NEWS FEATURE

Crucial role of belowground biodiversity

Once a "black box," soil's biology has come under increasing scrutiny from researchers. Their findings are both illuminating and potentially alarming.

John Carey, *Science Writer*

When scientists began to add nitrogen and warmth to different plots in Harvard Forest more than 20 years ago, they thought trees would grow faster. But in the fertilized areas of the Petersham, MA, forest, the pines died and hardwood growth didn't increase. Why? It turns out the added nitrogen changes the complex communities that live in soil. The symbiotic fungi the pines depend on are replaced with other species—and the overall rate of decomposition in the soil slows in the hardwood stands, reducing the nutrients available to the trees.

Meanwhile, the experimental warming, using buried heating wires, not only speeds up the rate of microbial activity, but, over time, it also creates a community of soil microorganisms with enhanced abilities to break down tough material in forest floor litter, like lignin in wood. The result is that more carbon dioxide is released into the atmosphere, contributing to planetary warming. Even changes in the type or abundance of a single member of the soil community can have big effects.

Researchers use these soil warming plots at the Harvard Forest Long-Term Ecological Research site in Petersham, MA, to study the response of soil biota to simulated climate warming. Plots have been warmed continuously to 5 °C above ambient temperatures for 10–24 years using buried heating cables. Control plots are still under snow cover. Image courtesy of Audrey Barker-Plotkin (Harvard Forest, Petersham, MA).

In areas where Thomas Crowther, now a postdoc at Netherlands Institute of Ecology, removed the little isopods, or pill bugs, that dine on soil fungi, rates of decomposition—and thus carbon emissions—jumped 25% (1). "That's a huge difference when you scale it up," says Crowther.

Such findings illustrate the recent expansion of knowledge about the complexity of life underground—and its importance to life above ground. When Vanessa Bailey, soil microbiologist and senior research scientist at Pacific Northwest National Laboratory (PNNL), got her Ph.D. 17 years ago, virtually every grant proposal described soil as a "black box" with mysterious and unknown inner workings. Since then, "we have come really, really far," Bailey says. "We know more about what's in the black box and what those microorganisms are doing."

As a result, there's also a growing sense of excitement and urgency among soil ecologists, along with an influx of young researchers to the field. In May, the first Global Soil Biodiversity Atlas (see https://globalsoilbiodiversity.org/?q=node/271) launched with contributions from 100 experts in 29 countries to compile what's known about soil biodiversity—and the threats it faces. "We want to draw attention to the many tasks that soil biota does for us," says an editor of the atlas, Diana Wall, University Distinguished Professor at Colorado State University (CSU) and a pioneer in the field.

New findings show that healthy and diverse communities of bacteria, fungi, nematodes, mites, and other organisms under our feet directly enhance the quantity and quality of food production, the ability of soils to hold water (and thus reduce both flooding and runoff of pollutants like phosphorus), and even human health. Conversely, scientists are beginning to demonstrate that declines in soil biodiversity impede many so-called ecosystem properties, such as aboveground plant diversity, nutrient retention, and nutrient cycling (2).

Perhaps most important, soil communities determine how these underground habitats will respond to a changing climate—and if soil will be a "sink" for carbon, helping to fight climate change, or will spew more carbon into the atmosphere. "Most people don't realize how much we depend on everything in soil," says Tandra Fraser, research fellow in rhizosphere and soil biodiversity at the University of Reading, and former executive director of the Global Soil Biodiversity Initiative at CSU.

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Full of Surprises

Scientists still understand relatively little about the consequences of altering soil biodiversity. "Our ability to say how much warmer the planet will be in 2100 is massively limited by our lack of knowledge of soil processes," notes Crowther. "In some ways, we are still in an observational stage," says University of New Hampshire soil ecologist Serita Frey. "We have this immense wealth of new data that we are struggling to analyze."

