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Advanced Spectroscopy in Precision Agriculture

An OSA Incubator Meeting explored the intersection of photonic technology and the effort to feed a growing world population.


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Like the electromagnetic spectrum that connects optical scientists, the growing world population includes a range of colors, fields and phases. Yet one thing common to all of us is the need to eat. Sustainable food production is crucial for maintaining a healthy population and planet—and, in turn, for geopolitical stability and prosperity.

Although the latter two subjects fall outside of the direct scope of optical and photonic technologies, those technologies are playing an increasingly important role in maximizing crop yields and conserving agricultural resources. The “holy trinity” of air, water and light ultimately enables all food production through the process of photosynthesis. The path through which this captured light energy reaches the dinner plate, however, is not only highly complex but sometimes staggeringly inefficient and wasteful.

With that in mind, the OSA Technical Groups for Environmental Sensing and Applied Spectroscopy convened a successful Agri-Photonics Incubator Meeting at The Optical Society (OSA) headquarters in Washington, D.C., USA, from 12 to 14 May 2019. The meeting’s purpose was to discuss the use of optical technology in agriculture, and how to better apply photonics to address important challenges in sustainable food production.

Agriculture’s big-picture challenges

The need for increased efficiency and reduced waste in agriculture and food distribution is well known. Seemingly unrelated factors, however, can directly impact agricultural yields and distribution efficiency, and an improved understanding of those factors and their scope is changing many long-standing practices. Photonic techniques—combined with information technology, precise positioning from GPS, data interpretation through artificial intelligence (AI), and advanced platforms like unmanned aerial vehicles (UAVs) and swarms of nanobots—enable collection of optical data from hard-to-reach places. Spectroscopy and imaging are versatile techniques that yield a broad base of information.

Attendees at the Agri-Photonics Incubator, posing in front of OSA’s Washington, D.C., headquarters.
OSA

Yet the acceptance and impact of these agri-photonic techniques are still very much limited, with some of the roadblocks including high cost and limited demonstrations of large-scale benefits. The OSA community can aid in overcoming these challenges—and one objective of the Incubator was to discuss practical steps in that direction.

The Incubator kicked off with a talk by co-host Amartya Sengupta of the Indian Institute of Technology (IIT), Delhi, India, on the motivation behind the meeting. He emphasized the importance of limited resources in many parts of the world, highlighting the large variation in food production efficiency between countries at various stages of development. All technological solutions, therefore, may not work in all geographic areas—particularly where the farming community has less experience with optical solutions.

Aparajita Bandyopadhyay of the IIT Delhi–Joint Advanced Technology Center followed with an overview talk on the emerging discipline of precision agriculture and its relationship to food security. She noted that the expected rise in world population to more than 10 billion by 2050 will require a considerable increase in food production. Yet some 90% of the 570 million farms worldwide are small, family-owned operations in areas already plagued by food insecurity. Furthermore, only nine crop species account for 66% of global food production.

These numbers present great challenges—but also tremendous opportunities for agri-photonics to have immediate impact. Identifying critical parameters (water, glucose, potassium and phosphorus content, for example) and efficient phenotyping (the physical expression of individual plant properties corresponding to a specific genetic profile) are needed to minimize waste and improve resource utilization through the use of optical technologies. Other practical challenges include system miniaturization, connectivity, sorting

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> Meeting the grand challenge of feeding 10 billion people in 2050 will rest partly on understanding and monitoring plant physiological processes.

the "big data" coming out of these tools, and strategic development of photonic-based green technology for recycling agricultural by-products and waste.

An eye on biological processes

Meeting the grand challenge of feeding 10 billion people in 2050 will rest partly on understanding and monitoring plant physiological processes—from the cellular and molecular level to larger understanding of biochemistry, genetics, and physiology. Plant physiology research can be categorized into metabolism and nutrition, growth and development, and response to the environment. These research questions deal with highly complex and dynamic processes that require sensitive, high-throughput detection technology combined with efficient data-mining capability. A key goal of the Incubator was to connect people working on the biological side of agriculture with the optics community, to identify challenges and solutions.

