COVER STORY

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# WATCHING THE

*A new push to integrate remote sensing, robotics, genomics, and big data into crop breeding could help feed and fuel a warming world.*

BY DAN FERBER

# CROPS GROW

**Addie Thompson is breeding better varieties of sorghum—but she's going about it the hard way. This spring, Thompson, a postdoctoral researcher at Purdue University, helped plant a 10-acre field of different genetic lines of sorghum in 144 large plots. Then she geared up to harvest data.**

When the weather was still cool and plants were not yet knee high, a colleague marked three plants in each plot with small plastic tags. Then, at least once a week, Thompson and a dozen other researchers planned to spend an afternoon in the field revisiting each tagged plant. They'll measure stem diameter with a caliper, height with a piece of PVC pipe marked off in inches. They'll count the leaves, mark the level of the highest leaf with a Sharpie, and use a handheld fluorometer to gauge the plant's greenness.

Each month, as the Indiana sun beats down and the plants grow taller, they will take detailed measurements, weighing stalks, leaves and seed heads, which contain grain. They'll drive mulchers with threatening five-foot spinning blades to harvest samples of each crop line. Back in the lab, the researchers will dry and weigh the samples for yield and perform one biochemical analyses after another to learn more about them.

"It's a lot of work to convince people to do the work. It's not fun to do. It's hot, sweaty, buggy, and not very safe," Thompson said.

If the research succeeds, Thompson and her colleagues will help breed new sorghum varieties that could grow tall and thrive despite poor soil, heat, and drought. These new varieties could produce more biofuel per acre than any sorghum ever grown, while slashing climate-disrupting carbon dioxide emissions compared with gasoline and today's most popular biofuel, corn-derived ethanol. And the technology the team develops could spark a revolution in crop breeding.

But before any of that happens, Addie Thompson is breeding sorghum the hard way. That's because, for now at least, it's the only way.

Addie Thompson examines sorghum plants that are being grown in a greenhouse to produce seed. *Photo: Purdue University*

## A NEED FOR SPEED

Less than a century ago, the average farmer produced enough food to feed between 10 and 12 people. Then came the Green Revolution. Through the middle of the 20th century, crop breeders developed new lines of staple grains, agronomists mechanized soil management and crop production methods, and scientists developed better fertilizer, herbicides, and pesticides. Now the average farmer feeds 120 people.

But providing food and clean fuels to Earth's nine billion people in 2050 will require farmers to double crop production per acre, said Joe Cornelius, a plant physiologist who directs the Transportation Energy Resources from Renewable Agriculture (TERRA) program at the Advanced Research Projects Agency-Energy (ARPA-E). And they'll need to do it while using much less water and protecting what's left for people to drink.

Before landing at ARPA-E, Cornelius worked for a quarter century at the agricultural biotech giant

Purdue University plant scientist Mitch Tuinstra's team aims to speed breeding of sorghum (background) for biofuel.
*Photo: Purdue University*

Monsanto, where he led efforts to breed new lines of crops to make more nutritious foods, vegetable oils, biodegradable motor oil, and biofuels. There he witnessed researchers use traditional crop breeding strategies and modern genetic engineering tools to develop better crop varieties. Yet time after time, they ran into dead ends.

Part of the problem was that crop plants take months to grow, so breeders can grow only a few generations each year. That limits how often they can pick winning varieties from each generation and discard the losers.

What's more, even though a plant variety's genetic characteristics are relatively easy to determine, scientists cannot predict how it will do in the field until they test it. This makes breeding crops as slow as watching plants grow.

As climate changes and global food and energy demand grows, we'll need to find or create crops that yield more, even in the face of drought, heat and other weather extremes—and to do so we'll need to breed them more quickly than ever before, Cornelius said.

The nation needs new bioenergy crops in particular to meet congressional mandates designed to reduce greenhouse gas emissions. By 2022, refiners must mix 21 billion gallons of renewable biofuels into gasoline and diesel. These fuels can be made from cellulose extracted and converted from plant material, including corn stubble, corncobs, wood chips, straw—and sorghum.

This ancient cereal crop grows like a weed. Even in poor soil with very little fertilizer, it reaches 20 feet tall. Originally from the Horn of Africa, it withstands hot, dry conditions that would wilt even a tough corn plant. Indeed, the U.S. Department of Agriculture has projected that it could replace fading crops like tobacco, cotton, peanut, rice, and citrus in a belt of land from eastern Texas to the southern Atlantic Coast—but only if crop breeders can develop better sorghum lines that are customized for biofuel production.

