THE FUTURE OF FOOD

Cultivating Better Health

Just as you have a microbiome, the soil beneath your feet has one too. And promising new research suggests it may have a surprising influence on food and human wellness.

BY MICHAEL BEHAR

It's late December in Boulder, Colorado, and I'm on the University of Colorado campus walking toward the Cooperative Institute for Research in Environmental Sciences (CIRES) lab. The native flora here is dormant, in a deep winter slumber, rendering the landscape in monochromatic tans. Almost nothing is growing outdoors.

That's not so inside CIRES, where billions of microorganisms are thriving. At the lab, Noah Fierer, Ph.D., a professor of ecology and evolutionary biology, introduces me to two graduate students who are hunched over workbenches, using pipettes to transfer batches of live bacteria from glass vials into a machine that will sequence their microbial DNA. In a nearby walk-in cooler, petri dishes are stacked on wire shelves—bacteria being cultivated for ongoing studies—along with a 12-pack of craft beer chilling on the floor. "You're not supposed to see that," Fierer quips.

As a preeminent soil scientist, Fierer is cited in scholarly journals perhaps more than any other researcher in the field. His efforts are focused on organisms that reside in the so-called rhizosphere, the topmost soil layer where plant roots interact with microscopic organisms, among them viruses, bacteria, fungi, protozoa and algae. It's a motley community, collectively termed the "soil microbiome," and it functions as the lifeblood of plants—promoting germination, stimulating roots, accelerating growth and bolstering resistance to disease.

Experts believe that these soil microbes could also have a big impact on the nutritional content of our food. Moreover, the plants we eat and the dirt we come in contact with may also directly fortify our own gut microbiomes. The discovery of this link between soil health and human health has commanded the attention of everyone from big food companies and farmers to scientists and environmental organizations—and has sparked a research boom that may soon tell us whether soil microbes are as important to our

Illustrations by Helen Musselwhite

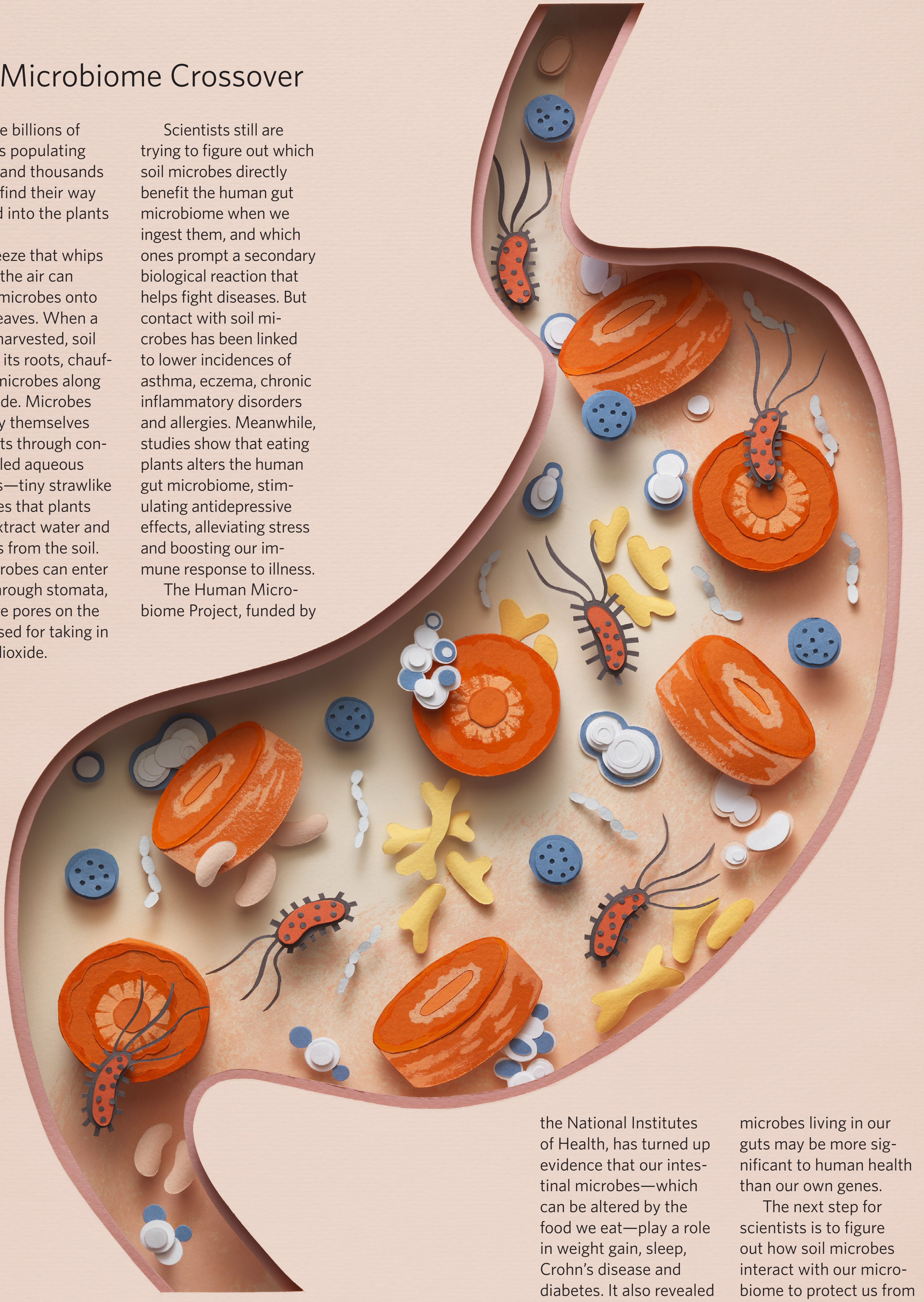
More Nutritious Food Starts with What's in the Soil

