How Microbes Can Help Feed the World

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Understanding the partnerships between microbes and plants could help to solve the global food crisis.

Feeding a global population projected to reach nine billion people by 2050 is one of the greatest challenges facing humanity. Gains from the Green Revolution have levelled off, there is a limited supply of arable land and clean water, and inputs like fertilizers and pesticides are both economically and environmentally costly. Intensifying current agricultural approaches is simply not a sustainable solution to the problem of food security; new approaches are desperately needed.

Fortunately, there is an area of science ripe to help solve this pressing problem – microbiology. For decades it was possible to study only those microbes that could grow in the laboratory, but about 20 years ago scientists began extracting and sequencing the collective DNA from a wide range of environments, including soil, ocean water, hot springs, and even the human body.

What became clear very quickly is that there were many more different kinds of microbes than scientists had ever expected. What also became clear is that all multicellular organisms, from plants to insects to humans, are dependent on complex communities of microbes.

What does this have to do with feeding the world? The answer is that all plants require microbial communities to support their growth. Over evolutionary time, microbial communities and plants have evolved together so that wild plants have microbial partners to help them grow and protect them from various environmental stresses.

When plants were domesticated for agricultural purposes, however, the critical role of their microbial partners was not yet recognized, so plants have been bred, adapted and grown around the world without attention to the microbial milieu in which they evolved. Rather, plant productivity was optimized through breeding and the application of fertilizers and other external inputs. Many lines of evidence now suggest that optimizing the microbial communities around crop plants has the potential to dramatically reduce fertilizer requirements and help plants withstand environmental stress such as drought or flooding.

To draw attention to this promising new area, in December 2012 the American Academy of Microbiology organized a colloquium to bring together experts in the fields of microbiology, plant science, evolutionary science, symbiosis and agronomy. The scientists were joined by development experts with experience in introducing new technologies to resource-limited countries, representatives from private companies that develop microbial products and policy-makers. During 2 days of intense discussions, the group discussed how plant–microbe interactions could be used to boost agricultural productivity in an environmentally and economically responsible way. The discussions at the colloquium were distilled into the report

How Microbes Can Help Feed the World, which is available for free download from the American Academy of Microbiology. It is summarized here.

Plants Depend on Microbes

The relationships between plants and microbes date back to the origin of plants, when a primitive cell and a cyanobacterium formed a new partnership; the cyanobacterium took up residence in the cell, eventually losing the ability to live independently and evolving into the organelle we now call a chloroplast, providing the cell with the capacity to transform sunlight and carbon dioxide into sugars and oxygen. This transformative evolutionary event allowed plants to compete in the crowded microbial world and evolve into myriad multicellular forms.

Chloroplasts are not the only example of a vital plant–microbe partnership; plants formed partnerships with microbes to acquire nitrogen and other nutrients, deter pathogens and grazers, and many other functions. Indeed, the number of recognized interactions is large and growing all the time. What is becoming increasingly clear is that plant health is intimately tied up with complex and largely invisible ecosystems in which literally thousands of species are competing or cooperating in response to constantly changing environmental conditions.

What Kinds of Services Can Microbes Provide?

Microbes play a part in virtually all plant physiological processes. At any given time, plants may or may not be dependent on microbes for any given service but, particularly under conditions of scarcity or stress, microbes are likely to be crucial for:

- acquisition of nutrients
- pathogen and predator resistance
- resisting environmental stresses of many kinds, such as drought, flooding, salinity, heavy metal or organic pollutant contamination, and high or low temperature.

The effect of arbuscular mycorrhizal fungi (AMF) on the growth of the cassava plant is an example of the dramatic effect microbes can have on plant productivity. Cassava is a staple crop in the tropics, but its productivity is limited by the typically nutrient-poor tropical soil, and farmers are obliged to use expensive phosphate fertilizers to boost crop yields. However, AMF can grow within cassava roots and extend their hyphae out into the soil to transport phosphorus, sulfur, nitrogen and other micronutrients to the cassava plant.

AMF have traditionally been difficult to grow outside their plant partners so generating enough fungal propagules for commercial application was not possible. Recently, a biotechnological mass production system has been developed allowing AMF to be grown in the laboratory. In vitro-produced AMF has been tested in large-scale commercial cassava cropping in Columbia, and improved yields significantly. Application of this approach to other plant–AMF partnerships may allow substantial productivity gains while simultaneously decreasing fertilizer use.

The theme that carries through all of these examples of beneficial plant–microbe interactions is that over billions of years plants have formed partnerships with a variety of microbes to allow them to survive when environmental conditions are not ideal. The implications of this realization for agriculture are profound. For millennia, farming practices have sought to provide ideal conditions for plant growth using irrigation, fertilizer and plant breeding to optimize plant productivity. The ecological approach that plants themselves have used to overcome environmental challenges has been almost completely ignored.

