Fall 2011

AGRICULTURE AND INFORMATION TECHNOLOGY

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The BRIDGE

LINKING ENGINEERING AND SOCIETY

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Editor's Note

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Editor's Note

Andrew Alleyne

Agriculture and Information Technology

The topics addressed in this issue of *The Bridge* respond to two major trends that affect our planet: population growth and urbanization. The predicted population growth for the first half of this century is daunting. Depending on the estimate, there will be 9 to 10 billion people by mid-century. The current population is just under 7 billion, meaning that there will be about a 50 percent increase from the beginning to the middle of this century. One may debate the relative accuracy of particular models, but they all agree that there will be many, many more mouths to feed in the coming decades.

In addition to the change in sheer numbers, there will also be a change in demographics by mid-century —a global trend toward urbanization—a shift from an agrarian lifestyle to a city-based lifestyle for the majority of people in the world. For the first time in human history, more people today live in cities than in rural areas. It should be obvious to everyone that population growth coupled with increasing urbanization will require a disproportionate increase in agricultural output.

One consequence of urbanization is a rising middle class and an accompanying change in diet, specifically a higher demand for protein. Protein requires significantly greater agricultural resources to produce than diets based directly on staple crops such as maize or rice. In addition to land and water requirements, protein requires feedstock crops, thereby creating a multiplier effect. Agriculture already consumes a large fraction of the total amount of water used by people. By increasing the amount of protein in people's diets, water use will increase dramatically as well.

Urbanization also leads to so-called secondary effects in overall agricultural demand. Populations concentrated in cities put a strain on the agricultural supply chain by increasing the geospatial separation between food production and food consumption. In addition, the increased need for transportation of agricultural products, either crops or animals, for processing and eventual consumption adds logistical burdens and increased costs for fuel, infrastructure, and time. Stretching a supply chain also increases its vulnerabilities to disruption and decreases its efficiency.

With this background in mind, the articles in this issue examine ways to meet increases in demand using the knowledge and natural resources currently at our disposal, including information technology (IT), which we feel has been underused in the agricultural context. IT is defined here as the use of information to enable or improve products or processes.

IT has transformed many other aspects of human endeavor and has helped create systems for responding to a wide range of societal needs. Indeed, transportation, communication, national security, and health systems are completely reliant on IT to perform even basic functions. However, information, and its automated technological embodiments, has not impacted agriculture to the same level.

Modern urban public transportation systems have become remarkably reliable and predictable with the incorporation of information and automation. Indeed, they would fail to operate without information flow. The same can not be said for modern farming.

Many National Research Council (NRC) studies have been published related to agriculture. A recent report on sustainable agriculture explored motivations for sustainability and even recommended agricultural procedures rooted in the concept of sustainability (NRC, 2010). Other studies on the role of technology for agriculture in developing nations (NRC, 2008) have explored the suitability of technologies for improving agricultural yields in global regions with high rates of poverty. To date, however, neither NRC nor NAE has conducted a study explicitly on the role of IT in the agricultural landscape.

A fundamental premise of this issue of *The Bridge* is that more could be done with information to tighten up the supply chain associated with agricultural production. The goal is to wring out inefficiencies and maximize the productivity potential of our current resources to meet predicted demand.

Conversations, technical and otherwise, about specific aspects of IT as it relates to particular areas of agriculture have been initiated. One subject of these conversations is the increased use of sensing modalities and the ubiquity of sensors across the agricultural spectrum, from overall crop performance and animal health to DNA reports on individual genomes. However, conversations relating IT to agriculture in a broader sense have not been as prevalent. The modest goal of this issue of *The Bridge* is to initiate broader conversations by illustrating the reality and potential of IT to impact the tremendous challenge of feeding a growing planet.

The first article, by Ting, Abdelzaher, Alleyne, and Rodriguez of the University of Illinois, provides a broad perspective on opportunities and challenges associated with integrating IT and agriculture. They begin by identifying individual challenges associated with meeting future agricultural goals. They then break the discussion down into a taxonomy and show how different elements of IT can be used to address these challenges. They also offer suggestions for accelerating the integration of IT and agriculture and point out potential challenges associated with the close coupling of IT and agriculture. Much like the unintended consequences of introducing a non-native species into a new habitat, the accessibility and malleability of information must be carefully considered during large-scale deployment of IT in agriculture.

