Around the world, farmers—in their continual quest for higher crop yields, lower production costs and better-quality products—are gaining an edge from optical sensing and lighting technologies.
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Few industries define human civilization as strongly as agriculture. And, as the world’s population continues to grow, few technologies are as poised to improve the cultivation of food, fiber and fuel crops as optics.

Whereas farmers throughout history have relied on hunches, prognostication and qualitative observations to improve their crops, today’s growers can gather crop data with unprecedented precision. And indoors, in the greenhouse, lower-cost solid-state lighting is boosting crop yields and even allowing biologists to fine-tune plants’ response to light for more nutritious vegetables.

**Searching for precision**

Food insecurity today is admittedly generally a problem of economics rather than drought; as of mid-2017, only four countries were considered to be in a state of famine. Yet Earth’s population continues to grow—rapidly enough that, by United Nations estimates, almost 4 billion more people will need food and clothing by 2100.

In today’s large-scale agribusiness, production efficiency commonly translates into the speed at which a field can be processed. To maximize that speed, farmers rely on huge equipment that treats each part of a given field just like every other part, says J. Alex Thomasson, professor of biological and agricultural engineering at Texas A&M University, USA. When GPS opened to civilian use in the 1980s, however, it created the opportunity for “precision agriculture”: recording data across the field from position to position, to let farmers manage crops according to plant needs at individual locations.

“Where optics come in,” Thomasson says, “is in collecting data with optical sensors that enable us to understand variation in soils, in plants, in weeds, insects, diseases, stresses on the plants, and all those types of things.”

Thomasson works at the crossroads of Texas A&M’s colleges of agriculture and life sciences. His education and experience typify the growing integration of farming and technology. During his graduate studies in agricultural engineering, he took courses in physical optics, engineering optics and radiative heat transfer. Today he often collaborates with his physics and engineering colleagues, and occasionally with outside companies, on optical sensors and visible and infrared spectroscopy and imaging to analyze agricultural materials.

Most remote sensing is performed with either visible or multispectral cameras, extending into the near-infrared range. Agricultural remote sensing can include everything from satellite remote sensing all the way down to the use of drones flying at a hundred meters or so above ground height. In 2015, the U.S. Federal Aviation Administration adjusted some of its regulations governing small unmanned aircraft systems (the formal name for drones), making them easier to use for business purposes, including agriculture.

**Not just food**

Precision agriculture has gone beyond food crops to cotton, which grows on roughly 2.5 percent of the planet’s arable land. The more data farmers acquire on their crops—and the faster they can acquire those data—the better their profit margins can potentially be.

The key determinant of cotton’s price is its fiber quality: its color, trash content, length, strength and maturity. The last criterion, maturity, is a measure of how much cellulose has been deposited in the initially hollow fiber tube during 40 to 50 days of growth of the cotton harvester with optical yield-measurement system.
cotton boll (the protective case that contains the payload of cotton fiber). A typical cotton fiber is roughly 15 μm in diameter, a third as thick as a human hair. Growers don’t collect data on the maturity of fibers individually. Instead, they consider a quantity called “micronaire,” a dimensionless measure of the air permeability of compressed bulk cotton fiber samples, and try to optimize that quantity for yarn spinning. As described in a 1966 bulletin from the University of Tennessee Agricultural Experiment Station, lab technicians put 50-grain (3.24-g) cotton samples, compressed to a given volume, into an airflow device and measure the air resistance of the sample. (An early commercially available machine was dubbed the Micronaire, hence the name.)

Micronaire is typically measured with cleaned cotton fiber that’s been ginned (separated from the seed). But raw cotton fiber, as it’s pulled into a mechanical harvester, remains connected to the seeds and contains leaves, sticks, stems and other detritus. Optically estimating fiber quality of the cotton fiber at the point of harvest requires using image analysis to differentiate between the actual cotton fiber in the image and everything else. The fiber quality in the image can be determined by its reflectance at certain wavelengths, such as particular near-infrared wavelengths, for estimation of fiber maturity.