Basil J. Nikolau from the Center of Metabolic Biology, Iowa State University, Ames, Iowa, and currently at the U.S. National Science Foundation (NSF), noted the challenge in measuring the extent and location of the interaction of molecules with plant metabolism. To date, mass spectrometry has primarily been used for chemical identification of targeted analytes. But approximately two-thirds of detected analytes are still "chemically unknown," so systematic new methods for non-targeted metabolomics are still needed. Currently, mass spectrometry techniques can resolve metabolic networks down to the cellular level. Understanding and possibly regulating a vast number of metabolic pathways, particularly at posttranslational level, could enable effective optimization of growth conditions.

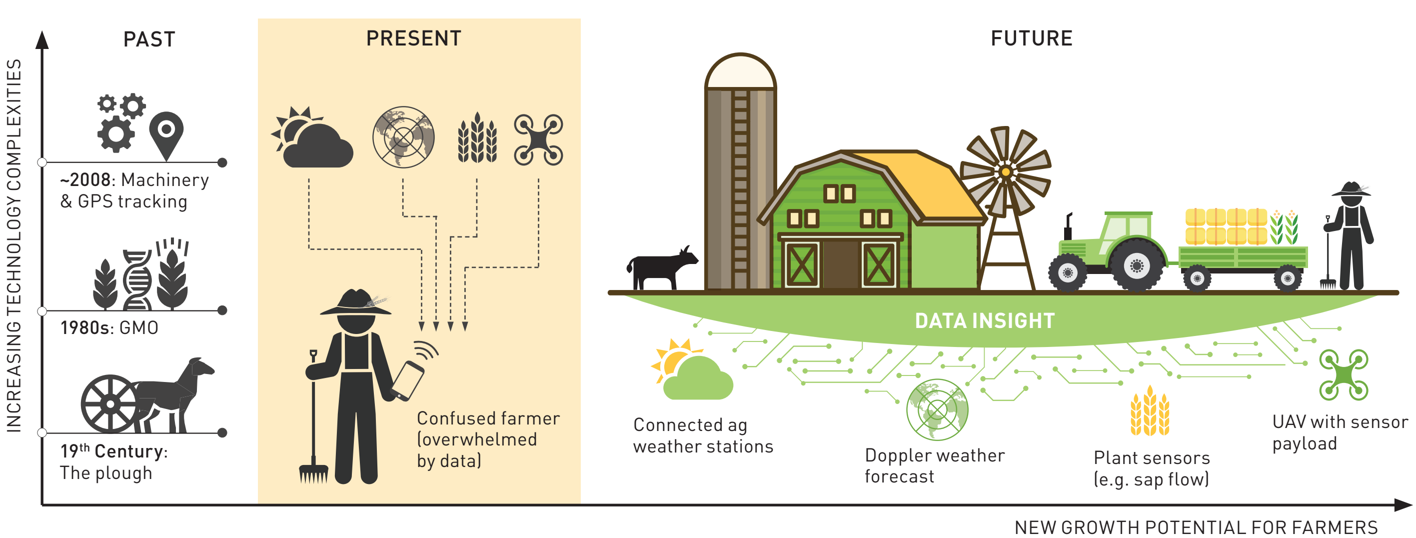
Nikolau underscored the need for integrated scientific and *in situ* technological advances to more predictively understand plant metabolism. As an example of this work, Yashwanti Mudgil of the University

The evolution of precision agriculture

Precision Technology: Photonics
- Sensing techniques for real-time monitoring
- Detection schemes for disease, plant phenotype, food quality control

Advanced Engineering
- Industrial heavy equipment
- Agri-bots with machine vision
- UAVs for large-area applications

Information Technology
- Smart display for GPS tracking
- Swarm technology
- Artificial intelligence



Adapted from original illustration by A. Bandyopadhyay of Delhi, India, described recent advances in optical techniques for detailed analysis and understanding of plant stress management mechanisms. Plants constantly face environmental changes that produce both abiotic and biotic stresses, so identifying the pathways that lead to healthy crops is essential. Biological methods, including transcriptomics, genomics and proteomics, have identified genes that are central players in stress-signaling pathways. Optical techniques, including fluorescence imaging followed by staining and terahertz spectroscopy, have shown promise in quantifying soil salinity and oxidative stress in the roots of individual plants.