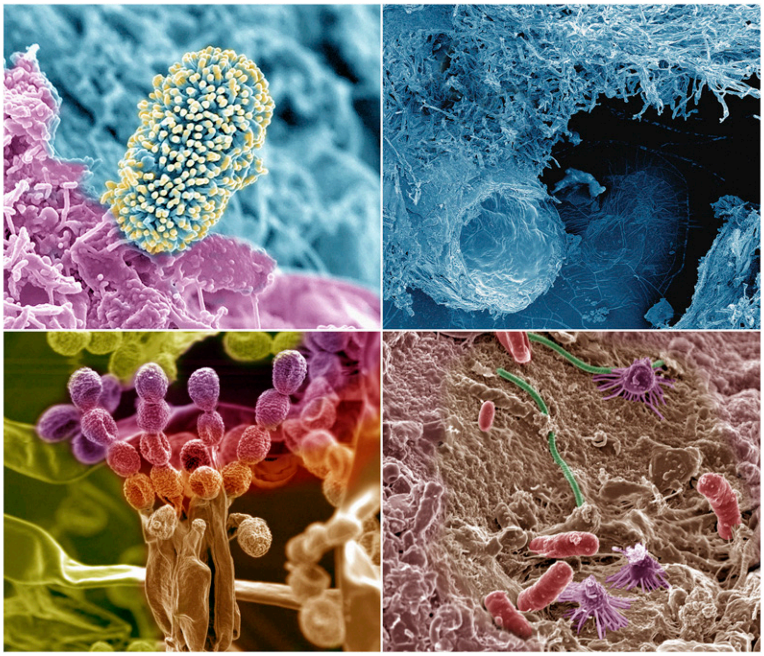
Already, the data have revealed surprises. Before genomics and other molecular tools, researchers could only study and count what they could culture in the laboratory—which turns out to be just a few percent of the microbes, fungi, and other organisms. "We had no way of testing what was there," says Janet Jansson, Division Director of Biological Sciences at PNNL. "People didn't anticipate there was such a concentration of unknown organisms in soil."

In fact, the numbers are staggering. There are up to 6 million species of fungi, 10 million species of bacteria, hundreds of species of nematodes, and countless protozoa, among others, that make up soil communities. More than 100 billion individual organisms can live in just a handful of dirt. One gram of soil can contain 60 miles of fungal filaments, called hyphae. And in one study, 162 different species of mites inhabited a square meter plot of soil 10 centimeters deep in a Kansas tallgrass prairie. "A graduate student of mine identified them all and said he'd never do it again," says Wall. Overall, says Frey, "soils are one of the most diverse habitats on Earth."

The makeup of underground ecosystems, however, varies significantly from place to place. Prairie soil communities are distinctly different from those in tropical forest soils or Arctic permafrost. Indeed, the numbers and types of species can change dramatically within just a few feet, such as the difference between the root zone of a tree in a field compared with the areas around it. Moreover, just about everywhere scientists have looked, from Brazilian sugarcane fields to British farms, they find that diversity declines as humans change the land through agriculture and urbanization. One recent study of soils in the United Kingdom, Sweden, Greece, and the Czech Republic showed that "intensive agriculture reduces soil biodiversity, making soil food webs less diverse and composed of smaller bodied organisms" (3).

However, in another study designed to bring attention to the astonishing wealth of life underground, a team of researchers analyzed 596 soil samples from New York's Central Park, about one sample every 50 meters. They expected to find large numbers of previously unknown archaea, bacteria, fungi, protozoa, and other organisms, and they did. But the results—given that the park is a mere 843 acres tucked inside a densely urban area—surprised even the scientists. "Central Park soils harboured nearly as many distinct soil microbial phylotypes and types of soil communities as we found in biomes across the globe (including arctic, tropical and desert soils)," the team reported (4).

