Phytoacoustics

Perhaps intelligence needs to be redefined and expanded to include plants.

By Karen Bakker

The historical divide between zoologists and botanists has persisted, but it is gradually being challenged by a small but growing group of scientists who are conducting experiments in plant acoustic signaling and behavior. Over the past decade, a series of publications by philosophers, botanists, and science educators has explored a quickly evolving frontier of research on plant sensing, from philosopher Michael Marder's *Plant-Thinking* to forest ecologist Suzanne Simard's *Finding the Mother Tree*, to evolutionary ecologist Monica Gagliano's *Thus Spoke the Plant*. As popularized by journalist Michael Pollan in a 2013 *New Yorker* article titled "The Intelligent Plant," these researchers have conducted experiments that demonstrate that plants possess memory, anticipate events, and even communicate with other plants and with animals. Plants, for example, have been shown to remember the precise timing of the last frost; orient themselves to the expected direction of a future sunrise, even if uprooted and displaced in an intentionally confusing manner; and display a kind of "swarm intelligence" via their roots. Plants express these capacities as they actively sense and respond to their surroundings. Botanist-turned-anthropologist Natasha Myers refers to the complex set of sensing mechanisms that underlie these behaviors as a "vegetal sensorium," the full scope of which researchers are only beginning to uncover. This research does not seek to assess whether plants sense things in a manner similar to humans; rather, as Myers puts it, researchers of plant sensing are developing a vegetal epistemology—a novel, plant-centered framework for analyzing how plants sense and signal to the world.

Phytoacoustics is one relatively understudied aspect of this emergent research field. By using sensitive microphones, researchers have detected some plants making ultrasonic sounds, beyond the upper limit of most human hearing. Drying leaves of both deciduous and evergreen trees produce ultrasound, perhaps related to drought stress. These ultrasonic sounds can be heard by some insects and mammals but are inaudible to humans. The precise mechanisms by which plants produce and perceive sound are still unclear. Some scientists believe that sounds might result from mechanical changes related to hydration (a wilting plant's mass, stiffness, and structure changes as it dries out); others believe that sounds might come from bubbles or changes in pressure arising from respiration and metabolic growth activity; still others have hypothesized that sounds could be caused by movements of organelles. These latter sounds are a byproduct of plant physiology, somewhat akin to our stomachs grumbling when hungry; as Potawatomi plant ecologist Robin Wall Kimmerer clarifies: "these are the sounds of being, but they are not the voice."

Scientists have also measured tiny vibrations emitted by plants. Using extremely precise instruments, such as laser doppler vibrometers, they have found that plants emit almost imperceptible vibrational frequencies. Young corn plants, for example, produce click-like sounds that vary according to their level of dehydration. In one study of tomato plants, a laser vibrometer was used to measure the relationship between the vibrational frequency of a leaf (after a force was applied) and the amount of water in a leaf; water-stressed leaves had lower vibrational frequencies. In another experiment, researchers detected the distinct sounds that tomato and tobacco plants make when water stressed or when their stems are cut—tobacco, it turns out, makes louder sounds when deprived of water and quieter sounds when cut. In this experiment, researchers successfully developed a machine learning algorithm that could identify the condition of the plants (dry, cut, or intact) based solely on the sounds they emitted. We have now designed computer programs that can detect the relative health of plants just by listening to them.

If our computers can listen, surely other organisms are listening as well. This gives rise to the following hypothesis: plants not only detect and respond to sound but also make sound that conveys information to other organisms. Scientists have begun to test this hypothesis; but in doing so, they are transgressing a scientific taboo. In the 1970s, the publication of a book titled *The Secret Life of Plants* raised a firestorm of disdain within the mainstream scientific community. The authors—Peter Tompkins (1919–2007), a journalist and former spy, and Christopher Bird (1928–1996), a Harvard graduate and Vietnam vet who worked at Rand Corporation—published several books that became icons of a New Age fringe intrigued by extraterrestrial communications and covert military operations. The book and follow-up documentary in

Scanning electron micrograph of a tiny thale cress trichome, or leaf hair, which can function like a mechanical acoustic antennae—selectively vibrating in the frequency range of the plant's primary insect predator