The relationship between soil microbes and plants is symbiotic. One example is **nitrogen fixing.** Nitrogen gas is plentiful in our atmosphere, accounting for 78% of the air we breathe. Plants need it in order to grow, but lack enzymes to break down nitrogen. In legumes, for example, a soil bacteria called **rhizobia** attach to legume roots and perform this task. In return, the plant establishes a dense root system that benefits the bacteria and feeds them carbon that it draws out of the atmosphere—which is also important for reducing greenhouse gases.

Fungi in the soil help plant roots tap into nutrients, such as phosphorus and zinc, among others. Plants require these minerals to generate chlorophyll, essential for photosynthesis, which produces glucose. Some of that glucose gets secreted back into the soil, where it feeds the fungi.

When soil has fewer microbes, this natural symbiosis can be disrupted, **leaving plants nutrient-deficient** and, subsequently, less nourishing to the humans who eat them.

The Microbiome Crossover



There are billions of microbes populating the soil, and thousands of them find their way onto and into the plants we eat.

A breeze that whips dirt into the air can deposit microbes onto plants' leaves. When a plant is harvested, soil clings to its roots, chauffeuring microbes along for the ride. Microbes also ferry themselves *into* plants through conduits called aqueous channels—tiny strawlike structures that plants use to extract water and nutrients from the soil. And microbes can enter plants through stomata, which are pores on the leaves used for taking in carbon dioxide.

Scientists still are trying to figure out which soil microbes directly benefit the human gut microbiome when we ingest them, and which ones prompt a secondary biological reaction that helps fight diseases. But contact with soil microbes has been linked to lower incidences of asthma, eczema, chronic inflammatory disorders and allergies. Meanwhile, studies show that eating plants alters the human gut microbiome, stimulating antidepressive effects, alleviating stress and boosting our immune response to illness.

The Human Microbiome Project, funded by the National Institutes of Health, has turned up evidence that our intestinal microbes—which can be altered by the food we eat—play a role in weight gain, sleep, Crohn's disease and diabetes. It also revealed that the DNA from microbes living in our guts may be more significant to human health than our own genes.

The next step for scientists is to figure out how soil microbes interact with our microbiome to protect us from illness.

longevity as daily exercise and a restful night's sleep.

