Look. Nothing flourishes here. Not even weeds.” Pius Floris picks up one of the dozens of stones scattered around him on the degraded, barren-looking soil. Decades of drought, monoculture, overuse of fertilizer, and excessive plowing have taken their toll on this field in the Spanish region of Castilla y León. As a result, wind and rain have washed away all but 25 centimeters of the fertile topsoil that used to nourish the grain here. For centuries, this area was a bread basket; today, yields are so low that farmers work the area only because of subsidies from the European Union.

Floris, a Dutch entrepreneur in plant health, wants to turn that situation around. With researchers at the University of Valladolid and a team of local farmers, he participates in an E.U.-funded pilot project that aims to make profitable agriculture possible again on such damaged soil, without irrigation.

Mycorrhiza fungi (yellow) help the roots of this soybean plant absorb nutrients and water; to return the favor, the plant excretes nutrients for the fungi.

THE LITTLEST FARMHANDS

Scientists are discovering thousands of microbes that help plants survive and thrive. Could these symbionts help farmers as well?

By Jop de Vrieze in Palencia, Spain

With researchers at the University of Valladolid and a team of local farmers, he participates in an E.U.-funded pilot project that aims to make profitable agriculture possible again on such damaged soil, without irri-
tion. His key collaborators: microbes.

One reason the soil here has gone to waste, Floris says, is that farming has destroyed its microbial ecosystem, which can help plants survive and thrive. His team has recently applied beneficial microbes—in particular fungi—that live on, around, or in plant roots in the soil. Many of these microbes, together called the rhizobiome, help plants one way or another, from providing nutrients to warding off crop pests and diseases. Small biotechnology and major plant science companies think they have huge potential benefits in agriculture and have recently begun a spate of new field trials. A 2013 report published by the American Academy of Microbiology (AAM), with the optimistic title How Microbes Can Help Feed the World, concluded that microbes have the potential to increase harvests while allowing farmers to use less fertilizer and pesticides; certain microbes can even enable plants to grow in very dry or salty places, which could help the world adapt to climate change.

A few denizens of the soil have been on the market for decades, such as Trichoderma fungi that suppress pathogenic fungi, and the now well-known caterpillar killer Bactillus thuringiensis, or Bt. (The gene for the bacterium’s toxin has also been introduced into some crops’ genomes.) Recently, major agrochemical companies such as Bayer have jumped on the biologicals bandwagon. “It’s a revolution of microbiology,” says Thomas Schäfer, vice president of microbial R&D at Novozymes, a company developing microbial fertilizers and pesticides that recently struck a deal with agriculture giant Monsanto. Schäfer believes farmers are heading for “precision agriculture,” in which they can add beneficial microbes, or support the microbial ecosystem, which can help plants withstand stress, including so-called mycorrhizae or root fungi, which form a complex symbiosis with fungi and plants.

**Underground world**

Vast numbers of organisms—presented here along with their average number of genes and their numbers per gram of soil—live in and around a plant’s root system.

<table>
<thead>
<tr>
<th>Organism</th>
<th>Genes</th>
<th>Organisms per gram of soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>37,500</td>
<td>10,000–1 million</td>
</tr>
<tr>
<td>Protozoa</td>
<td>15,500</td>
<td>100–1000</td>
</tr>
<tr>
<td>Fungi</td>
<td>14,000</td>
<td>1000–100,000</td>
</tr>
<tr>
<td>Archaea</td>
<td>1300</td>
<td>10 million–100 million</td>
</tr>
<tr>
<td>Viruses</td>
<td>45</td>
<td>10 million–1 billion</td>
</tr>
<tr>
<td>Nematodes</td>
<td>18,000</td>
<td>1000–1 million</td>
</tr>
<tr>
<td>Algae</td>
<td>13,000</td>
<td>100 million–1 billion</td>
</tr>
<tr>
<td>Bacteria</td>
<td>6500</td>
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</tbody>
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and viral species that inhabit the human gut, skin, and other tissues.

Studies have shown that there are up to 10 billion bacterial cells per gram of soil in and around plant roots, a region known as the rhizosphere. This domain is tremendously diverse; in 2011, a team led by soil microbiologist Jos Raaijmakers of the Netherlands Institute of Ecology in Wageningen detected more than 33,000 bacterial and archaeal species on sugar beet roots. Dozens of species appear to suppress plant disease by excreting substances that ward off pathogenic microbes or occupying niches otherwise taken up by the pathogens. A study of vineyards in New York, published in March, showed that the composition of the rhizobiome depends heavily on the soil type.

Lab and greenhouse experiments have also shown that microbes make a variety of nutrients and minerals in the soil available to plants, produce hormones that spur growth, stimulate the plant immune system, and trigger or dampen its stress responses. “In general, we can say that a more diverse soil microbiome results in fewer plant diseases and higher yield,” Raaijmakers says.

Among the most helpful microbes are so-called mycorrhizae or root fungi, which form a dense network of thin filaments reaching far into the soil, acting as extensions of the plant roots they live on or in. These fungi facilitate the uptake of water and a wide range of nutrients—Floris calls them “the plant’s shopping carts.”

Microbes can also help plants survive extreme conditions. A 2007 study showed that a complex symbiosis with fungi and viruses makes it possible for a grass called Dichanthelium lanuginosum to thrive in geothermal soils in Yellowstone National Park, where temperatures reach 60°C. The fungus, now thoroughly studied and introduced in the U.S. market in 2014 for application on corn and rice, triggers a stress response that the plants can’t switch on themselves.

