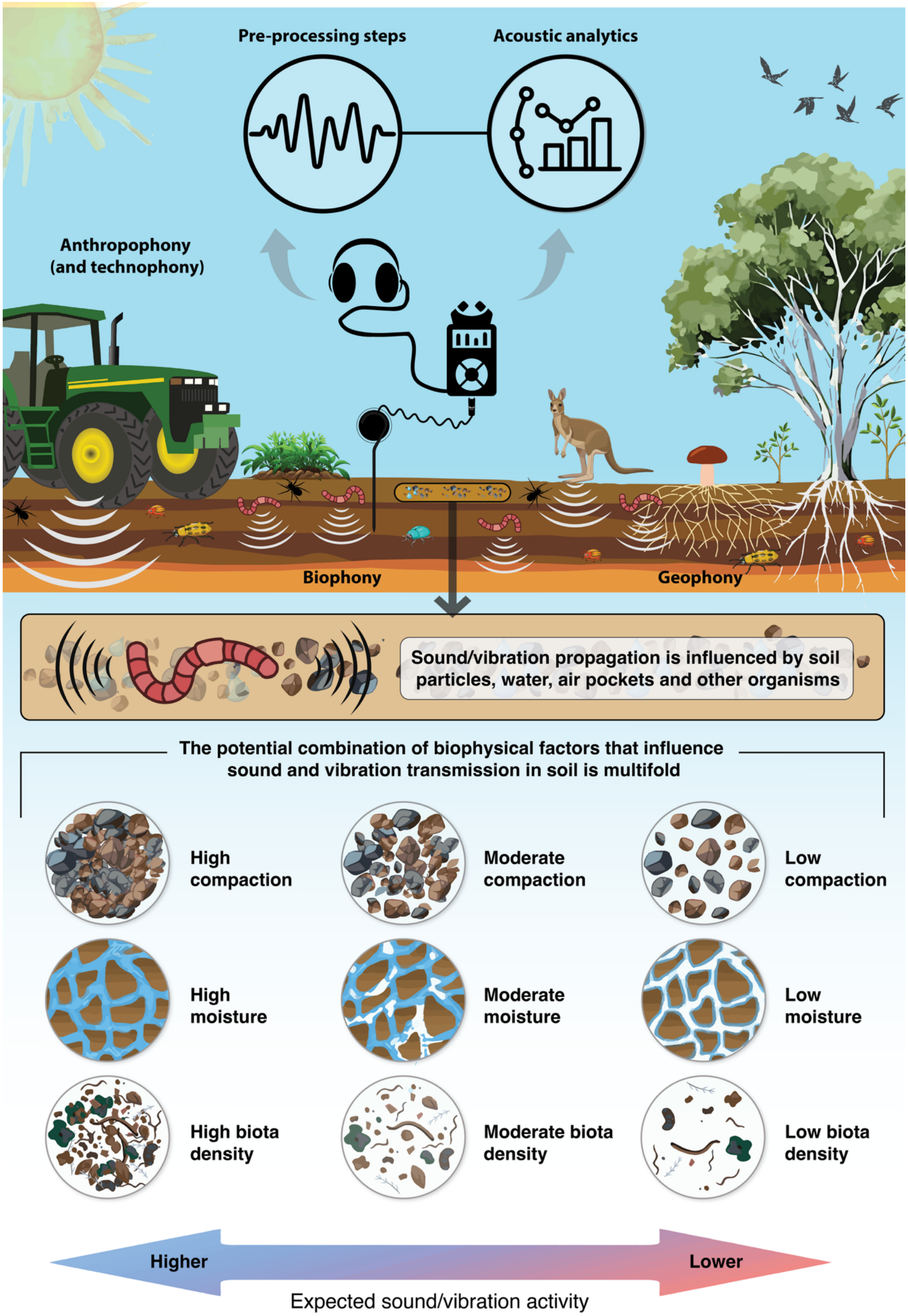
What is most relevant for soil ecoacoustics is that, unlike air or water, soils are highly heterogeneous at small scales: texture, porosity, compaction, and moisture content each influence the attenuation or amplification of signals[32,33]. Moreover, soil acoustic environments are dynamic, shifting with hydrological regimes and weather fluctuations. To advance soil ecoacoustics, robust empirical data are needed on how different signals propagate through soils, alongside the development of soil-specific models. Methods used in terrestrial and marine bioacoustics—such as controlled playback and attenuation experiments, paired-source–receiver designs, and mapping detection spaces—provide a valuable starting point for designing such studies in soils.

Biological rhythms in soil

Similar to other environments, a core challenge in soil ecoacoustics is the variability of biological sound production. The activity of many invertebrates follows **diel**, seasonal and weather-dependent cycles[17,39-41]. For instance, earthworms, isopods and termites exhibit sporadic and cyclical horizontal and vertical movement and feeding behaviours, often linked to soil temperature, humidity and precipitation[42,43]. Consequently, invertebrate sound recordings can be temporally variable. Long-term monitoring is beneficial because it can establish ecological baselines by capturing natural variability in soil acoustic activity over time. In contrast, relying only on short recordings risks conflating silences with either genuine dips in biotic activity or artefacts of unsuitable recording conditions.

Spatial scale

At the molecular scale, the acoustic properties of soils are shaped by the binding of water molecules to mineral surfaces and organic matter, influencing the dielectric and mechanical properties of soils[32]. At the micro- to meso-scale (~0.01 mm–25 cm), the **bioturbation** action of individual organisms alters soil structure and generates acoustic signals[30]. At the field or landscape scale (0.1–1,000 ha), vegetation type, land use, and climate likely modulate faunal composition and their acoustic behaviours[19,44]. Regionally and globally, soil ecoacoustics are likely to reflect broad ecological patterns such as biodiversity gradients and responses to climate-driven shifts in faunal communities (Figure 1), and they may also provide insights into restoration trajectories when linked to independent biodiversity and soil function metrics (e.g., increases in acoustic activity or diversity of signal types accompanying recovery in degraded sites). However, there are few studies characterising these spatial components.



Pre-processing steps
Acoustic analytics
Anthropophony
(and technophony)
Biophony
Geophony
Sound/vibration propagation is influenced by soil particles, water, air pockets and other organisms
The potential combination of biophysical factors that influence sound and vibration transmission in soil is multifold
High compaction
Moderate compaction
Low compaction
High moisture
Moderate moisture
Low moisture
High biota density
Moderate biota density
Low biota density
Higher
Lower
Expected sound/vibration activity

Figure 1. Key biophysical factors in soils that influence sound and vibration propagation and different sources (incl. anthropophony/technophony, biophony and geophony) and soil characteristics (e.g., water, particles, air, organisms). Some of the factors that influence propagation include reflection (the bouncing of sound waves off boundaries such as soil layers or particles), refraction (the bending of sound waves as they pass through materials with different densities or moisture contents), and acoustic impedance (the resistance of a medium to sound transmission, determined by its density and elasticity). While metal probes/wave guides (as shown in this figure) can be used to detect vibrations, they are not always essential; sensors may also be directly buried at various soil depths, as is common in soil science for temperature and moisture sensing.