The second article, by Bull, Davis, and Skroch of Monsanto, describes how IT is used in plant breeding. The use of biotechnology to isolate specific desired traits in crops is akin to techniques used in the pharmaceutical industry. A combinatorial approach is used to identify novel genes for traits, such as insect resistance, herbicide tolerance, and drought tolerance. This information is then coupled to large-scale trials for determining the most viable candidates. The process generates many terabytes of data each day that must be sifted through, correlated, and used in a decision-making process to cull less effective options. IT is a crucial enabler for turning these data into useful product-development decisions.

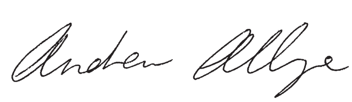
The third article, by John Reid of John Deere, describes the history and state of the art in agricultural mechanization. Reid begins with a historical perspective on the importance of mechanization to increasing agricultural productivity. He also discusses the role of information and communication technology (ICT) in current agricultural systems. These ICT-integrated systems started on machines (tractors, combines, etc.) but are rapidly spreading to the entire agricultural production chain. Machine-to-machine communication and machine-to-field communication have become current practice. The author ends with a look to the future farm-site, which will be automated and information rich with agricultural mechanization systems acting as both information gatherers and physical implements. This level of information would influence the production value chain before and after the farm-site itself and afford us an opportunity to meet future agricultural demands.

The fourth article, by Denesuk and Wilkinson of IBM, describes how information is used to track and trace food in a supply chain. The authors emphasize benefits that accrue when the "physical" world meets the "digital" world. The article also provides a list of key priorities for supporting a maximum impact on agricultural business productivity and efficiency throughout the value chain

The final article, by Chaubey, Cherkauer, Crawford, and Engel of Purdue University, is an overview of sensing methods and modalities for agriculture. The authors describe the specific physical quantities that must be converted into information, as well as the transduction mechanisms that perform the conversion. In addition, they discuss the need for integrating agricultural sensing systems that operate on a wide range of spatial and temporal scales.

One clear message that permeates the collection of articles is the complexity associated with integrating agriculture and IT. Another message is the imperative that we move forward from where we are. In fact, we really have no other choice.

We recognize that this issue of *The Bridge* will not be the final word on the topic, but we hope it will be a valuable part of the conversation between technologists and policy makers working to ensure a secure future for our nation and our planet.



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Innovation and Urgency: Toward a New Green Revolution

Mike Baroni is vice president, Economic Policy, Archer Daniels Midland Company.

Of all the factors underlying agriculture's productivity gains in the past 60 years—better seeds, irrigation, fertilizer, crop protection, soil management, more sophisticated machinery—the most critical may have been a sense of urgency. When Norman Borlaug, the father of the Green Revolution, exported his disease-resistant wheat from Mexico to India and Pakistan in the 1960s, he was driven by a desire to achieve "a temporary success in man's war against hunger and deprivation." The revolution that followed was based both on scientific innovation and a determination to alleviate human suffering.

This same sense of purpose, coupled with new technology, is inspiring individuals and organizations throughout the agricultural value chain to meet the challenges of a global population headed toward 9 billion by 2050. To ensure that agriculture can meet future needs, the world will have to (1) reduce the millions of metric tons of post-harvest crops lost to pests, disease, and inferior storage methods each year; (2) make better use of the crops and biomass already grown while using water and other inputs sparingly; and (3) increase yields on existing land in ways that minimize the need to bring additional acres into production. As you will learn in this edition of *The Bridge*, better information technology is already furthering progress toward each of these goals.

Applying existing knowledge and processes in regions where agriculture has been slow to realize its potential could produce additional gains. For example, the UN Food and Agriculture Organization has demonstrated that farmers in the developing world can reduce post-harvest losses from 15 percent of what they grow to near zero just by using basic metal silos to protect harvested crops. Results such as this demonstrate why we have established the ADM Institute for the Prevention of Postharvest Loss at the University of Illinois.

To make better use of crops farmers already grow, we are teaching cattle feeders to replace grain in their animals' rations with corn stalks, cobs, and leaves treated with slaked lime—a process first described in scientific journals in the late 1950s. And in west Africa, we're helping cocoa farmers improve yields and quality simply by providing training in sustainable agronomic practices, access to basic market information, and other services often taken for granted in the developed world.

In our view, these simple innovations and interventions—along with the information technology, seed technology, and equipment being developed today—suggest that the world might be on the verge of a new Green Revolution. Despite constraints on water, arable land, and other resources, we believe that with ongoing innovation, investments in agricultural research and infrastructure, and partnerships throughout the value chain agriculture can meet the needs of a growing world sustainably and responsibly.