It's Not Just Dirt

The rhizosphere is habitat to a complex ecosystem that scientists call the "brown food web." At its foundation is the soil microbiome, which is involved in numerous processes that promote and sustain plant growth. Some microbes, for instance, act like stomachs, digesting and decomposing organic matter into nutrients that nourish plants. Another action involves mycorrhizae, silk-like fungi that form vast spindly webs that can span several miles underground. These filaments are like the internet of the soil microbiome—facilitating communication between plants. Experiments have demonstrated that when predators, such as aphids, attack a plant, it can warn its neighbors—signaling them through the mycorrhizal network—that a threat is imminent. The other plants will then engage their natural defenses, often a chemical produced in the leaves, to help repel the invaders.

Soil bacteria and fungi also work in tandem to make minerals in the ground water-soluble. "And if they're soluble, a plant can suck them up with its roots," explains David Montgomery, Ph.D., a professor of earth and space sciences at the University of Washington in Seattle, and co-author of *The Hidden Half of Nature,* about the soil microbiome. Microbes also enable plants to produce antioxidants. "Other bacteria and fungi partner together to pry things like phosphorus out of the soil and transport them into the fungal hyphae," adds Montgomery. Fungal hyphae form a network of web-like filaments (made of mycorrhizae) that perform a synergistic dance with a plant's roots. As the plant naturally secretes sugars into the soil during photosynthesis—sugars that help nourish the hyphae—the hyphae respond by providing the plant with nitrogen, phosphorus and various other micronutrients, such as copper, zinc, magnesium, potassium and iron. It's an equitable trade because plants—like people—need these minerals to exist.

A damaged soil microbiome, however, can disrupt this process, lowering the concentration of these nutrients in our food and, subsequently, in our diet. And a lot of farmland today has indeed been degraded. Montgomery tells me about studies that have tracked a rapid decline in the mineral content of fruits, vegetables and grains over the past 50 years. One survey reported that zinc in vegetables had plunged 59%, magnesium fell 26% and iron tumbled 83%. A similar analysis, published in the *Journal of the American College of Nutrition*, examined 43 different crops, comparing present nutrient levels to those recorded in 1950 by the U.S. Department of Agriculture (the USDA has been collecting this data since 1892) and found that protein, calcium, iron, phosphorus and vitamins B_2 (aka riboflavin) and C had all dropped markedly. "Mineral deficiency is estimated to afflict more than a third of humanity, causing health problems in both developed and developing countries," he says. "Mineral elements are essential for hundreds of critical enzyme reactions, and inadequate levels have been implicated in a wide range of maladies." These include cardiovascular disease, neurological disorders, anemia, increased risk of infection and depression.

There is disagreement among scientists about whether an ailing soil microbiome is partly or wholly responsible for the nutrient decline. (One explanation is that plant breeds are typically selected for productivity or pest resistance rather than nutritional density.) But there is little debate that conventional farming of higher-yield crops—that is, more plants per acre—depletes nutrients from the soil and saps it of microbes. Use of chemical fertilizers, pesticides, herbicides and fungicides, as well as antibiotics given to animals that then get excreted into the soil, can kill soil microorganisms, making it harder for plants to extract minerals from it. And monoculture (cultivating the same crop year after year) damages the soil microbiome too. Repeatedly growing corn, for example, sucks up more nitrogen and phosphorus than other crops, eventually starving soil microbes of nutrients they need to proliferate.

The Race to Decode Soil's Secrets

While scientists believe that promoting healthy soil bugs could have a profoundly positive impact on human health, the problem is figuring out which microbes are intrinsic to our well-being and how to help them thrive. The diversity—and how relatively little is known about them—is mind-boggling. As Fierer explains while directing me down a staircase to the CIRES basement, a soil sample from wild grasslands in Kansas could contain more than 20,000 distinct species of microorganisms. A second specimen taken from the same site a mere centimeter away could harbor an entirely different population of microbes, also numbering in the tens of thousands. The sheer biomass of microbes within a single acre of healthy soil weighs more than 2.7 tons, equivalent to a large SUV. Fathoming the soil microbiome is like trying to chart every star in our galaxy—billions and billions. "We know they're there," Fierer says. "We just don't know what most of them do and how they interact with each other."

