# DISCOVERY REPORT

An ACS member exclusive

ACS Chemistry for Life®

# Feeding the world

**Climate change is coming for crops. Can chemists help agriculture adapt?**

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# How we'll feed the world

Few positive things can be said about the effects of climate change. One, however, is that it exposes shortcomings in how society is structured so that people can find solutions. Nowhere is this more evident than in the food system.

Climate change and agriculture are inextricably linked. Modern agriculture makes it possible to produce food for the world's 7.8 billion people. At the same time, it clears forests, destroying a sink for the greenhouse gas carbon dioxide. It requires nitrogen fertilizer, which is produced by an energy-intensive chemical reaction that emits more $CO_2$ globally than any other industrial process that makes a chemical. As Earth warms, changes in temperature and rainfall patterns make harvests less productive. Extreme weather events disrupt food supply chains, leading to spoilage and food waste. Farmers find themselves increasing their use of synthetic herbicides and pesticides to compensate.

It's a vicious cycle. Chemists understand that the time has come to break it. Inside this Discovery Report, you'll learn about start-ups producing cocktails of beneficial microbes to help crops tolerate dry, nutrient-deficient soils. You'll read about meat substitutes that require less land and water than livestock, pheromone-based pest control, and more.

Contributing editor Carmen Drahl, who has covered organic chemistry and green chemistry for C&EN, edited this report. It includes a reading list of papers and patents curated by our sources, as well as by information scientists at the CAS division of the American Chemical Society.

As an ACS member, you get exclusive access to the Discovery Report, a quarterly publication bringing you cutting-edge research defining the chemical sciences and our industry. Look for the next one in the first quarter of 2021.

Amanda Yarnell

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# INSIDE




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c&en

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CHEAT SHEET

# 5 questions and answers about climate-proofing the food supply

## Q. How does climate change impact agriculture?

» **Some plants grow more quickly** with modest increases in temperature and carbon dioxide levels in the atmosphere. On balance, however, climate change is likely to make it difficult for farms to continue business as usual.

» **Lower concentrations of protein and minerals** in staple crops like wheat and rice are associated with rising atmospheric $CO_2$.

» **Extreme weather events like droughts and floods** damage crops, so farms can't produce as much. Even slight shifts in rainfall patterns can prevent planting and harvesting at optimal times.

» **Weeds, fungi, and insects** like warmer, wetter environments. Farmers may encounter new pests.

## Q. What are the limitations of today's approaches to farming?

» **Cultivating single crops and frequent plowing** strip soil of organic matter—which provides food for microbes and nutrients for plants—and beneficial root ecosystems. The soil absorbs less water, thus intensifying the effects of drought, and is more susceptible to erosion, which exacerbates flooding.

» **Production of ammonia fertilizer** is energy intensive, consuming up to 2% of the world's energy supply and emitting 1% of its $CO_2$.

» **Indiscriminate use of synthetic fertilizers, pesticides, and herbicides** contributes to pollution from runoff and breeds resistant insects, weeds, and fungi.

## Q. What sorts of innovations could make crops more resilient?

» **Genetic modifications** can make plants grow with less land, less irrigation, and less fertilizer. They can also make plants shorter in order to better withstand wind and rain.

» **Innovative formulations of plant extracts** can boost plants' survival in the face of stresses from the environment or pests.

» **Cocktails of beneficial microbes** could improve the health of crops and help them thrive in nutrient-deficient soils, dry conditions, or high temperatures.

## Q. What solutions may address crops' surroundings?

» **Encapsulation strategies, precision-spraying drones,** and other approaches could help farmers reduce pesticide and herbicide doses.

» **New classes of targeted insecticides** are designed to leave beneficial bugs unharmed. Insect control strategies involving pheromones stymie reproduction without killing pests, which may delay resistance.

» **Reducing the carbon footprint and energy input** of fertilizer production would help slow global warming.

## Q. What challenges loom for the food supply?

» **With more people emerging from poverty, demand for meat** has risen dramatically—along with the corresponding need for livestock and their feed. This greater consumption, combined with projected population growth, will require the agriculture industry to increase production 56% by 2050, according to one estimate.

» **Public perspective remains divided about genetic modification.** When US adults were asked whether genetically modified foods are worse for human health than foods with no genetically modified ingredients, roughly half said yes, according to a 2018 survey.

» **The root of the climate change problem**—emission of heat-trapping gases into the atmosphere—must still be addressed.

# 8 experts identify the biggest hurdles to feeding a warming world

## Sophie Attwood

**» Senior behavioral scientist, Better Buying Lab, World Resources Institute**

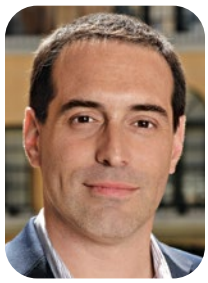
Growing livestock for meat is resource-intensive, and consequently "the growth of beef and lamb is a big obstacle to feeding a growing world population in the face of climate change," Sophie Attwood says. Current consumption patterns aren't sustainable; by 2050, they would require farmers to produce 56% more crop calories than were produced in 2010, according to an estimate by the World Resources Institute. Meanwhile, cattle, sheep, and goats contribute half of agriculture's production-related greenhouse gas emissions. The solution, Attwood says, is to shift to more-plant-rich diets, which will require some behavioral engineering.

Attwood and her colleagues launched the Better Buying Lab when they realized that the foods people should be eating don't receive the kind of marketing and advertising that meat does. Her background in behavioral science helped her develop a playbook of strategies that food companies and restaurants can use to nudge diners toward more sustainable choices. The strategies include offering more plant-based menu choices, using evocative language on menus, and making plant-rich dishes tastier and more visually appealing.

The Better Buying Lab's commercial partners are enthusiastic about marketing vegetarian items because they want to do something for the climate, and their young urban customer base is demanding plant-based foods. "It's kind of incredible that just by changing the words on a menu you can change behavior," Attwood says.

> **"Wasted food contributes over 4 gigatons of carbon dioxide to the atmosphere every year."**

## Jamie Bacher



**» Cofounder and CEO, Boost Biomes**

"Wasted food contributes over 4 gigatons of carbon dioxide to the atmosphere every year," Jamie Bacher says. Reducing that waste will help farmers grow food in a changing climate while simultaneously cutting greenhouse gas emissions, he believes.

Some of the waste comes about when pathogenic fungi spoil fruits and vegetables. Bacher is using his background in molecular biology and ecology to help farmers by finding guilds of microbes that work well together to slay fungi.

"Groups of microbes are superior to single microbes because a group uses multiple modes of action to kill fungi," Bacher says. Multiple modes of action increase killing efficiency, and the risk that a fungus will develop resistance to two different microbial weapons is quite low. Bacher's start-up is the first to develop technology that builds fungus-killing microbial ecosystems from the bottom up. The team collects soil samples containing billions of microbes, cultures them, and maps how the microbes interact with one another and the targeted fungal pest. Using bioinformatics, the scientists sift through the interactions to find the best microbial networks.

Boost Biomes' first product is a treatment that contains two different microbes and kills more than six important pathogenic fungi on fruits and vegetables such as grapes and cucumbers. "Our technology can tap into some of the most exciting areas in food and agriculture today by increasing crop yields, food availability, and food safety," Bacher says.

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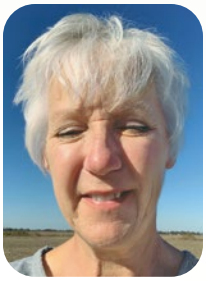


# Betsy Bower

**» Agronomist, Ceres Solutions Cooperative**

"The biggest challenge that farmers face is making sure they have enough water in place when they need it," Betsy Bower says. The US Midwest is already experiencing more heavy rainfalls and extreme heat events, both of which stress crops. But by building soil health, farmers can prepare their land to capture and store water, thereby preventing erosion when it rains and storing water for spells of hot, dry weather, she says.

Bower's farm goods cooperative partners with farmers to enhance the sustainability of their operations and bottom line. Using GPS systems, she helps growers track the links between crop yields and their soil's underlying water, nutrient, and organic matter content.

Farmers who don't overturn soil by tilling leave crop residue on fields, which increases rainwater infiltration and cuts evaporation. After harvest, when farmers plant cover crops such as cereal rye, the vegetation cover reduces water and nutrient runoff and stores water in soil by adding absorbent organic matter and improving soil structure. "Farmers who adopt the conservation practices are the last ones to start irrigating and the first ones to stop," Bower says.

As conservation catches on with Bower's clients, some are signing up with a sustainable agriculture program run by farmer cooperative and dairy company Land O'Lakes. The program provides a digital platform that analyzes growers' data on fertilizer use and soil erosion, providing insights that help Bower work with farmers to improve their operations. "What keeps me going is the new technologies that allow us to make better decisions," she says.

# Helga Dögg Flosadóttir

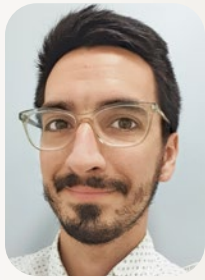
**» Cofounder and chief research officer, Atmonia**

Farmers need fertilizer to maximize crop yields. But today's synthetic nitrogen fertilizer is produced by the Haber-Bosch nitrogen-fixation reaction, which is responsible for 1% of the world's annual $CO_2$ emissions. Helga Dögg Flosadóttir's start-up aims to overhaul the 100-year-old process with an electrochemical catalyst powered by renewables.

