Below Our Feet, a World of Hidden Life

The soil teems with billions of hidden microbes. Researchers have begun to catalog how these organisms are changing the world.

By Elizabeth Svoboda

Types of soil in the U.S. include (clockwise from top left) the Honga, Madison, Coxville, Cowarts, Lynn Haven, Green Level, Leon, Hiwassee, Tuxekan, and Appling series. All are found in the Southeast except for the Tuxekan series, which is located in Alaska.

Janet Jansson first started to wonder about the vast universe of underground life as a student at New Mexico State University in the late 1970s. A handful of soil contains about 10 billion bacteria, but at the time, earth scientists knew very little about what these microbes were and what they did. Later, as a young microbial ecologist at Stockholm University in Sweden, she started to catalog the microorganisms she collected during soil sampling trips, deciphering their genetic code so she could understand both their internal workings and how they fit into their underground habitat.

As Jansson dug, though, she kept running into a problem. The main method then used to amplify and analyze stretches of DNA wasn't powerful enough to reveal all the workings of a single microorganism, much less an entire community of them. "You could get information about specific genes, but sequencing technologies were very slow," said Jansson, now a division director of biological sciences at Pacific Northwest National Laboratory (PNNL) in Richland, Wash. She knew the layers of sediment she studied held a treasure trove of biological finds, but she didn't yet have the tools she needed to unearth them.

Then, soon after the turn of the century, new high-octane DNA sequencing methods made it possible to sequence thousands or even millions of genes almost instantly. These new, speedier methods meant researchers could easily sequence the collective genomes of the sample, known as a metagenome, for the first time. Suddenly, it was possible to scan the overall composition of habitats as diverse as stagnant bogs and frozen tundra, producing a detailed portrait of the microbial life they held. The gene and protein sequences from these wide-ranging scans — the first of their kind — would, once decoded, illuminate what the microbes were actually doing within each ecosystem. The data would help researchers understand how microbes capture and store carbon dioxide from the atmosphere, how they break down organic matter so that plants can access its nutrients, and how they neutralize soil toxins known to threaten human health. "You can just sequence everything," Jansson said. "That's where the metagenomic approach has really been an advantage."

Almost everything about Jansson's current surroundings is big and bold: the 600 acres of sycamore-studded PNNL campus rolling across eastern Washington, the endless blue sky she can see through her picture window, the fridge-size gene sequencing machine where her team deposits soil samples. But, as ever, what drives Jansson is the lure of the microscopic and the unseen — the challenge of mapping the contents of the soil microbiome, a teeming global community whose functions have never been fully understood. "Soil," Jansson said, flashing a grin, "is the ultimate complex system."

The Underground Prairie

Once metagenomics began opening up a whole new subsurface world to soil scientists, Jansson found herself faced with a fresh set of challenges. The scope of this emerging field she had helped to create was immense — a single teaspoon of soil may contain tens of thousands of species, and there are perhaps millions of species worldwide that have not yet been discovered. To tackle the staggering task of understanding their function, she formed a collaborative venture in 2010 called the Earth Microbiome Project, along with Rob Knight of the University of California, San Diego, and Jack Gilbert of Argonne National Laboratory in Argonne, Ill. The project aims to catalog 200,000 microbe-rich samples from locations around the world. (As of last year, it had analyzed more than 30,000 samples.) But Jansson also knew that to really dig deep, she had to narrow the dizzying array of research possibilities before her to a handful that she could tackle within a lifetime.

Janet Jansson on an expedition to Greenland.

To begin, she and her team set out to study the prairie soils that dominate much of the American heartland. Thousands of soil microbes around the roots of grasses help the Midwestern Great Prairie to store more carbon than any other region in the continental United States. By producing proteins that slice and recombine carbon dioxide molecules, these microbes work in tandem with the grasses to capture atmospheric carbon dioxide and turn it into solid, carbon-rich biological matter that gets stored underground. That's a huge boon to humanity, because the more carbon dioxide a landscape can store, the less will be left as a greenhouse gas that drives planetary warming.