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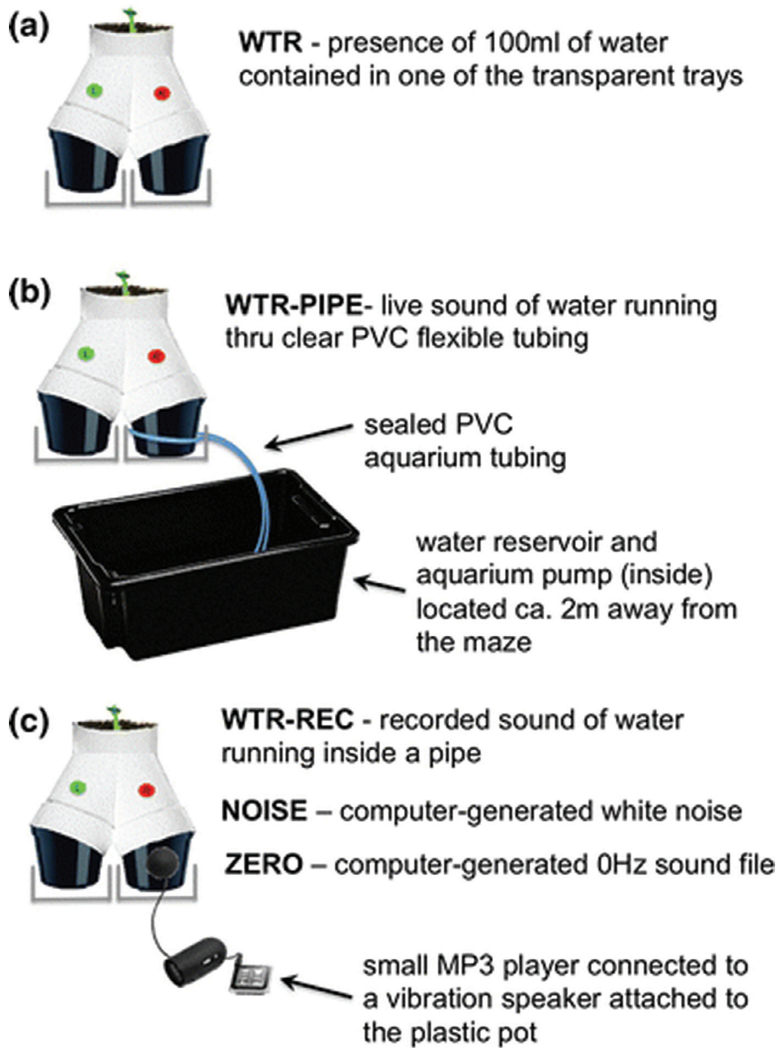
1979 (which featured a soundtrack by Stevie Wonder) told of plants hooked up to lie detectors, and was suffused, as the *New York Times* put it, with a "popular-science pastiche of New Occult hopes glibly tailored for middle-class respectability." The books were best sellers, but for professional scientists they were enraging emblems of New Age pseudoscience; hence the taboo on research on the topic of plant sounds.

One of the first scientists to break this taboo was Monica Gagliano, who directs the Biological Intelligence Lab at Southern Cross University in Australia. Her initial question was deceptively simple: What if we applied experimental protocols usually reserved for animals, like playback experiments, to plants? This might seem like an innocuous query, but as Gagliano said, "Researchers are often castigated for asking 'what if?' questions at the frontier of scientific exploration." Gagliano's follow-up questions indeed generated controversy. She next asked: What if the experimental results demonstrated that the plants could respond to sound? And what if we began studying plants with an open mind, asking whether they could make, sense, and respond to sound? Gagliano decided to conduct an experiment using an acoustic playback design—a type of experiment that is frequently used with animals but never with plants.

Designing an acoustic playback experiment for plants is more complicated than it seems. In a typical animal behavior playback experiment, specific frequencies are used to test whether animals respond to specific sounds with detectable behavior. For example, by carefully emitting a series of sounds ranging from 0 to 1,000 hertz (Hz) in 100 Hz intervals, researchers can watch when a bird flies away, thereby determining the specific range of sounds to which the particular bird species might be sensitive. By repeating the experiment, the range of frequencies can be determined with a relatively high degree of precision and accuracy.