Atmonia produces aqueous ammonia, a popular form of nitrogen fertilizer, instead of the anhydrous liquid ammonia the Haber-Bosch process makes. Unlike Haber-Bosch, which sources hydrogen from natural gas, Atmonia's process sources hydrogen from water, Flosadóttir says. And whereas Haber-Bosch applies high temperature and pressure to split the triple bond of gaseous nitrogen, Atmonia reduces $N_2$ at ambient temperature and pressure. This sustainable route for making ammonia came about when cofounder Egill Skúlason used theoretical calculations of electrochemical reactions to design a transition metal nitride catalyst that reduces atmospheric nitrogen to ammonia. "One of the biggest challenges was finding a catalyst selective enough for nitrogen, otherwise the catalyst gets covered with protons," Flosadóttir says. Skúlason's calculations identified five catalysts that sidestep this problem.

Flosadóttir is studying the catalysts in the lab. She has a refrigerator-sized prototype that can be connected to wind or solar power to eventually produce 1 metric ton of ammonia per year. "Unlike the Haber-Bosch process, which must run nonstop to maintain pressure, our electrochemical system can be run when needed and be scaled up or down," she says. The system's manageable size could mean that instead of shipping ammonia, individual farmers in remote areas could easily make their own when they need it.

> **"The biggest challenge that farmers face is making sure they have enough water in place when they need it."**



# Juan Jimenez

**» Director of protein engineering, Protera Biosciences**

"Proteins made from precision fermentation are a great solution to a whole range of food sustainability challenges," Juan Jimenez says. The technology involves inserting genes encoding animal or plant proteins into yeasts or fungi that then produce the protein at scale using fermentation—the process used to make beer or yogurt. Compared with raising livestock, precision fermentation creates animal protein with less water and land use and fewer greenhouse gas emissions.

Alternative proteins aren't just for disrupting the meat industry. They can also fight food waste, a major source of greenhouse gases. For instance, Protera's first product is a protein that prevents mold growth when added to bread. Jimenez and his team developed it with Protera's proprietary software, Madi. Drawing on amino acid sequences of proteins that exist in nature, Madi uses deep learning to predict the structure and function of these proteins. When asked, the Madi algorithm proposes proteins that accomplish a certain function, such as blocking mold growth. The mold-fighting protein, which is manufactured through fermentation, more than doubles the shelf life of bread

compared with conventional preservatives and has potential to prevent spoilage of other food items.

Protera is now completing development of an enzyme that hydrogenates vegetable oil into saturated fat—essential for cookies and pies—without the artery-clogging trans fats that accompany the synthetic hydrogenation process. Jimenez notes that the current replacement for hydrogenated oils is palm oil, the production of which contributes to the destruction of rain forests.

## Fatma Kaplan

**» Cofounder, CEO, and chief scientific officer, Pheronym**

Fatma Kaplan sees climate change intensifying crop loss from pests as plant ranges shift and winters become warmer. Fighting back with conventional pesticides will inevitably lead to resistance as pests evolve to tolerate once-deadly agents. But leveraging the pheromones from insects and their predators could enable farmers to control pests while avoiding resistance and the health concerns of synthetic pesticides, she says.

Kaplan and her team have developed their first product, Nemastim, a pheromone mixture that boosts the activity of tiny nematode worms that naturally seek out and kill harmful, soil-dwelling weevil grubs. Nematodes enter grubs to feast on them from the inside out. The nematodes release symbiotic bacteria from their guts that multiply inside the grub, turning its innards into nutritious soup. After feeding on the host tissue and bacteria, the nematodes reproduce and abandon the grub cadaver to move on to a new victim.

Kaplan wanted to make the nematodes more efficient killers, so she identified a suite of pheromones released by the worms that motivate them to abandon a dead host and find a new one. Testing Nemastim-treated worms in soil against pecan weevil grubs, the worms killed 78% more grubs than untreated worms. The treated worms also traveled further to find grubs, and three times as many treated worms entered grubs. "Nemastim gives farmers a lot more tools to control pests in an unpredictable future climate," Kaplan says.

## Karsten Temme

**» Cofounder and CEO, Pivot Bio**

About half the nitrogen in synthetic fertilizer that farmers apply to fields enters the crop. The rest either volatilizes as nitrous oxide—a potent greenhouse gas—or runs into the sea to create dead zones like those in the Baltic Sea, East China Sea, and Gulf of Mexico. Karsten Temme realized that these problems could be addressed by nitrogen-fixing microbes that occur naturally in soil.

Pivot Bio has developed symbiotic bacteria that adhere to the roots of cereal crops like corn and wheat, dispensing ammonia to the plant with zero waste. These bacteria have lived symbiotically with cereal crops for thousands of years, but their genes that reduce atmospheric nitrogen to ammonia went dormant when farmers started applying excess nitrogen to fields.

Temme and his team combed through the microbiome of cereal crops, isolating bacteria that had potential for fixing nitrogen. The scientists used nontransgenic gene-editing techniques to activate the microbes' natural ability to fix nitrogen, even where nitrogen was readily available. The researchers exposed corn plants to the edited bacteria, measured nitrogen fixation, and repeated the cycle of editing and testing.

The result is Pivot Bio Proven, a microbe solution, launched in 2019. Applied to corn at the time of seeding, the product works alongside synthetic fertilizer, providing 20% of the crop's nitrogen needs. A long-term goal is to provide 100% of those needs. "If we can help scale this product to improve sustainability while maintaining profit for farmers, it will inspire others and push science to new levels," Temme says.

## Stephanie Schollaert Uz

**» Applied sciences manager, NASA Goddard Space Flight Center**

The bird's-eye view provided by NASA's satellite fleet helps farmers feed the world, Stephanie Schollaert Uz says. The satellites generate data for remote regions that lack soil and crop monitoring on the ground, and they can uncover large-scale features that develop over time, such as an impending drought.

NASA's satellite sensors measure global soil moisture and plant health to give governments and farmers early warning of crop failure. The monthly reports in 2018 and 2019 helped governments in southern Africa prepare for food shortages.

Additionally, in western Africa, climate change has altered the ebb and flow of ephemeral water sources, making it more difficult for herders to take their cattle to water. The herders now consult a cell phone app powered by NASA's satellite imagery to find the nearest water.

NASA's newest project maps evapotranspiration, in which water transfers to the atmosphere as soil moisture evaporates and the leaves of plants exhale. Scientists use evapotranspiration as a surrogate for water consumption, both of which are trending upward with climate change. In a pilot program, NASA's data recently helped grape growers in California's wine country ensure that their fields were neither too dry nor too wet, cutting down on irrigation and runoff. The program will launch for 17 western states in 2021 and eventually capture other regions around the globe.

"We're always pushing the boundary of knowledge forward by developing new technology that helps us observe what makes Earth habitable, and how Earth works as a system," Schollaert Uz says. ■

CREDIT: COURTESY OF STEPHANIE SCHOLLAERT UZ (UZ)

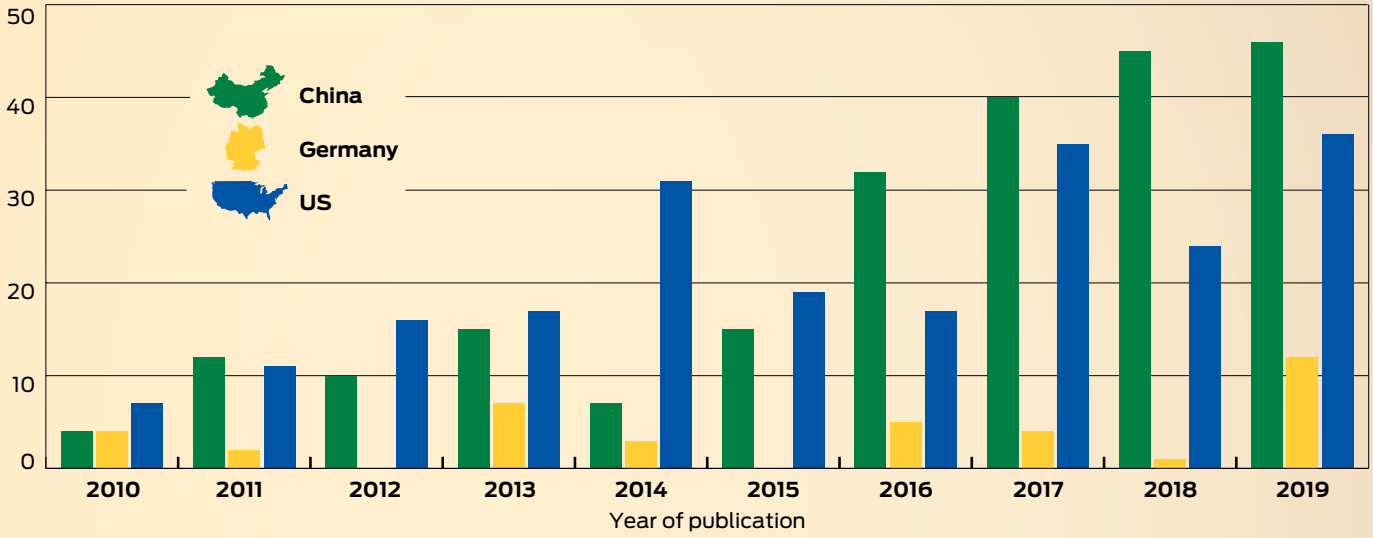
BY THE NUMBERS

# Discover trends in genetically modified crop patents

## Sowing innovation

**From 2010 to 2019, China overtook the US as the top patenter of gene-modified crops, while Germany held steady in third place.**

