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Photos by Chris Maggio

The Corn That Grows Itself

How microbes could upend America's toxic dependence on nitrogen fertilizer

Andrew Zaleski, Jun 13, 2019

Crabs, clams, and worms die almost immediately. Fish, shrimp, and any animal that can swim quickly enough make valiant, though often doomed, efforts to flee. There are few places to go in a dead zone that can reach the size of New Jersey.

The Gulf of Mexico hypoxic zone—or "dead zone," as it's more commonly known—is a stretch of seawater where vast swaths of slimy algae bloom annually. When the algae eventually die, they decompose, sucking up so much of the water's oxygen that all nearby aquatic life suffocates. In 2017, this dead zone measured 8,776 square miles, the largest since scientists at the National Oceanic and Atmospheric Administration began recording it in 1985. This summer's dead zone is expected to be the second-largest on record at 8,717 square miles, according to scientists at Louisiana State University.

You can find the source of the dead zone by traveling north out of the Gulf, up the Mississippi River, and through its tributaries as they branch

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out into the agricultural nervous system of the U.S. In the rich, black soil of the Midwest, you'll find the culprit: nitrogen fertilizer, the backbone of modern industrial farming.

Farmers around the world use 120 million tons of nitrogen fertilizer each year. (Another 54 million tons is added in the form of things like manure and atmospheric deposition.) In the U.S., much of the fertilizer goes into the Corn Belt—an area stretching from Nebraska to Ohio, Minnesota to Missouri. There, 6 million tons of nitrogen fertilizer are spread across farmland every year.

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While nitrogen fertilizer deserves considerable credit for driving a century-long global increase in crop yields, it's also nasty stuff. The chemical factories that produce the material expel as much greenhouse gas into the atmosphere as all of the houses in America combined. Fertilizer is finicky and its application is often wasteful. Because it's easily washed away by rain, farmers are often forced to spend more time and money applying more fertilizer.

And, as the hypoxic zone indicates, nitrogen fertilizer is a huge environmental hazard: Close to 100 million tons of nitrogen added to the world's crop fields are lost to the environment every year, either as gas emissions or as runoff. Nitrogen feeds the algae that blooms in the Gulf: more runoff equals more algae, which equals a bigger dead zone. According to the International Nitrogen Management System, a project led by UN Environment, the world must halve its usage of the agricultural chemical by 2050, or else prepare for poisoned water that creates more dead zones across the world's oceans.

But what if farmers didn't need nitrogen fertilizer? What if they could fertilize their crops, increase their yields, continue to feed a growing population—and do it all without putting a single atom of nitrogen in the soil?

More than 100 years after the last breakthrough in nitrogen technology, we're on the precipice of finding out. Pivot Bio, a Silicon Valley startup, believes it can convince farmers to swap out nitrogen fertilizer in favor of specially-fermented soil bacteria that can fuel crop growth organically, without the waste and ecological hazard of traditional methods. The eight-year-old company is armed with more than $86 million in financing from the likes of the Gates Foundation, DARPA, and Breakthrough Energy Ventures, an investment fund that includes bigwig billionaires like Jeff Bezos and Richard Branson.

There's one obstacle, though. Creating a next-gen fertilizer, says Pivot Bio CEO Karsten Temme, "is the hardest problem in agriculture."

Trials show that the startup's nitrogen-producing bacteria is tenacious, and can deliver a steady stream of nutrients across an entire growing season. When mixed in with traditional fertilizer, Pivot Bio's microbes can increase production by nearly eight bushels per acre. For someone like Indiana farmer Jake Misch, who tries squeezing at least 170 bushels of corn out of every acre, that's 448 more pounds of crop he can turn into cash. Misch is Pivot Bio's first customer.

After a year of beta tests and five years of field trials, the startup is selling its product on the open market, just another step toward its ultimate goal: completely replacing chemical nitrogen fertilizer. Misch says that for about $100 apiece, he purchased 16 boxes of microbes, enough for 80 acres.

"I hope it works," says Misch. "I hope we see good results. I think we will. But time will tell."

Long before the invention of synthetic fertilizer, many types of soil bacteria evolved over millions of years to naturally fertilize plants by "fixing" nitrogen: sucking in nitrogen gas from the atmosphere, where plants can't use it, and converting it into a nutrient form that plants could take up through their roots. Some are "free-living" bacteria, just hanging out in the dirt. Other bacteria form a symbiotic relationship with certain crops: Root nodules on legumes like peas and beans provide homes for rhizobia bacteria, which fixes nitrogen naturally. Soybeans, the second-biggest crop in the U.S. after "king corn," are able to self-fertilize because of rhizobia.

