soil systems

Opinion

Sounds of Soil: A New World of Interactions under Our Feet?

Matthias C. Rillig [1,2,*], Karine Bonneval [3] and Johannes Lehmann [4]

[1] Institut für Biologie, Freie Universität Berlin, 14195 Berlin, Germany
[2] Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), 14195 Berlin, Germany
[3] 6 Chemin des Vignes, Pesselières, 18300 Jalognes, France
[4] College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA
* Correspondence: matthias.rillig@fu-berlin.de; Tel.: +49-30-838-53165

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Abstract: Soils are biodiversity-dense and constantly carry chemical flows of information, with our mental image of soil being dark and quiet. But what if soil biota tap sound, or more generally, vibrations as a source of information? Vibrations are produced by soil biota, and there is accumulating evidence that such vibrations, including sound, may also be perceived. We here argue for potential advantages of sound/vibration detection, which likely revolve around detection of potential danger, e.g., predators. Substantial methodological retooling will be necessary to capture this form of information, since sound-related equipment is not standard in soils labs, and in fact this topic is very much at the fringes of the classical soil research at present. Sound, if firmly established as a mode of information exchange in soil, could be useful in an 'acoustics-based' precision agriculture as a means of assessing aspects of soil biodiversity, and the topic of sound pollution could move into focus for soil biota and processes.

Keywords: soil; sound; vibration; disturbance; biodiversity

1. Background

Soils are rich in biodiversity [1], and as a consequence of this diversity of life, information flows in soil are omnipresent. The rhizosphere has been described frequently as an 'information superhighway' for the exchange of chemical signals between plants and soil microbes and among soil organisms [2]. All this exchange of information (e.g., symbiont recognition, quorum sensing, allelopathy) is thought to be chemical in nature, and the prevalent impression of soil is that it is dark and quiet. But what if sound, or more generally vibrations (with sound being the vibrations humans can hear), is tapped by soil biota as a source of information as well (Figure 1)?

There certainly is plenty of evidence that soil organisms produce sound, which might be perceived by microbes. For example, a recent paper measured the sounds produced by earthworms or growing roots using piezoelectric sensors [3]. There is also evidence, albeit scarcer, that soil organisms can respond to sound or vibrations. For example, earthworm grunting is a technique used to harvest earthworms that involves the use of sound produced by rhythmically scraping a wooden stake inserted into the ground, which was studied experimentally [4]. The biological backdrop is likely that earthworms can either sense a predator or falling rain, which produces sound in similar frequencies. Isopods have been shown to exhibit behavioral responses to acoustic stimuli under lab conditions [5]. Plants also have mechano-reception, and roots may alter their growth in reaction to certain vibrations and sounds [6]. The list of organisms that utilize sound also includes microbes: several studies have shown that microbes can respond to sound under laboratory conditions by changing gene expression and metabolism (e.g., yeast [7], bacteria [8]). In fact, physical transmission of information in soil comes with its distinct advantages, especially for microbes: it is extremely fast, energy-efficient, and potentially operating over larger distances compared to the limits imposed by the production and diffusion of chemical signals in soil [9]. For example, quorum sensing typically operates in the range of micrometers, whereas physical signals, such as sound, can be operational over distances up to centimeters, depending on the properties of the medium [9].

Figure 1. An artist's impression of sounds in soil. This installation, created by Karine Bonneval, is entitled 'Listen to the Soil' and consists of a layer of soil and a set of 12 ceramic pieces (myxomycete fruiting body-like objects) that emit sounds from different types of soils. The installation was created in collaboration with Fanny Rybak, a bioacoustician at NeuroPSI, Orsay, Paris Sud University. Ceramics were made by Charlotte Poulsen, with the help of Diagonale Paris-Saclay and DRAC Centre-Val de Loire, Micro Onde art center. Artist Karine Bonneval was hosted by the Rillig lab. The installation is meant to offer observers another way to experience the typically invisible soil inhabitants through the sounds they produce. Photo by K. Bonneval, showing part of the installation.