In the CIRES basement, we enter a mostly empty 800-square-foot lab where Fierer and graduate student Corrine Walsh are conducting an experiment on soil microbes favorable to wheat. What resembles a large white refrigerator sits in the center of the space. It is an environmental growth chamber for cultivating plants, illuminated with blinding-white LEDs. Fierer swings open its heavy door and a waft of humid, musty air escapes. He slides out a clear bin containing 12 square plastic plates lined with seed germination paper. On each sheet are eight wheat seeds in various stages of growth. Some are a couple of inches tall, with sprouts and roots clambering along the paper's surface. Others appear stunted. And a few haven't germinated at all.

Walsh, who is leading the experiment, collected soil samples from 220 different sites around the U.S. "About half were from farms," Fierer says, "and half were from unmanaged, natural systems, mainly forests and grasslands." Walsh mixed each sample with water, concocting a slurry to douse onto individual wheat seeds. Later, she'll use a gene sequencer to analyze the slurries applied to the seeds that sprouted the heartiest roots and shoots. "We'll look to see if there are particular species of microbes that can explain why some wheat seeds grew better than others," says Fierer, who plans to publish the results with Walsh later this year.

Their study is a step toward understanding which soil microbes influence plant growth and, in turn, how those organisms might affect another aspect of human health—the gut microbiome.

Boost Your Garden's Microbiome

Increase the abundance of microorganisms with these practices and make everything you grow more robust and nutritious.

1 Set up a permanent bed and use the same soil each season. And add only natural fertilizers (worm castings or manure) to maintain the soil's overall integrity, while creating a stable habitat in which microbes can flourish.

2 Harvest plants gently to keep the soil intact.

plant your plate

3 Plant cover crops. They help safeguard the soil microbiome during the winter, and the plants will decompose, creating natural compost in the spring. Try planting buckwheat, rye, clover or hairy vetch. There are also seed-mix combo bags available from home-and-garden retailers, some containing more than a dozen cover-crop varieties.

4 Apply compost. It helps return carbon, nitrogen and mineral nutrients to the soil microbiome and aerates the ground. What's more, composting saturates the soil with organic material, which microbes "digest" into the nutrients that nurture plants.

5 Never till. It disrupts the community of microbes by essentially destroying its food source—the roots of vegetables and other plants in the garden. (Turning a small amount of soil to add new plants is fine. It won't disrupt the soil as deep down and broadly as tilling the whole garden would.)

6 Diversify! Cultivating a garden with different vegetables, herbs and fruits—any combo of plants will do—bolsters the type and variety of microbes in the soil, making it healthier. The wide range prevents a single plant from hoarding too much of any one nutrient and creating an imbalance that can harm the microbiome.

Benefits for Mood & Immunity

Dirt is where soil microbes live. But they're also peripatetic, hitching themselves to leaves, infiltrating root systems, entering through stomata (pores that let plants breathe carbon dioxide) and aqueous channels, which transport water and nutrients from the soil into the plants. Inside and out, plants are steeped in microbes, which we ingest whenever we munch on foods like broccoli, berries or lentils. "A single spinach leaf has over 800 different species of bacteria that it gets from the soil and the environment," says Christopher Lowry, Ph.D., a professor of integrative physiology and neuroscience at the University of Colorado Boulder. Once in our intestines, these microbes can fortify the human gut microbiome.

We're also exposed to these bugs through soil itself. The biology at play isn't entirely understood, but studies have shown that people who live and work in farming and rural communities, where they have regular contact with dirt—and the microbes it contains—are more resistant to allergies and asthma, while mice experiments have demonstrated that even modest soil exposure can strengthen the immune system's response to harmful pathogens, including parasites, bacteria and viruses.

Rob Knight, Ph.D., directs the Center for Microbiome Innovation at the University of California San Diego and co-founded the American Gut Project and the Earth Microbiome Project—which are studying the trillions of organisms associated with humans and soils, primarily by sequencing the DNA of the microbes. He's not sure yet whether there is a direct link between the bugs in dirt and human health and longevity—the science is still emerging—but his research has revealed that people who eat a wide array of fruits and vegetables tend to have a more diverse gut microbiome. And studies suggest that individuals with diseases linked to chronic inflammation, such as obesity, cancer, heart disease, asthma and diabetes, tend to have lower diversity.