Patents and applications for gene-modified corn, soybeans, rice, and wheat




## Who's who

**State research organizations dominate the top five gene-modified crop patenters in China, while corporations lead in the US.**

China

| Assignee | Patents and applications, 2010–19 |
|---|---|
| Institute of Crop Sciences, Chinese Academy of Agricultural Sciences | 21 |
| Institute of Genetics and Developmental Biology, Chinese Academy of Sciences | 20 |
| Huazhong Agricultural University | 11 |
| China Agricultural University | 10 |
| Pioneer Overseas Corp. | 10 |

US

| Assignee | Patents and applications, 2010–19 |
|---|---|
| Pioneer Hi-Bred International (now part of Corteva Agriscience) | 39 |
| Dow AgroSciences (now part of Corteva Agriscience) | 35 |
| Monsanto Technology (now part of Bayer) | 30 |
| The Regents of the University of California | 13 |
| US Department of Agriculture | 11 |

## Climate and ag stats

**Stay current with our selection of facts and figures.**

**10.5%**
Estimated share of US greenhouse gas emissions attributed to agriculture in 2018

**19.4 million**
Acres of US cropland left unplanted in 2019, largely due to Midwest flooding

**75%**
Percentage of global deforestation attributable to agriculture

**Sources:** CAS, a division of the American Chemical Society; CGIAR; US Department of Agriculture.
**Notes:** Patents may be registered in certain territories and administrative regions, and such patents are counted separately from those of corresponding governing nations. Figures for Germany include patents published after a long delay that were filed in the former East Germany.

ANALYSIS

Farmers harvest soybeans in the US Midwest.

CREDIT: SHUTTERSTOCK

# Protecting the harvest

**MELODY M. BOMGARDNER,** C&EN STAFF

As spring approaches in the breadbaskets of the world, farmers are getting ready for a busy planting season. In Adams County, Iowa, the plans of corn and soybean grower Ray Gaesser revolve around one critical goal: planting his 2,200 hectares as quickly as possible to beat the rain.

What Gaesser once did in the course of a week, he must now accomplish in 4 days. Planting crops in half the time is a logistical challenge, but necessary. In Iowa and much of the Midwest, changes in weather patterns mean that for stretches of April and May, the soil is much too wet to plant in.

Since 2010, it's not unusual for 15–20 cm of rain to fall in 1 day, sometimes pounding down at rates of 10 cm/h, Gaesser says. His family's years of work building the soil, terracing the fields, and installing waterways are "not anywhere near adequate to protect the soil from those rain events," he says. The dry times are tougher, too: during the growing season, when plants need moisture, the Midwest can experience long stretches of no rain. And at harvest time the rain returns.

Gaesser expects his family won't have it any easier in the future. Climate models agree. In fact, farmers all over the world will face similar challenges and worse. As global temperatures rise, weather extremes will be amplified in the midlatitude regions, home to the world's major breadbaskets: wet weather patterns will get wetter, and dry ones drier.

Meanwhile, a warming climate will cause a parallel decrease in productivity in warmer and drier regions, particularly in developing countries in

Africa and Asia, where most farmers are already hampered by small landholdings, unproductive soil, and lack of access to fertilizers and pesticides. According to the United Nations, more people around the world are going hungry each year, and climate change is partly to blame.

To ensure that the world's growing population will have enough to eat, innovations that help farmers withstand the impacts of climate change need to reach farmers in developed and developing regions alike.

## Help on the horizon

Climate models can forecast the effect of warming temperatures on agriculture, but they cannot model the impacts of extreme weather, and it's difficult to predict how climate change will affect the world's food production capacity. What researchers know is that higher global temperatures intensify weather systems and keep them in place for longer periods of time.

Amid the uncertainty, one trend is clear: new technologies that help food producers combat rising temperatures and alleviate crop stress caused by overwhelming rains, heat, and droughts will be in extremely high demand.

Chemists have long helped farmers preserve yields when weather conditions are not ideal, primarily by developing pesticides and disease treatments. But those tools are not available to every farmer who needs them. What's more, the pace of chemical innovation has slowed considerably, even as older products are being phased out because of concerns about environmental and human health effects and because pests have become resistant to them.

That means the role of chemists and life scientists in support of crop production is changing. They will be called on to help farmers produce more food using less fertilizer and energy and fewer pesticides.

Reflecting these concerns, ag giant Bayer's R&D pipeline has shifted from an emphasis on traditional chemical-based insecticides and herbicides to include more work on fungicides, crop traits, and microbial products that boost plant health.

"We are working with multidisciplinary solutions," says Bob Reiter, head of R&D at Bayer Crop Science. "Farmers are our customers, but the industry is aligning for the best outcomes for consumers and the planet," he told attendees at the 2019 World Agri-Tech Innovation Summit.

Fungicides fend off mildew and mold organisms that consume germinating seedlings and can even kill plants late in the season. The wet, cool soils that now predominate at planting times on farms like Gaesser's host huge populations of these pathogens. Bayer is developing molecules to reduce plant diseases in corn, soy, cereals, rice, and oilseed crops like canola. Future products will target disease organisms including leaf spot and soybean rust.

> **"Farmers are our customers, but the industry is aligning for the best outcomes for consumers and the planet."**

Meanwhile, major agriculture firms and start-ups are screening thousands of microbes to find beneficial ones that might be given to crops as a climate-proofing probiotic cocktail. Helpful microorganisms colonize soils, plant roots, stems, and leaves, making nutrients from the environment available to plants by fixing nitrogen from the air and breaking down inorganic phosphates in soil.

Novozymes, a microbe specialist, is working with Bayer to develop products that enhance early plant vigor. Faster, stronger root and shoot growth helps plants withstand stress from low moisture and can improve yields. Bayer is also backing microbe start-ups Pivot Bio and Ginkgo Bioworks.

Most companies have been developing microbe products aimed at growers in the US, Brazil, and Europe. It is not clear when or how similar products will reach developing regions or how well they will perform in tropical or semitropical climates.

However, Marcus Meadows-Smith, CEO of BioConsortia, a start-up developing teams of yield-enhancing microbes, says there will be opportunities to expand into developing countries. He says these products have the potential to be easier to use than traditional yield boosters, such as fertilizers, because they are potent in small volumes. Microbial populations grow along with the plant. That could make distribution cheaper and easier compared with today's bulky pesticides and fertilizers. And it could save farmers the expense and work of reapplying chemicals.

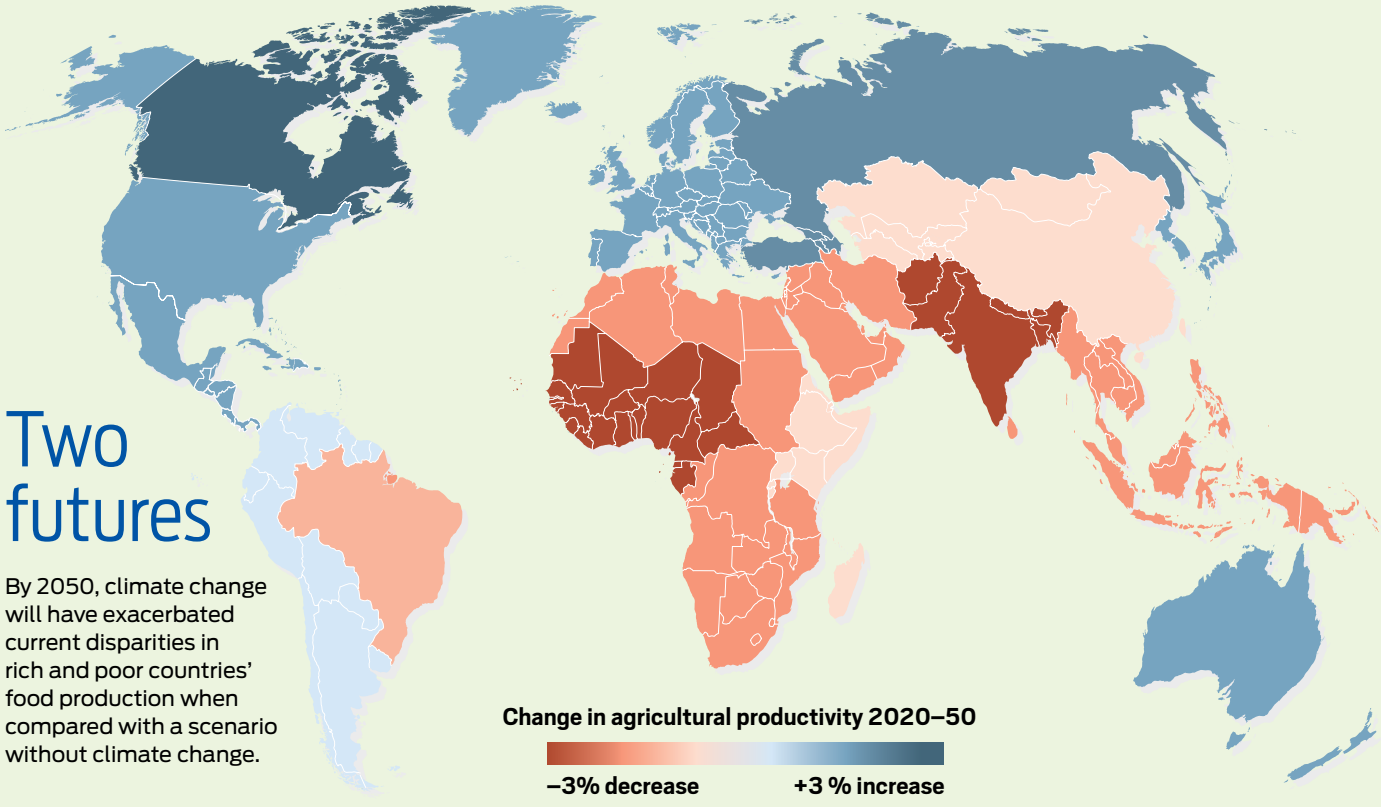
BioConsortia researchers are using fluorescent tagging to learn how well its microbe groups colonize different soil environments. Meadows-Smith says the factors that govern whether microbes flourish are likely soil temperature and pH, both areas of focus for the company's researchers.