With precision-agriculture techniques that could include applying an imaging sensor on a cotton harvester, Thomasson says, cotton growers can begin to map the revenue or the profitability of every location in a given field, based on the yield of the cotton plants and the quality of the fiber at each field position. Farmers can use the data to assess methods to improve their crops. Also, since cotton growers can actually sell their output on the cotton futures market before they process it, predicting a crop’s quality during harvesting gives the farmers an added advantage.

“If the price happens to be good for a particular grade of cotton at the moment of harvest, if sensors on board your harvester tell you that you’ve got it, you can go ahead and sell futures at that price,” Thomasson says. “If you don’t know for six weeks, until it goes through the cotton gin and samples get sent to the classing office, the price may have come down by then and you will have missed an opportunity.”

**High-throughput phenotyping**

The marriage of optics and precision agriculture can also help in leveraging the fruits of biotechnology. For

**On the farm; in the greenhouse**

Here are a few ways that optics and photonics are changing the face of modern farming.

**Remote sensing**

From orbiting spacecraft to drones hovering a few tens of meters above a field, remote sensing has reached new heights of utility to agriculture. Cameras attached to unmanned aerial vehicles can give farmers a visual perspective on variations in soil type, fertilizer needs and pest infestation across their fields.

**Multispectral and hyperspectral imaging**

The combination of imaging and spectroscopy results in unprecedented amounts of data. Multispectral imaging (3 to 15 channels) has been shrinking in size and cost. Although hyperspectral instruments (hundreds of data channels) are much more expensive, researchers have been exploring how to use them to monitor crops for early signs of disease.

**Solid-state horticultural lighting**

Some crops must be started or grown in greenhouses or other types of indoor facilities. Artificial light can supplement sunlight in these facilities for optimal plant growth. In addition to their energy-saving and other advantages, LEDs can be tuned to the precise wavelengths that crops will best absorb.

**High-throughput phenotyping**

An organism’s phenotype is its set of physical characteristics—including, for agricultural purposes, parameters such as crop yield, growth rate and disease resistance. Modern technology has automated a large amount of genomic analysis, but similar studies of plant phenotypes are still done manually and slowly, leading to the “phenotype bottleneck.” Automating this painstaking process through imaging, spectroscopy and data-crunching yields new insights that can boost the production and profitability of farms.
example, hot on the heels of the well-known genomics revolution has been a revolution in “phenomics.” An organism’s genotype is defined as the set of genes it carries; a phenotype is a physical expression of those genes. If a human carries genes for both brown (dominant) and blue (recessive) eyes, the phenotype will probably be brown eyes. Phenomics is the study of large numbers of observable characteristics of individual members of a particular species. Comparing plant genotypes with phenotypes helps biologists identify the genes that produce these characteristics, so that plant breeders can develop future crops with desirable characteristics: high growth rate, drought resistance, pest and disease resistance and so forth.

Historically, says Thomasson, virtually all plant phenotyping work has been done by hand. Workers (and perhaps graduate students) count seedlings, measure leaf sizes and estimate the ripeness of fruits. Now that scientists have sequenced the genomes of a number of important agricultural plants, phenotyping needs to catch up, or else farmers will face a bottleneck of genetic data that has not been matched to crop characteristics. “Right now it’s relatively easy and cheap to genotype,” says Trevor Garnett, director of technology development at the Australian Plant Phenomics Facility. “But the harder thing is: what do those genes mean?”

