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Can Microbes Help Feed the World?

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New research tools offer hope for improving global agriculture

Gwyn Beattie, professor of microbiology and plant pathology at Iowa State University, says that research on soil microbes has the potential to improve agricultural production. Photograph: Robert Elbert, Iowa State University, University Relations Office.

An oft-quoted fact from the Food and Agriculture Organization of the United Nations resonates with the local farmer growing corn and soybeans on an Iowa field as surely as it does with development officers around the world: By the year 2050, the Earth will need to support 9 billion humans.

To help meet the challenge for food, scientists are using new technologies to better understand the role that soil microbes might play in bolstering agricultural production. This growing field of research brings together microbiologists and plant pathologists, computer scientists, and biostatisticians to make sense of the vast amount of microbial data.

Researchers have long looked at the relationship between plants and microbes. In recent years, some of that work has taken a turn away from the traditional approach of identifying harmful pathogens and toward a greater understanding of microbes' beneficial roles. According to Gwyn Beattie, a professor of plant pathology and microbiology at Iowa State University, the tools available today to study microbes have blown open the door to a fundamentally different approach to studying them. In the past, the study of bacteria, for example, required culturing the ones in question. This approach worked well for identifying the pathogens associated with disease.

"But if we can take a community and extract all their DNA and look at individual DNA sequences," Beattie says, "we can begin to profile the numbers and types of organisms in that community. So it's given us a handle on understanding what's there. It's the same revolution that's happening in medicine as well, with the human microbiome."

Just as doctors—and even some patients—have long understood that bacteria in the human gut play an important role in digestion, Beattie says, farmers have known that some soils are more beneficial to plants than are others, even if they haven't always understood why that is. "Even the Romans—they would take certain soils from very productive fields and put them on other fields and find they were more productive," says Beattie. "And they didn't know the basis of it. They didn't know there was a microbial element to it." And in the nineteenth century, Dutch microbiologist Martinus Beijerinck described the role of rhizobia in providing legumes with usable nitrogen.

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Over the last decade, the accumulation of such knowledge accelerated rapidly. According to a 2013 report by the American Academy of Microbiology (AAM), *How Microbes Can Help Feed the World*,

> In the last ten years, scientists have made tremendous progress in describing the incredible diversity of this microbial world and have begun to dissect the elaborate networks of communication and cooperation among plants, insects, invertebrates, grazers, and microbes and to determine the precise molecular mechanisms of such interactions. Commercial applications of these discoveries are already being used to support plant growth, health, and productivity. However, the as-yet-unrealized benefits of understanding how microbes support plant vitality could be immense.

Jan Leach, professor of plant pathology, works in her Colorado State University greenhouse with students Paul Langlois (left) and Rene Corral. They are surrounded by different varieties of rice plants, which the team grows and evaluates for resistance to blight disease and other traits. Photograph: John Eisele, Colorado State University Photography.

The AAM report is the result of a colloquium that brought two dozen scientists to Washington, DC, to formally consider the role of microbes in increasing food production. The researchers conclude that a more robust understanding of the relationships between plants and the microbes in, on, and associated with them could have profound effects on production agriculture.

Tiny organisms' grand challenges

In order to contribute to overarching efforts to increase agricultural yields, the AAM colloquium participants put forward three recommendations specifically related to microbes. The first recommendation is to invest in fundamental research. They also advocated collectively taking on at least one grand challenge, such as fully characterizing the microbiome of a crop plant, characterizing the reaction of specific plant–microbe communities to a certain stress, or increasing yields by 20 percent over 20 years while reducing the use of fertilizer and pesticides by 20 percent. And, finally, they proposed creating a practical way to transfer discoveries from the lab to farm fields.

Once *How Microbes Can Help Feed the World* came out, the AAM researchers discovered that their counterparts at the American Phytopathological Society (APS) had also begun to look at expanding research on the positive impacts of microbes and insects on food production, such as how these organisms influence plant health and nutritional quality. Jan Leach, a professor at Colorado State University, in Fort Collins, and the chair of the APS Public Policy Board, says that when the AAM report came out, it became clear the that two groups had separately come to prioritize this concept of harnessing microbes for good.

"We were working down that path and we had come up with this initiative that we call the phytobiome initiative," Leach said. One difference between the two groups' approaches, she added, is that the APS project includes eukaryotes, too. "There are other things than just microbes that are interacting with plants and changing how the plant responds to the environment," Leach says, "or interacting with the plants in good or bad ways."

Still, it became clear to both organizations that they could combine their efforts. As Beattie noted, the availability of sequencing tools that allow for more-complex exploration than was formerly possible is a critical link in making a drive to harness microbes for agriculture practical. The soil microbial community in any given place is vast in terms of the diversity of life.