As the world's population exploded at the turn of the 20th century, the world needed more nitrogen, and fast. A global hunt for nitrogen ensued. Several countries even fought in the 1800s over precious, nitrogen-packed deposits of bird poop covering islands off the Peruvian coast.

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Then, in the early 1900s, chemists Fritz Haber and Carl Bosch flipped the script. They devised a method to import atmospheric nitrogen gas and make it biologically available. The Haber-Bosch process, as it became known, invented the modern chemical fertilizer—and, in turn, hoisted a righteous middle finger to contemporary scaremongers who foretold of worldwide famines.

Yet the invention and proliferation of man-made fertilizer over the last century broke the link between microbes and farming. Once farmers realized that nitrogen could magically boost yields, they spread chemical fertilizer generously. Cereal crops became dependent on synthetic fertilizers; half the fertilizer used worldwide goes to the growth of wheat, rice, and corn. Meanwhile, as free-living bacteria grew accustomed to nitrogen-rich soil, they stopped fixing nitrogen. "The ones that were free-living nitrogen-fixers were just outcompeted by synthetic fertilizer," says Caitlin Hodges, a doctoral candidate in soil science and biogeochemistry at Penn State University.

Because fixing nitrogen requires an intense amount of energy, microbes shuffling about in soil soaked with chemical fertilizer stopped expending the energy to carry out the process. Those microbes, in a sense, turned off.

In 2011, Karsten Temme and Alvin Tamsir founded Pivot Bio in order to find an environmentally sustainable way to create nitrogen production. Based in Berkeley, California, the startup now employs 90 people, with two-thirds involved in microbe research and development.

At first, the two co-founders wanted to create a genetically modified plant that could play the part of both crop and microbe. As a doctoral candidate in bioengineering at the University of California, Berkeley, Temme had studied synthetic biology: the analysis, reconfiguration, and tweaking of an organism's genome to get it to do something brand-new. If he could decode how some microbes created usable nitrogen for fertilization, he could effectively upload those instructions into corn and other crops. "Then we could potentially make a self-fertilizing plant by taking the whole DNA program and putting it into a plant," says Temme.

Corn kernels in Misch's field

Doing so would upend the entire nitrogen fertilizer industry. Synthetic nitrogen fertilizer dominates the market, and for good reason: It is remarkably efficient. "Put simply," writes Thomas Hager, author of *The Alchemy of Air*, the invention of industrial nitrogen production "is keeping alive nearly half the people on earth."

Over the last one hundred years, nitrogen fertilizer proliferated across farmland to the detriment of our planet. During a meeting in New York City at the beginning of 2018, nitrogen experts who met as part of the International Nitrogen Management System concluded that the amount of synthetic nitrogen in the environment has outstripped the Earth's capacity to process it naturally. Around the world there are now hundreds of dead zones of varying size just like the one in the Gulf of Mexico. According to researchers at Lund University, one dead zone in the Baltic Sea reaches 20,000 square miles.

To fix the fallout of Haber and Bosch's miracle chemistry, the world's farms need to double the efficiency of their nitrogen use. Do that by 2050, and the planet has a reasonable shot at halving the amount of nitrogen that's dumped into the environment, ensuring our rivers and oceans don't turn into toxic, barren cesspools incapable of fostering aquatic life.

But developing genetically modified, self-fertilizing corn crops proved too difficult for Temme and Tamsir. It didn't help that genetically modified plants have high hurdles to clear when it comes to federal regulation and public acceptance. The company dropped the GMO effort and Pivot Bio, well, pivoted.

"There's only two ways in nature that nitrogen fixation occurs," says Sarah Bloch, the startup's associate director of research strategy and employee number five. "One is a lightning strike that fixes some of the nitrogen in the atmosphere. The other is by the bacteria that have evolved the set of genes to carry out the process."

Pivot Bio set out to find microbes that might work for corn, tweak the dormant parts of their genome to make them fix nitrogen once again, and distribute them to farms.

With Bloch leading the charge, Pivot Bio's researchers scoured the soils of the Corn Belt for several years, collecting samples. Using tools crucial to synthetic biology—like quick, accurate genome sequencing—Pivot Bio found the microbe it needed. It was hiding in the soil of Bloch's childhood home in Missouri.

"The soil sample that actually contained the microbe that became our first product came from lands that my dad owns for his business," she says. "It's not a farm, but it is in the Mississippi River basin, surrounded on three sides by a farm."

These are the microbes Pivot Bio packages and sells to farmers today. While synthetic biology is used in their production, the bacteria themselves are not genetically engineered—not as we generally know it. The GM crops grown in most industrial American farms are transgenic, which means that genes from another species with a valuable trait are transferred into the plant. So, for instance, a gene from an insect-resistant bacteria is introduced into corn, which then safeguards the crop against bugs.