Lowry, who has been investigating how soil microbes can impact our immune system and even our emotions, agrees: "There is a broad consensus that enhancing gut microbiome diversity is good, even if we don't understand all the reasons why. The safest bet to do that is through consuming a varied diet of plants—and consuming plants frequently."

He points to a questionnaire given to volunteers in the American Gut Project. The participants were asked how many different types of plants they consumed in a typical week, and then were asked to provide a stool sample for analysis. The fecal data revealed that volunteers with the highest variety of good gut bacteria were also those who ate the broadest range of fruits and vegetables. "When I learned that, I went to Whole Foods, picked out 30 different plants and threw them in a blender," he says. "Now I have 4 tablespoons every night with dinner."

For the past two decades, Lowry has been particularly interested in a species of microbe called *Mycobacterium vaccae*, common in almost every soil around the world. He and his collaborator, Graham Rook, M.D., a professor of medical microbiology at University College London, wanted to know whether *M. vaccae* was among the gut microbes that could dispatch signals to the brain. (The notion of a gut-brain axis—meaning that our intestinal bugs can somehow "talk" to our central nervous system—has been pondered and studied for several centuries.)

The two scientists conducted experiments in mice, injecting them with *M. vaccae*, which under a microscope look like translucent yellow maggots. "The bacteria activated a very specific subset of serotonin-containing neurons in the brain. These neurons are known to govern emotions, especially depression," Lowry tells me. "People were taken aback by the idea that bacteria from the soil could have antidepressant-like effects." Lowry and Rook published their results in 2007, and a media deluge followed. Here was tangible evidence that microbes from the soil—when introduced into the body—could potentially impact health.

Lowry and Rook continued experimenting, homing in on the biological mechanism responsible for the antidepressive effects. It turns out that *M. vaccae* triggers a kind of emotional armor. "It protects against inflammation in the brain in response to stress," Lowry explains. By 2016, he was able to demonstrate in animal studies that *M. vaccae* could alleviate symptoms in a range of psychiatric disorders, such as stress-induced colitis and post-traumatic stress disorder. Lab rats can be conditioned to react to fear using behavioral training. A mild shock or sudden puff of air is paired with a light; eventually, the rats will flinch when seeing only the light. Once a fear response is established, it can take weeks or even months to undo. "But the rats that received the bacteria extinguished their fear within 24 hours," Lowry says. "It was mind-blowing to me."

Lowry and his colleagues also wondered if *M. vaccae* could mitigate the precipitous mental decline that occurs in about 40% of people who undergo major surgery after the age of 60. It's called postoperative cognitive dysfunction, or POCD, and it's believed to result from a powerful inflammatory response during and after surgery. They developed a series of cognitive tests to gauge the impact of surgery on aged rats and then inoculated them with *M. vaccae* prior to surgery. "The bacteria completely prevented this cognitive impairment," he says.

So I ask Lowry: Why aren't we all taking *M. vaccae* supplements? Granted, the results need to be replicated in humans. But the short answer is that the strain of *M. vaccae* he studied is not available as a supplement, at least not yet. Like other soil scientists I spoke with, Lowry also reckons that bacteria exhibit strength in numbers—it takes legions of them orchestrating in unison to build a hardy disease-quelling gut microbiome. And it will take more research to tease all that out.

Regenerating Diversity

Humans evolved in lockstep with soil bacteria, which likely explains why our

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microbiomes share similar microbial DNA—as well as some of the same strains of bacteria. *Lactobacilli*, for instance, can be found in both soil and humans. Those beneficial probiotic bacteria (present in foods like yogurt) help break down food and release nutrients inside our gut; their role in soil is the same. A 2019 study published in the journal *Microorganisms* documented this unique kinship between human and soil microbiomes: "They contain the same number of active microorganisms," the authors noted, adding that "it may be useful to adopt a different perspective and to consider the human intestinal microbiome as well as the soil/root microbiome as 'superorganisms,' which, by close contact, replenish each other with inoculants, genes and growth-sustaining molecules."