"We're talking not just thousands or millions but billions of microbes in a gram of soil along a root," Beattie says. It remains impossible to identify them all, but that is not the goal. Rather, she says, modern tools make possible community-level sequencing. Where once the focus had to be on select bacteria, now researchers can consider whole communities.

"As our technical capacities have expanded, these whole new worlds have opened up," says Linda Kinkel, another colloquium participant, who is a professor at the University of Minnesota. "The explosion in molecular technologies that really let us look at the genome of these microbes…" she said, "that's been completely game changing."

The magnitude of the possibilities is tempered by the need to make sense of vast quantities of data. Often, experts in biostatistics or computer science are brought in to help find meaning in the genomic sequences. And that expertise has not kept pace with the expansion of the tools that make sequencing available around the world. Beattie says that, in less scientifically robust countries, where one could argue the need for greater food production is most pressing, the tools are available, but the volumes of data become almost useless unless or until someone can accurately make sense of them.

Beattie does see progress on the horizon, though, in the form of a standard procedure for data analysis. "We're on our way" toward a pipeline that would provide a kind of recipe for data analysis, she says.

University of Minnesota professor Linda Kinkel looks at plants growing at the Sand Plain Experiment Research Farm, in Becker, Minnesota, during a 2014 Potato Grower's Field Day. Photograph: Dave Hansen.

In Linda Kinkel's lab at the University of Minnesota, Streptomyces *samples such as these are being analyzed to learn how they interact with plants to promote growth or to prevent disease. Photograph: Linda Kinkel.*

The potential fruits of research

Once the ability to interpret the data matches the tools used to generate it, what exactly will the scientists be looking for in their vast stores of information? Beattie is interested in how existing farming practices might be altered or amended to maximize plant health. She took soil samples from fields where a decade's worth of crop rotations had previously been studied. Her focus is tolerance to drought and changes in salinity. By sampling the fields during specific points in the crop rotation, she determined that soil pH can play an important role in what kinds of microbes are present.

"[Acidity] has turned out to be a huge factor in soil microbial communities," she said, and knowing that will help her design future experiments. Beattie would like to identify the role of bacteria in how plants develop resistance to drought. After experimenting with different levels of water among plants growing in the same soil, Beattie found certain bacteria that seem to be present under drought conditions. Her next steps include targeting a specific bacterium and seeing whether she can culture it, put it into soil, and force the same drought resistance. If there's a correlation, she can then seek out the bacterium in a natural setting, using its genetic profile, which she likens to a fingerprint. "Could we use this fingerprint in plant breeding?" she asks.

Contributions to plant breeding are one possible outcome from greater understanding of microbes—and one that has a pretty straight path into farm fields, once new types of seeds are developed and tested.

Other challenges in which microbes might be tapped to play a more important or deliberate role—or where their existing role might be better understood and optimized—include growth promotion and the prevention of disease.

Kinkel says that looking at the positive impacts that microbes can have is a shift in frame of reference for plant pathology. "As our technical capacities have expanded, these whole new worlds have opened up," she says. It used to take a visible wilt or tumor or some other obvious sign of stress to prompt inquiry at the microbial level.

"The vast majority of microbes out there are ones that we have tended to overlook," Kinkel argues. Although that is likely to be the case forever, given the immense number of bacteria, Kinkel has hope that many more can now be studied. She aims to uncover in greater detail the many ways that *Streptomyces* communities may support plants. The genus *Streptomyces*, Kinkel says, is prolific as an antibiotic producer (most antibiotics of bacterial origin used in human health come from this genus).

Her group is now trying to "systematically explore the correlates or predictors of when these populations [are] most likely to be good at suppressing plant pathogens or at promoting plant growth." Because soils around the world have indigenous microbial communities, Kinkel is hopeful that, when these connections between certain bacteria and certain plant benefits are established, it will be possible to apply the research in any location to maximize the microbial potential of local soils.

She plans to approach this goal in two ways. From a single-taxon perspective, she will try to determine the functionality or means by which the taxon affects plant growth in controlled situations. Then, if it benefits the plant in its own community, can the taxon be applied to a different landscape to achieve the same benefit? In terms of aggregate microbial communities, she hopes to profile how they look when a plant is doing well and compare that to the microbial

This soil core was collected by a researcher at the University of Minnesota working in Linda Kinkel's lab group. Photograph: Dave Hansen.

communities when a plant is faring poorly. This raises an important question: Does the microbial community show signs of poor health because the plant is doing badly, or is the plant not doing well because of shortcomings in the microbiome?