“This is the first version of the iPhone. It does something that never was possible before.”

Instead, what Bloch and her fellow researchers are doing is gene editing, working with only the genetic material already inside soil bacteria. By removing a signal in the microbe’s DNA that otherwise prevents it from producing nitrogen when living in fertilized soils, Pivot Bio’s bacterium is able to fertilize a cereal crop like corn. The research team likens it to remodeling a room by rearranging furniture. Temme describes it as breaking a negative feedback loop in the genome.

“When that happens, the microbes can produce nitrogen again, even though you might have heavy fertilizer use in a field,” he says. “This is the first version of the iPhone. It does something that never was possible before.”

It’s the last day of April, and Jake Misch would much rather be up in the cab of his John Deere tractor, hitched to a planter almost as wide as the length of a semi-trailer. He needs to till the fields, drop seeds, and dispense fertilizer, all in preparation for the first week of June, when his corn crops enter a period of rapid growth.

Jake Misch

But the rain outside keeps Misch stuck inside his cavernous barn, watched over by a poster of a St. Pauli girl plastered high on the wall. He’s a 36-year-old, fourth-generation farmer who looks every bit the part: boots, jeans, a checked button-up shirt, and a trucker hat hiding a crew cut. As Misch will tell you, farming is a tough life.

His day usually begins at 6:30 in the morning, and sometimes doesn’t end until 8 or 9 at night. The economics aren’t tilted in farmers’ favor. Misch’s father likes to say that farming is the only business where the owners buy at retail and sell at wholesale. And soybean crops, which Misch also grows, are currently hurting as a result of President Donald Trump’s tariffs.

The trade restrictions have virtually stopped Chinese imports of American soybeans—a flow of goods that brings about $14 billion to American farmers every year. Trade disputes, combined with dropping prices, led Republican Sen. Jerry Moran of Kansas to recently write to the Department of Agriculture that many farmers in the Plains states "are on the verge of financial collapse." Last month, the White House announced it would pay out $14.5 billion to farmers hit hardest by the tariffs.

When it comes to corn, a good annual yield for the Misch family farm in northwest Indiana is anywhere between 170 and 240 bushels per acre. With a single bushel of corn worth just $4.25—a price that fluctuates throughout the year—and a planting cost of roughly $600 an acre, Misch needs to make at least $750 per acre to keep operating in the black.

"There really are no regulations on how to use synthetic fertilizers. Most farmers are trying to be good managers of it. It's just that Mother Nature doesn't always cooperate."

Nitrogen fertilizer is key to meeting that number. Farmers usually "side-dress" their corn crops, applying a bit of fertilizer about a foot away on either side of their rows of growing plants. Over time, a corn's roots intersect with nitrogen-rich soil, taking up fertilizer to the stalk as a result. Misch typically uses 200 pounds of nitrogen per acre of corn across a farm with 1,300 acres dedicated to the crop. At today's market prices, that works out to a cost of almost $90,000 per year on fertilizer alone. That's still not taking into account excessively rainy days, like this one in April, that can wash nitrogen from the field. The only way to mitigate that runoff is dumping more fertilizer, to the detriment of both the farmer's checkbook and the environment downstream.

"There really are no regulations today on how to use synthetic fertilizers," says Misch, referring to his home state. "Most farmers are trying their level best to be good managers of it. It's just that Mother Nature doesn't always cooperate."

That's why Misch is changing things up this year. Back in the barn, near a pile of corn seed, are white boxes, each about the size of a large binder. Over a small corner of his farm—just 80 acres—he's replacing some of the synthetic fertilizer used in each acre with what's in the boxes: microbes from Pivot Bio. This spring, he spritzed a mixture of microbes-in-water directly onto his corn seeds. The mixture costs Misch twice as much as standard fertilizer, but he justifies the expense as "risk management": From day one, the microbes will produce little bits of nitrogen that the corn roots absorb directly, which means it won't leach into the soil and potentially run off later.

A major reason he considered Pivot Bio's product to begin with was due to the example of a friend. Kyle Morrow used to be the production agronomist at Moon Island Farms, about 20 minutes away from Misch's property. Last year, 30-year-old Morrow oversaw one of Pivot Bio's more than 11,000 beta tests. He applied the startup's microbes to six acres of corn crop at Moon Island Farms. When he harvested the corn from those six acres, he counted an increase of seven bushels over a typical yield per acre. Misch stopped by just before harvest, and what he saw impressed him.

"The plants were mature, but what I could see was bigger stalk diameters, a little more ear-fill on the tips, and some deeper kernels," he says. "Those things all add up to yield."