When Cornelius joined ARPA-E, he saw an opportunity to advance bioenergy sorghum, and also advance crop breeding more broadly. By finding a faster way to grow and select sorghum varieties, he realized he could lay the groundwork for technologies that would usher in the next generation of superplants.

The research would be risky, bringing together new technologies and costing more than the private sector would pay. To make that happen, in June 2015 ARPA-E

## CROP MONITORING BY GROUND OR BY AIR

Camera- and sensor-loaded robots and UAVs could detect subtle changes in individual plants to spot rare varieties that yield more sorghum for advanced biofuels—and better technology to breed other crops faster.

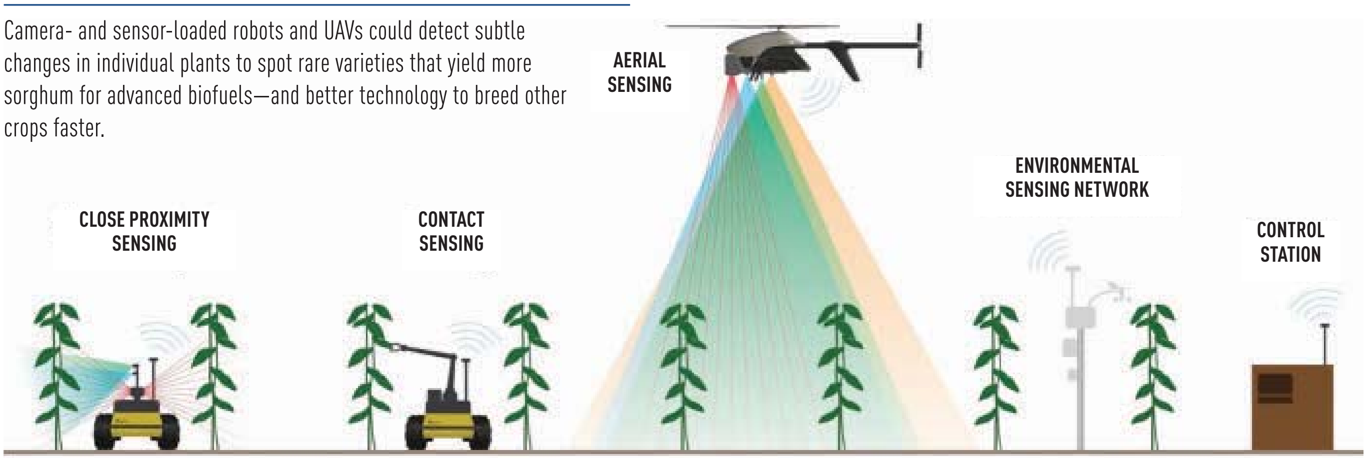



*Image: Steve Kresovich, Clemson University* launched TERRA. Their goal was to speed the breeding of bioenergy sorghum varieties, and they allocated more than $3 million to each of six interdisciplinary research groups, including the Purdue team.

## BREEDER BOTS

To get the most biofuel from the least land, farmers must maximize the yield of raw plant material per acre per year, while using a minimum of fertilizer and chemicals. To rapidly develop crops that do that, sorghum breeders and other scientists want to identify the traits, or phenotypes, that predict which plants will be biggest and have the most biomass to convert into fuel. Such phenotypes may include early season growth rates, the number of leaves on a plant, how well it uses soil nutrients, and many more.

Right now no one knows exactly which of these many traits best predict biomass yield. To find out, TERRA-funded teams plan to monitor a diverse array of genes and traits in thousands of individual sorghum plants from the ground and the air.

They're using robots, UAVs, sensing technologies, and big data to make that happen.

None of these technologies are entirely new to the farm. For the past decade, farmers have been using UAVs to determine where they need to apply water and farm chemicals, thereby increasing productivity and profit while reducing farm pollution. Other farmers have begun using bots for labor-intensive tasks. In California, for example, self-propelled bots prune and monitor grape vines and smart, rolling lettuce bots thin out budding lettuce plants.

Until now, few have tried to adapt these technologies for crop breeding. For millennia, crop breeders who wanted better varieties walked their fields and tracked their plants to note which plants grew taller, for example, or withstood insects or yielded more grain or vegetables.