For large-scale "smart" agriculture, Joseph Shaw of Montana State University, Bozeman, Mont., USA, showed how hyperspectral imaging combined with machine learning can identify herbicide-resistant weeds and monitor produce ripeness. This technology is being used in airborne instruments to enable rapid and periodic monitoring of large crop fields. The results, according to Shaw, have been extremely encouraging—greater than 98% accuracy of identification in greenhouse settings, 70% accuracy in outdoor field experiments using a tripod-mounted imager, and approximately 56% accuracy in outdoor experiments with a drone-mounted imager.

John Reich of the Foundation for Food and Agricultural Research, Washington, D.C., presented an interesting set of requirements for indoor plant cultivation to enable agriculture in areas where natural resources are limited. He echoed the need for a better understanding of metabolomics and non-invasive measurements of phytochemicals, biologically active compounds in plants that enhance favorable properties including disease resistance.

A lively panel discussion, moderated by Incubator co-host Gombojav Ariunbold of Mississippi State University, Starkville, Miss., USA, further explored the potential fruitful connections between the optics/photonics and plant biology communities. One theme was how to balance the goals of fundamental understanding and practical commercial implementation, and the need for increased collaboration between the agriculture and optics communities toward that end.

In particular, the urgency of developing *in situ* techniques to identify complex biochemical pathways and dynamic evolution with the highest sensitivity—down to a few parts per billion—has emerged as an issue of the utmost importance. Facing these and other challenges will require urgent action to raise literacy and awareness of them among scientific communities as well as STEM teachers and students.

Spectroscopy for precision agriculture

With that review of high-level challenges as background, the second Incubator session offered presentations on

Recent experiments at Montana State University tested drone-mounted hyperspectral imaging as a method for distinguishing plant phenotypes, including herbicide resistance.

Courtesy of J. Shaw, Montana State University, USA

Although the study of crops and food in the field is clearly important, measuring the quality of food once it is produced also holds a key to reducing waste and improving nutrition.

several spectroscopic techniques used in precision agriculture, and their commercial implementation. Martin Koch of University of Marburg, Germany, showed data obtained with a field-deployable prototype spectrometer-in-a-box using terahertz technology. The system can sense the diurnal variation of the water needs of plants, providing a view of their underlying metabolic shifts based on the available light energy. However, this technique still has limited sensitivity for large-scale application in "smart grid" irrigation systems for optimal water usage.

In a similar vein, Gombojav Ariunbold described advances and challenges toward future application of coherent anti-Stokes Raman spectroscopy (CARS) in understanding and monitoring complex biochemical plant processes. Combining CARS with optical microscopy enables *in situ* measurement of plant histology. Ariunbold's recent research work identifying plant stress indicator pigments has highlighted the potential application of Raman spectroscopy in precision agriculture.

On the commercial side, Jaakko Lehtinen of Spectral Engines, Helsinki, Finland, presented a line of customizable near-infrared (NIR) handheld sensor products that use MEMS-based Fabry-Pérot interferometers with extended InGaAs detectors to measure spectra in the 1.1-to-2.45-μm wavelength range. The platform enables both contact or standoff measurements, and, by hands-on examination of the sensor, the audience had the opportunity to envision its use in cloud-connected "smart farm" applications. For example, Lehtinen noted that a swarm of these sensors could generate a broad pattern of nitrogen-need data for vegetation based on the NIR response of chlorophyll, and thereby initiate automatic changes in the fertilizer application.

To close the session, Bernd Sumpf of the Ferdinand-Braun Institut, Berlin, Germany, chronicled development of a distributed Bragg reflector (DBR) laser-based dual-wavelength compact probe for shifted-excitation Raman difference spectroscopy (SERDS). This portable system-in-a-box, with handheld sensors, can be operated outdoors in the presence of daylight. The reconstructed SERDS spectrum removes the high background noise of daytime operation by taking differential data at two distinct but stable laser wavelengths from the source. Sumpf showed the application of the system in quality control for the meat industry, in fruit orchards and, possibly, in integrated systems for site-specific soil management.