Of the more than 13 million tons of agricultural nitrogen used in the U.S., about 30% ends up in the environment. For now, management efforts are focused on containing dead zones like the one in the Gulf of Mexico. Across the Corn Belt, a 12-state task force is currently trying to reduce nitrogen runoff in each state by 45% compared to 1980s levels. States report mixed success: Illinois, for instance, has shown a reduction in nitrogen loss, while Iowa is still trying to do so.

"Our goal is to replace as much synthetic nitrogen as we can."

"The idea is to bring those levels down to values where scientists can predict how big that dead zone is going to be," says Reid Christianson, a researcher at the University of Illinois' Department of Crop Sciences. "I'm hoping, at some point, there's going to be a huge breakthrough on this front that's going to solve these challenges associated with agricultural nutrient loss."

Other research indicates at least a 59% reduction in nitrogen runoff is needed to shrink the Gulf dead zone to the federal target of 1,950 square miles—smaller than the size of Delaware. Meanwhile, a true breakthrough is what Pivot Bio is working toward.

"Our goal," Bloch says, "is to replace as much synthetic nitrogen as we can."

It's a goal that's of increasing interest to both tech companies and traditional agricultural giants. In 2017, for instance, Bayer formed a $100 million partnership with the Boston-based synthetic biology company Ginkgo Bioworks to form Joyn Bio, one of a chorus of new enterprises also attempting to use microbes for fertilizing cereal crops such as corn, wheat, and rice.

"The concerns have grown about the environmental impact of synthetic fertilizers, particularly in the last five years," says Mike Miille, CEO of Joyn Bio, which aims to engineer a microbe that can reduce traditional chemical nitrogen fertilizer needs by up to 50%. "People are more desperate than ever to understand what, if any, alternatives there are."

Temme says that changing how American farmers fertilize their corn crops is only the beginning.

"We're entirely motivated to help farmers keep their family businesses alive and improve their economics, especially in places that are still developing around the world," he says. "So we've got microbes in the pipeline for more crops, and microbes in the pipeline that do even better at supplying more nitrogen to corn."

But whether introducing nitrogen-fixing bacteria into soil leads to other unintended consequences is worth consideration, says Susan Fisk, director of science communications at the Crop Science Society of America.

"Hopefully adding microbes to the soil that weren't there previously won't have harmful side effects," she says. "Putting the microbes in the soil also doesn't assure that they will work cooperatively with the plants, or that the form of nitrogen is 'digestible,' if you will, by the plant."

Still, given the energy-intensive process of making nitrogen fertilizer in chemical factories, Fisk says the potential is exciting—even if Pivot Bio and other startups can't fully eliminate the need for synthetic nitrogen fertilizer. "That's okay," she says. "Every step helps."

Right now, Pivot Bio's microbe is only meant as a supplement to other nitrogen fertilizer, and not as a full replacement. Although the company, like others in the field, aims to eventually replace artificial fertilizers altogether. But it's not only about making the science work. No amount of microbial technology will matter if it doesn't work for farmers. Globally, the market for synthetic fertilizer is worth $155 billion, and disrupting it is a tall order.

"A synthetic nitrogen fertilizer, you put it in and it works every time," says Misch. "It's a very repeatable thing." Misch says he needs to see an increase in yield across the 80 acres where he's using microbes in order to warrant further investment.

During a break in the rain, Misch brings his planter rumbling to life and steers it onto his fields. As the machine plods across the landscape, black, loamy topsoil gives way to a layer of yellowish sand underneath. This type of soil presents a challenge for reducing nitrogen runoff: The sand means any nitrogen not taken up by cornstalks just seeps into the water table below. Eventually it runs off into the nearby Kankakee River, which becomes the Illinois River, which snakes its way to the Mississippi, which ultimately empties into the Gulf.

Misch in his tractor

It's an even more acute problem for corn growers this year, as heavy rains, the "wettest on record," according to the *Washington Post*, drenched their fields. Waterlogged fields can lead to more nitrogen runoff. Fortunately for Misch, the rain let up just long enough for him to get his corn seed in the ground, including those 80 acres where Pivot Bio's microbes, he hopes, are working—for reasons related to both economics and the environment.

"I'm the fourth generation, and I hope the fifth and sixth can farm in this land," Misch says. In this, the fortunes of Midwestern farms and a Bay Area startup are bound together. Cornstalks on Misch's farm poked out about three inches above the ground in May, readying themselves for their June growth spurt. How his corn climbs from there will reveal part of the future of farming—and whether fertilizer remains the stuff of chemical synthesis. Pivot Bio is optimistic. But, like farmers always have, all Misch can do is watch, and wait for the harvest.