The researchers also analyzed the variety of microbes in humans and soils and found that not only is the diversity of both plummeting—it's occurring at roughly the same rate. They identified several reasons for the decline: our transition from an agrarian society to an industrial one, modern hygiene, and our Western diet filled with low-fiber, highly processed foods. When we changed our farming practices, stopped growing our own food—which involved touching a lot of dirt—and began eating more Big Macs than plants we fractured the beneficial relationship between ourselves and the soil.

So the focus now is on repairing that relationship. Phil Taylor, who earned a Ph.D. in global ecology from the University of Colorado (Fierer was a member of his dissertation committee) is the co-founder and executive director of Mad Agriculture, a consulting firm that "helps farmers build healthy soil and make money doing it," as he puts it. Taylor suggests I read about the work of Sir Albert Howard, an English botanist who traveled the world during the early 20th century. "He wanted to know whether soil health translates into healthy food," Taylor explains. While Howard couldn't identify the exact mechanism, after visiting hundreds of communities he had enough anecdotal data to answer the question for himself unequivocally: soil microbes forged a conduit between healthy crops and healthy humans. Initially ridiculed for his theories, Howard would become a pioneer in organic cultivation and soil microbiology, advancing methods that Taylor employs for his clients.

These days, Taylor says, "the science is playing catch-up to what some farmers already understand to be true." More specifically, he means that the soil microbiome flourishes best—and conveys the biggest benefit to humans—when farmers embrace a hands-off approach and let the brown web do its job, with little or no external input from things like pesticides and fertilizers. His advice to farmers who hire him generally hinges on time-tested regenerative-farming principles, which increase the abundance and diversity of microorganisms in the rhizosphere. In practice, this entails minimizing plowing, maintaining living roots in the ground year-round (via a cover crop), cultivating a variety of plants and integrating livestock onto the land (because grazing and manure foster soil microbes).

And the science appears to support this approach. A recent review of 56 studies published in the journal *PLoS One* found that soil from farms that didn't till or use synthetic chemicals and employed practices like cover cropping, biodiversity and crop rotation contained 32% to 84% more microbial mass (an indicator of healthy soil) than that from conventional farms. And research at The Rodale Institute found that oats, peppers, tomatoes and carrots grown on organic or regeneratively managed farms contained 18% to 36% more minerals and antioxidants than their conventional counterparts. (Healthy soil has other benefits, too, of course, such as promoting carbon sequestration and water retention, which can help mitigate climate change.)

Plant-growth-promoting microorganisms, or PGPMs, have also come on the scene. They're part of a newer class of fertilizers, called biofertilizers. Think probiotics for dirt, which, as it turns out, is a booming industry, despite the absence of evidence proving which microbes work best. Even so, the notion that a farmer could resuscitate barren soil with a microbial cocktail is not exactly outlandish. Numerous agribusiness startups are pursuing PGPMs, including Boston-based Indigo Agriculture, which has hired Fierer to run a yearlong study to develop a microbial inoculant that can turbocharge crop growth. Other firms are creating "biotic" fertilizers. Like vitamins for the soil microbiome, biotic fertilizers typically are developed from a type of blue-green algae called cyanobacteria. When cyanobacteria decay, they leave behind carbon, nitrogen and other nutrients that nourish the bugs in the soil and jump-start the microbial life cycle. The same process occurs naturally in healthy soil, just much more slowly.

There are no quick fixes, but there is a real movement underway to undo the damage and bring the bugs back. On my way out of the lab, Fierer shows me two large framed photos hanging on the wall. The images were taken in 2017 in Antarctica; he and his research team spent two months there collecting soil samples from exposed ground in the Transantarctic Mountains. "We wanted to see what types of microbes can live in the extreme conditions found in this area—cold, dry and salty soils," he says. Indeed, they found bacteria and fungi surviving in areas that had recently been covered in ice. What he discovered was that soil microbes are terrestrial die-hards. After all, they have been around for an estimated 4 billion years. "Don't worry about them being eradicated," says Fierer. That's good news, because as humans continue to pursue strategies to live longer and healthier, the soil microbiome may be the one thing in the end that helps save us all.

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