Importantly, the spatial component of soil ecoacoustics is not limited to the soil surface or upper horizon—many soil invertebrates and sound-producing organisms burrow into deeper layers, and sensor placement should reflect this vertical heterogeneity. In practice, the sampling approach should respond to soil depth and structure to ensure meaningful data capture, as shallow or mismatched sensors may miss or distort key activity zones.

Recording hardware

Based on a systematic search, 51 studies have conducted soil acoustic and substrate-borne vibration sampling in relation to biodiversity in the field and laboratory settings (Table S1; Figure 2). Various sensors have been used, from accelerometers to microphones and piezo-electric contact microphones to laser vibrometers[12,45,46]. At present, no single sensor type can be recommended universally, as performance depends on the target signals and soil conditions. For example, accelerometers and vibrometers are well-suited to detecting substrate-borne vibrations, piezo-electric contact microphones provide cost-effective access to soil-borne signals, and standard microphones can capture airborne components where soil–air coupling is relevant. Future comparative studies are needed to establish sensor performance across different soil types, depths, and ecological contexts.

Until such evidence is available, researchers should align sensor choice with the ecological questions posed—e.g., selecting vibration-sensitive sensors for invertebrate locomotion versus broadband microphones for mixed soil–air interactions. In solids and substrates such as soils, mechanical (non-compressional) waves propagate in and within the surface of the media (e.g. water-air, solid-water) and are detected by mechanoreceptors[47-49]. Since the physical structure of soil largely prevents visual sensing by fauna and limits the mobility of many soil-dwelling organisms[50], substrate-borne waves provide the most ecologically and biologically relevant information flows within the soil domain. Many sensors used in **biotremology** (e.g. accelerometers, geophones) primarily detect these vibrational waves, in addition to pressure waves.

Different approaches will likely be required for different environments, soil types and research questions. Additionally, it is unknown how sensitive many of these sensors are for detecting meso-fauna of smaller sizes (<5 mm). Some sensors can detect low-amplitude sounds, such as plant root growth, in controlled conditions[30]. However, in field studies, the possibility of detecting such low-power signals in the cacophony of the broader soundscape (including aboveground sounds and **recorder self-noise**) is yet to be determined. Hardware costs also pose a challenge to global research, particularly if seeking to monitor at scale. Currently, a single standard soil ecoacoustic hardware set-up consisting of a microphone, pre-amp, impedance filter and recording unit generally costs between AUD*$400* - *$3,000,* which may be expensive for practitioners and citizen scientists.

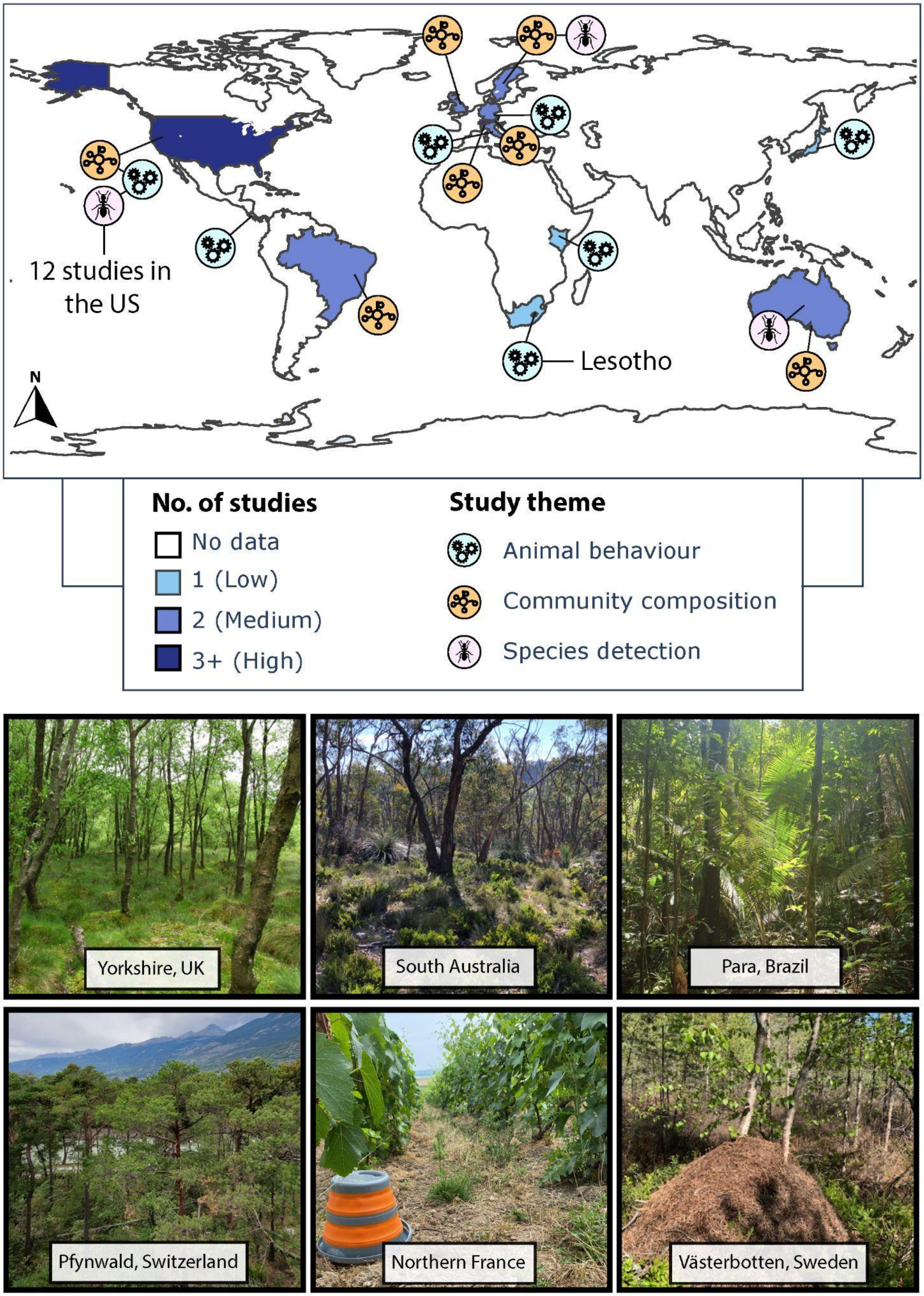

12 studies in the US
Lesotho
N
No. of studies
No data
1 (Low)
2 (Medium)
3+ (High)
Study theme
Animal behaviour
Community composition
Species detection
Yorkshire, UK
South Australia
Para, Brazil
Pfynwald, Switzerland
Northern France
Västerbotten, Sweden

Figure 2. Global soil ecoacoustics studies. (A) The distribution of soil ecoacoustics (and biotremology) studies across the world. Colour gradient indicates the number of studies, and symbols indicate study theme (see Table 1 for more details). (B) Photos include examples of locations/ecosystems of soil ecoacoustics studies conducted by the authors in the UK[12], Australia[19], Brazil[41], Switzerland[44], France (in preparation) and Sweden[15]. These illustrate the diversity of biomes in which soil ecoacoustics studies have been conducted.