Photo: LemnaTec

The largest field-crop analysis robot in the world, LemnaTec's 30-ton, 200-meter field scanalyzer moves its Volkswagon bus-sized instrument module like a line scanner to assess crops growing beneath it. The module's payload of cameras and sensors far exceeds any field robot or drone, yielding unprecedented data on individual crop plants from emergence to harvest.

Thompson and her supervisor, plant geneticist Mitch Tuinstra, and their colleagues augment these traditional methods by using low-tech devices and some modern lab equipment to laboriously screen for phenotypes.

To monitor crops from the ground, both the Purdue team and Clemson University's ARPA-E BOOST team are developing self-driving, instrument-equipped bots or vehicles that steer themselves through a breeding plot without trampling plants.

At Purdue, Tuinstra, crop physiologist Chris Boomsma and engineering professors Ed Delp and Ayman Habib are modifying a commercial sprayer to give it onboard data storage and autonomous steering capabilities.

By combining data generated from all these sensors, they plan to create a 3-D view of plants that reveals structure, including stem size, and the number, locations, dimensions, and angle of leaves. And by integrating these data, they hope to uncover clues about the plant's future growth.

The BOOST team, in contrast, is building a low-riding three-foot-long robot with a scaled-down version of the LIDAR laser scanner used in autonomous cars. The robot will roll by rows of crops, using cameras and a line scanner (a type of LIDAR) to create a 3-D, high-resolution model of the plants, said

Image: George Kantor

George Kantor of Carnegie Mellon University, the lead roboticist on the project.

A manipulator arm on the rolling robot will be able to reach out and touch a plant, performing tasks for which a crop breeder like Thompson would use a handheld instrument. "From my perspective as a robotics researcher, this is one of the most exciting parts," Kantor said. For example, the arm will attach a clothespin-like sensor to leaves to measure the plant's chlorophyll levels, the gases it exchanges with air, and the leaf's response to light.

The Purdue team will also monitor crops from the air using a fixed-wing UAV. It will carry a laser scanner and standard RGB cameras—ordinary digital cameras that capture the same red, green, and blue light as the human eye—to provide an overhead view of the crop. It will also carry a hyperspectral camera, which detects hundreds of colors, including some the eye can't see, and a thermal camera, which detects infrared light. Together, these will determine crop canopy temperature, which indicates crop stress.

The scientists will use high-end GPS and inertial measurement units (GPS/IMUs) to pinpoint the locations of the phenomobile and UAVs. This will enable them to integrate image and sensor data from the different vehicles. "Between the UAVs and the ground-based platforms, it's going to be extremely precise—down to the centimeter level, which is crazy," Boomsma enthused.

The BOOST team also uses a rotary-wing UAV being developed at Near Earth Autonomy, a spinoff from Carnegie Mellon University. There, engineer Paul Bartlett and his team are mounting a 5.5-foot, 35-pound helicopter UAV with LIDAR and high-resolution RGB cameras to detect plant shape and structure, and hyperspectral cameras that sense red and infrared light. Again, the goal is to take a spectrometric fingerprint of plants that reveals greenness, nitrogen content, dying leaves, and other biological phenotypes.

"In 15 minutes, we can get a snapshot of the whole field," Bartlett said.

Another ambitious TERRA-funded project comes from Lemnatec, a German company that has built the

Sorghum's genetic diversity makes it ripe for breeding.
*Photo: Steve Kresovich, Clemson University*

largest field-scanning robot in the world: a giant 30-ton steel gantry that sits near Maricopa, Arizona. Its instrument module—the size of a Volkswagen bus—moves down two 200-meter tracks and can scan the field one 1.5-meter band at a time. The module carries two metric tons of instruments, far more than a UAV or ground robot, and Lemnatec is loading it with sensors to see which ones generate the most useful data. "We can image the plants from emergence to harvest and all the stages in between, with a variety of sensors throughout the season," said Todd Mockler, a plant biologist at the Donald Danforth Plant Science Center in St. Louis who's working with Lemnatec on the project. "This will be uncharted territory."