How are such diverse soils possible within a city? Not only does Central Park have a wide variety of habitats, such as forests and grassy fields, but "people from all over the world bring in microbes," speculates Crowther,



The diverse communities of microbes in soil have critical roles in generating organic matter and mediating chemical processes, particularly in the rhizosphere, the soil zone around plant roots. In these colorized scanning electron microscope images, (*Upper Left*) a soil bacterium (blue and yellow), less than a micrometer in size, makes its home on the root surface of an *Arabidopsis* plant; (*Upper Right*) a fungus mesh clings to a pine tree root; and (*Lower Left*) *Penicillium* spores exemplify the pharmaceutical potential in maintaining soil biodiversity. (*Lower Right*) A healthy mix of microbes also plays a critical role in the storage and release of carbon in soil. Images courtesy of Pacific Northwest National Laboratory.

a member of the team. The researchers also concluded that heavy management of the landscape with fertilizers, compost, mulching, and irrigation is another likely reason for the healthy biodiversity of its soils. They suggest that further study of the park and places like it might point to methods of managing land to promote soil biodiversity and of restoring it where soils are degraded.

Diversity in Depth

These new findings also show that underground diversity matters more than previously thought. Farmers traditionally have focused mainly on inputs of fertilizer, rather than on the life already in the soil, to boost productivity, explains soil scientist Johan Six of the Swiss Federal Institute of Technology (ETH-Zurich). "The conventional farming community argued they were able to increase yields drastically without ever paying attention to microbes," he says.

Six himself used to be sympathetic to that view. But then, study after study showed him that the soil organisms do matter. "One of the surprises I've had was seeing that, when the biota is more diverse, it inherently helps the system," he says. Lots of fungal hyphae draw more organic matter down into the soil, for instance, boosting productivity, in addition to storing more carbon. Microbes make phosphorus more available to plants, reducing the need for added fertilizers that can cause harmful algal blooms downstream. Microorganisms also form symbiotic relationships with plants, functioning like a second plant genome to boost plant growth and health (5), which helps explain why losing soil biota contributed to the death of the pines in Harvard Forest.

Healthier, more diverse soil communities also bind the soil tighter, reducing human illnesses caused by fine particles of dust or pathogens that blow off fields, like the *Coccidioides* fungus that causes a respiratory infection known as Valley Fever. In a recent review, Six, Wall, and another colleague describe the many possible links between robust microbial and invertebrate communities living underground and better human health (6), ranging from the ability of diverse soils to make pathogens like anthrax less accessible and dangerous, to soil's contributions to healthier food and cleaner water. Experiments also showed that greater numbers of microbes in the soil result in tomatoes with higher amounts of flavonoids (7), plant molecules thought to provide human health benefits. The greater the microbial mass, the more micronutrients available to the plants, "leading to the formation of these secondary compounds in the tomatoes," Six speculates.

"Will soil biodiversity be the one thing to stop the Zika virus?" says Wall. "No, but when we are looking for new tools [for fighting diseases], soils are critically important."

Carbon Capture

Because they contain so much carbon, soils play a key role in climate change, with widespread human impacts, including indirect effects on health. Scientists estimate that Earth's cultivated land has already lost more than half of its stored carbon to the atmosphere (along with much of the original biodiversity) due to deforestation, plowing (which breaks up the fungal hyphae that pull carbon into the soil), and other human influences (8).

Soil is the major buffer system for environmental changes, and the microbial community is the basis for that resilience.

—Vanessa Bailey

Moreover, much more soil carbon is now poised to churn out into the air as the permafrost melts. When PNNL's Jansson used the new genetic and molecular biology tools to probe Arctic soils, she discovered microbial activity even in frozen subzero soils, with bacteria able to tap iron for energy. Then, when the permafrost does warm, the soil communities are able to make a swift transition to dining on stored organic matter (9). "There is a rapid conversion of this community into one that can release greenhouse gases," Jansson says. "We didn't expect the shift to go so quickly." That would bring more rapid planetary warming—and further permafrost melting in a powerful feedback loop.