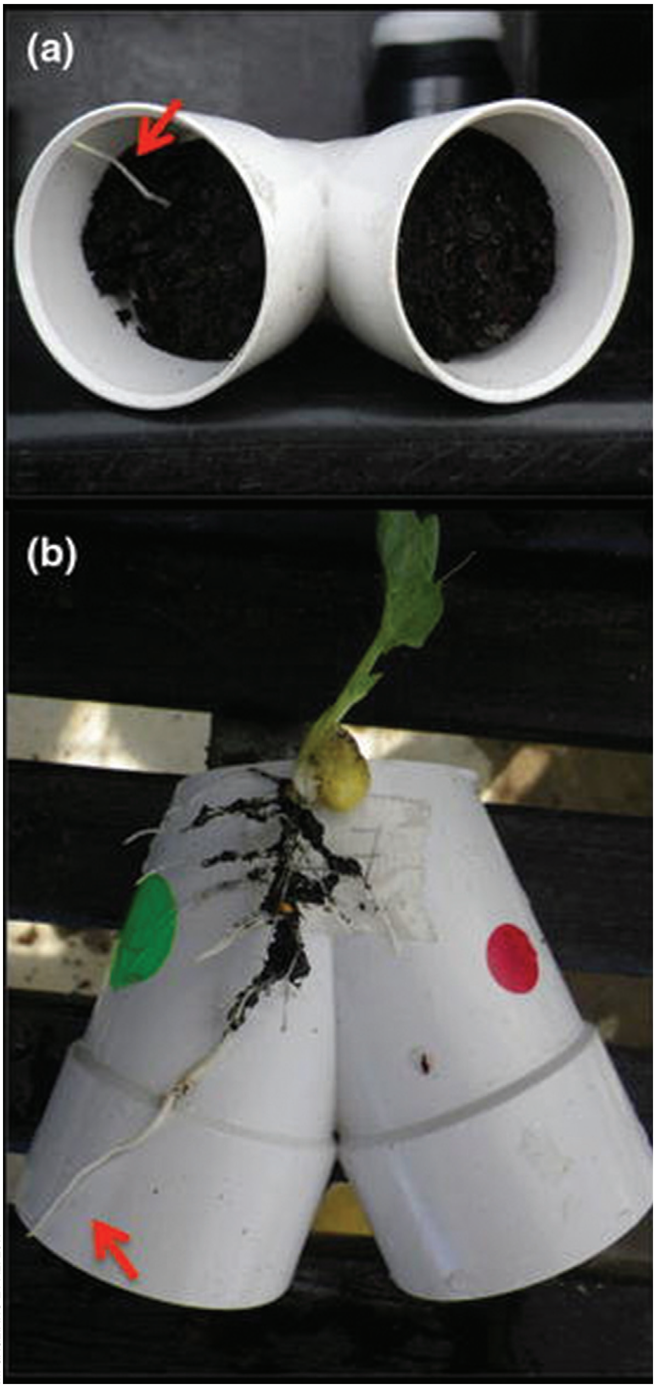


M. GAGLIANO ET AL. 2017

Schematic representation of experimental treatments to determine if plants use sound to locate water

Adapting this animal playback method for use with plants posed two challenges for Gagliano. First, plants don't have obvious mobile behavior—they just stand still. In animal playback experiments, the independent variable is sound; the dependent variable is the animals' movement. If plants don't move, which dependent variable should be used? Second, demonstrating that any particular behavior was a response to sound would be tricky, as most plants don't respond immediately to stimuli; the longer time frame needed for a response could introduce confounding variables. Eventually, Gagliano settled on an easily observed phenomenon that could be monitored in a tightly controlled environment: the bending of roots, which is a well-known and widely studied response in plants. Her research question thus came into focus: Would roots bend in response to certain sonic frequencies? She decided to test this hypothesis with baby corn plants. Newly germinated plants were arranged in identical pots in the lab and exposed to a range of sound frequencies. After multiple exposures, Gagliano determined that the plants' roots bend when exposed to acoustic tones in the range of 200 to 400 Hz, but not below or above that.