Other research is focused on fungal endophytes, including some work that has already led to commercial products for enhancing crop production. Rusty Rodriguez participated in the AAM colloquium as both a plant pathologist and an entrepreneur. He is the chief executive officer of Adaptive Symbiotic Technologies, a Seattle-based firm that studies fungi and carefully selects ones that have the potential to benefit plants. After identifying fungi using DNA sequence analysis, his team then works to determine the function of a particular fungus.

The way Rodriguez describes the process, it is more detective work than biotechnology. "We're not genetically modifying the organisms we're working with," he says. "We designed strategies for letting nature do the selecting for us." He, too, counts on the idea of genetic "fingerprinting" to isolate certain organisms, "so we can track them and follow them around." He deploys various molecular tools to understand where the fungus grows in the plant and how the plant and fungus communicate. "We continue to develop tools for visualizing the association and understanding the association" between plant and fungus, he says. "We've been focusing all of our efforts on three major stressors." These stressors are those associated with a warming climate: drought, salinity changes, and extreme temperatures.

Rodriguez says that, so far, the company has worked in North America, with field trials just beginning in South America. Recent organic certification may expand business in the United States, where US Department of Agriculture–certified organic growers are not allowed to use most chemical inputs. With the certification, these fungi-derived products are permitted. But Rodriguez says the intention is not only to serve the high-end US organic market.

"Farmers in developing countries can use this just the same as corporate farmers in the developed world," Rodriguez says. And for smaller producers abroad, fungi-derived products may ultimately offer a cheaper solution than do commercial seeds with chemical insecticide coatings, for example, or buying fertilizer, both of which are often out of reach for smallholder farmers.

Plenty of larger companies are also harnessing microbes for farming. BASF has a line of inoculants that capitalize on the well-established relationship between soybeans and rhizobia. Early this year, Monsanto launched the BioAg Alliance, a collaboration with Novozymes, a company already working on microbial solutions to agricultural challenges.

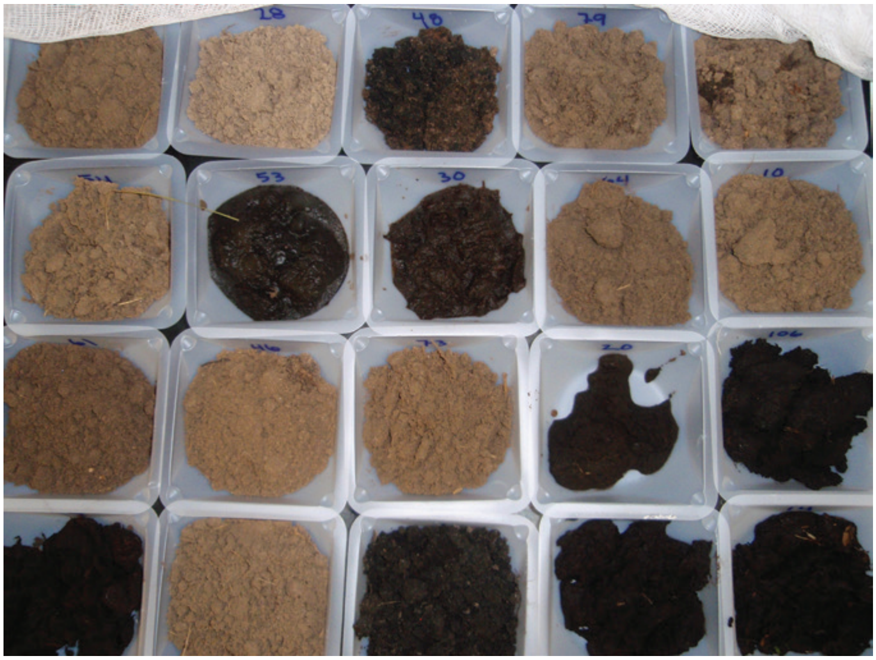
The AAM report acknowledges existing commercial products that depend on microbes. "Biopesticides, a category that includes biological agents used as insecticides, herbicides, pesticides, and fungicides have been estimated to constitute a $2.1 billion per year industry—about 5 percent of the $44 billion per year chemical pesticide industry," according to the report.

In a 2013 study in the *Journal of Agricultural and Applied Economics*, Holcer Chavez and colleagues looked at the application of microbial inoculants on apple production in the United States. In this study, they found that supplementing existing pesticides with microbial inoculants did not reduce pesticide use but did have a positive impact on yields.

Although one of the AAM goals is to reduce the use of chemical inputs such as insecticides and pesticides, documenting the positive effects of inoculants within the context of pesticide or insecticide use may be a necessary part of the process. The AAM report cites progress in the study of cassava, an important tropical food crop, and arbuscular mycorrhizal fungi (AMF), which is almost always found with wild cassava.

