Here’s how we can genetically modify soil microbiomes to reduce use of synthetic fertilizers and improve yields

There has been a great deal of buzz in recent years about the importance of the human microbiome; much of it focused on the gut microbiome and the importance of these microbial inhabitants to our health. From deciphering more information about probiotics in our food products to routinely performing previously unimaginable procedures like fecal transplants, the possibilities of marshaling the mysteries of the microbiome seem endless.

An intricate relationship like that between humans and microorganisms also exists between microorganisms and our soil. Mimicking the impact of deciphering the microbiome on human health, could an improved comprehension of the soil microbiome lead to a better understanding of complex environmental problems and perhaps offer new solutions? Might knowing more about the soil microbiome even provide us with new approaches to the formidable problem of climate change? Could this research lead to a sharp reduction in the use of polluting synthetic fertilizers?

The use of fertilizer has long been recognized as essential but problematic. Without macro and micro fertilizers, nature struggles to replenish nutrients in the soil. Crops can grow without them but may be feeble. Over time, the nutrients in the soil decrease because when crops are harvested, essential nutrients are carried along and end up at the dinner table. If the soil is not replenished with nutrients through fertilization, crop yields will diminish.

As always in agriculture, there are tradeoffs. Too much fertilizer can be harmful to the environment. Naturally occurring microorganisms in soil can be harmed by the chemicals in the fertilizers. They can destroy an area’s soil fertility and reduce the soil’s organic matter and humus content. And they can also lead to the release of greenhouse gases.

Scientists have spent years studying the intricacies of how nutrient cycling mechanisms of the soil microbiome affect our food crops and environment. An example is the nutrient nitrogen, an essential building block of all organisms. It is abundant in the air, but unfortunately, in a form unusable by most plants. In the soil, nitrogen can be scarce, but certain plants, such as legumes, harbor on their roots a type of bacteria known as rhizobia, which form nodules to fix atmospheric nitrogen into readily accessible ammonia.

This relationship is highly specific and only exists between certain plants and soil microorganisms. For this reason, the farming of staple crops such as cereals requires the application of fertilizers. Artificial fertilizers have been a godsend for preventing widespread starvation, but because many of them are produced from petroleum products and various other reasons, it is ultimately not an environmentally friendly solution.

Synthetic ammonia production (e.g., the Haber-Bosch process for N-fixation) and its application accounts for around 5 percent of global greenhouse gas emissions. If no such process had been invented, the number of people the planet could feed adequately would have reached its ultimate capacity many years ago. As we rapidly move toward a global population of 10 billion, we need to double our agricultural productivity.

Doing so is far from straightforward, however. The overuse of fertilizer results in excess fertilizer runoff into waterways, creating anoxic dead zones and releasing N_2O, a greenhouse gas 300 times more potent for global warming than CO_2. Thus, understanding the relationship between crops and the soil microbiome will be vital to our food security and the reduction of agricultural greenhouse gas emissions. One way to do that is to get microorganisms to fix more nitrogen for crops to use.

Genetically engineering bacteria

Using the same tools driving breakthroughs in research on the human microbiome, we can now exploit the soil microbiome to solve some of the connected problems of food security and environmental sustainability. A "pivotal" moment arrived a couple of years ago when scientists demonstrated that bacteria could be genetically engineered to perform nitrogen fixation within the roots of non-legume crops, such as corn, in a way that drastically reduces the use of fertilizers. Partial replacement of fertilizers with gene-edited bacteria would also reduce nitrogen runoff and N_2O emissions.

The multi-year, multi-site study throughout the corn belt provided a pathway for agricultural startup company Pivot Bio to commercialize and make widely available this exciting technology in the form of a liquid applied to soil or as a powder coating seeds. Recently, the company showed that its products could replace a quarter of synthetic nitrogen without reducing crop yield.

That discovery could be momentous. Pivot Bio's products are already used on over three million acres of U.S. farmland, on a variety of crops such as corn, wheat, and sunflower. That has already reduced the amount of synthetic fertilizer applied to U.S. farms in 2022 by 32,000 tons, resulting in an estimated reduction of 220,000 tons of CO_2 released, or the equivalent of burning 1,200 rail cars of coal. These savings come from the estimated reduction of emissions needed to produce synthetic fertilizer, combined with the prevented release of NO_2 from the soil.

Others have been working on cereal plants that create their own fertilizer. At the Whitehead Institute at MIT, Jing-Ke Weng's research group has been studying how plants and microorganisms signal to each other to initiate the nitrogen fixation process in legumes as a prelude to introducing an analogous signaling pathway into cereal crops.

Similarly, Eduardo Blumwald's research team at the University of California, Davis, has used gene editing to modify rice to increase the production of chemical compounds, boosting the activity of nitrogen-fixing bacteria at the plant roots.

Professor Lisa Stein, a microbiologist at the University of Alberta, is exploring another aspect of the problem by creating nitrification inhibitors — chemical compounds that reduce nitrous oxide emissions by suppressing soil microorganisms' conversion of nitrogen into nitrate. Combined with fertilizers, they prevent the production of N_2O and its pollution of waterways.

Blue algae?

Cyanobacteria, sometimes called blue-green algae, can spread across fresh-water lakes and ponds, hijacking the oxygen and nutrients. They can form biofilms on water or land and cause illness.

image

Image not found or type unknown

Biofilms on water. Courtesy: Genetic Literacy Project

Among the oldest organisms on earth, they are ubiquitous, can be used as a food source, and are also suitable as a source of natural dyes and alternative fuels. They produce a wide range of antimicrobial metabolites. Cyanobacteria are also a promising alternative to artificial fertilizers, as they, too, can fix nitrogen from the air and make it available to plants.

Not all cyanobacteria species can form the necessary strong symbiosis with every crop type, but when it does form, the cyanobacteria can attach and even penetrate the plants' intercellular spaces so that both bacteria and host can benefit from nutrient exchange. Cyanobacteria that are applied to the soil surrounding crop plants in the form of biofilms, which exist as surface-attached communities or suspended aggregates, can offer other advantages. They can provide beneficial secondary metabolites to plants and increase the soil's water retention.

Cyanobacteria do not need to be grown on arable land, and their cultivation is carbon-negative, meaning that more carbon is captured via photosynthesis than is released into the environment. Thus, cyanobacteria can create fertilizer at a fraction of the cost and without using fossil fuels.

Together, all of these products could revolutionize sustainable food production by reducing the need for today's vast application of synthetic fertilizers. This could address complex environmental problems like nitrogen runoff and nitrous oxide emissions.

Analogous to our rapidly improving knowledge of the human microbiome, advances in understanding the soil microbiome will significantly change our agricultural practices, improving crop yields while reducing dependency on synthetic nitrogen and the damage it causes to our environment. Just as our growing comprehension of the human microbiome is revolutionizing medicine, our increasing familiarity with the soil microbiome will transform agriculture.

Kathleen L. Hefferon is an instructor in microbiology at Cornell University. Find Kathleen on X @KHefferon

Henry I. Miller, a physician and molecular biologist, is the Glenn Swogger Distinguished Fellow at the American Council on Science and Health. He was the founding director of the FDA's Office of Biotechnology. Find Henry on X @henryimiller

A version of this article was originally posted at the American Council on Science and Health and is reposted here with permission. Any reposting should credit both the GLP and original article. The ACSH can be found on X @ACSHorg