Israel's STK Bio-Ag Technologies is specifically targeting markets outside the midlatitudes. The company makes crop protection products based on plant extracts as well as hybrids that combine these extracts with chemical active ingredients. STK sells products in several countries in South America. In 2010, it expanded to the Philippines and South Korea, and now it is entering China, with hopes to go to India.

Shay Shaanan, STK's head of R&D and business development, says the products are more expensive than generic pesticides but that farmers growing high-value crops such as fruit and vegetables can usually afford them. Because the products contain up to 100 active molecules and have many modes of action, they can help plants survive multiple environmental stresses and pest pressures, Shaanan says. He reports that STK's products are popular with banana growers in the Philippines, tomato farmers in Brazil, and rice growers in Colombia.

# Two futures

By 2050, climate change will have exacerbated current disparities in rich and poor countries' food production when compared with a scenario without climate change.




## In developed countries

- High agricultural productivity
- High per capita arable land
- Net food exporters
- High use of inputs per hectare
- People spend less than 10% of wages on food
- High availability of affordable, high-quality protein
- Postharvest, preconsumer rate of food waste: 5–10%
- Less than 10% of population works in farming
- Large investments in agricultural technology

## In developing countries

- Low agricultural productivity
- Low per capita arable land
- Net food importers
- Low use of inputs per hectare
- People spend more than 50% of wages on food
- Low availability of affordable, high-quality protein
- Postharvest, preconsumer rate of food waste: over 30%
- More than 50% of population works in farming
- Small investments in agricultural technology

SOURCES: UNITED NATIONS FOOD AND AGRICULTURE ORGANIZATION, JOHNS HOPKINS CENTER FOR A LIVABLE FUTURE.

A more straightforward way to close the yield gap between farmers in resource-poor and resource-rich settings would be to ensure they have the same level of access to fertilizers, particularly nitrogen ones. This could, however, exacerbate the problem of climate change by boosting carbon emissions in Africa and Asia: ammonia production is a major contributor to agriculture's carbon footprint.

Greener alternatives for making nitrogen would be a boon for agriculture around the world but require significant investments in R&D and capital spending. Unfortunately, industry does not yet have a way to recoup those investments—and that has stymied progress, says Runeel Daliah, an analyst at Lux Research.

An ideal approach would be to replace today's massive fertilizer plants with smaller regional ones that run on renewable energy. Daliah points to efforts by Atmonia, an early-stage start-up based in Iceland. Its scientists have identified potential catalysts, used in an electrochemical cell, that can reduce atmospheric nitrogen to aqueous ammonia. The technology needs further development to reduce the amount of energy needed so that it can run on solar power, but the concept is promising, Daliah says.

## Delivering on food quality

As these technologies for boosting productivity slowly make their way out of the lab and to farmers in the developed world, major problems will remain in resource-poor regions. The UN projects that food-insecure countries will be forced to increase imports of commodities like wheat and rice

to meet caloric demands of growing populations.

But merely importing more grains is not the solution, says Martin Bloem, director of the Johns Hopkins Center for a Livable Future. He sees a conflict between two laudable goals: combating malnutrition and combating climate change. Stunting, caused by a lack of dietary choline and essential amino acids, negatively affects brain and organ development, particularly in children 5 years old and younger. Only quality protein, such as that in eggs and milk, can deliver those nutrients. Low-income families often rely on plant-based diets, heavy in starchy grains, that fall short in those nutrients. "The best climate diet is not best for prevention of stunting," Bloem says.

Innovations in food science could help the world resolve these apparently conflicting needs. The now-expanding list of better-tasting alternatives to meat, eggs, and dairy products could benefit populations in developing regions and deliver essential nutrients missing in diets heavy in starchy grains.

In India, Varun Deshpande is working to pave the way for alternative protein products in his role as managing director for the country's affiliate of the Good Food Institute, an advocacy group for plant-based food. "We can create products that offer affordable protein, are micronutrient rich, and are good interventions to prevent malnutrition," he says.

Demand for meat is growing among countries with developing economies, particularly in India, where families have a strong desire for a more westernized diet and try to eat meat at least once a week, Deshpande says. "They are rapidly ramping up demand for protein and meat, especially as incomes rise. But we may undo a lot of work on sustainability taking place now."

People in India spend a majority of their incomes on food, so Deshpande is looking for alternative protein products that are less expensive than meat. Chemists working in the food and packaging industries can create new, alternative protein products that are shelf stable, making them more affordable and easy to distribute to far-flung communities.

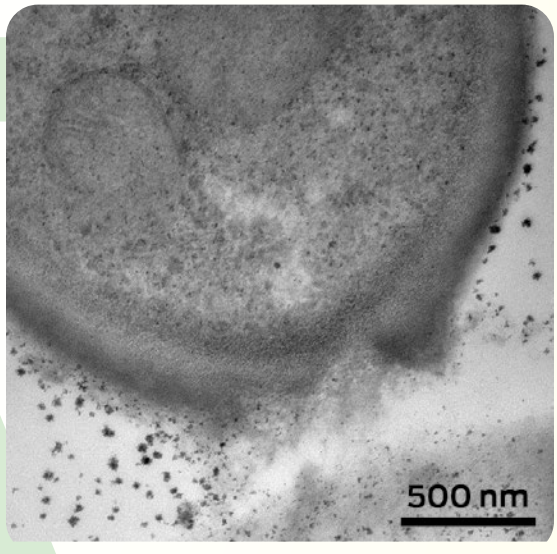
Deshpande says he would like to see India's farmers adopt crops that can be used to make alternative protein locally. Those include beans and peas that fix nitrogen in the soil. Another useful crop is millet. It thrives in low-nutrient, dry soils and provides nutrients, such as calcium, iron, zinc, and iodine, that are often missing in the diets of people living in developing countries.

"We need to encourage the best, most functional, nutritious crops for our regions and help companies formulate products with those crops," Deshpande says.

Iowa farmer Gaesser, who leads overseas agriculture education and trade missions, says farmers everywhere are hungry for innovation. On his travels, he says, farmers ask him, "'What practices will allow me to adapt to extreme events?'" He would like to see governments increase spending on research that benefits agriculture and not rely as much on for-profit companies to lead.

> **"We learn as we go how to adapt, adopt, and innovate with new practices."**

**These bananas, grown in the Philippines, were treated with a broad-spectrum biofungicide from STK Bio-Ag.**




**STK Bio-Ag's plant-derived fungicide destroys the cell wall of a crop-threatening fungal organism.**

Gaesser will keep experimenting to find the best seeds, chemistries, and land management practices to align with the new climate reality. "We've always invested in continuous improvements, and we learn from our mistakes," he says. "We learn as we go how to adapt, adopt, and innovate with new practices."

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CREDIT: STK BIO-AG (BOTH)

# How we'll reengineer crops for a changing climate

**Laura Howes,** C&EN STAFF

**Efforts to improve the genetics of food crops are as old as agriculture. Crossbreeding plants to select for traits is nothing new, but synthetic biology techniques, including CRISPR-Cas9 and other gene-editing systems, have sped up the process and made new approaches possible. As climate change threatens the world's food-growing systems, plant scientists, industry, and governments hope to use these powerful methods to make plants hardier and land more productive. Here are some of their targets.**