Information technology could have as big an impact on agriculture in the next half-century as mechanization had in the previous century.

Information Technology and Agriculture

Global Challenges and Opportunities

K.C. Ting, Tarek Abdelzaher, Andrew Alleyne, and Luis Rodriguez

K.C. Ting

Tarek Abdelzaher

Andrew Alleyne

Luis Rodriguez

The world population is on track to increase by approximately one-third—to more than 9 billion people—in the next 40 years. Feeding a population that large, which may require doubling agricultural productivity, will only be feasible with significant, even revolutionary, improvements in agricultural processes and equipment. In the past, agriculture has benefitted from, and often driven, improvements in technology. For example, in this country, increased mechanization on modern farms led to the change from an agrarian to an urban demographic (NAE, 2000).

K.C. Ting is professor and head of the Department of Agricultural and Biological Engineering; Tarek Abdelzaher is a professor in the Department of Computer Science; Andrew Alleyne is Ralph and Catherine Fisher Professor of Engineering and associate dean for research; and Luis Rodriguez is an assistant professor of agricultural and biological engineering and has an appointment in the Information Trust Institute. All are at the University of Illinois, Urbana-Champaign.

In this article we explain how information technology (IT), a relatively recent field that began a little more than 60 years ago (Shannon, 1948), could have at least as big an impact on agriculture in the next half-century as mechanization had in the previous century. We present a systems-level perspective on the challenges and opportunities afforded by the integration of agriculture and IT.

Agricultural Challenges

In this section we outline five challenges associated with agriculture that must be overcome to achieve the desired increases in productivity: inherent heterogeneity; unanticipated disturbances; large geospatial dispersion; security and safety requirements; and constraints.

Inherent Heterogeneity

By its very nature, agriculture works with biological systems that are inherently heterogeneous in composition and processes. Fields can vary in soil type and moisture content down to a resolution of a square meter. Weather patterns can vary spatially and temporally in terms of sunlight and rain. Raw materials themselves have basic genetic variations from plant to plant and animal to animal. Indeed, genetic variation is often biologically useful for increasing resistance to diseases and pests. But compare this heterogeneity with the homogeneity of other industrial processes, such as Henry Ford's assembly line, and the challenges associated with maximizing product yield using a minimum of resources become apparent.

Unanticipated Disturbances

Agricultural processes are much more vulnerable to unanticipated disturbances than many other industrial processes. The weather can cause floods or bring hail storms that can devastate crops. Pest or disease infestations can rapidly affect, if not wipe out, large quantities of raw material. When we contrast this environment to the carefully controlled (temperature, humidity, etc.) clean-room environment of the semiconductor fabrication industry, we immediately understand that, because of external forces, the levels of precision in crop or herd yield are far lower than in other industries.

Large Geospatial Dispersion

Various points in an agricultural supply chain are widely dispersed, and the overall agricultural system can be segmented into interconnected sub-processes (Figure 1). Because agriculture is land-intensive, it requires significant acreage for the in-field parts of the process chain, which are usually not collocated with upstream or downstream processes.

Another challenge related to geospatial dispersion is that the processing of some raw materials such as livestock and perishable crops is time critical. Thus, long distances between processing points in the supply chain introduce risks into the overall viability of the entire process.

Security and Safety Requirements

Security and safety are paramount for agricultural systems on two separate time scales. On a short time scale of days or weeks, the safety of food is critical because many products are eventually ingested by humans. Protecting human health requires tight process management of the agricultural supply chain on a global scale.

On a longer time scale of years or decades, sustainability of the natural environment is critical to long-term societal health. Agricultural enhancements, such as pesticides or fertilizers, must be used in ways