Data analysis

Soil ecoacoustics presents several unique data analysis challenges. The high dimensionality and complexity of acoustic data, sometimes comprising long-duration recordings across multiple frequency bands, necessitate advanced data processing techniques. This multifrequency complexity reflects the coexistence of diverse signal sources—including in-soil vibrations, surface activity and airborne sounds—that overlap and interact within the soil matrix, requiring careful interpretation[88]. Acoustic indices, such as the Acoustic Complexity Index (which quantifies short-term variability in sound intensity over time) or the Acoustic Diversity Index (which quantifies the distribution of acoustic energy across frequency bands), have been widely applied in aboveground soundscape studies. However, their transferability to belowground environments remains uncertain, as most indices were designed for broad-frequency airborne soundscapes and may not relate well to the frequency and temporal characteristics of biological signatures and soundscapes specific to soil systems[81] without adaptation.

Another challenge is a low **signal-to-noise** ratio, which is a challenge in diverse ecological contexts (not just soils). However, in soils, sounds and substrate-borne vibrations produced by the biota tend to be quiet and are attenuated over short distances[17]. In addition, soil recordings often include abiotic sounds such as rain or human activity (e.g., vibrations from nearby infrastructure), which can mask or mimic biotic signals[81]. Developing robust noise reduction and/or feature extraction methods that preserve ecologically relevant sounds without introducing artefacts is an ongoing challenge. Importantly, not all 'noise' is irrelevant: anthropogenic sounds can directly affect soil ecology and may therefore represent meaningful ecological data. Rather than excluding such signals post hoc, the approach should be context-dependent—where the aim is to study human-modified environments, anthropogenic sounds form part of the ecological signal, whereas in other cases, minimising interference (e.g., by careful site selection or recording design) may be more appropriate. One solution could be robust classification algorithms that are currently gaining traction in both terrestrial and underwater research[91], although obtaining sufficient training data in such an understudied environment presents an obstacle.

Temporal variability also adds a further layer of complexity. Soil biological activity is highly dynamic and influenced by diel cycles, weather conditions and seasonal changes[17]. Sonic phenology—the study of seasonal and diel patterns in acoustic activity—is a general ecological phenomenon across terrestrial and aquatic systems. Within soil ecoacoustics, strong temporal dynamics pose a particular challenge[41], and these patterns should be considered when interpreting soil soundscapes. This requires **time-**

series analysis that can accommodate non-stationary (time-varying) data and detect meaningful patterns over variable timescales[41,92].

Interpreting analyses remains challenging as statistical models can yield predictions without easily interpretable ecological implications. Bridging the gap between acoustic patterns and ecological functions (e.g., decomposition rates, invertebrate diversity) requires interdisciplinary approaches (and multimodal devices that sense other soil parameters simultaneously) that integrate sound data with other forms of ecological, chemical and physical soil information. Moreover, unlike aboveground and aquatic ecoacoustics, where bird, mammal and insect sounds can often be classified using curated libraries, soil vibro- and soundscapes lack comprehensive reference datasets[93-95].

Identifying taxa and associating them with their acoustic signatures remains a significant challenge in ecoacoustics. This difficulty is compounded by a shortage of trained taxonomists and the limited availability of comprehensive acoustic reference libraries. Developing comprehensive **reference databases** of soil organismal sounds to enable **taxonomic resolution** in ecoacoustic studies would require considerable advancements in our understanding of soil community dynamics (e.g., knowing which signals are incidental or otherwise) and in the technology used to detect soil organisms.

Towards standard operating procedures

Collaborative research requires global data compatibility. Currently, a key challenge is the lack of standardised methods for sampling soil soundscapes[96]. A critical requirement will be to create globally accepted standard operating procedures (SOPs). This will open opportunities for researchers to compare data worldwide[97]. A preliminary SOP should be structural rather than overly prescriptive of specific hardware and pipelines. This will allow flexibility for various research questions and budgets. Several SOP levels could be valuable (Figure 3), i.e., a flexible and accessible SOP for citizen scientists, a robust yet adjustable and accessible SOP for researchers and practitioners, and a specifically prescribed SOP for participants of larger, better-resourced global projects.

When designing sampling strategies, guidance on recording schedules, distance between recording units, waveguide depth, and soil properties should all be considered. Sampling can be done with a sensor directly coupled (or indirectly coupled via a waveguide) to the soil, an audio recording unit, a pre-amp to increase the sensitivity for detecting lower energy signals, and an impedance filter to reduce machine noise during the recordings. Sensors used include standard microphones, contact microphones, hydrophones (particularly effective in water-saturated soil), accelerometers, geophones and laser doppler vibrometers[74,79,88].

A key pre-processing step in some analyses is to isolate biophony from other components of the soundscape (geophony, anthropophony, and device self-noise)[98,99]. This approach is generally used in bioacoustic or species-specific signal studies, where the primary aim is to detect or classify biological activity. By contrast, in ecoacoustic research, often the full soundscape—including geophony and anthropophony—is considered ecologically relevant and typically retained to capture the complexity of real-world conditions. An SOP should provide guidance on the best software approach for noise reduction (and when this step is appropriate) to minimise background noise while maintaining the biotic signals. For the results to be globally comparable, the raw data should ideally be stored in an open-access database. The SOP should therefore include instructions and code to assist researchers in making their pre-processed and processed data publicly accessible.