If soils can't respond nimbly to new conditions, that can be just as worrisome in a world with a changing climate. "Soil is the major buffer system for environmental changes, and the microbial community is the basis for that resilience," explains PNNL's Bailey. To test this adaptability, researchers at PNNL moved chunks of soil 500 meters (in vertical elevation) down the slopes of Rattlesnake Mountain in southeastern Washington more than 20 years ago. They also moved other samples 500 meters higher. The higher location has an average monthly maximum temperature of about 9 °F (5 °C) cooler than the lower site, with about 2 inches (5 centimeters) more rain per year.

Seventeen years later, the researchers analyzed the transplanted soils and compared them to untouched areas.

The results, described in *PLoS* in March (10), were unexpected. The microbes from the higher site originally had a higher respiration rate than those from the lower area, due to the wetter conditions and a more plentiful supply of carbon. But even after 17 years in their new, lower location, the transplanted microbes still had the high respiration rate. Similarly, bacterial activity in the samples that were moved up the mountain had barely changed. "That was really weird, and very sobering in the face of planetary change," says Bailey, one of the authors. "If the soil microbial community is not as resilient as we had assumed, then it calls into question the resilience of the overall environment to climate change."

Bolstering Biodiversity

The research results are complex, with some soil communities responding quickly to new conditions and others stubbornly staying the same. And biodiversity changes may need to be quite large to have any actual effect on function. Even so, some researchers say the findings boil down to one simple but crucial overall message: The potential importance of biodiversity means humans should make every effort to maintain it, or even enhance it.

Some of those efforts are already beginning. Six is planning experiments with combinations of organic and inorganic fertilizer treatments to try to boost soil biodiversity in sweet potato fields in Mozambique. The goal is to improve the nutritional quality of the crop. "In general, if you increase soil health, there can be an increase in beta-carotene in the sweet potato," he explains.

Similarly, Six has worked with farmers in California to reduce the amount of tilling of the raised beds between irrigation furrows. The results (11) include more microbes and earthworms in the soil, higher yields, and 50–100% reductions in the amounts of the fine particles linked to health problems that are blown into the air, Six says.

Such practices may also help slow climate change. An analysis appearing in *Nature* in April argues that as much as four fifths of the greenhouse gases spewed from power plants and other human activities could be captured in soils through smarter soil management (12), although some experts, including Six, believe that number to be overly optimistic. "We will never be able to do this in practice," he says.

Still, possible effective strategies include switching from plowing to no-till practices, using more cover crops (especially those with deep roots, such as ryegrass), and adding trees to farmers' fields. Trees and their roots create a permanent refuge for soil biota, including earthworms, while also adding carbon—in tree roots and expanded soil communities that decompose organic matter on the ground—to the soils. "Soils are already huge stores of carbon, and improved management can make them even bigger," says geoscientist Dave Reay, a University of Edinburgh professor and one of the authors of the analysis.

So now, soil scientists say, they need to do more than just illuminate the remaining dark corners of this erstwhile black box. They also need to convey to the world, to everyone from government officials to rural farmers, the urgent need to preserve and enhance soil biodiversity. Until now, soil communities have largely been ignored in decisions about growing crops, cutting down forests, and building cities, according to Wall. That must change, researchers say. "Healthy soils not only mean dollar signs," says Wall, "they are also critical to human health and to reaching the world's sustainable development goals."

Governments have begun to heed this call. In April, the Department of Energy's Advanced Research Projects Agency-Energy announced $30 million in funding for projects aimed at improving "root and soil function that will help plants to store more carbon in the ground and take up nutrients and water more efficiently" (www.energy.gov/articles/arpa-e-announces-60-million-funding-two-innovative-new-programs). In May, the Obama Administration launched a $121 million National Microbiome Initiative to study the microbial communities in people, oceans, the atmosphere—and soils. The once-mysterious black box under our feet, it seems, is finally getting the attention it needs.

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