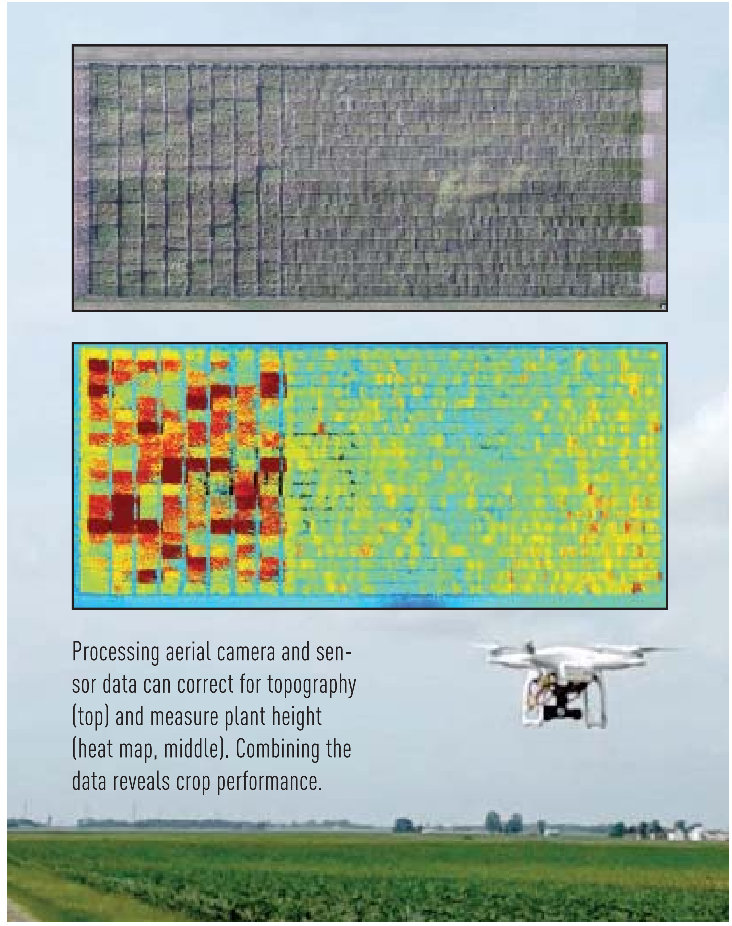
## FARMING DATA

Once the data from the various sensors is downloaded, researchers will process and analyze it. This task requires a combination of data analysis and machine learning. "This is Big Data," said Melba Crawford, a Purdue professor of agronomy and civil and electrical and computer engineering who's coordinating the group's machine-learning efforts.

First, the engineering team will develop new image-processing algorithms to sift through processed sensor data to discern a variety of phenotypes, such as height, leaf number, position and angle, chlorophyll, water content, and other indicators of plant health.

Once scientists have information on various traits, they'll need to mine it for correlations that predict the biomass yield for a given sorghum variety, says Artur Dubrawski, a computer scientist and mechanical engineer at Carnegie Mellon University who's doing similar work on the BOOST project. Understanding these correlations will enable researchers to scrutinize plants the way medical devices monitor human patients in the intensive care unit. "This forecasting ability should help us make those decisions in advance of crops completing their whole growth cycle," Dubrawski said.

To make even better decisions, both the scientists are also tapping existing knowledge of sorghum genetics, using advanced statistics and machine learning to relate genetic variations, or genotypes, to the plants' phenotypes. The computations are challenging because multiple genes can influence each trait, just as multiple genes influence human height or build. What's more, a single gene can influence multiple traits. TERRA-funded scientists are also using advanced statistics and machine learning to build models that predict plant traits of interest.



Processing aerial camera and sensor data can correct for topography (top) and measure plant height (heat map, middle). Combining the data reveals crop performance.

Photo: Purdue University

Ultimately, such computations would help identify key genes that help plants grow faster, tolerate drought, or thrive with less nutrients. This could lead to high-end computational tools that combine artificial intelligence, superhuman recall, and the latest advances in biology. Such a system could game potentially winning phenotypes before they're even planted, much the way computational fluid dynamics helps engineers choose designs. "It's almost like IBM Watson for breeding," Mockler said.

Like all ARPA-E programs, TERRA aims to spin off commercial technologies. These could range from powerful sensors and improved field robots, UAVs to better computational methods. What's more, a lot of the engineering will translate into field-scanning technology that any crop breeder can ultimately use.

"We're bringing together genomics, engineering, breeding, and computational analytics," Cornelius said. "We have this complete suite of technologies that are working together, and now we can pluck out the needle from the haystack." **ME**

**DAN FERBER** is a senior editor at *Mechanical Engineering* magazine.