A few-years back, some researchers defined so-called high-throughput phenotyping as the study of hundreds of plants per day. But other researchers dream bigger and faster than that. For example, the U.S. Department of Energy’s ARPA-E program funds a consortium of U.S. universities in the Transportation Energy Resources from Renewable Agriculture Phenotyping Reference Platform (TERRA-REF) project, which aims to match genotypes and phenotypes of more than 400 varieties of sorghum. As part of TERRA-REF, University of Arizona scientists built a 30-ton robotic steel gantry that carries a large camera and sensor package above rows of crops. A climate-controlled building autonomously guides more than 1,000 potted plants per day through cabinets for fluorescence, multicolor and near-infrared imaging. Piloted ground-based vehicles and drones are also adding to TERRA-REF’s data stream, which will be analyzed on high-performance computers.

Australia’s investment in high-throughput phenotyping, meanwhile, is based at two sites: the University of Adelaide, South Australia, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Australian National University, both in Canberra. Though much of the continent is harsh outback, a narrow belt along the southern Australian coast is suited to wheat and other cereal (grain) crops.

According to Garnett, the Australian facility is studying wheat to improve its drought tolerance, salt tolerance and uptake of nitrogen-based fertilizer. The country’s wheat crops actually grow during the Southern Hemisphere winter and are harvested at the beginning of summer, which is too hot and dry for the
With drones flying RGB and infrared cameras, the Australians can determine the biomass of a single row of wheat in the field as it grows.

species. Scientists want to know the amount of wheat biomass that will maximize the grain yield from the comparatively thin and poor Australian soil. Most wheat is self-pollinating, Garnett says, and scientists want to minimize the time between flowering and grain development because of frequent droughts.

Australia has plenty of money available for grain research, Garnett says, because a governmental organization assesses a small levy for research on each ton of grain harvested and marketed in the country. The phenomics facility has also worked on non-cereal crops from sugar cane to cotton to grapes, depending on the customers—who could be research scientists or agricultural businesses, says Xavier Sirault, director of the facility's High-Resolution Plant Phenomics Center in Canberra.

With drones flying RGB and infrared cameras, the biomass of a single row of wheat in the field can be determined as it grows, Garnett says. His colleagues haven't flown a hyperspectral camera on a drone yet, because such equipment costs half a million Australian dollars—a lot to entrust to a small unpiloted vehicle.

The Australian facility has also developed a ground-based wheeled platform that rolls down a row of plants and images them with RGB and hyperspectral cameras and lidar equipment to measure the growth and aging of crops. The latest version, designed for easy transportation, has been dubbed the “Phenomobile Lite.” In addition, the facility offers its customers fixed infrared sensors, mounted on poles and transmitting data wirelessly, for measuring the temperature of crop canopies and thus assessing plant stress and water uptake.

High-performance computing—which, these days, runs on optical networks—allows scientists to make sense of all the images and spectral data. The Australian facility was started with AU$600,000 of computing infrastructure, Garnett says, but now all images are stored offsite and processed in the cloud, which offers nearly limitless capacity.

**LEDs for greenhouse lighting**

Farming in some regions, and for some crops, takes place largely indoors, in greenhouses—which, stresses Anja Dieleman, a senior horticultural scientist at Wageningen University and Research in Wageningen, Netherlands, are much more than just glass houses. They may, for
example, be completely enclosed structures of glass or plastic or partially enclosed row covers and tunnel-like “hoop houses” to shelter delicate crops from downpours. Dieleman’s group designs protective buildings for crops all over the world, from northern Europe to the tropical lowlands of Indonesia.

While greenhouses were invented to exploit sunshine, artificial lighting has become an important supplement for crops that cannot get enough solar photons during short winter (or overcast) days. Typically, large-scale commercial greenhouses use high-pressure sodium (HPS) or metal halide high-intensity discharge lamps. As with countless other applications, though, researchers and lighting manufacturers are eagerly exploring LED lighting for horticulture.

As with office and habitation lighting, LED grow lights throw off much less waste heat than their gas-discharge cousins. To a business with 5 hectares (ha) of greenhouses with a desired illumination intensity of 200 micromoles (μmol) of photons per square meter per second, LEDs could reduce the energy consumption of lighting, not to mention the ventilation of excessive heat buildup. Dieleman says the energy efficiency of HPS lamps is about 1.85 μmol/J, but today’s most efficient LEDs are roughly 2.7 μmol/J, a 50 percent increase.