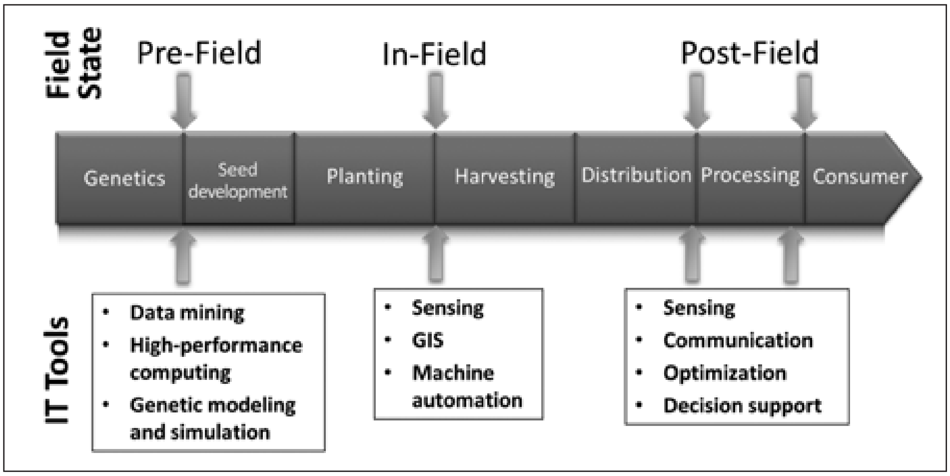

FIGURE 1 Chain of processes for agricultural crops. In the pre-field state, much of the work in crop science and genetics is associated with bio-informatics. In the in-field state, much of the work depends on agricultural mechanization. In the post-field state, logistics, large-scale processing, and supply chain management are key factors.

that increase productivity without adversely affecting the overall quality of life. Similarly, resources, such as land and water, must be used in ways that can be sustained indefinitely.

Constraints

All of these challenges must be met within the constraints inherent in the agricultural process. For example, the amount of arable land is relatively fixed globally, particularly in more developed countries. Time is also a key constraint, particularly for time-sensitive systems, such as livestock and perishable produce. There is a finite window of time during which these agricultural products are viable during processing. Finally, the first four challenges must be met within the constraints of economic viability (i.e., cost).

Opportunities Enabled by Information Technology

The challenges described above also provide significant opportunities for using IT. Indeed, if agriculture can be seen as a supply chain, then many of the existing paradigms for managing supply chains are already available.

Besides upgrading physical infrastructure, the efficiency of supply chains can be improved by the acquisition and exploitation of information resident in the chain itself. Access to these data makes monitoring of existing processes, rapid responses to changes in the supply chain, and optimal allocation of resources more feasible. These approaches can be summed up as information gathering, information processing, and decision making, the same principles that apply to management of supply chains in other industries.

Information Gathering

The ability to gather agricultural information through advanced sensing systems has been improving steadily over the past two decades, and the unit cost per bit of information has decreased in line with similar cost decreases in other industries. For agriculture, there are three major types of sensing systems: physical, biological, and human.

Physical Sensors

Physical sensors, the most prevalent of the three types of sensing systems, are used throughout the chain shown in Figure 1. DNA sequencers for crops gather genetic information about crop varieties and provide input for bio-informatics algorithms that can identify promising strains (e.g., herbicide-resistant soy or wheat) (Gale and Devos, 1998). Moisture sensors correlate soil-to-capacitance changes for the in-field monitoring of moisture. In addition, nitrates and other chemical compositions can be sensed by in-field devices that are commercially available (Ehsani et al., 1999).

Remote sensing is used to collect broad geospatial information about in-field systems (Nowatzi et al., 2004). For example, Figure 2 shows different electromagnetic reflections for two health states of sugar beet crops as the result of complex absorption and reflection of solar energy. A thorough understanding of this spectrum for specific crops can be used to calibrate a sensor that can provide health or growth data on particular agricultural systems. A similar technique can be used to monitor livestock by sensing, for example, methane emissions.