"Different species of AMF have dramatically different effects on cultivated cassava," the report says, "ranging from no effect to a 20 percent increase in yield." Figuring out which species would have the greatest benefit, if it were applied to fields as an inoculant, was made more difficult by the challenge of growing AMF in the lab. But the report says that significant progress has been made toward a biotechnological method of mass production, leading to the hope that, ultimately, it will encourage higher cassava yields and less dependence on phosphate fertilizer.

In a 2013 citrus study published in *Scientia Horticulturae* (doi:10.1016/j.scienta.2013.09.010), researchers from China and India noted that AMF symbiosis can offer plants better growth, higher nutrient uptake, and better tolerance to both biotic and abiotic stresses and may also improve the soil structure for the host plant.



Each gram of soil contains billions of microbes, and even samples taken near each other can vary widely. New tools make it possible to conduct community-level sequencing, which may eventually help lead to a better understanding of how microbes could be harnessed to benefit crop plants. Photograph: Lindsey Otto-Hanson.

Three ways microbes could increase food production.

Gwyn Beattie, a professor of microbiology and plant pathology at Iowa State University, participated in the American Academy of Microbiology's colloquium that produced the report *How Microbes Can Help Feed the World*. She has given presentations to science educators that emphasize three agricultural challenges in which a greater understanding of microbes could contribute:

Closing the yield gap. Currently, many farmers do not harvest as much as their plants should be able to produce because of constraints on water, nutrients, pests, and diseases.

Reducing chemical inputs. To resolve the yield deficit, many agriculture systems rely on chemical fertilizers and other additives to replenish nitrogen, combat rootworms and nematodes, and ward off diseases.

Expanding food production into marginal lands, without causing environmental damage. When farmers today cultivate certain less-than-ideal plots, irrigation, chemical inputs, or other processes are required, and those activities may pollute waterways or hasten erosion.

Helping farmers reap the benefits

With these kinds of discoveries under way, laying the groundwork for the lab-to-field transition becomes increasingly important. “For many of us, this is one of the biggest challenges,” Kinkel says. “There’s not at present a clear pipeline from the lab to the field.”

If, for example, Beattie’s research on crop rotations leads to recommendations for how to plant in order to optimize the role of microbes, the challenge will be educating farmers on which crops to rotate and why to plant a crop that may be less profitable in the short term, even if it is expected to improve the yield of a highly valued crop the next year. Changing farmers’ practices can be a slow process, although research and outreach from university scientists typically play an important role, especially in the United States. Over time, growers are adaptable, Kinkel adds. “If we can show them things that work, and if we can give them the information they need to implement them on their farms,” she said, education efforts will lead to the adoption of new practices.

The AAM colloquium was international, with participants from North America, Europe, and South America. But Beattie says it may be small farmers in less-developed countries that stand to benefit the most from the results of research on microbes’ benefits. In the United States, she says, research and experimentation and the high stakes of large-scale farming have led to highly developed practices that may already be pushing microbes close to their maximum benefit. But that is not the case in much of the world. In poorer countries with more depleted soils, she says, “you have a much greater capacity for the microbes to make a measureable improvement in yield.”

Beattie acknowledges that a research endeavor that is most likely to reap its greatest benefits outside of the United States rather than within its borders could be a tough sell to federal funding agencies. “The hope is that’s going to translate at some point into a recognition that we need to invest in a fundamental understanding of what microbes can do for plants… and are doing,” Beattie said.

Arbuscular mycorrhizal fungi is difficult to grow in a lab, but researchers are studying its relationship with cassava (shown here) because certain species appear to have a potentially dramatic impact on this important food crop. Photograph: Mokkie.

She added that the simultaneous work of the APS has played a critical role, bringing to Capitol Hill arguments for myriad applications of work on microbes, including biofuels, animal digestion, and cleaning up pollution.

The APS’s Leach says that making the case for funding also connects to the international scope of the work. “We are trying to promote this to [the US Agency for International Development] or other international agencies,” Leach says,” because, clearly, this could help. “We’re also pressing the international arena,” she says. “This is not something that the US can do by itself. Not only are we pressing the international community for research but also the application of that research.”

Perhaps one of the greatest advantages that microbial research has is the enthusiasm that researchers bring to the challenge. Now that the identification and exploration of these vast but mostly hidden communities is imaginable, Beattie says that she has been recruiting graduate students to the endeavor. “My students have really grasped this notion” of the positive influence of microbes, Beattie says. And she is intrigued by their ideas. For example, one student suggested dipping grape plant roots in a microbial mix that might lead, eventually, to a variety better suited to Iowa.

Beattie and Kinkel have presented the general ideas of *How Microbes Can Help Feed the World* to science educators. Beattie expects that a new generation of researchers will embrace the idea. “Most students want to do something that makes a difference,” she says. And little microbes have the potential to make a big difference in agriculture.

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