2. How Sound Might Carry Useful Information for Soil Biota

How specifically might sound carry useful information for soil microbes? We do not know this yet. Perhaps, filamentous fungi can perceive the sound of hyphal grazers. There would be advantages of vibration detection as a warning signal: the fungal mycelium could avoid advancing into areas of intense animal activity, for example of collembola or earthworms (the distribution of animals in soil tends to be quite clustered), or the fungus could mount defense-related actions (induced defense) when it encounters an impending attack by microarthropods or nematodes [10]. Beyond avoidance in space and upregulation of defense, a third possible fungal response to sound could be increased sporulation. Such an early detection of enemies would carry a selection advantage compared to an unprimed status. A similar 'warning' function could also be in place for bacteria and their predators (e.g., protists and nematodes). For soil bacteria, protozoa are a major source of mortality, and thus defenses against these predators are present in the form of chemical defenses, surface modification, micro-colony formation, and increased motility [11]. Bacterial biofilm formation has also been shown to be sensitive to vibrations under controlled conditions [12]. Clearly, flight responses could be triggered by sound, and to the extent that these substances are inducible and not constitutively expressed, also secondary metabolites functioning in defense might be upregulated. Such warning signals could be specific to the particular predators of fungi or bacteria, but an alternative is that sound and vibration in general could be perceived as a 'danger' signal. For example, the sounds produced by earthworms or digging animals (like gophers) could signal a disturbance that would be expected to rupture the mycelium of filamentous fungi or bacterial biofilms, and thus it may be worth reacting to such sound cues.

Clearly, signals of danger are one possibility for how sound could carry information. Given that roots also produce sound when growing [3], perhaps this sound can be perceived by root-colonizing or root-associated microbes, indicating a source of carbon. Such sound signals could complement the biochemical signals already known to be in operation in the rhizosphere [2]. In addition, the possibility of communication by physical signals, including sound, among bacteria has also been discussed [9].

3. Potential Applications in Biodiversity Monitoring and Agricultural Management

With sounds aboveground and in aquatic ecosystems becoming captured more frequently to describe soundscapes for biodiversity monitoring purposes ('eco-acoustics' [13,14]), it is interesting to speculate if in the future we could use similar sound profiles from soil to arrive at non-destructive estimates of soil biodiversity, at least initially for soil animals; depending on the importance of interfering factors, perhaps this could work from the body size of microarthropods up. Specific sounds, like those that some insect pests are known to produce (e.g., tree-inhabiting insects; [15]), could even be used to specifically track agricultural pests and direct the use of insecticides to areas that have been detected using the sounds these insects produce: a kind of acoustics-based precision agriculture.

In addition, one could imagine that pests may react to sounds in various ways that could reduce their activity or change their behavior, thereby decreasing crop damage. Can we produce sounds that could act as 'acoustic pesticides'?

4. Soil Sound Pollution?

One may also wonder if the sounds we produce, especially in urban areas or near roadways or those emanating from heavy agricultural machinery, might adversely affect soil biota, much like what has been demonstrated to be the case in aquatic environments. Some sounds travel extremely well in soils, which is exploited in worm grunting, and could thus affect relatively large areas. Can acoustic pollution interfere with communication in the soil or could it mimic signals of danger?

5. Approaches for Studying Sound

If we accept that there is a physical layer of communication in the soil, how can we study it? This requires a methodological retooling that will not be straightforward, since capturing, recording, and replaying relevant sounds in an acoustically insulated environment at the scale required is a challenge [3,16]. One of the potential challenges is sound attenuation in porous media, which has been studied in the context of localizing buried objects [17]. Studies such as this have documented that the acoustic attenuation coefficient depends on soil properties such as water content and degree of compaction. This will impose limits on the measurement and external validity of examinations of sound. Interference from other sounds produced in soil may also present an important problem to overcome. For example, Naderi-Boldaji et al. [18] showed that physical changes in soil produce acoustic emissions; also, other processes, like water flow, shrinking, and swelling may produce such emissions that would need to be disentangled from biological signals.

6. Conclusions

Sound does not yet appear in the soil science, ecology, or microbiology curriculum, and thinking about sound is currently very much at the fringes of investigating and managing soil biota. It is important to keep in mind that this was also once the case for plant communication via volatiles, now an established topic. Perhaps it is now time for a concerted research effort into the perception of sound and its consequences for ecology and evolution of biota in the soil: a whole new world may be waiting for us and, perhaps, also a new way to relate to soil biota, which can be explored in soil science research.

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