But since over 90 percent of all soil bacteria can't be grown in the lab, researchers have long been unsure just how they contribute to carbon cycling. A metagenomic analysis of these prairie microbes, Jansson thought, would help reveal the extent of their involvement in carbon storage and illuminate whether rainfall and human land cultivation change that role.

Jansson's team fanned out across the central third of the country to see what microbial novelties they could find. At field sites in Iowa, Kansas and Wisconsin, they took soil samples using tools called corers — foot-long hollow tubes designed to slice through the soil. When the corer emerges, it pulls up a log-shaped sample with all its layers — and, ideally, its microorganisms — intact. The chunk of dirt is then preserved on dry ice and sent back to the lab. There, technicians sequence the sample's DNA and RNA.

Once this process is complete, project scientists have a good idea which microbial genes are contained in each sample and what biological jobs the microbes perform. If a soil sample contains bacterial genes that produce enzymes used to convert carbon dioxide from the atmosphere into solid carbon, and these genes are active, researchers can conclude that microbes within the sample are actively storing carbon.

At each site, the research team sampled native, undisturbed prairie soil, as well as soil that had been farmed for many years. The sequenced samples revealed that the native prairie dirt contained a different mix of microbes from the farmed soil, which may in part be due to fertilizers that are used during farming. “When we looked at those comparisons, there were strong microbial signatures, almost like a biomarker of cultivation,” Jansson said. She suspects that there are differences in the way microbes store carbon in native and cultivated soil, a topic she plans to explore further in future research.

The Frozen Tundra

Meanwhile, Jansson and her team were also exploring the soils of the Arctic, one of the world’s fastest-changing climates. Jansson had long been curious about how these rapid temperature changes were affecting the underground microbial community, and whether these changes had any surprising side effects. “There’s so much organic carbon trapped in permafrost,” she said, “and we don’t really know what’s going to happen as the climate warms.” At the outset of her work, Jansson suspected that warming trends might activate bacterial processes that break down stored carbon, releasing it into the atmosphere and fueling climate change. But since she didn’t know for sure, she decided to study how the microbial community mix varied in three distinct types of Alaskan terrain: frozen permafrost, surface soil that freezes and thaws as the seasons change, and relatively warm, waterlogged bog soil.

As she suspected, Jansson found substantial differences among the microbial communities at these locations. Overall, there were few genes and proteins in the permafrost samples. But in the freezing and thawing soil layer, sequencing showed that bacteria within the soil samples were producing some intriguing proteins, including enzymes that snip long chains of carbon molecules, like cellulose from plants, into shorter, simpler sugar compounds that the bacteria can use as fuel. When this happens, previously “locked-down” carbon is released back into the atmosphere. “When [the soil] thaws,” Jansson said, “it starts to transition more into decomposition.” In warmer soils, in other words, bacterial carbon breakdown processes start to show up clearly in sequencing data. So just as some observers have feared, warming temperatures could release formerly inert carbon from the soil. This raises the worrying prospect of runaway carbon release as temperatures continue to rise.


Soil cores are transported back to the lab, where researchers can analyze the dense microbial populations.

Most strikingly, the warmest soil sample in Jansson's study — the spongy bog soil — revealed an array of microbial genes and proteins involved in the production of methane, a greenhouse gas more than 20 times as potent as carbon dioxide. One such protein was methyl-coenzyme M reductase, which is involved in transforming carbon dioxide into methane. This finding might imply that warming trends will drive local microbes to produce larger amounts of methane. Next, Jansson plans to investigate whether rapid thaws affect soil microbe populations differently from more gradual thaws, since both will likely become commonplace as the planet warms.