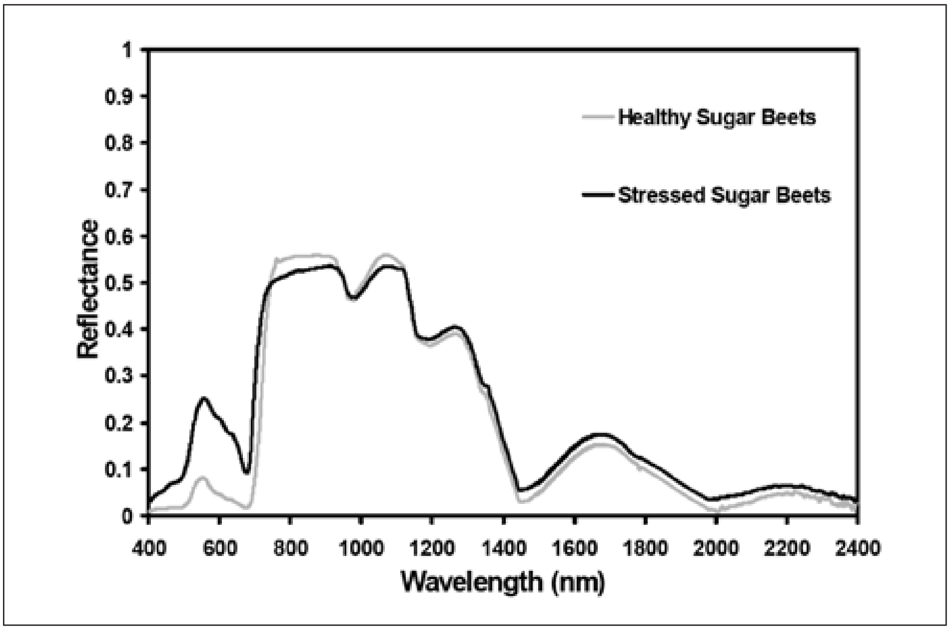

FIGURE 2 Spectral signatures of two contrasting states of sugar beet crops (Nowatzi et al., 2004). The different wavelengths of the electromagnetic spectrum range from short (deep UV) to long (infrared). Source: Adapted from Nowatzi et al., 2004.

Information gathering in agricultural processing facilities is done with many of the same sensing modalities used for monitoring conditions (e.g., temperature, mass flow, chemical composition, etc.) in chemical processing facilities.

Global information systems (GIS) can pinpoint geospatial locations of agricultural units in a supply chain using radio frequency identification and global positioning systems (Attaran, 2007). These systems can track and monitor crops and livestock as they progress "from farm to fork."

Biological Sensing

Biological sensing, sometimes called indirect sensing, is physical sensing augmented by biological cues. The state of produce can be inferred based on the monitoring of a biological agent, such as an insect or bacterial population. This can be done in-field or during post-field transport and processing. An illustrative example would be a model for the relationship between crop yields and the presence of pollinators. This model would both monitor pollinator counts and provide a basis for inferring future crop yields (Garibaldi et al., 2011).

Humans in the Loop

Not all data about agricultural systems come from engineered instrumentation and sensors, such as those mentioned above. Humans in the loop are an important data source that should not be overlooked. Indeed, networking advances in this age of IT can significantly improve our understanding of the workings of highly distributed, poorly automated socio-physical systems that may nevertheless significantly impact the planet's food supply. This is especially pertinent in developing countries, where cell phone penetration is extensive, especially compared to other technologies such as computers or personal vehicles. Although "crowdsourcing" has been used effectively in other domains,[1] its application in the agricultural domain is still largely unexplored.

Opportunities for information gathering in agriculture are primarily in networking individual pieces of information from many sources throughout the supply chain. The individual pieces of sensed data contain local information at time and spatial resolutions that allow for increasing levels of "separability" or granularity. Taken together, these data provide a global view that is more useful than any individual unit of information. The combination of simultaneously separating and aggregating information is the real power behind information gathering (Sonka et al., 1999).

Information Processing

Processing of information entails manipulating data to change it from a less useful form to a more useful form. This computational activity turns the binary 1s and 0s of the data world into information that can be used by humans. In this section we describe modeling and data mining, two major aspects of information processing related to agriculture.

> *The simultaneous separation and aggregation of information is the key to effective information gathering.*

Modeling

The purpose of modeling is to represent the physical world in computational simulations, which can provide a basis for making predictions. Currently, many different types of models are being developed, each one tailored to a specific use and community. For example, models of genetics are associated with bio-informatics. Models of nutrients and water flow (Robinson et al., 2000) throughout a field may be cued to in-field growth models and used to predict yields. Models can also be used to predict the behavior of the overall supply chain (Stutterheim et al., 2009). Even though the accuracy of these models is often debated, they are useful for scenario-based planning and decision making.

Data Mining

Data mining is a technique for extracting knowledge and information from unstructured data sets. Data-mining tools have been used in limited ways for agriculture, but there are still enormous untapped opportunities. Much like modeling, data mining has so far been focused largely on individual uses and communities.

Today, data-tagging protocols and search patterns are being used to tease out hidden relationships to

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[1] See *http://www.google.org/flutrends/*.

predict trends in agricultural processes (Mucherino et al., 2009). A pure data-mining approach would make possible inferences based solely on data, thereby eliminating the need for developing infrastructure associated with modeling.

Opportunities for the Future

Although data mining based on specific knowledge of a particular agricultural system usually provides more insight than completely unstructured searches, modeling tools, used in conjunction with data mining, provide a framework for searching for hidden correlations or relationships. The coupling of models and data frameworks also has the potential to provide insights into the entire supply chain as a system.