Granted, the initial conversion of greenhouses from gas-discharge to LED fixtures would incur one-time costs, but over time the utility savings would add up. In the Netherlands, with 10,000 hectares—0.25 percent of the nation’s land area—covered with greenhouses, LED grow lighting could become a significant market. (The Netherlands isn’t the European country with the most greenhouses; that honor goes to Spain, where one southeastern province alone has a nearly 200-square-kilometer greenhouse complex that can be seen from space.)

HPS lights are widely used for outdoor night lighting, but their red-yellow emission is better suited to human vision than plants’ needs. Thanks to their chlorophyll molecules, crop leaves absorb red and blue wavelengths, so growers can ignore the response of the human eye and illuminate plants with red and blue LED grow lights. Adjusting the proportions of red and blue lights can change the way plants grow—for example, adding more blue light can cause certain ornamental flowering plants to grow to a more desirable compact size. One 2012 study found that adding a period of supplemental LED red light to HPS lighting increased the antioxidant content of leafy vegetables such as spinach, parsley and dill.

The small size of LEDs, plus their easy integration with digital controls and their low levels of waste heat, makes them ideal for horticultural research. According to Dieleman, biologists are studying vegetable plants’ response to far-red light, which may yield larger and more nutritious tomatoes, and to so-called “intra-canopy” lighting. In the latter, LEDs are placed to illuminate the lower leaves on tall tomato (or other) plants for extra fruit production; HPS lamps in the same positions would cause heat stress. Several studies at other institutions found that intra-canopy lighting increased cucumber production by 11 percent and cowpea production by 50 percent.

LEDs could make other types of urban farming more feasible. In vertical farming, plants are stacked on vertical shelves to grow large amounts of short plants, such as lettuce, salad greens and herbs, in a small footprint. Although some people have suggested that abandoned factory buildings could be repurposed into indoor farms, Dieleman and others think such projects are not yet economically feasible, because the high-priced produce from these heavily
The small size of LEDs, plus their easy integration with digital controls and their low levels of waste heat, makes them ideal for horticultural research.

remodeled buildings would have to compete with crops grown under free sunlight.

**Toward single-plant management**

The goal of precision agriculture is to optimize crop production on a finer-grained level. Right now, farmers try to improve their crops based on a coarse-grained reference frame of management zones. They might break a 100-acre (40-hectare) field into three or four zones, but each of those zones still has wide variability of water needs, fertilization, weeds, insects or diseases.

“There’s a lot of potential for us to get more productivity on a plant-by-plant basis if we get down to management at something as close to the single-plant management level as possible,” Thomasson says. Getting close to that single-plant-level assessment, and then automating that kind of assessment, will be extremely challenging.

For example, an observer walking across a freshly plowed, bare-dirt field might see that the color of the soil varies from point to point—a clue that the soil’s ability to hold water and provide it to plant roots also fluctuates across the field. Insects commonly don’t infest every part of a field equally, so farmers would like to spray pesticides only where needed for both economic and environmental reasons. According to Thomasson, remote sensing techniques developed over the past decade have helped reduce pesticide applications to certain crops.

The idea of agricultural optimization, says Thomasson, includes two aspects: profitability and environmental risk management. Obviously, the fewer pesticides farmers need to apply to their crops, the better they serve both of those aspects.

Certainly agriculture has come a long way from the ideal of the small family farm, with a couple of cows and chickens and a garden patch, as depicted in children’s books. Optical measurement techniques—by quantifying crop production and maximizing the efficient use of resources—should help the world’s food inventory keep up with the planet’s population.

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**References and Resources**

- Y. Zou and H. Lieth. “LED technology for crop production in controlled environments,” online at http://ucfianews.ucanr.edu/
- Australian Plant Phenomics Facility, www.plantphenomics.org.au