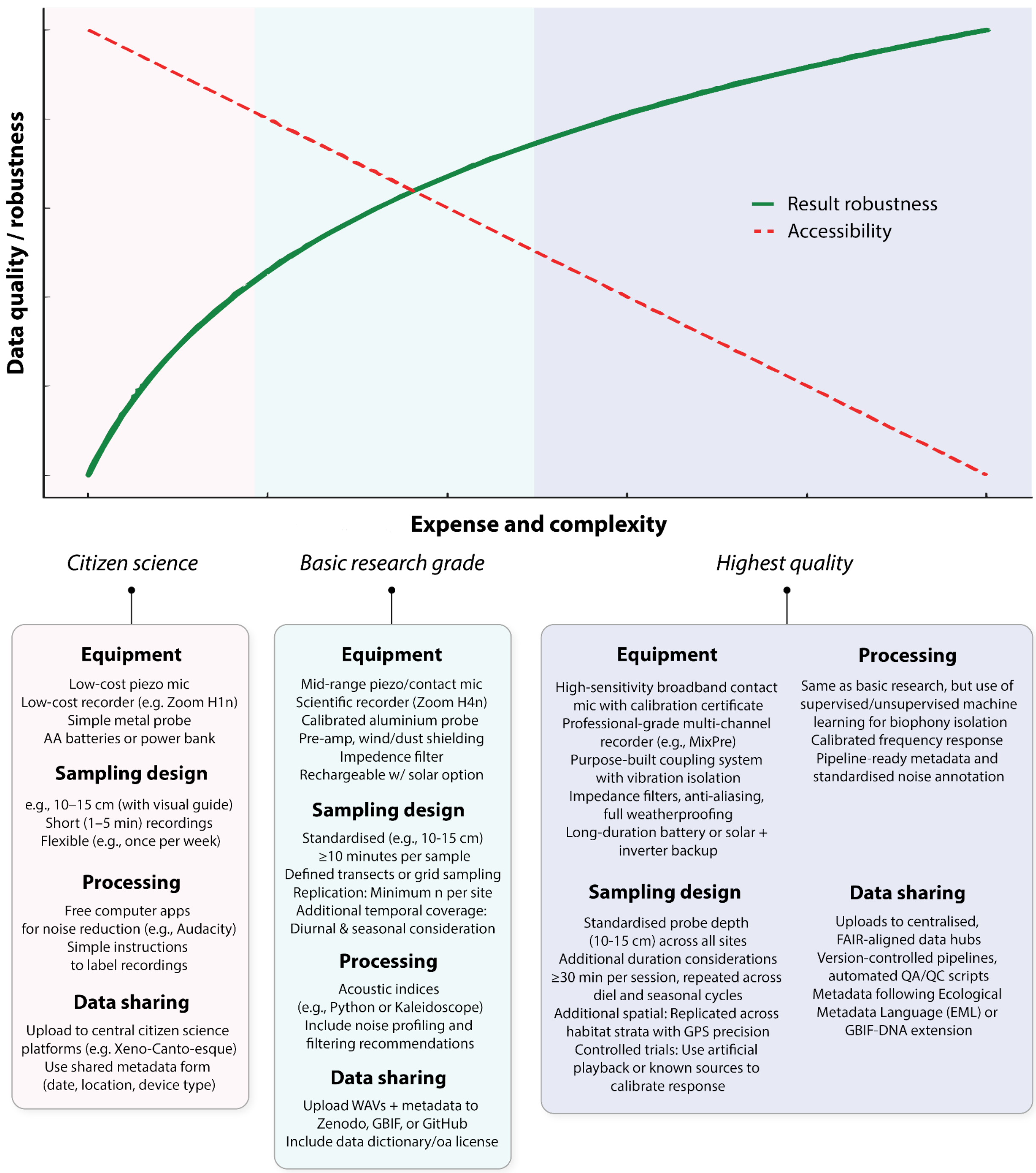


Figure 3. Example of a multi-level SOP framework. A hypothesis to be tested is that as project/equipment expense and complexity increase, so does the quality of the acquired data, while accessibility decreases. Data quality/result robustness could plateau at mid-range levels where sufficient quality is achieved for many research purposes. Beyond

this, gains may be marginal while accessibility continues to decrease, although such approaches are often necessary to tackle particularly complex research questions.

Democratising soil ecoacoustics

To ensure soil ecoacoustics continues to develop in an accessible manner, open-access databases and tools will be required. Options are abundant in ecology; for example, the Atlas of Living Australia[100] and Global Biodiversity Information Facility[101] hold open-access biodiversity (and other environmental) databases as map layers for various environmental conditions. These can be accessed by practitioners, researchers, and citizen scientists. Democratising research is particularly effective in engaging citizen scientists, furthering databases, collaboration, and authorship[102]. Methods training could be delivered in workshops that help develop capacity on field methods and data access, and analysis. This democratisation has been done with bird and frog calls with software like BirdNET[103] and FrogID[104], which could provide useful models.

Providing broader access to soil ecoacoustics has the potential to shift societal perceptions of soil health by making below-ground biodiversity more tangible and relatable (e.g., Sounding Soil initiative in Switzerland)[11,105]. Engaging citizens through participatory research can raise awareness of the ecological importance of soil and generate large volumes of geographically diverse data[106,107]. These data could be used both scientifically to progress soil ecoacoustics and in practical settings, for example, helping land managers, restoration practitioners and policymakers make soil health decisions.

Coordinated efforts should open new funding avenues for shared, openly accessible data repositories. To advance soil ecoacoustics meaningfully, there are four essential priorities: (1) the further development and adoption of open-source standard operating procedures (SOPs; Figure 3) to ensure data comparability across sites and projects; (2) the creation of a global platform for community-based data sharing and co-governance. This would not only support collaboration and equitable decision-making but also accelerate the integration of soil ecoacoustics into restoration monitoring and soil health frameworks; (3) the establishment of a global soil ecoacoustics research network to maximise open science, methodological innovation and global cooperation (Box 1); and (4) standardisation of terminology to address soil environments and bring together biotremologists and bioacoustics in this area.

Box 1. Realising the potential of soil ecoacoustics through a global network.

Soils are among the most heterogeneous habitats on Earth, shaped by climate, geology, vegetation, land use and their diverse biotic communities [108,109]. Localised ecoacoustic studies, while valuable, cannot capture the global picture of belowground activity or identify general patterns across ecosystems. To realise the potential of soil ecoacoustics as a toolkit for biodiversity detection and soil health monitoring, a coordinated international effort is needed. We propose the Soil Ecoacoustics Research Network (SERN): a collaborative, decentralised initiative to standardise, expand, and democratise soil sound research.

Core objectives of SERN:

1. Develop and share open-source protocols for recording and analysing soil soundscapes.
2. Establish globally distributed sites across ecosystems and land uses for long-term monitoring.
3. Facilitate analyses across environmental gradients to identify both universal and context-specific acoustic indicators of soil function.
4. Create an open-access platform for storing, visualising, and analysing acoustic data and metadata.
5. Support training for diverse stakeholders, including citizen scientists, early-career researchers, land managers, underrepresented regions and Indigenous communities.
6. Co-develop practical applications with restoration practitioners and policymakers.