Gagliano then went one step further. Humans, she reasoned, emit sounds we can hear; we both vocalize and listen in roughly the same range of frequencies. By analogy, if plants are responding to sound in specific frequencies, it seems reasonable to ask whether they are also emitting sounds at these frequencies. Listening with sensitive microphones, she was able to detect sounds made by the baby corn plants, and, as she suspected, these sounds were within the same frequency range at which the corn responded to sound. Her paper describing the results was the first



M. GAGLIANO ET AL. 2017

After five days of exposure to various sound frequencies, it was shown that the primary roots of pea plants, growing in a PVC custom-designed Y-maze, bend in the 200 to 400 Hz range. The plants also emit sounds at these frequencies.

peer-reviewed journal article with experimental proof that plants have the capacity to detect sound, make sound, and exhibit a behavioral response to sound.

Upon publication, Gagliano's experiment provoked a firestorm of controversy. Her methods were clearly described, the experiment was easily replicable, and the results were approved for publication by independent reviewers. But many scientists voiced concerns about the vocabulary she used to describe her results. Some opponents referred to her choice of terminology—Gagliano used terms like *plant learning* and *plant intelligence*—as "inappropriate" and "bullshit." Although plants might display behavior that can be labeled with terms like *learning* and *memory*, Gagliano's opponents cautioned that these do not necessarily imply intelligence; some argued this term should be reserved for organisms with a brain and neurons. Gagliano and her allies argued, in response, that the term *intelligence* should be defined, more broadly, as an ability to perceive and respond effectively to changes and challenges in one's environment. Defining intelligence as a behavior confined to organisms with neurons, Gagliano argued, displayed a bias that privileged animals. She and other researchers have argued that our concept of intelligence needs to be redefined and expanded to include plants.

In pushing back against her critics, Gagliano also argued that plants have evolved analogues of other human senses: touch (a root, for example, reacts when it encounters a solid object); sight (plant leaves react differently to light versus shadow, as well as to different wavelengths of light); smell and taste (plants emit, sense, and respond to biochemicals in the air or on their bodies). Why would plants not possess an analogue to the human sense of hearing? In a follow-up experiment, she demonstrated that the roots of pea plants detect the sound of running water and grow in that direction. The plants exhibit this behavior even when the water is isolated within a watertight tube, and no difference in soil humidity can be detected. Again, Gagliano designed a classic protocol used in animal experiments: she put her young pea plants in a maze. On one side, there was the sound of running of water; on the other side, white noise, a silent recording, or nothing at all. Her experimental setup was designed to test three questions: Do plants know how to find water? Can plants find water solely by the sound of water in a localized area? And can plants specifically find water in the context of complex soundscapes (as opposed to simply growing toward any sound at similar frequencies)? In each case, her experiments returned an affirmative answer. When offered a choice between sound and silence, the pea roots grew toward sound. And notably, when offered a choice between white noise and the recorded sound of water—both played at identical frequencies—the pea plants' roots grew toward the sound of water. In the absence of a humidity gradient, Gagliano's pea plants were able to detect the sound of running water, and distinguish this from a similar sound without ecological significance.

Other researchers have found similar behavior in other plants. Ecologist Heidi Appel at the University of Toledo found that *Arabidopsis thaliana* plants (a common and widely studied model organism in plant science) produced defensive chemicals when a recording of a caterpillar chewing a leaf was played nearby, even though the plants hadn't been touched by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When being chewed by a caterpillar, plants release a defensive chemical. The sound of the chewing can prompt the release, even if the sound is coming from a nearby recording and the plant is untouched.

the insects. The plants were also able to distinguish between vibrations caused by predators chewing on leaves and vibrations caused by wind or insect song; the latter sounds did not induce the same defensive response.

In follow-up studies, Appel also found evidence of plant learning and memory. She exposed one set of *A. thaliana* plants to caterpillar vibrations but left a control group alone; after a period of time, she exposed both sets of plants to a new round of caterpillar-chewing sounds. The plants that had previously been exposed to the sound displayed higher levels of defensive secretions than the control group. *A. thaliana*, in other words, both remembers and *anticipates* the effects associated with the sounds of specific predators chewing on leaves. Appel's plants even distinguished between the sounds of different insects, responding defensively to sounds associated with insect predators but ignoring the sounds of insects that posed no threat.