## Resisting disease

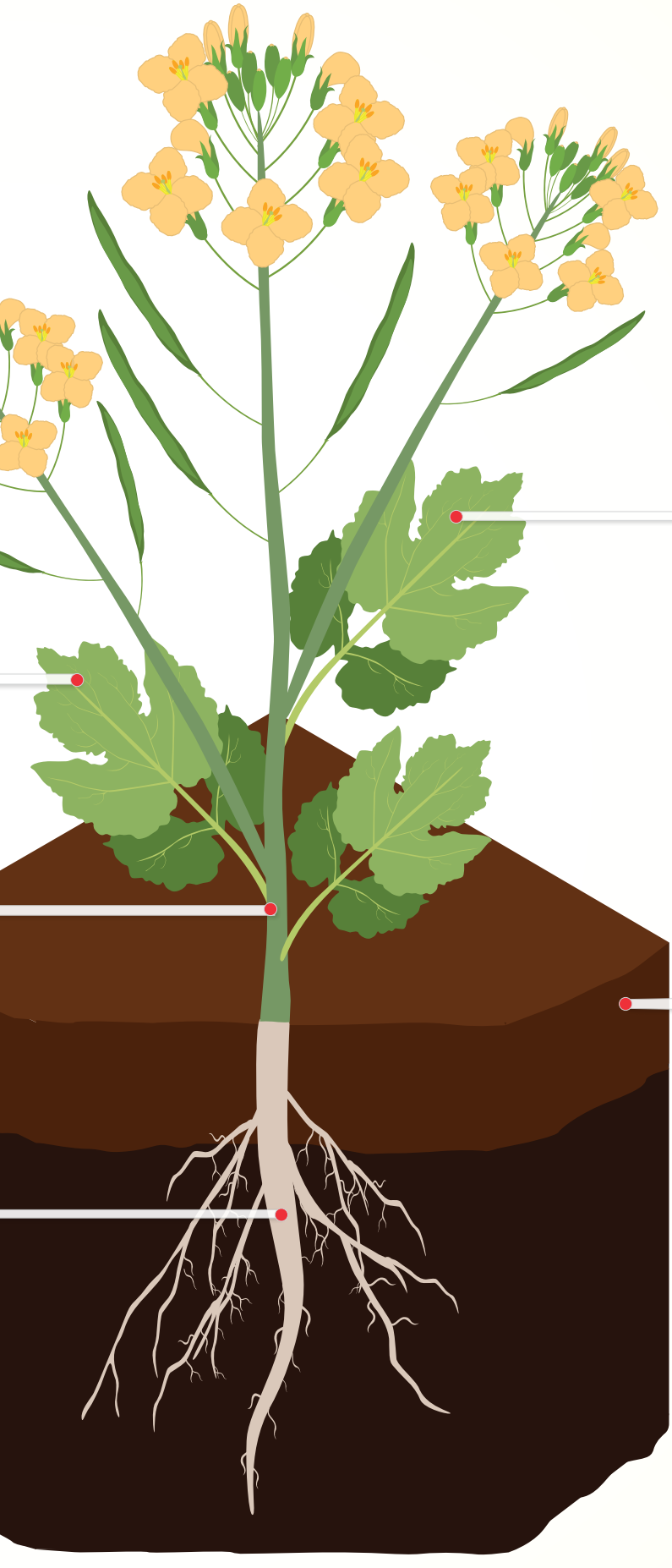
Researchers say it is not always clear how rising carbon dioxide levels will affect the relationship between crops and disease, but changes in temperature and water availability can make plants more susceptible to disease. The genomes of many bananas and plantains share a dangerous secret that illustrates this: a virus that can cause farmers to lose their harvests. The banana streak disease, which primarily affects the leaves, is activated under stress conditions such as drought and extreme heat, which are likely to become more common as a result of climate change. That will be especially problematic in countries like Tanzania and Kenya, where these crops are important sources of calories. To get ahead of this problem, a research team led by Leena Tripathi of the International Institute of Tropical Agriculture in Nairobi, Kenya, used CRISPR-Cas9 to edit the genome of a type of plantain commonly grown in East and Central Africa. Her team successfully neutralized the banana streak disease sequence inside it (*Commun. Biol.* 2019, DOI: 10.1038/s42003-019-0288-7). The researchers are now working on making bananas resistant to other diseases.

## Shrinking stems

In the 1950s, Norman Borlaug bred a wheat plant with a shorter, stronger stalk that doesn't fall over in the wind or if the grain head gets heavy. Today, Bayer Crop Science is betting that the corn of the future will also be short statured to protect against stronger winds caused by climate change. Its R&D teams are developing and field-testing conventionally bred and genetically modified corn varieties that are a meter or more shorter—and much sturdier—than any corn that farmers have previously grown. According to Bob Reiter, head of R&D for Bayer Crop Science, farmers should be able to pack more of the smaller plants into the same area, thereby producing more food on the same land, along with preventing stems from breaking in the wind.

## Expanding roots

Roots are critical for water and nutrient absorption, physical support, and carbohydrate storage in plants. Several groups are working to boost crop yields by improving and increasing root formation. Researchers at the Salk Institute for Biological Studies are taking the idea one step further by making plants with roots that are not only bigger but also resistant to decomposition, potentially enabling them to store more carbon underground. The team worked with other researchers to locate single genes that regulate how deeply roots burrow into soil (*Cell* 2019, DOI: 10.1016/j.cell.2019.06.021) and is now trying to increase the amount of suberin in the root cells of plants. Suberin is a waxy substance present in plant cell walls that resists decomposition, enriches soil, and helps plants tolerate stress. Once they've learned what they can from their work with model plants, the researchers hope to build suberin-charged crop plants that, "on a large scale, . . . could suck enough carbon out of the atmosphere to slow down climate change," according to the *Guardian.*



CREDIT: YANG H. KU/C&EN/SHUTTERSTOCK

## Supercharging photosynthesis

For plant engineers, photosynthesis and the related process of photorespiration are ripe for improvement. As part of the Realizing Increased Photosynthetic Efficiency project, researchers at the University of Illinois at Urbana-Champaign are targeting a respiration protein called RuBisCO. They recently showed that their engineered tobacco plants had 40% greater crop yields in field trials (*Science* 2019, DOI: 10.1126/science.aat9077). If it works in food crops, modified RuBisCO could help farmers reduce the impact of climate change by creating crops that thrive with increased carbon dioxide levels and hotter temperatures. In contrast, members of the $C_4$ Rice Project are trying to push rice to use a photosynthetic pathway, known as $C_4$, that is used by crops like maize and that is more efficient in hot, dry environments. Some of them are trying to add $C_4$ machinery into cells; others are attempting to engineer rice that has the physical characteristics of a $C_4$ plant. University of Oxford researchers and colleagues have achieved one step toward that goal by introducing a single maize gene into the rice plant, which increased the volume of chloroplasts and mitochondria in cells surrounding leaf veins (*Curr. Biol.* 2017, DOI: 10.1016/j.cub.2017.09.040). Such efforts to supercharge photosynthesis could allow farmers to produce more calories using less land and fertilizer.

## Surviving soil extremes

As extreme weather events become more frequent and more severe, crops will need to weather the attendant, more intense stresses. So plant scientists are engineering staple crops that are better able to tolerate extreme drought and the high mineral levels that result from irrigation or flooding. For example, scientists at Pioneer, formerly DuPont Pioneer and now a subsidiary of Corteva, used CRISPR-Cas9 to rewrite a particular gene in maize so that it does not stop growing when water is scarce *(Plant Biotechnol. J.* 2016, DOI: 10.1111/pbi.12603). And last year, scientists at Huazhong Agricultural University and Shanghai Agrobiological Gene Center successfully eliminated a gene in rice, resulting in improved tolerance to elevated salt concentrations (*Mol. Breed.* 2019, DOI: 10.1007/s11032-019-0954-y).

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# We chose 20 promising companies developing the future of farming technology

AGRAGENE

» **Agragene**
» **agragene.com**
» **Based:** San Diego
» **Founded:** 2017
» **Money raised to date:** $5.2 million
» **Key partnerships:** Ospraie Ag Science
» **Strategy:** Agragene breeds sterile male versions of crop-damaging pests by editing their genes using CRISPR technology. The sterile males mate with wild females in the field, effectively suppressing pest reproduction and controlling the population without pesticides.
» **Why watch:** In September, the company's cofounders published a new strategy that halts the introduction of gene-altering technology into wild populations. It is designed to mitigate concerns about releasing such technology in the field.

AgroSpheres

» **AgroSpheres**
» **agrospheres.com**
» **Based:** Charlottesville, Virginia
» **Founded:** 2016
» **Money raised to date:** $14.1 million
» **Key partnerships:** Adama Agricultural Solutions, Institute for Advanced Learning and Research, Orion Integrated Biosciences, Virginia Tech
» **Strategy:** AgroSpheres's core technology comprises 400 nm wide bioparticles arising from fermentation of bacterial cells. The particles encapsulate biobased and chemical pesticides, helping farmers lower pesticide doses.
» **Why watch:** The Wells Fargo Innovation Incubator selected AgroSpheres as one of the six firms in its 2020 cohort of start-ups. The program gives the company access to research space and resources at the Donald Danforth Plant Science Center, an important plant research center in Saint Louis.

Atmonia
Towards a sustainable future

» **Atmonia**
» **atmonia.com**
» **Based:** Reykjavík, Iceland
» **Founded:** 2016
» **Money raised to date:** $310,000
» **Key partnerships:** Grein Research, Innovation Center Iceland, University of Iceland
» **Strategy:** The standard process for taking nitrogen from the air and converting it into ammonia is the energy-intensive, carbon dioxide-emitting Haber-Bosch process. Atmonia instead does this electrochemically, creating a solution of ammonia in water at ambient temperature and pressure (see page 5).
» **Why watch:** Danish start-up valuation firm Valuer listed Atmonia as one of 12 European start-ups most creatively tackling the 12th of the United Nations Sustainable Development Goals, which is ensuring sustainable consumption and production patterns.

BioConsortia

» **BioConsortia**
» **bioconsortia.com**
» **Based:** Davis, California
» **Founded:** 2014
» **Money raised to date:** $37 million
» **Key partnerships:** Ballance
» **Strategy:** BioConsortia's technology unearths teams of beneficial microbes that boost crop yields or promote desired traits (see page 9). Current research efforts include enhancing drought and salt tolerance.
» **Why watch:** The company is searching for a partner to bring to market a wheat seed treatment that boosts yields by improving nutrient uptake by roots.