A global network would allow researchers to address fundamental and applied questions: How do soil soundscapes vary with land use, latitude or rainfall? Can acoustic signals act as early-warning indicators of degradation or restoration success? How do global change drivers, such as climate warming, intensification, or invasive species, reshape belowground acoustic activity, and are these shifts linked to biodiversity loss? Integration of soil acoustic data into biodiversity infrastructures such as GBIF [110] and GEO BON [111] would enhance the visibility and policy relevance of soil life.

While current methods may not yet identify species reliably (although we have developed a promising technique for leaf litter communities), they offer strong potential as proxies for soil health and as complementary indicators in restoration and monitoring frameworks [11]. Challenges include the need for standardised yet flexible protocols across diverse environments, infrastructure for storing and analysing large datasets and equitable participation across regions [112,113]. Ethical considerations, such as data sovereignty [114] and community engagement, must be central, alongside sustained funding and collaboration with existing biodiversity networks [115,116].

SERN could help place soil organisms – the 'hidden majority' of life – on the map and advance both ecological knowledge and non-invasive practical tools for managing and restoring the world's soils.

Concluding remarks

Soil ecoacoustics represents an exciting frontier in ecology—one that has the potential to improve how we detect and monitor soil fauna, and understand, restore and manage soil health. By tuning into the vibrations of soil fauna and the wider sound- and vibroscape context, we can uncover new indicators of biodiversity and ecosystem functioning with minimally invasive and scalable monitoring tools. Yet, this field is still in its infancy. Realising its full potential will require collaborative, interdisciplinary efforts to address ecological, technological and methodological challenges, from disentangling biophony, geophony and anthropophony to developing accessible standard operating procedures and globally compatible datasets. We propose a federated and inclusive approach to research infrastructure: a global network of soil ecoacoustics experiments underpinned by structural SOPs and a commitment to open science. Such an initiative could democratise participation, accelerate innovation and build new bridges among communities, scientists and policymakers. As global ecosystems face mounting pressures, there is an urgent need to monitor and respond more effectively to soil health. Soil ecoacoustics could help fill that gap by amplifying the often-unheard dimensions of our ecosystems, contributing knowledge to the science and practice of restoration and sustainable land management (see Outstanding Questions).

Acknowledgements

This research was supported by funding from the Australian Research Council (grant DP250101476), the New Zealand Ministry of Business Innovation and Employment (grant UOWX2101) and the National Environmental Science Programme (NESP). This review was primarily written on the lands of the Kaurna People, Tarntanya/Adelaide, South Australia, to whom we pay our respects.

References

1. Anthony, M.A. et al. (2023) Enumerating soil biodiversity. *Proc. Natl. Acad. Sci.* 120, e2304663120-e2304663120. 10.1073/pnas.2304663120
2. Blakemore, R.J. (2025) Biodiversity restated: 99.9% of global species in Soil Biota. *ZooKeys* 1224, 283-316. 10.3897/zookeys.1224.131153
3. Yu, Y. et al. (2020) Loess Plateau: from degradation to restoration. *Sci. Total Environ.* 738, 140206-140206. 10.1016/j.scitotenv.2020.140206
4. Pennock, D. et al. (2015) Status of the world's soil resources. Technical Summary *FAO,* Rome, Italy. Online: efaidnbmnnnibpcajpcglclefindmkaj/https://www.fao.org/fileadmin/templates/lon/Items/Dan_Pennock_IYS_2015.pdf
5. Kraamwinkel, C.T. et al. (2021) Planetary limits to soil degradation. *Commun. Earth Environ.* 2, 249
6. Kopittke, P.M. et al. (2022) Ensuring planetary survival: the centrality of organic carbon in balancing the multifunctional nature of soils. *Crit. Rev. Environ. Sci. Technol.* 52, 4308-4324
7. Delgado-Baquerizo, M. et al. (2020) Multiple elements of soil biodiversity drive ecosystem functions across biomes. *Nat. Ecol. Evol.* 4, 210-220. 10.1038/s41559-019-1084-y
8. Neemisha et al. (2020) *Role of Soil Organisms in Maintaining Soil Health, Ecosystem Functioning, and Sustaining Agricultural Production*. In, pp. 313-335, Springer Int. Publ.
9. Cameron, E.K. et al. (2018) Global gaps in soil biodiversity data. *Nat. Ecol. Evol.* 2, 1042-1043. 10.1038/s41559-018-0573-8
10. Guerra, C.A. et al. (2020) Blind spots in global soil biodiversity and ecosystem function research. *Nat. Commun.* 11, 3870-3813. 10.1038/s41467-020-17688-2
11. Robinson, J.M. et al. (2024) Monitoring soil fauna with ecoacoustics. *Proc. R. Soc. B.* 10.1098/rspb.2024.1595
12. Robinson, J.M. et al. (2023) The sound of restored soil: using ecoacoustics to measure soil biodiversity in a temperate forest restoration context. *Restor. Ecol.* 31, n/a. 10.1111/rec.13934
13. Mankin, R.W. and Lapointe, S.L. (2003) Listening to the larvae: acoustic detection of *Diaprepes abbreviatus* (L.).
14. Janowiecki, M.A. et al. (2024) Effect of soldiers on vibroacoustic alarm response in workers of subterranean termites (Blattodea: Rhinotermitidae). *Insectes Soc.* 71, 75-83. 10.1007/s00040-023-00945-0
15. Sørensen, L.V. et al. (2024) Continuous measurement of red wood ant (*Formica ru*fa) outdoor behaviour using passive acoustic monitoring. *Eur. J. Soil Biol.* 123, 103687
16. Hill, P.S.M. and Wessel, A. (2016) Biotremology. *Curr. Biol.* 26, R187-R191. 10.1016/j.cub.2016.01.054
17. Maeder, M. et al. (2022) Temporal and spatial dynamics in soil acoustics and their relation to soil animal diversity. *PLoS One* 17, e0263618-e0263618. 10.1371/journal.pone.0263618