Similarly, a bacterium called Stenotrophomonas rhizophila has been shown to strongly increase drought tolerance in crops like sugar beets and maize. A 2013 study offered an explanation: The microbe excretes a variety of molecules that help plants withstand stress, including so-called osmoprotectants, which prevent the catastrophic outflux of water from plants in very salty environments. Microbes can even affect the flavor of food plants: A bacterium called Methylobacterium extorquens increases the production of furanones, a group of molecules that gives strawberries their characteristic flavor.

**SCIENTISTS AND FARMERS** have long seen microorganisms primarily as problems. A fungus-like unicellular organism named Phytophthora infestans and chemical fertilizers, and whether concertuated task. Also unclear is whether microbes benefit plants most, how they do it, or so staggering that finding out which organisms benefit plants most, how they do it, or what combinations work best is a gargantuan task. Also unclear is whether microbes can dramatically curb the use of pesticides and chemical fertilizers, and whether conventional farmers will trust these new options. The central question, some scientists say, is: How much can microbiology replace chemistry in agriculture?
The services provided by microbes are apparently hugely important to plants, as they put in a lot of energy to return favors. Studies have shown that up to 30% of the carbon fixed by plants is excreted from the roots as so-called exudates—including sugars, amino acids, flavonoids, aliphatic acids, and fatty acids—that attract and feed beneficial microbial species while repelling and killing harmful ones.

**THE GROWING ACADEMIC** understanding of the rhizobiome has increasingly made its way into the corporate world and onto farmers’ fields. One early example was Serenade, a biopesticide containing a *Bacillus subtilis* strain that has antifungal and antibacterial properties and promotes plant growth. It was discovered by AgraQuest, a biotech in Davis, California. “So many pharmaceutical products were extracted from the soil, but for agriculture, this potential was hardly exploited,” recalls Denise Manker, who co-founded the company in 1995. Serenade, registered by the U.S. Department of Agriculture in 2001, can be applied in a liquid form on the plants and in the soil to fight a range of pathogens. “Initially, most of our customers were organic farmers,” Manker says. “Soon, she says, innovative conventional farmers started experimenting with the product as well, and some became converts.

So far, the market for such products has been modest. Almost all of the registered ones are biopesticides; the AAM report estimated that they bring in about $1 billion annually, which pales compared with the global markets for chemical pesticides and fertilizer, estimated at $850 billion and $60 billion annually, respectively. But big agrochemical companies see the potential of microbial alternatives. “It took us 17 years to get the big companies interested, but we made it,” Manker says: In 2012, German agro giant Bayer bought AgraQuest for $425 million. Manker became Bayer’s director of global agronomic development of biologicals, a job that comes with a €10 million annual research budget. She’s using it to field-test dozens of new fungi and bacteria to replace chemical pesticides or serve as biopesticides, which promote the health and growth of crops.

One explanation for Bayer’s interest: Growing public resistance against chemical pesticides and a 2009 European directive aiming to reduce their use caused the market for chemical crop protection to stagnate, whereas the demand for biologicals was growing close to 10% per year. Given that, it’s not surprising that Bayer’s competitors have made similar moves. Syngenta and BASF acquired smaller companies developing microbial products last year; so did Dupont in April of this year. Monsanto’s new partner, Novozymes, has invested heavily in a biofertilizer containing the soil fungus *Penicillium bilaii*, and a bioinsecticide that contains the fungus *Metarhizium anisopliae*.

The list of potentially suitable microbes is endless, says Matteo Lorito, a plant pathologist at the University of Naples Federico II in Italy, and that poses a daunting task for companies. “The challenge they are facing is selection of the ones that are commercially viable and effective,” Lorito says, especially because many microbes are plant-specific and the composition of the rhizobiome can change rapidly.

Traditionally, selected microbes were first tested and investigated extensively in labs and greenhouses. But promising strains often failed to prove effective in the field, because of soil, climate, and ecosystem effects. Today, most companies use a “field-first approach,” in which hundreds or even thousands of microbial strains are tested on field plots. If one proves successful, the mechanism of action is unraveled in the lab later. But even a promising field...
modern crops. The effort could yield common and symbiotic microbes that could benefit wheat ancestor Triticum aestivum (Chanel's common wheat ancestor) and their wild relatives in the natural environment. The hope is to identify plant traits that may be better equipped to attract beneficial microbes, such as wild beans in Colombia and the goatgrass (Aegilops longissima) in Spain, to improve crops' ability to attract beneficial microbes. This is a laborious and expensive process, as it requires detailed study to understand the interactions between plants and beneficial microbes. Identification and characterization of beneficial microbes are critical in developing effective solutions.

But Floris wants to see just how far he can push his microbial helpers. On that May day, he and his team inspected the crops every 2 meters. The hip-high oats and vetch fields, bending over in the breeze, made for a pleasant walk. The team was searching for signs of success in the experiment. Floris's colleague Pedro Alonso dug a deep hole in the driest parts of the year. "The idea is to see if we can develop a system that is sustainable and beneficial for both the soil and the crops," he says.

The experiment consisted of three zones in the 100-hectare field. Zone A was treated with chemical fertilizer and pesticides, zone B received only artificial fertilizers and a dose of natural bacteria, and zone C received no artificial fertilizers or pesticides. Zone A, which received the most artificial inputs, produced the lowest yield. Zone B, which received a dose of natural bacteria and no artificial fertilizers, produced a yield that was almost as high as zone A. Zone C, which received no artificial inputs, produced the highest yield of all.

Floris's vision is more radical than most: "I'm trying to create a new system of agriculture that is sustainable and beneficial for both the soil and the crops," he says. "I want to see if we can develop a system that is sustainable and beneficial for both the soil and the crops." The results of the experiment have been encouraging, but Floris is not ready to give up on the idea. "There is still a lot of work to do," he says. "But I'm optimistic that we can develop a system that is sustainable and beneficial for both the soil and the crops."