By using a combination of these technologies, we should be able not only to predict behavior, but also to gather enough information to determine whether the predictions are accurate. Moreover, macro-scale models and data frameworks can be incorporated into local, high-resolution models and data frameworks to clarify overall supply chain behavior.

Bringing together disparate types of information processing will be challenging but could provide many benefits. For example, we would be able to "zoom in" to see how micro-scale activities, such as individual systems in the supply chain, might be affected by macro-scale processes acting as boundary conditions to those systems. Simultaneously, this modeling and data-mining capability would allow us to "zoom out" and see how macro-scale processes influence, or even dominate, interconnected networks of micro-scale sub-systems.

Currently, global decision making and local decision making are loosely coupled.

Decision Making

Moving effectively from data to decisions can often mean the difference between success and failure for an enterprise. Many individual organizations have integrated information systems to assist in making decisions on a space and time scale relevant to their particular interests. For example, manufacturers of agricultural equipment have adopted systems that allow GIS sensor data to flow to machines and control the site-specific applications of seeds, fertilizers, or pesticides. Similarly, seed companies have the ability to monitor crop growth trials in several different fields and select useful genetic varieties for market in a time frame suitable for future planting seasons.

However, agriculture has several domains and several stakeholders within these domains (Figure 1), and our current ability to gather information across the supply chain outpaces our ability to synthesize and make time-critical decisions that affect the system as a whole.

Levels of Decision Making

Decision making in agricultural systems occurs on many levels. On the micro-scale, individual economic and technical decisions can be made down to the level of an individual animal or plant. For example, a decision can be made about how much of a fertilizer to apply to a single plant based on the cost of the fertilizer and the potential yield of the plant. Currently, micro-scale decisions at one point in the supply chain are made independently of micro-scale decisions at other points in the supply chain.

On the so-called macro-scale, global decisions that affect multiple aspects of the overall supply chain must be made about agricultural policy. Decisions at this level include how much surplus of a staple crop to store in reserve or whether to allow genetically modified foods into a given country. Currently global decision making and local decision making are only loosely coupled, particularly in developing countries where there is relatively little use of IT in agriculture.

The Need for Coordinated Decision Making

Opportunities for decision making in agriculture are enhanced and enabled by the ubiquity of information gathering and the power of modern information processing. If, for example, data analytics associated with data mining tools can be combined with contextual or situational information from models or sensor data, the combined data could provide input for powerful computing algorithms that could provide support for the right decision choice at the right time. Moreover, such decisions could be made scalable so decisions for one geospatial location or one agricultural product would not conflict with other decisions.