18. Farina, A. (2019) Ecoacoustics: A quantitative approach to investigate the ecological role of environmental sounds. *Mathematics* 7, 21. 10.3390/math7010021
19. Robinson, J.M. et al. (2024). Sounds of the underground reflect soil biodiversity dynamics across a grassy woodland restoration chronosequence. *J. Appl. Ecol.* 61, 2047-2060.
20. Farina, A. and Mullet, T.C. (2025). The Sonoscape of a Rural Town in the Mediterranean Region: A Case Study of Fivizzano. *Acoustics.* 7, 23.
21. Oliveros, P. (2006) Improvisation in the Sonosphere. In *Contemporary Music Review.* doi.org/10.1080/07494460600989986
22. Farina, A. and Salutari, P. (2016) Applying the ecoacoustic event detection and identification (EEDI) model to the analysis of acoustic complexity. *J. Mediterr. Ecol.* 14, 13-42
23. Farina, A. (2013) Sonic patterns III: Sounds and vibrations from soils. In *Soundscape Ecol.: Principles, Patterns, Methods and Applications,* pp. 209-220, Springer
24. Roberts, L. and Wickings, K. (2022) Biotremology: Tapping into the World of Substrate-Borne Waves. *Acoust. Today* 18, 49. 10.1121/AT.2022.18.3.49
25. Sueur, J. and Farina, A. (2015) Ecoacoustics: the Ecological Investigation and Interpretation of Environmental Sound. *Biosemiotics* 8, 493-502. 10.1007/s12304-015-9248-x
26. Dröge, S. et al. (2021) Listening to a changing landscape: Acoustic indices reflect bird species richness and plot-scale vegetation structure across different land-use types in north-eastern Madagascar. *Ecol. Indic.* 120, 106929. 10.1016/j.ecolind.2020.106929
27. Hintze, F. et al. (2021) Bioacoustics for in situ validation of species distribution modelling: An example with bats in Brazil. *PLoS One* 16, e0248797-e0248797. 10.1371/journal.pone.0248797
28. Šturm, R. et al. (2022) Is It Time for Ecotremology? *Front. Ecol. Evol.* 10. 10.3389/fevo.2022.828503
29. Farina, A. and Mullet, T.C. (2025) Composition and Dynamics of the Sonosphere Along a Soil-Surface Ecotone at an Agricultural Site in Northern Italy: A Preliminary Approach. *Geosciences* (Basel) 15, 34. 10.3390/geosciences15020034
30. Lacoste, M. et al. (2018) Listening to earthworms burrowing and roots growing - Acoustic signatures of soil biological activity. *Sci. Rep.* 8, 10236-10239. 10.1038/s41598-018-28582-9
31. DiCarlo, D.A. et al. (2003) Acoustic measurements of pore-scale displacements. *Geophys. Res. Lett.* 30,
32. Oelze, M.L. et al. (2002) Measurement of Attenuation and Speed of Sound in Soils. *Soil Sci. Soc. Am. J.* 66, 788-796. 10.2136/sssaj2002.7880
33. Lu, Z. and Sabatier, J.M. (2009) Effects of Soil Water Potential and Moisture Content on Sound Speed. *Soil Sci. Soc. Am. J.* 73, 1614-1625. 10.2136/sssaj2008.0073

34. Pulido-Moncada, M. et al. (2022) Characterisation of soil pore structure anisotropy caused by the growth of bio-subsoilers. *Geoderma* 409, 115571. 10.1016/j.geoderma.2021.115571
35. Tyack, P.L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *J. Mammal.* 89, 549-568.
36. Yip, D.A., et al. (2017). Sound attenuation in forest and roadside environments: Implications for avian point-count surveys. *Condor* 119, 73-84.
37. Stowell, D. and Sueur, J. (2020) Ecoacoustics: acoustic sensing for biodiversity monitoring at scale. *Remote Sens. Ecol. Conserv.* 6, 217-219. 10.1002/rse2.174
38. Karaconstantis, C. et al. (2020) Spatio-temporal heterogeneity in river sounds: Disentangling micro- and macro-variation in a chain of waterholes. *Freshw. Biol.* 65, 96-106. 10.1111/fwb.13439
39. Bonato Asato, A.E. et al. (2023) On the phenology of soil organisms: Current knowledge and future steps. *Ecol. Evol.* 13, e10022-n/a. 10.1002/ece3.10022
40. Martay, B. and Pearce-Higgins, J.W. (2018) Using data from schools to model variation in soil invertebrates across the UK: The importance of weather, climate, season and habitat. *Pedobiologia* 67, 1-9. 10.1016/j.pedobi.2018.01.002
41. Metcalf, O.C. et al. (2024) Listening to tropical forest soils. *Ecol. Indic.* 158, 111566. 10.1016/j.ecolind.2024.111566
42. Ruiz, S.A. et al. (2021) Global earthworm distribution and activity windows based on soil hydromechanical constraints. *Commun. Biol.* 4, 612-612. 10.1038/s42003-021-02139-5
43. Hassall, M. et al. (2018) Interspecific variation in responses to microclimate by terrestrial isopods: implications in relation to climate change. *ZooKeys* 801, 5-24. 10.3897/zookeys.801.24934
44. Maeder, M. et al. (2019) Sounding soil: An acoustic, ecological artistic investigation of soil life. *Soundscape J.* 18, 5-14
45. Mankin, R.W. et al. (2000) Eavesdropping on Insects Hidden in Soil and Interior Structures of Plants. *J. Econ. Entomol.* 93, 1173-1182. 10.1043/0022-0493(2000)093(1173:EOIHIS)2.0.CO;2
46. Keen, S.C. et al. (2022) Non-native species change the tune of tundra soils: Novel access to soundscapes of the Arctic earthworm invasion. *Sci. Total Environ.* 838, 155976-155976. 10.1016/j.scitotenv.2022.155976
47. Hill, P.S. (2008) *Vibrational communication in animals*. Harvard Univ. Press
48. Hill, P.S.M. (2009) How do animals use substrate-borne vibrations as an information source. *Naturwissenschaften* 96, 1355-1371. 10.1007/s00114-009-0588-8
49. Hill, P.S.M. et al. (2019) Biotremology: Studying Vibrational Behavior (Animal Signals and Communication, 6, 1st 2019. edn), Springer Int. Publ.
50. Erktan, A. et al. (2020) The physical structure of soil: Determinant and consequence of trophic interactions. *Soil Biol. Biochem.* 148, 107876. 10.1016/j.soilbio.2020.107876
51. Heth, G. et al. (1987) Vibrational Communication in Subterranean Mole Rats (Spalax ehrenbergi). *Behav. Ecol. Sociobiol.* 21, 31-33. 10.1007/BF00324432
52. Rado, R. et al. (1987) Seismic signalling as a means of communication in a subterranean mammal. *Anim. Behav.* 35, 1249-1251