Bacterial Terroir

Soil microbes are not just carbon processors, as the work of Jansson's colleagues reveals. Not only do the vast microbial communities underfoot affect air quality and global temperatures, they can also affect the taste and quality of the food we grow. Thomas Mitchell-Olds of Duke University wanted to see if the microbial populations in and around plants' roots could affect the way the plants matured. He and his student Maggie Wagner took soil samples from four different collecting sites in rural Idaho and isolated microbes from each sample. They then inoculated soil-filled pots with these four microbial samples and planted a common strain of mustard plant, *Boechera stricta*, in them. Certain types of microbes in the soil seemed to speed plant flowering time, the team found, while others, such as members of the *Proteobacteria* phylum, slowed it down.

The study underscored just how necessary microbial activity is to plant health and productivity. "Soil microbes had already been linked to drought tolerance, growth rate and other aspects of plant performance. Our experiment added flowering time to this list," Mitchell-Olds said. "The potential for soil microbes to tweak flowering time — whether to improve yield, buffer against climate change, or both — is intriguing." Such a prospect might interest not just farmers looking to increase their bounty, but also, say, wine growers in California's Napa Valley, who know how dramatically bloom time can affect the development of grapes and the taste of the resulting vintage. The famed terroir of places like Napa, in fact, may arise from thousands of microbes humming along in unseen harmony.

Other sequencing studies have illustrated the critical role soil microbes play in breaking down pollutants. When scientists at the University of Delhi in India took soil samples from a pesticide dump and compared them with samples from a cleaner control site, they reported that the soil from the waste site contained a higher concentration of gene sequences from certain bacterial groups, such as *Pseudomonas*, *Novosphingobium* and *Sphingomonas*, that are known to degrade common pesticides like hexachlorocyclohexane. Microbes, it seems, can adapt to help fouled landscapes recover, which presents the exciting possibility of deploying the bugs in bioremediation efforts. “Soils are a buffer against all kinds of insults to our ecosystem,” said Vanessa Bailey, a microbiologist who works closely with Jansson at PNNL.

The researchers working on the Great Prairie project have managed to compile about 1.8 trillion bases of DNA data, but Jansson thinks those data describe only a fraction of the microbial communities in prairie soil, given that the soil contains between 1 billion and 10 billion individual cells per gram. “We’re still at the discovery phase,” she said. “We have a lot to do just to assemble a soil metagenome.” She and other scientists are trying various techniques to streamline the gene analysis process, such as discarding less common gene sequences in a particular sample in order to focus on more prevalent ones.

The more Jansson and her colleagues are able to learn about previously unknown communities of microbes, the better they’ll be able to predict how these communities will react to different conditions — droughts, warmer weather or floods, just to kick off the list. They hope to build these predictions into computer models that would illustrate what microbial activity a given environmental change might create, as well as the expected results of that activity. Such models could help environmental planners cultivate microbial mixes that achieve a desired end — which could be soil that locks up gigatons of atmospheric carbon, or that sloughs off pollution with ease, or that yields the kinds of grapes vintners dream about. “By having knowledge of the microbes that are present in the best-case scenario,” Jansson said, “you can tweak the system to optimize that combination of microbes.”

But achieving the right microbial balance isn’t always as simple as inoculating soil with certain strains of bacteria. “If the conditions are favorable for the microbes you want to flourish, they will flourish,” Jansson said. “If you seed and the conditions aren’t favorable, they will just die.” The ideal approach, then, will often be to engineer the kind of landscape that beneficial microbes naturally flock to. In warming areas that grow boggier every year, this might mean ensuring that there is enough oxygen-rich moving water, which would make the area less hospitable to anaerobic microbes that belch large quantities of methane. In cultivated areas of the Great Prairie, farmers might choose fertilizers that preserve natural microbial diversity, yielding plentiful food crops and maximizing carbon capture from the atmosphere.

Still, insights like these are gradual and hard-won, and Jansson knows future scientists will need to take up the cause of discovering all the ways soil microbes affect the rest of the planet. For now, Jansson relishes playing the role of soil surveyor, mapping the variety and breadth of microbial communities so others can someday benefit from the knowledge. “We know more about the movement of celestial bodies,” Leonardo da Vinci once mused, “than about the soil underfoot.” More than 500 years later, Jansson wants to be the scientist who finally proves him wrong.

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