Putting Microbes to Work

Theoretically, plant–microbe partnerships offer nearly limitless opportunities to improve agricultural productivity in an environmentally and economically sustainable way. Practically, though, progress will require continued investment in basic discovery because only a tiny fraction of microbial diversity has been identified and mechanistic understanding of plant–microbe interactions is in its infancy. Advances in basic knowledge must be coupled with practical attention to the process of moving discoveries from the lab to the field and addressing the many technical, regulatory, marketing and end-user education issues that will play a major role in the success of microbial interventions.

The scientific challenges facing this field require a new layer to traditional approaches that focus on one plant–microbe partnership at a time. In addition to continued efforts to determine the mechanisms of interactions between particular plants and individual microbes, progress will require getting into the mindset of understanding every organism as a member of a series of interacting ecosystems.

Continued effort will need to be invested simply in identifying “who is there”. The microbial world is so vast and diverse that characterizing it completely may be impossible. However, even the development of a comprehensive catalogue of the microbial community associated with one plant species, in one environment, has never been done. A certain amount of census-taking is currently warranted to establish broad patterns.

Technical advances are making it easier to take a census of the microbial community associated with any given plant. However, efforts to know “who is there” must be accompanied by an effort to understand what fraction of that diversity is truly required for optimal plant health in any given environment. The vast diversity of microbes in the soil may represent a genetic reservoir of which only a fraction is drawn on by the plant under any particular circumstances.

There is undoubtedly a great deal of functional redundancy among different soil microbes, making the quest to identify key drivers daunting. High throughput techniques to identify the entire genetic repertoire of a microbial community do not necessarily provide any information about what each of the genes does and when they do it.

Finally, if the ultimate goal is the development of interventions that improve plant productivity and resistance to disease and pests, it will be necessary to determine at which points these complex systems are susceptible to manipulation. Treatments that work in the simplified conditions of the laboratory frequently fail when they are tested in the more complex conditions of the field. Developing an understanding of how new microbes can be introduced into existing communities, or encouraging the growth of certain community members over others, will require greater understanding of the resilience and population dynamics of microbial communities.

Understanding resilience and stability will also be critical to assessing the risks and benefits of introducing novel microbes into agricultural settings. Public acceptance of microbial supplements will require a thorough evaluation of the environmental impact of adding microbes.

Technological advances have been critical to the genesis of this new field of inquiry, but more, faster and cheaper approaches to characterizing complex microbial communities are still needed. In particular, techniques that go beyond sequencing nucleic acids – such as techniques to survey proteins and metabolites – may be a much more direct way to evaluate plant–microbe interactions than knowing which genes are present.

Much of the interaction between and among plants and microbes takes the form of chemical signaling. The ability to listen in on these conversations would be transformative.

Getting Discoveries to Farmers

Several decades ago, a burst of interest and research in the use of microbes to protect plants from disease led to the development of several successful products. But many microbe-based treatments that looked promising in the laboratory failed to produce satisfying results in the field, and enthusiasm for the approach waned.

It seems likely that earlier failures resulted from poor understanding of the conditions that would allow an introduced microbe to become established and provide the desired service. While that complexity is now better understood, it is still not possible to predict the conditions that guarantee successful intervention.

As this extremely promising field of science develops, an integrated approach that ties basic discovery to eventual practical application will maximize the value of basic research and lessen the risk of overselling the science. Participants in the colloquium suggested that support of research in this area adopt a three-pronged approach.

First, continued investment in basic, investigator-originated, peer-reviewed research is critical. The sheer volume of unexplored territory in the field of plant–microbe interactions is so vast that supporting the researchers who ask the best questions is the simplest and most effective path to dramatic and unexpected discoveries.

Second, the participants advocated the adoption of one or more grand challenges. Setting a major challenge toward which individual projects could aim can be inspiring, both for scientists and the general public, and can be structured to include investment in infrastructural and technological needs that benefit the wider scientific community. Possible challenges suggested by the group included:

- 20:20 in 20 – increase yields by 20% while reducing fertilizer and pesticide use by 20% in 20 years
- fully characterize the microbiome of a single important crop plant
- characterize the response of a variety of plant–microbe communities to a particular stress.

The participants recommended that funding agencies establish a process for moving discoveries from the lab to the field, including encouraging researchers to identify potential applications of basic discoveries, supporting a large number of pilot projects aimed at evaluating treatments based on basic discoveries, and supporting comprehensive field trials of the most successful pilot projects.

Finally, involving a broad base of stakeholders, including farmers, extension agents, regulatory agencies, consumer groups and others as early as possible, preferably at the pilot stage, will provide opportunities for these groups to learn from each other and contribute to successful adoption of new treatments.

Enlisting Trillions of Tiny Partners to Solve a Big Problem

Achieving food security for a still-expanding global population is an enormous challenge. Increasing agricultural productivity without encroaching on natural environments or consuming more fossil fuels and chemical fertilizers will require more than simply understanding and exploiting plant–microbe interactions.

However, potentially all crops, no matter where they are grown, could benefit from optimization of their microbial partners. The time is right to enlist the capabilities of the microbial world to help solve this pressing human problem.