BORAGEN

» **Boragen**
» **boragenbio.com**
» **Based:** Durham, North Carolina
» **Founded:** 2015
» **Money raised to date:** $15.3 million
» **Key partnerships:** Bayer, Bill & Melinda Gates Foundation, Dole, Syngenta
» **Strategy:** Boragen is betting big on the boron atom, which is rarely found in traditional agrochemicals. The bioactive boron compounds in the company's pipeline include a fungicide with a new mechanism of action and a product that eradicates fungal diseases and nematode worms to protect plant roots.
» **Why watch:** The firm, one of C&EN's 2017 10 Start-Ups to Watch, is teaming up with Dole to find ways to outmaneuver the banana fungal disease

black sigatoka, which devastates banana crops and has become resistant to multiple fungicides.


- **Enko Chem**
- **enkochem.com**
- **Based:** Woburn, Massachusetts
- **Founded:** 2017
- **Money raised to date:** $66 million
- **Key partnerships:** Bill & Melinda Gates Foundation, Germin8 Ventures, Novalis LifeSciences
- **Strategy:** Enko uses DNA-encoded chemical libraries to find new pesticides. The strategy, borrowed from the pharmaceutical industry, is cheaper than traditional high-throughput screening and allows the company to screen billions of compounds against multiple targets.
- **Why watch:** Market intelligence organization AgTech Breakthrough named Enko Chem its inaugural company of the year.


- **GreenLight Biosciences**
- **greenlightbiosciences.com**
- **Based:** Medford, Massachusetts
- **Founded:** 2009
- **Money raised to date:** $215 million
- **Key partnerships:** Continental Grain, Lewis & Clark AgriFood, Morningside Ventures
- **Strategy:** GreenLight Biosciences is applying its cell-free RNA production process to both human health and agriculture. The company makes an experimental RNA interference pesticide that targets the Colorado potato beetle and leaves beneficial insects unaffected.
- **Why watch:** The company has hired veterans of Corteva AgriScience and Bayer Crop Sciences to commercialize its products.


- **Indigo Ag**
- **indigoag.com**
- **Based:** Boston
- **Founded:** 2014
- **Money raised to date:** $1.2 billion
- **Key partnerships:** Anheuser-Busch, John Deere Operations Center, Mahyco Grow
- **Strategy:** Indigo treats seeds with microbe collections sourced from hardy plants thriving in harsh environments. The company says its seed products, available for crops like corn, wheat, and cotton, help plants thrive in nutrient-deficient soils, extreme temperatures, or dry conditions.
- **Why watch:** The company has expanded beyond seed coatings, launching an effort to incentivize farmers to enrich their soil's carbon content and a digital marketplace to help farmers find crop buyers.


- **MoA Technology**
- **moa-technology.com**
- **Based:** Oxford, England
- **Founded:** 2017
- **Money raised to date:** $8 million
- **Key partnerships:** Not disclosed
- **Strategy:** MoA Technology offers three herbicide discovery platforms for natural or synthetic weed control ingredients that work in new ways. The company says its in vivo plant model predicts herbicidal activity better than traditional in vitro approaches.
- **Why watch:** To boost its herbicide discovery process, the company uses an informatics platform from San Francisco–based Collaborative Drug Discovery that is more typically sold to early-stage pharmaceutical and biotechnology companies.


- **Nature's Fynd**
- **naturesfynd.com**
- **Based:** Chicago
- **Founded:** 2012
- **Money raised to date:** $113 million
- **Key partnerships:** Not disclosed
- **Strategy:** Nature's Fynd, one of C&EN's 2019 10 Start-Ups to Watch, produces edible protein from an extremophile fungus that cofounder Mark Kozubal discovered at geothermal springs in Yellowstone National Park. The fungus forms a matted structure similar to meaty muscle fiber but requires a fraction of the land and water resources needed for meat production.
- **Why watch:** In March, the company opened a 3,300 $m^2$ manufacturing facility on the site of Union Stockyards, Chicago's historic meatpacking district.


- **Nileworks**
- **nileworks.co.jp**
- **Based:** Tokyo
- **Founded:** 2015
- **Money raised to date:** $22.7 million
- **Key partnerships:** Not disclosed
- **Strategy:** Nileworks manufactures agricultural drones that hover 30–50 cm above the tops of plants. The company says its drone's mounted camera can see the shape of a field and ensures highly accurate spraying of small doses of agrochemicals from the drone to plants below, thus reducing chemical consumption.
- **Why watch:** The company plans to use its funding for drone upgrades, such as the ability to infer crop health from plants' appearance and dose pesticides accordingly.


- **OerthBio**
- **oerthbio.com**
- **Based:** New Haven, Connecticut
- **Founded:** 2019
- **Money raised to date:** $55 million
- **Key partnerships:** Not disclosed

» **Strategy:** OerthBio is a joint venture between Bayer and biotechnology company Arvinas. The company aims to extend targeted protein degradation technology from drug development to agriculture, with the goals of controlling insects, weeds, and disease.
» **Why watch:** CEO John Dombrosky comes with experience as the head of AgTech Accelerator, which nurtures start-ups, and in multiple roles at agriculture firm Syngenta.


» **Pheronym**
» **pheronym.com**
» **Based:** Davis, California
» **Founded:** 2017
» **Money raised to date:** $725,000
» **Key partnerships:** Joywell Foods
» **Strategy:** Pheronym's pipeline contains products that direct microscopic roundworms called nematodes to behave in ways that benefit plants (see page 6). The water-soluble pheromones can keep parasitic nematodes from damaging roots or get beneficial nematodes to pursue and kill insect pests.
» **Why watch:** Pheronym blasted beneficial nematodes into space, supported by a grant from the International Space Station US National Laboratory. One study suggests that the tiny worms could be part of a pest control strategy for interstellar agriculture.


» **Pivot Bio**
» **pivotbio.com**
» **Based:** Berkeley, California
» **Founded:** 2010
» **Money raised to date:** $186.7 million
» **Key partnerships:** Bayer Group, IN10T
» **Strategy:** Many soil microbes have the natural capacity to convert atmospheric nitrogen to ammonia—the form of nitrogen that plants can take up through their roots and use to make protein. Decades of farmers' reliance on synthetic fertilizer made by the energy-intensive Haber-Bosch process blunted this ability. Pivot Bio reawakens microbial ammonia-making pathways with machine learning, computational modeling, and genetic engineering (see page 6).
» **Why watch:** Farmers currently must apply Pivot Bio's microbes in the channels, or furrows, between rows of crops, but the company says a seed treatment option is in the pipeline.


» **Protera**
» **proterabio.com**
» **Based:** Paris
» **Founded:** 2018
» **Money raised to date:** $5.6 million
» **Key partnerships:** Doosan Group, Hi-Food, Nvidia
» **Strategy:** Protera leverages its deep-learning platform to understand how organisms build proteins. It then uses fermentation—the same process used to craft beer or yogurt, to make alternative food-grade proteins (see page 5). The firm's flagship candidate, soon to begin trials with food manufacturers, has anti-mold effects to increase the shelf life of baked goods.
» **Why watch:** The company, one of C&EN's 2020 10 Start-Ups to Watch, in July joined a community of high-impact food start-ups within the European Institute of Innovation & Technology, a body created by the European Union.


» **Provivi**
» **provivi.com**
» **Based:** Santa Monica, California
» **Founded:** 2013
» **Money raised to date:** $114.5 million
» **Key partnerships:** Not disclosed
» **Strategy:** Perfuming crops with sex pheromones from female insects confuses males and curbs mating without killing pests outright. The cost of making the hormones is prohibitive for large-scale crops, however. Provivi, one of C&EN's 2015 10 Start-Ups to Watch, cuts synthesis costs by using mutated versions of enzymes to reduce the steps needed to make the pheromones.
» **Why watch:** The company's cofounder is Frances Arnold, a 2018 Nobel laureate in chemistry. Renowned primatologist and conservationist Jane Goodall is a company ambassador.


» **RNAissance Ag**
» **rnaissanceag.net**
» **Based:** Overland Park, Kansas
» **Founded:** 2019
» **Money raised to date:** $250,000
» **Key partnerships:** Not disclosed
» **Strategy:** RNAissance Ag focuses on developing RNA-based insecticides. Rather than affecting insects broadly, the technology is intended to target a specific pest. The company says its RNA interference system has the potential to work on insects previously thought to be resistant to RNAi.
» **Why watch:** In June, the firm completed the acquisition of RNAgri, a start-up with a platform for economical RNA production and one of C&EN's 2018 10 Start-Ups to Watch. Field trials of the technology against the diamondback moth and fall armyworm are underway.


» **STK Bio-AG Technologies**
» **stk-ag.com**
» **Based:** Petach Tikva, Israel
» **Founded:** 1994
» **Money raised to date:** $90 million
» **Key partnerships:** Adama Agricultural Solutions, Manus Bio, Summit Agro USA
» **Strategy:** STK Bio-AG's crop protection portfolio includes plant extracts like tea tree oil, as well as combinations of plant extracts and chemical fungicides or pesticides (see page 9).
» **Why watch:** One of the company's products, a hybrid fungicide that combines botanical extracts and the

synthetic pesticide difenoconazole, is available in 15 countries, including the US as of this fall. The firm says the botanical extract in the fungicide enhances the activity of the synthetic component.