53. Aicher, B. and Tautz, J.r. (1990) Vibrational communication in the fiddler crab, Uca pugilator: I. Signal transmission through the substratum. *J. Comp. Physiol. A* 166, 345-353. 10.1007/BF00204807
54. DeVries, P.J. (1990) Enhancement of Symbioses Between Butterfly Caterpillars and Ants by Vibrational Communication. *Science* (Am. Assoc. Adv. Sci.) 248, 1104-1106. 10.1126/science.248.4959.1104
55. Shipley, C. et al. (1992) Seismic Communication in Northern Elephant Seals. In, pp. 553-562, Springer US
56. Hill, P.S.M. and Shadley (1997) Substrate vibration as a component of a calling song. *Naturwissenschaften* 84, 460-463. 10.1007/s001140050429
57. Narins, P.M. et al. (1997) The Use of Seismic Signals by Fossorial Southern African Mammals: A Neuroethological Gold Mine. *Brain Res. Bull.* 44, 641-646. 10.1016/S0361-9230(97)00286-4
58. O'Connell-Rodwell, C.E. et al. (2001) Exploring the Potential Use of Seismic Waves as a Communication Channel by Elephants and Other Large Mammals. *Am. Zool.* 41, 1157-1170. 10.1093/icb/41.5.1157
59. Elias, D.O. et al. (2003) Seismic signals in a courting male jumping spider (Araneae:Salticidae). *J. Exp. Biol.* 206, 4029-4039. 10.1242/jeb.00634
60. Kimchi, T. et al. (2005) Evidence for the use of reflected self-generated seismic waves for spatial orientation in a blind subterranean mammal. *J. Exp. Biol.* 208, 647-659. 10.1242/jeb.01396
61. Devetak, D. et al. (2007) Sand as a medium for transmission of vibratory signals of prey in antlions Euroleon nostras (Neuroptera: Myrmeleontidae). *Physiol. Entomol.* 32, 268-274. 10.1111/j.1365-3032.2007.00580.x
62. Catania, K.C. (2008) Worm Grunting, Fiddling, and Charming—Humans Unknowingly Mimic a Predator to Harvest Bait. *PLoS One* 3, e3472-e3472. 10.1371/journal.pone.0003472
63. Barbero, F. et al. (2009) Queen Ants Make Distinctive Sounds That Are Mimicked by a Butterfly Social Parasite. *Science,* 323, 782-785. 10.1126/science.1163583
64. Barbero, F. et al. (2009) Acoustical mimicry in a predatory social parasite of ants. *J. Exp. Biol.* 212, 4084-4090. 10.1242/jeb.032912
65. Gordon, S.D. and Uetz, G.W. (2011) Multimodal communication of wolf spiders on different substrates: evidence for behavioural plasticity. *Anim. Behav.* 81, 367-375. 10.1016/j.anbehav.2010.11.003
66. Shier, D.M. et al. (2012) Beyond masking: Endangered Stephen's kangaroo rats respond to traffic noise with footdrumming. *Biol. Conserv.* 150, 53-58. 10.1016/j.biocon.2012.03.007
67. Kojima, W. et al. (2012) Vibratory communication in the soil: pupal signals deter larval intrusion in a group-living beetle *Trypoxylus dichotoma*. *Behav. Ecol. Sociobiol.* 66, 171-179. 10.1007/s00265-011-1264-5
68. Hager, F.A. and Kirchner, W.H. (2013) Vibrational long-distance communication in the termites *Macrotermes natalensis* and *Odontotermes* sp. *J. Exp. Biol.* 216, 3249-3256. 10.1242/jeb.086991

69. Wu, C.-H. and Elias, D.O. (2014) Vibratory noise in anthropogenic habitats and its effect on prey detection in a web-building spider. *Anim. Behav.* 90, 47-56. 10.1016/j.anbehav.2014.01.006
70. Oberst, S. et al. (2017) Cryptic termites avoid predatory ants by eavesdropping on vibrational cues from their footsteps. *Ecol. Lett.* 20, 212-221. 10.1111/ele.12727
71. Hayashi, Y. et al. (2018) Four types of vibration behaviors in a mole cricket. *PLoS One* 13, e0204628-e0204628. 10.1371/journal.pone.0204628
72. Mortimer, B. et al. (2018) Classifying elephant behaviour through seismic vibrations. *Curr. Biol.* 28, R547-R548. 10.1016/j.cub.2018.03.062
73. Görres, C.M. and Chesmore, D. (2019) Active sound production of scarab beetle larvae opens up new possibilities for species-specific pest monitoring in soils. *Sci. Rep.* 9, 10115-10119. 10.1038/s41598-019-46121-y
74. Roberts, L. (2021) Substrate-borne vibration and sound production by the land hermit crab *Coenobita compressus* during social interactions. *J. Acoust. Soc. Am.* 149, 3261-3272. 10.1121/10.0004988
75. Brandhorst-hubbard, J.L. et al. (2001) Mapping of Soil Insect Infestations Sampled by Excavation and Acoustic Methods. *J. Econ. Entomol.* 94, 1452-1458. 10.1603/0022-0493-94.6.1452
76. Mankin, R.W. et al. (2007) Acoustic indicators for mapping infestation probabilities of soil invertebrates. *J. Econ. Entomol.* 100, 790-800. 10.1603/0022-0493(2007)100[790:AIFMIP]2.0.CO;2
77. Bishop, A.M. et al. (2015) Good vibrations by the beach boys: magnitude of substrate vibrations is a reliable indicator of male grey seal size. *Anim. Behav.* 100, 74-82. 10.1016/j.anbehav.2014.11.008
78. Inyang, E.I. et al. (2019) Subterranean acoustic activity patterns of Vitacea polistiformis (Lepidoptera: Sesiidae) in relation to abiotic and biotic factors. *Insects* (Basel, Switzerland) 10, 267. 10.3390/insects10090267
79. Podlesnik, J. et al. (2019) Prey detection in antlions: propagation of vibrational signals deep into the sand. *Physiol. Entomol.* 44, 215-221. 10.1111/phen.12295
80. Šturm, R. et al. (2021) Hay meadow vibroscape and interactions within insect vibrational community Hay meadow vibroscape and interactions within insect vibrational community. *iScience* 24, 103070
81. Metcalf, O.C. et al. (2024) The efficacy of acoustic indices for monitoring abundance and diversity in soil soundscapes. *Ecol. Indic.* 169, 112954. 10.1016/j.ecolind.2024.112954
82. Lewis, E.R. and Narins, P.M. (1985) Do Frogs Communicate with Seismic Signals? *Science* (Am. Assoc. Adv. Sci.) 227, 187-189. 10.1126/science.227.4683.187
83. Narins, P.M. (1990) Seismic Communication in Anuran Amphibians. *BioScience* 40, 268-274. 10.2307/1311263
84. Narins, P. et al. (1992) Seismic signal transmission between burrows of the Cape mole-rat, Georychus capensis. *J. Comp. Physiol.* **A** Sens. Neural Behav. Physiol. 170, 13-21. 10.1007/BF00190397