The lively panel discussion after the session produced several takeaway observations. Everyone agreed that optical systems for food and agriculture should be customizable for specific use cases. The trade-offs between system sensitivity, size, cost and complexity will determine the application scope of a particular technology. Representatives of the commercial community concurred that this "task versus tariff" trade-off is the biggest issue that needs to be addressed for future success of photonics in agricultural sector. And the curve, they noted, is still heavily tilted toward the tariff end—which could prove challenging for photonics in this sector at present, even given the promise of substantial future turnover.

Assessing food quality

Although the study of crops and food in the field is clearly important, measuring the quality of food once it is produced also holds a key to reducing waste and improving nutrition. The scope of the Agri-Photonics Incubator spanned not just the agricultural production sector, but looked further—all the way to the consumer.

The third session covered a range of areas in technologies and applications for use at later stages of the food production and manufacturing cycle. Lasers are the core of most optical sensor systems, and meeting co-host Joachim Sacher of Sacher Lasertechnik, Marburg, Germany, opened with a review of mid-infrared lasers for use in gas sensing. A novel MEMS-based external cavity diode laser (ECDL) in a compact butterfly package is a versatile tool for spectroscopy in the 1.9-to-2.2-μm wavelength band, where strong absorption peaks of noteworthy gas species can be found. The presentation included a demonstration of this kind of spectroscopy in measuring biogas—a use case with direct application in agriculture.

Over the past several years, many companies have commercialized compact spectrometers with broad potential applications in agriculture and food production. Steve Buckley of Ocean Insight (formerly Ocean

At the Incubator, Jayshri Sabarinathan presented results from customized multispectral cameras for outdoor fields and greenhouses conducted as part of a collaborative project between Western University and A&L Canada Labs.

J. Sabarinathan, Western University, London, Ontario, Canada

Optics), USA, and Dana Hinckley of Hamamatsu Corp., USA, overviewed this technology. Hamamatsu offers a range of handheld micro-spectrometers spanning the UV/visible to NIR spectral bands. These instruments have been deployed in applications ranging from measuring the elemental content of soil to in-line inspection of food in production lines. Similarly, the Ocean Insight platforms have been used in pesticide detection, measurements to authenticate whiskey, and other applications.

To complement these commercial perspectives, Haibo Yao of Mississippi State University described an interesting use of optics for combating contamination of corn by the toxic, carcinogenic fungal by-product aflatoxin—a widespread problem in food production, particularly in warmer climates. Visible and NIR spectroscopy can detect the compound non-destructively at the below-100-ppb level needed for effective application. This technology is now being commercialized in a form factor compatible with use in resource-limited settings. This work, funded by the U.S. Department of Agriculture (USDA), is a good example of optical technology transitioning into practical use.

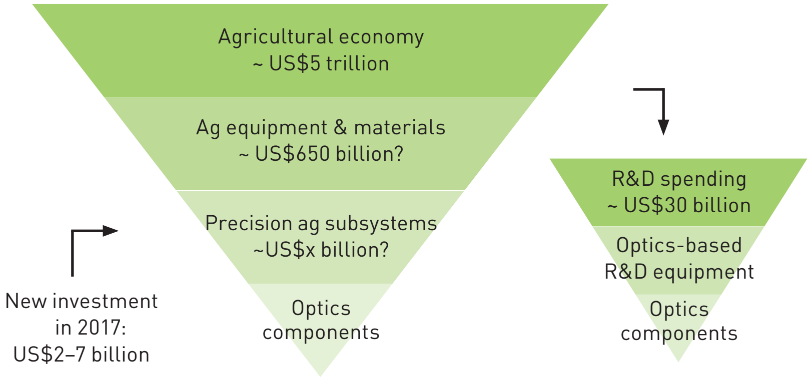
Markets, funding and public/private collaboration

On its second day, the Agri-Photonics Incubator turned to issues related to the broad market for these technologies, and how to fund future advances. OSA Senior Industry Adviser Tom Hausken kicked off the morning session with a market overview, assembled by OSA Industry Development Associates (OIDA). A good understanding of the market structure is crucial to identifying opportunities to insert optics into the agriculture and food production economy, and Hausken provided useful statistics and numbers providing such insights.