Gagliano's and Appel's research provides robust evidence of three capacities in plants: an ability to detect sound; an ability to respond to sound; and an ability to distinguish ecologically relevant sounds from a mixture of irrelevant sound frequencies. Why wouldn't plants, along with their animal denizens, have developed a sensitivity to nature's sounds? As noted by plant biologist Daniel Chamowitz: "[Human] music is not ecologically relevant for plants, but there are sounds that could be advantageous for them to hear."

The question is no longer whether plants can perceive sound but how and why they do so. This raises a perplexing conundrum: Without ears or nerves, how do plants "know" what they are listening to? For example, how do they recognize that a sound is made by running water versus white noise? And how do they recognize the signals arising from feeding caterpillars: vibrations (sonic or mechanical), the removal of tissue (mechanical), oral secretions (biochemical), or some combination of all three? Scientists still do not have a comprehensive understanding of plant signaling mechanisms, although they do know that perception of a sound vibration can cause changes in plant hormones, gene expression, and emissions of volatile organic compounds—which are used frequently by plants as defensive signals against predators.

As scientists continue to unravel the mysteries of signal transduction in plants, evidence of the importance of acoustic signals continues to accumulate. Vibration sensing is an ancient system in evolutionary terms, arising before the emergence of vascular plants on Earth. Microalgae, for example, have mechanosensory proteins that respond to vibration. Gagliano speculates that sound is an important signal because vibrational signals have faster transmission speeds than other signals (e.g., chemical) sent via plant tissues. As she puts it: "Chemistry works up to a certain point, but sound is so much faster. If you have an aggressive predator, you want to [detect and] tell other plants quite quickly." In contrast to a complex biochemical signal, like a pheromone, sound is a high-speed signal that is easy to detect at

Computer programs can now detect the relative health of a plant. A drought-stressed plant, such as this apple tree, emits a different sound.

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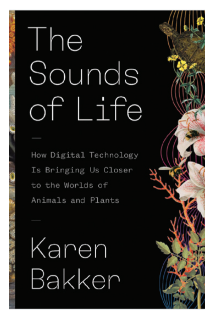
little cost. And sound also travels farther, and through more diverse substrates—air and water, soil and stone. Plants' ability to provide rapid systemic responses to stress via acoustic signals may mean that the ability to emit and sense sound conveys an evolutionary advantage, since it increases plants' odds of survival. If so, the ability to sense sound is likely to be both ancient and universal in plants.

This insight seems less startling when we consider that sound is a fundamental form of transmitting energy. It has been omnipresent as organisms have evolved over time, so plants (and other organisms) should have evolved the capacity to make use of it. Those organisms that hear better adapt and survive better in their environments. Scientists call this the auditory scene hypothesis. Just as organisms evolved an ability to sense energy in the form of heat (energy flowing as a result of temperature differences), they evolved an ability to sense sound.

From this perspective, plants' hearing abilities are, in fact, unsurprising: given that the environment contains many sounds that convey useful information, an ability to detect and respond to sound should have adaptive value for plants, just as it does for animals.

But does this mean that plants can "hear," in the human sense? Some scientists remain skeptical. The precise physical mechanism by which plants detect sound is still unclear, although some speculate that anything with hairlike cilia cells—including crustacean antennae, coral cilia, or plant roots—can respond to sound. Scientists are also exploring the possibility that mechanosensors in cell walls or plasma membranes can be triggered by certain sounds, causing fluxes of specific biochemicals, plant hormones, and even the rapid expression of genes.

In plants, the senses of touch (mechanoreception) and sound may be intimately interrelated. For example, Appel's *Arabidopsis thaliana* plants detect sound through tiny hairs (called trichomes) on the surface of their leaves; the hairs, which selectively vibrate in the frequency range of the plant's primary insect predator, function like mechanical acoustic antennae, exquisitely tuned to environmental threats. If plants listen with their bodies, from the tips of their roots to their leaves, their sense of hearing would be profoundly different from, and orders of magnitude more sensitive than, our own.



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