Terramera

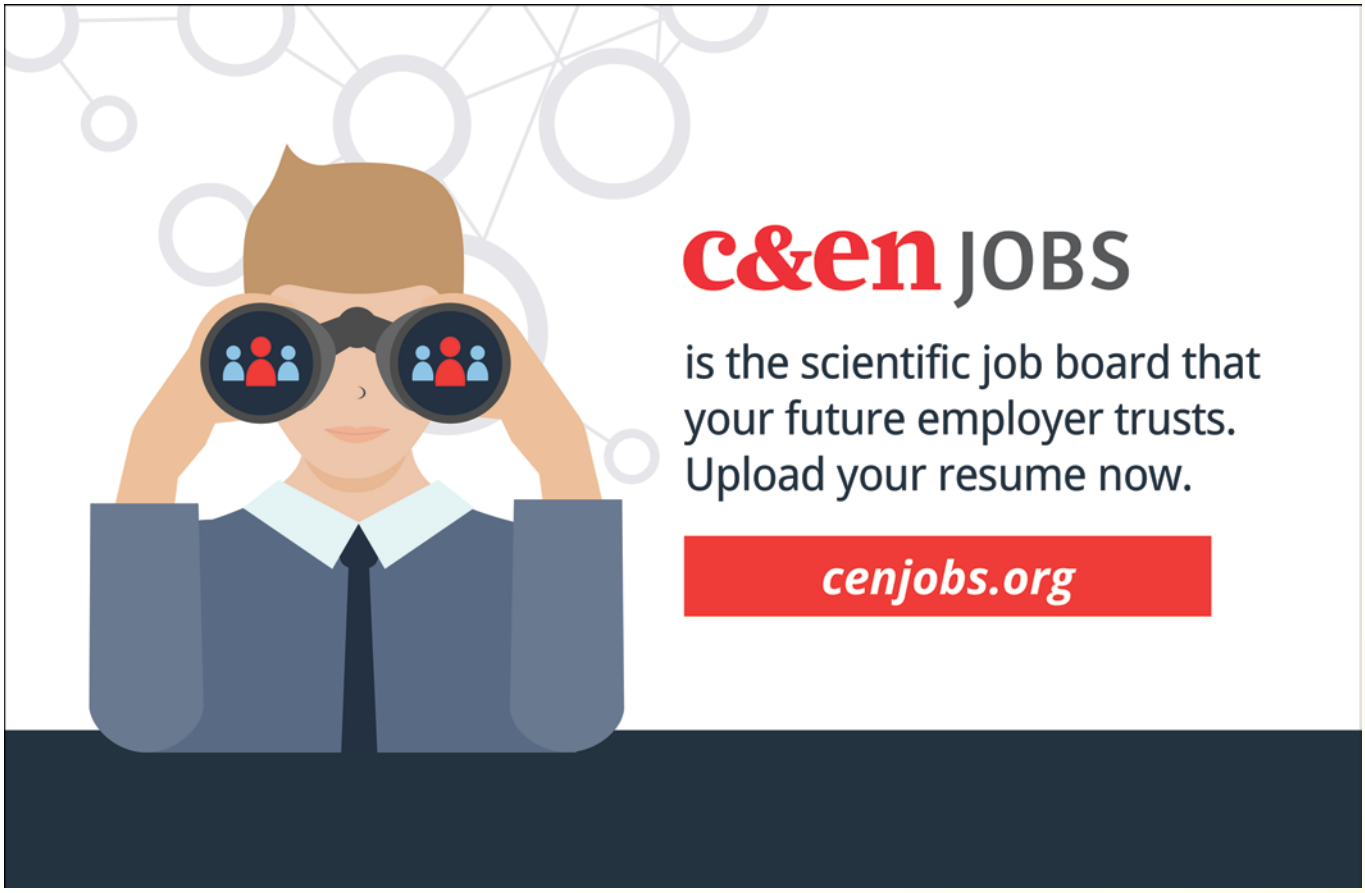
- **Terramera**
- **terramera.com**
- **Based:** Vancouver, British Columbia
- **Founded:** 2010
- **Money raised to date:** $82.8 million
- **Key partnerships:** Agriculture and Agri-Food Canada, Ikea GreenTech, Sightline Innovation
- **Strategy:** Terramera aims to help farmers grow more food with less synthetic pesticide and fertilizer. Its active ingredient delivery technology makes plant-based crop protection ingredients outperform synthetic fertilizers and pesticides by ferrying them straight to target cells rather than relying on the traditional spray-and-pray approach.
- **Why watch:** This summer, the firm landed a grant from the province of British Columbia to develop new antifungal formulations with machine-learning approaches in collaboration with Simon Fraser University.

**Note:** Companies were included because of the novelty and promise of their methods, amount of capital raised, number of partnerships, and number and identity of investors.

**Sources:** Crunchbase (accessed October 2020), company websites, news reports.

VESTARON
THE POWER OF PEPTIDES™

- **Vestaron**
- **vestaron.com**
- **Based:** Durham, North Carolina
- **Founded:** 2005
- **Money raised to date:** $89.2 million
- **Key partnerships:** Capua BioServices, Wilbur-Ellis
- **Strategy:** Vestaron aims to move agriculture away from synthetic pesticides and toward naturally occurring peptides with insecticidal properties. The company's bioinsecticides act on the nicotinic acetylcholine receptor in pests like caterpillars or aphids. They do not affect fish, birds, pollinators, or people.
- **Why watch:** The US Environmental Protection Agency gave Vestaron one of the 2020 Green Chemistry Challenge Awards, administered with the American Chemical Society (ACS publishes C&EN).

# Inari Agriculture: Harnessing CRISPR to engineer crops with the aim of reducing land, water, and pesticide use

**MEGHA SATYANARAYANA,** C&EN STAFF

In the past, the standard strategy for genetically modifying crops involved removing, or knocking out, undesirable genes, says Catherine Feuillet, the chief scientific officer of Inari Agriculture. It's a straightforward process, she says, but killing gene expression isn't always the best way to breed a better plant. This is where CRISPR, with its ability to more subtly change the expression of genes, can make a big difference in crop science.

"We're creating a lot of new diversity that doesn't exist," Feuillet says.

**Ponsi Trivisvavet (left) and Catherine Feuillet**

Headquartered in Cambridge, Massachusetts, Inari is targeting soy, corn, wheat, and tomatoes as the first crops it will use its CRISPR technology to edit, says Ponsi Trivisvavet, Inari's CEO. The firm wants to engineer these so-called big foods to take up less land and require less water and fertilizer. University of California, Berkeley, biochemist Jennifer Doudna, who shared the 2020 Nobel Prize in Chemistry for CRISPR, sits on the scientific strategy board of Inari, which was publicly launched by the life sciences venture capital firm Flagship Pioneering in 2018.

"Corn consumes the largest amount of chemical fertilizer in the world," Trivisvavet says. "Soybean causes a lot of deforestation in the world, and wheat is using a lot of pesticides. We want to address the challenges of the environment."

Trivisvavet says Inari's first products—modified soy and corn—are ready for greenhouse development, and the company estimates they will be on the market in about 2 years. One of the firm's biggest hurdles is education: in an environment where genetically modified organisms have been controversial, Feuillet and Trivisvavet want people to understand that with gene editing, they aren't introducing foreign genes into their products but altering the existing ones.

Inari recently opened an office in West Lafayette, Indiana, to test and optimize growing conditions for the firm's seeds and an office in Ghent, Belgium, to take advantage of gene-editing talent in Europe.

Agricultural biotech, like its counterpart in health care, is male dominated, Feuillet says. But it looks as if this may be changing: "With new technologies, that may mean more ways for women" to rise in leadership, Feuillet says. "We are very proud to be a company that the leadership team is 50% women."

## Inari Agriculture at a glance

- **Launched:** 2018
- **Based:** Cambridge, Massachusetts
- **Strategy:** Gene-edited food crops such as soybeans and corn
- **Funding:** $200 million

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CREDIT: KAYANA SZYMCZAK

HOT SHEET

# Droplets of an herbicide-loaded hydrogel stick their landing

A droplet of dicamba-laden hydrogel sits on a leaf of *Chenopodium album*, a weed that plagues corn and soy crops.

**XIAOZHI LIM,** SPECIAL TO C&EN

A new herbicide-carrying hydrogel's droplets can land on leaves and stay there without bouncing off or breaking up (*ACS Sustainable Chem. Eng.* 2020, DOI: 10.1021/acssuschemeng.0c03396). Such hydrogels could help reduce agrochemical losses when they are sprayed, potentially cutting the amount needed to achieve the same level of crop protection.

Although herbicides and pesticides are usually sprayed onto crops, not all the droplets stay on the foliage, where they need to be to kill weeds and insects. By one estimate, 50% of agrochemical droplets bounce or roll off leaves (*Sci. Adv.* 2017, DOI: 10.1126/sciadv.1602188). These losses not only are costly but also waste water and could pollute the environment, says Scott McCue, a mathematician at Queensland University of Technology who was not involved in the study.

Typically, agrochemical companies address this problem by adding surfactants to their pesticide formulations to reduce the surface tension of each droplet, says McCue, who helps companies model how droplets behave when they hit leaves. Although adding surfactants helps each droplet adhere to a leaf's surface, these mixtures could produce smaller droplets that are more easily carried by the wind. Surfactants also add to the cost of a formulation, and some of them may not be environmentally friendly, he notes.

Hoping to come up with herbicide formulations with sustainable components that benefit plants, Chong Cao and Qiliang Huang of the Chinese Academy of Agricultural Sciences and their colleagues turned to hydrogels containing folic acid and zinc—essential plant nutrients—instead.