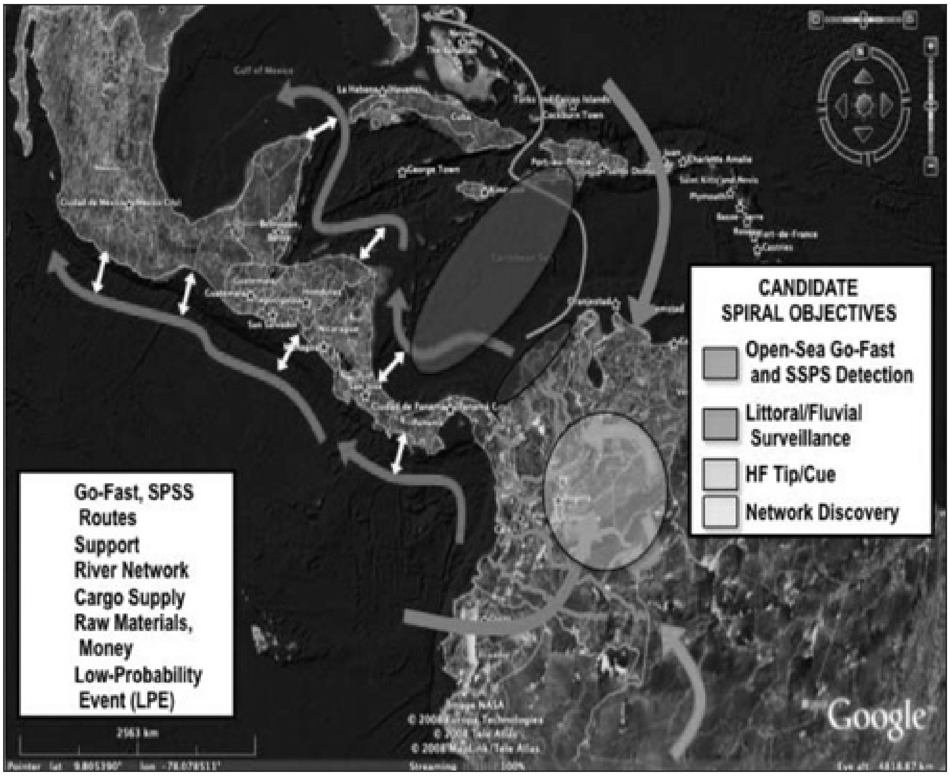


FIGURE 3 A visualization by the Thunderstorm Program showing multiple sources of information that are fused to support rapid decision making and resource deployment over a large geospatial area.

This level of coordinated decision making on a regional basis is currently lacking in modern agricultural practice, despite the significant benefits it would provide in yield and efficiency. Lessons can be learned from other fields, such as the U.S. Department of Defense (DOD), which often has to make large-scale, time-critical, distributed decisions that affect a value chain or supply chain.

An illustrative example (Figure 3) shows how DOD fuses information from multiple intelligence, surveillance, and reconnaissance (ISR) platforms to come up with near real-time predictions and decisions to commit resources (Lemnios, 2010). The goal of this program, named Thunderstorm, is to demonstrate the identification of fast-moving threats (drug runners) from large data sets and make decisions about where to place interception points. This requires massive amounts of information from maritime and satellite ISR platforms, intensive computing based on oceanographic models and data-mining techniques, and decision-making tools for detecting threshold levels for taking action.

An analogy to agriculture would be the sudden emergence of crop pests or livestock disease that must be detected (information gathering), damage levels and transmission paths that must be predicted (information processing), and global or local interdiction strategies that must be created and implemented (decision making).

Although current capabilities in agriculture are not on the level of the DOD example given above, the future of agriculture and IT lies in this direction. Specifically, the integration of information can help address many of the challenges identified in the opening section of this article: inherent heterogeneity; unanticipated disturbances; geospatial dispersion; security and safety requirements; and constraints.

Exploiting Opportunities and Meeting Challenges

Capitalizing on the kinds of opportunities described above will require using technologies in a coordinated way. Information gathered must be fed to processing systems housed in data centers of respective agribusinesses. The data can then be mined and used in decision making, either automated or by humans. Relevant decisions could include the type and quantity of information to be gathered in the first place.

By taking advantage of the combined capabilities of information gathering and information processing techniques, decisions can be made that address the challenge of inherent heterogeneity by accommodating it, and even exploiting it when this would be advantageous. For example, GIS and site-specific application can exploit heterogeneities in soil in a field by spatially varying the application of seed or fertilizer to minimize the total amount used.

Unanticipated disturbances, such as changes in weather or outbreaks of disease, are inevitable occurrences in the agricultural setting. As genetic modifications to crops and livestock produce increasingly monocultural, biological systems, susceptibility to such disturbances increases. One can react to these disturbances, or one can predict and anticipate them. In either case, information can inform and accelerate the response.

On a shorter time scale, such as months, an unexpected flood might cause local food shortages creating subsequent food security issues. In this situation, resources can be re-routed based on supply chain information.

On a longer time scale, computational modeling can be used to predict climatic changes and their effects, and sensing can be used to validate and calibrate modeling predictions and extrapolations. This information capability can then be used in scenario-based planning to guide decisions about the types of genetic enhancements of crops or livestock that would be most suitable for coping with predicted environmental changes.

Currently, the challenge of geospatial dispersion is addressed by using IT to "tag" individual crops or animals in the supply chain and geo-locate them in space and time. As the price of tags and readers comes down, the ubiquity of sensed information will certainly increase.

Security and safety challenges can be met by improving awareness of all aspects of the supply chain. Continuous monitoring of crops or livestock can alert us to the presence of potentially threatening biological elements, enabling a prompt response. If a malicious activity occurs, data-mining techniques coupled with appropriate information gathering along the supply chain can be used to pinpoint the location of the security breach and provide information about how it propagates. This information can then be used to make a decision about the appropriate response.

As IT is increasingly used to exploit opportunities and address challenges, agricultural output will increase, despite the challenging, inherent constraints. Higher output per unit time, unit cost, or square meter of land will follow, along with faster and better time-critical decisions.