85. Sanborn, A.F. and Phillips, P.K. (1995) No acoustic benefit to subterranean calling in the cicada *Okanagana pallidula* Davis (Homoptera: Tibicinidae). *Great Basin Nat.* 55, 374-376
86. Zhang, M. et al. (2003) Acoustic Identification and Measurement of Activity Patterns of White Grubs in Soil. *J. Econ. Entomol.* 96, 1704-1710. 10.1603/0022-0493-96.6.1704
87. Günther, R.H. et al. (2004) Seismic waves from elephant vocalizations: A possible communication mode? *Geophys. Res. Lett.* 31, L11602-n/a. 10.1029/2004GL019671
88. Mankin, R.W. and Benshemesh, J. (2006) Geophone detection of subterranean termite and ant activity. *J. Econ. Entomol.* 99, 244-250. 10.1603/0022-0493(2006)099[0244:GDOSTA]2.0.CO;2
89. Cokl, A. et al. (2006) Transmission of stridulatory signals of the burrower bugs, *Scaptocoris castanea* and *Scaptocoris carvalhoi* (Heteroptera: Cydnidae) through the soil and soybean. *Physiol. Entomol.* 31, 371-381. 10.1111/j.1365-3032.2006.00530.x
90. Napier, T. et al. (2024) Advancements in preprocessing, detection and classification techniques for ecoacoustic data: A comprehensive review for large-scale Passive Acoustic Monitoring. *Expert Syst. Appl.* 252, 124220. 10.1016/j.eswa.2024.124220
91. Ulloa, J.S. et al. (2018) Estimating animal acoustic diversity in tropical environments using unsupervised multiresolution analysis. *Ecol. Indic.* 90, 346-355
92. Yoh, N. et al. (2024) Time series methods for the analysis of soundscapes and other cyclical ecological data. *Methods Ecol. Evol.* 15, 1158-1176. 10.1111/2041-210X.14361
93. Kasten, E.P. et al. (2012) The remote environmental assessment laboratory's acoustic library: An archive for studying soundscape ecology. *Ecol. Inform.* 12, 50-67. 10.1016/j.ecoinf.2012.08.001
94. Foundation, X.-C. (2025). *Xeno-Canto: Sharing bird sounds from around the world.* Online: https://xeno-canto.org/
95. Greenhalgh, J.A. et al. (2025) The Freshwater Sounds Archive. *bioRxiv*, 2025.2005.2007.652412
96. Metcalf, O. et al. (2023) *Good practice guidelines for long-term ecoacoustic monitoring in the UK.* Online: efaidnbmnnnibpcajpcglclefindmkaj/https://ebaker.me.uk/pubs/2023_02_Guidelines.pdf
97. Abrahams, C. et al. (2021) Pond Acoustic Sampling Scheme: A draft protocol for rapid acoustic data collection in small waterbodies. *Ecol. Evol.* 11, 7532-7543. 10.1002/ece3.7585
98. Sun, Y.J. et al. (2022). soundscape_IR: A source separation toolbox for exploring acoustic diversity in soundscapes. *Methods Ecol. Evol.* 13, 347-2355.
99. Wang, M. et al. (2025). Animal acoustic identification, denoising and source separation using generative adversarial networks. *Methods Ecol. Evol.* 16, 2472-2486.

100. Australia, A.o.L. (2025). *Atlas of Living Austalia.* Atlas Living Aust. Online: https://www.ala.org.au/

101. Facility, G.B.I. (2024). *GBIF Occurrence Download.* Glob. Biodivers. Inf. Facil. Online: https://www.gbif.org/

102. Herodotou, C., Kenny, I. and Scanlon, E., 2024, September. Democratising Research Practices through Community Citizen Science. In *Proceedings of the 2024 International Conference on Information Technology for Social Good* (pp. 68-75). https://doi.org/10.1145/3677525.3678642

103. Kahl, S. et al. (2021) BirdNET: A deep learning solution for avian diversity monitoring. *Ecol. Inform.* 61, 101236. 10.1016/j.ecoinf.2021.101236

104. Museum, A. (2025). FrogID: Australia's national frog call recording project. *Aust. Mus.* Online: https://www.frogid.net.au/

105. Development, B.F.f.E. (2025). *Sounding Soil - healthy soil makes noise.* Online: https://www.biovision.ch/en/project/sounding-soil/

106. Stroud, J.L. (2019) Soil health pilot study in England: Outcomes from an on-farm earthworm survey. *PLoS One* 14, e0203909-e0203909. 10.1371/journal.pone.0203909

107. Stroud, J.L. et al. (2023) Working with UK farmers to investigate anecic earthworm middens and soil biophysical properties. *Ann. Appl. Biol.* 182, 92-100. 10.1111/aab.12795

108. Franklin, R.B. and Mills, A.L. (2009) Importance of spatially structured environmental heterogeneity in controlling microbial community composition at small spatial scales in an agricultural field. *Soil Biol. Biochem.* 41, 1833-1840. 10.1016/j.soilbio.2009.06.003

109. Chung, Y.A. (2023) The temporal and spatial dimensions of plant–soil feedbacks. *New Phytol.* 237, 2012-2019. 10.1111/nph.18719

110. Telenius, A. (2011) Biodiversity information goes public: GBIF at your service. *Nord. J. Bot.* 29, 378-381. 10.1111/j.1756-1051.2011.01167.x

111. Secretariat, G.o.E.O.B.O.N. (2015). Global Biodiversity Change Indicators. 1.2 ed. *GEO BON. Online:* https://www.geobon.org/downloads/biodiversity-monitoring/technical-reports/GEOBON/2015/GBCI-Version1.2-low.pdf

112. Stephenson, P.J. (2020) Technological advances in biodiversity monitoring: applicability, opportunities and challenges. *Curr. Opin. Environ. Sustain.* 45, 36-41. 10.1016/j.cosust.2020.08.005

113. Bradfer-Lawrence, T. et al. (2025) Deriving meaning from acoustic data in hyper-diverse ecosystems. *Trends Ecol. Evol.* 40, 431-435. 10.1016/j.tree.2025.03.004

114. Reyes-García, V. et al. (2022) Data Sovereignty in Community-Based Environmental Monitoring: Toward Equitable Environmental Data Governance. *BioScience* 72, 714-717. 10.1093/biosci/biac048

115. Lopez-Gonzalez, G. et al. (2011) ForestPlots.net: a web application and research tool to manage and analyse tropical forest plot data. *J. Veg. Sci.* 22, 610-613. 10.1111/j.1654-1103.2011.01312.x

116. Anderson-Teixeira, K.J. et al. (2015) CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change. *Glob. Change Biol.* 21, 528-549. 10.1111/gcb.12712