The fourth session of the Incubator, on "Photonics Industries for Precision Agriculture and Food Security," started with an overview by Jayshri Sabarinathan of the Western University in London, Ontario, Canada, of existing successful cooperation between precision agriculture and photonic detection methods. Ontario has a large farming sector with a significant amount of greenhouse farming. Sabarinathan reported on research work on hyperspectral and multispectral imaging for greenhouse monitoring and compared the two imaging techniques with respect to spatial resolution, generated data, information losses through data reduction, and costs of instrumentation. She also noted a university partnership with A&L Canada Labs, which has supported precision agriculture for more than 20 years.

Joshua Yuan of Texas A&M University, USA, next reviewed

The agri-photonics value chain



Source: OIDA estimate (2019), from CIA Fact Book, USDA data, and trade press

The Incubator generated discussion of needs in an important area—and helped to forge connections between researchers, funding agencies and the optical instrument industry.

Raman-based types of *in situ* monitoring of plant performance. Terpenes constitute significant by-products from plants, with applications in food, health care and natural fuel generation. Yuan reported on significant recent efforts toward optimizing plants and their growth conditions accordingly. For *in situ* monitoring of the plant performance, he noted, several detection methods are applicable, including fluorescence and Raman spectroscopy and in particular CARS and stimulated Raman spectroscopy (SRS).

CARS and SRS allow a quantitative detection, at a microscopic level, of terpenes, limonene, and their storage in plant-cell organelles. Applying such advanced imaging methods and techniques can improve fundamental understanding of biological processes—and their transformation into the engineering of efficient production systems for fuels, chemicals and materials.

Wrapping up the session were presentations by Steven Thomson of the USDA National Institute of Food and Agriculture (NIFA), Washington, D.C., and Basil Nikolau of Iowa State University/NSF on R&D funding opportunities in agri-photonics and bioengineering. Thomson, discussing NIFA grant programs applicable to optical sciences and precision agriculture, indicated that the institute's engineering program now allows proposals that include outreach and education components.

Thomson discussed in particular two programs of NIFA and NSF that he administers and for which NIFA provides funding: the National Robotics Initiative (NRI) and Cyber-Physical Systems (CPS-Ag). The number of proposals for both programs has seen significant increases over the past year. NIFA sets aside 11.25% of its granting budget for strengthening eligible institutions, and Thomson sketched out the qualifications for and mechanics of this program. Special considerations for achieving success in precision agriculture were also discussed, and Thomson indicated how NIFA's engineering programs are tailored to meet those needs.

Nikolau, meanwhile, provided the perspective of the NSF Division of Molecular and Cellular Biosciences (MCB), beginning with a brief introduction to the organization and structure of NSF. This agency is strongly encouraging cross-disciplinary research of the kind required in bioengineering. Nikolau stressed that research in bioengineering that has diagnosis- or treatment-related goals and that applies engineering principles to problems in biology and medicine, while still advancing engineering knowledge, is eligible for support. He added that bioengineering research to aid persons with disabilities also is eligible.

Topics of support include research at the smallest scale of biological organization, emphasizing quantitative, predictive and theory-driven science aimed at understanding complex living systems at molecular, subcellular and cellular levels. MCB achieves its mission, Nikolau said, by supporting multidisciplinary research that integrates biology with math, physics, chemistry and engineering. The subsequent discussion session in the Incubator highlighted significant interest among the audience in the reported funding opportunities for advancing in bioengineering and precision agriculture.

Conclusions and outlook

The Agri-Photonics Incubator generated substantial discussion of needs in an important area—and helped to forge connections between researchers, funding agencies and the optical instrument industry. The Environmental Sensing and Applied Spectroscopy Technical Groups will facilitate future meetings on the subject, including planned sessions in the 2020 OSA Sensors Congress. The Incubator will, we hope, mark the the start of increased participation by the OSA community in developing techniques and instruments that will help in sustainably feeding a growing world population. OPN

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