Cao mixed together aqueous solutions of folate ions, zinc ions, and the herbicide dicamba, and after 20 min, a viscous, orange-yellow liquid formed. The folate and zinc cross-linked into a loose 3-D network with large gaps housing the dicamba molecules. This network is flexible enough to allow the hydrogel to be sprayed like a liquid, but strong enough to hold individual droplets together and help them recover when they hit leaves, Cao explains.

> "There's so much time and energy being put into this problem."

The researchers sprayed the hydrogel on the waxy, hydrophobic leaves of *Chenopodium album*, a weed that interferes with corn and soy crops in North America and Europe, in a wind tunnel to simulate how pesticides are applied in the field. Using a high-speed camera, the researchers observed that droplets of the hydrogel fell flat like pancakes on contact and then recovered as spherical droplets that stuck to the leaves. In contrast, droplets of aqueous solutions of dicamba, folate ions, or zinc ions shattered on impact, forming smaller droplets that then bounced off.

"There is evidence in this study that splashing and bouncing of droplets is reduced through this hydrogel," McCue says. But he notes that the study is preliminary, and there is a long way to go before commercial adoption. He suggests that the researchers repeat their experiments on different leaf surfaces and use a nozzle that produces smaller and faster droplets to better mimic commercial spraying. "There's so much time and energy being put into this problem in industry, any new idea for designing agrochemical spray practices that reduce environmental impact is definitely worth following up on," McCue says.

The researchers have successfully incorporated a fungicide, thifluzamide, into a similar hydrogel system. They are also investigating the mechanism through which dicamba is released from the gel to kill weeds.

XiaoZhi Lim is a freelance writer based in Massachusetts.

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CREDIT: CHONG CAO

READING LIST

# Our picks of the patent and journal literature on agriculture for a warming planet

## 2020


» Clark, Michael A., Nina G. G. Domingo, Kimberly Colgan, Sumil K. Thakrar, David Tilman, John Lynch, Inês L. Azevedo, et al. **"Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets."** *Science* 370 (Nov. 6, 2020): 705–8. https://doi.org/10.1126/science.aba7357.

» Fynder Group. **"Filamentous Fungal Biomats, Methods of Their Production and Methods of Their Use."** US Patent 10,787,638, filed Dec. 5, 2019, and issued Sept. 29, 2020.

» Agnolucci, Paolo, Chrysanthi Rapti, Peter Alexander, Vincenzo De Lipsis, Robert A. Holland, Felix Eigenbrod, and Paul Ekins. **"Impacts of Rising Temperatures and Farm Management Practices on Global Yields of 18 Crops."** *Nat. Food* 1 (Sept. 15, 2020): 562–71. https://doi.org/10.1038/s43016-020-00148-x.

» Hanifpour, Fatemeh, Arnar Sveinbjörnsson, Camila Pía Canales, Egill Skúlason, and Helga Dögg Flosadóttir. **"Preparation of Nafion Membranes for Reproducible Ammonia Quantification in Nitrogen Reduction Reaction Experiments."** *Angew. Chem., Int. Ed.* (Aug. 28, 2020). https://doi.org/10.1002/anie.202007998.

» Pheronym. **"Nematode Dispersant Composition and Method."** US Patent 10,736,326, filed Jan. 4, 2017, and issued Aug. 11, 2020.

» Indigo Agriculture. "**Seed Endophytes across Cultivars and Species, Associated Compositions, and Methods of Use Thereof."** US Patent 10,667,523, filed Dec. 30, 2015, and issued June 2, 2020.

» Provivi. **"Yeast Strains with Reduced Fatty Alcohol Oxidase Activity and Method for the Production of Omega-Hydroxy Fatty Acids and Dicarboxylic Acids."** US Patent 10,640,796, filed Aug. 13, 2018, and issued May 5, 2020.

» Pivot Bio. **"Methods and Compositions for Improving Plant Traits."** US Patent 10,556,839, filed April 16, 2018, and issued Feb. 11, 2020.


## 2019


» Shukla, Priyadarshi R., Jim Skea, Eduardo Calvo Buendia, Valérie Masson-Delmotte, Hans-Otto Pörtner, Debra C. Roberts, Panmao Zhai, et al., eds. **"Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems."** Intergovernmental Panel on Climate Change. (Aug. 8, 2019). https://www.ipcc.ch/srccl/

» University of Massachusetts. **"Plants with Enhanced Photosynthesis and Methods of Manufacture Thereof."** US Patent 10,337,024, filed Dec. 24, 2014, and issued July 2, 2019.

» Schollaert Uz, Stephanie, Alex C. Ruane, Bryan N. Duncan, Compton J. Tucker, George J. Huffman, Iliana E. Mladenova, Batuhan Osmanoglu, et al. **"Earth Observations and Integrative Models in Support of Food and Water Security."** *Remote Sens. Earth Syst. Sci.* 2 (Feb. 11, 2019): 18–38. https://doi.org/10.1007/s41976-019-0008-6.


## 2018


» Mukherjee, Shreya, David A. Cullen, Stavros Karakalos, Kexi Liu, Hao Zhang, Shuai Zhao, Hui Xue, et al. **"Metal-Organic Framework-Derived Nitrogen-Doped Highly Disordered Carbon for Electrochemical Ammonia Synthesis Using $N_2$ and $H_2O$ in Alkaline Electrolytes."** *Nano Energy* 48 (June 2018): 217–26. https://doi.org/10.1016/j.nanoen.2018.03.059.

» Perfect Day. **"Food Compositions Comprising One or Both of Recombinant Beta-Lactoglobulin Protein and Recombinant Alpha-Lactalbumin Protein."** US Patent 9,924,728, filed Feb. 21, 2017, and issued March 27, 2018.


## 2017


» Justice, Nicholas B., Andrew Sczesnak, Terry C. Hazen, and Adam P. Arkin. **"Environmental Selection, Dispersal, and Organism Interactions Shape Community Assembly in High-Throughput Enrichment Culturing."** *Appl. Environ. Microbiol.* 83 (Aug. 4, 2017): e01253-17. https://doi.org/10.1128/AEM.01253-17.

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**Note:** This list was chosen by experts who work in the field, CAS information scientists, and C&EN editorial staff.

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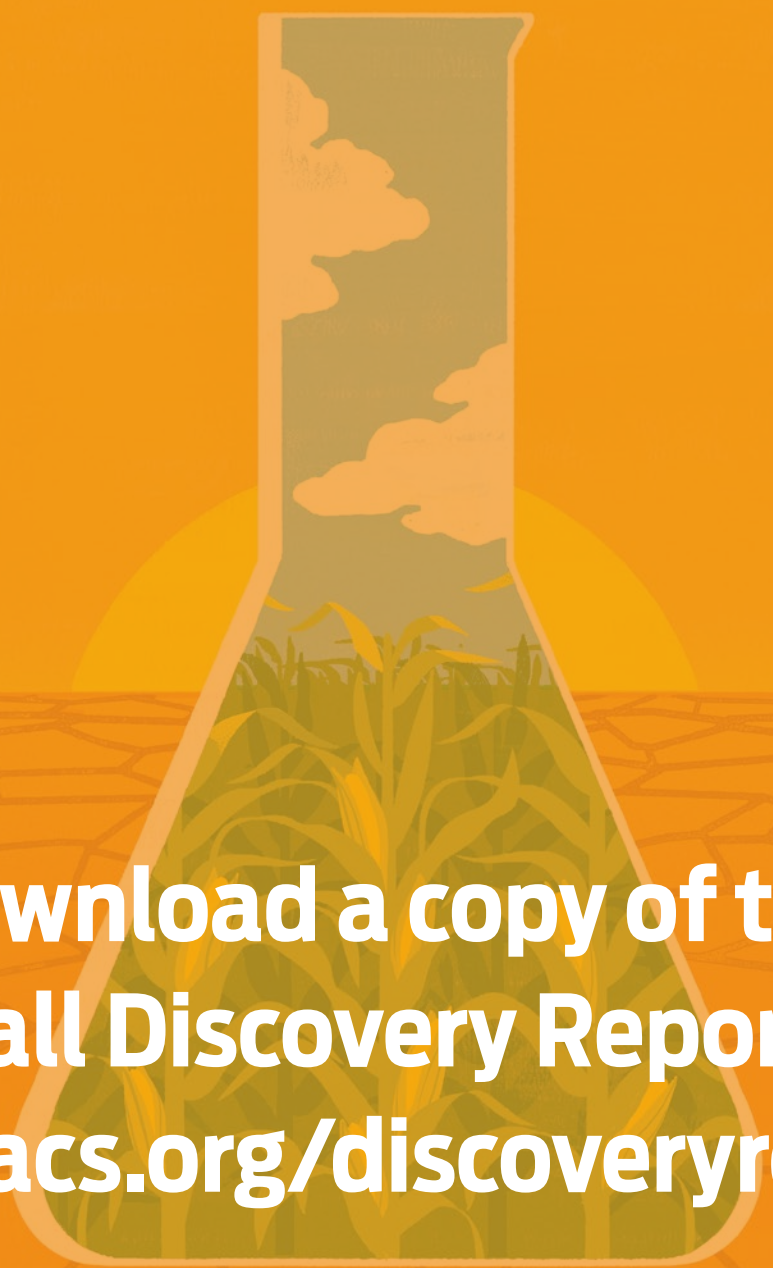

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