Future Needs

Many of the technologies and techniques discussed above are already being pursued by individual organizations and companies. What we need now is closer collaboration and integration among stakeholders to accelerate the introduction of IT into agricultural processes.

Industries such as telecommunications have benefitted greatly from collaboration leading to standardization in the IT space. We believe that agriculture would benefit similarly if industry-government partnerships were to define agriculture-specific goals and standards for information thereby introducing uniformity and unleashing innovation similar to innovation in the telecom and computing industries. This could be particularly important in developing countries where modern IT infrastructure (e.g., the cellular communication network) tends to leapfrog established frameworks.

Summary

Agriculture is a critical human activity that will become increasingly important as the world population grows. In fact, given the necessity of feeding a growing planet, we have no choice but to increase our output with available resources, and IT, which offers many opportunities for addressing challenges to increasing global agricultural output, must play a central part in meeting that goal. Although IT has influenced many industries and greatly improved the management of supply chains, to date it has only influenced agriculture in a relatively localized way. It will take buy-in by all stakeholders and coordinated, communal efforts on a global level to integrate agriculture and IT to meet the needs of a hungry world.

References

Attaran, M. 2007. RFID: an enabler of supply chain operations. Supply Chain Management: An International Journal 12(4): 249–257.

Ehsani, M.R., S.K. Upadhyaya, D. Slaughter, S. Shafii, and M. Pelletier. 1999. A NIR technique for rapid determination of soil mineral nitrogen. Precision Agriculture 1(2): 219–236.

Gale, M., and K. Devos. 1998. Comparative genetics in the grasses. Proceedings of the National Academy of Sciences 95(5): 1971–1974.

Garibaldi, L., M. Aizen, A. Klein, S. Cunningham, and L. Harder. 2011. Global growth and stability of agricultural yield decrease with pollinator dependence. Proceedings of the National Academy of Sciences 108(14): 5909–5914.

Lemnios, Z.J. 2010. Transforming U.S. Defense R&D to Meet 21st Century Challenges. Plenary presentation to SPIE Defense Security and Sensing Symposium, Orlando, Fla., April 2010.

Mucherino, A., P. Papajorgji, and P. Pardalos. 2009. Data Mining in Agriculture. Springer Optimization and its Applications, Vol. 34. New York: Springer Verlag.

NAE (National Academy of Engineering). 2000. Greatest

Engineering Achievements of the 20th Century. Available online at *http://www.greatachievements.org/*.

Nowatzi, J., R. Andres, and K. Kyllo. 2004. Agricultural Remote Sensing Basics. NDSU Extension Report AE 1262. Available online at *http://www.ag.ndsu.edu/pubs/ageng/gis/ae1262.pdf*.

Robinson, B., H. Viswanathan, and A. Valocchi. 2000. Efficient numerical techniques for modeling multicomponent ground-water transport based upon simultaneous solution of strongly coupled subsets of chemical components. Advances in Water Resources 23(4): 307–324.

Shannon, C. 1948. A mathematical theory of communication. Bell System Technical Journal 27(July and October): 379–423 and 623–656.

Sonka, S., R. Schroeder, S. Hoving, and D. Lins. 1999. Production agriculture as a knowledge creating system. International Food and Agribusiness Management Review: 165–178.

Stutterheim, R., C.N. Bezuidenhout, and P.W.L. Lyne. 2009. A framework to simulate the sugarcane supply chain, from harvest to raw sugar. International Sugar Journal 111(1324): 250–255.

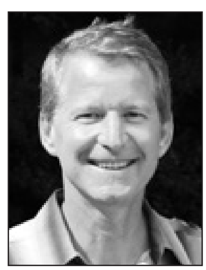
Rapid advances in biotechnology, breeding, and agronomics require equally sophisticated information systems.

How Smart-IT Systems Are Revolutionizing Agriculture

Jason K. Bull, Andrew W. Davis, and Paul W. Skroch

Jason K. Bull

Andrew W. Davis



Paul W. Skroch

Corn production in the United States has doubled in the last 40 years (Figure 1), primarily as a result of improved cultivars that exploit agronomic advances in soil management and increased planting density (Hallauer et al., 1988). Monsanto, together with other key industry partners, is committed to helping farmers double the yields of corn, soy, and cotton again by 2030 through a mix of advances in biotechnology traits, breeding, and agronomics.[1]

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[1] See *http://www.monsanto.com/ourcommitments/Pages/sustainable-agriculture-producing-more.aspx.*

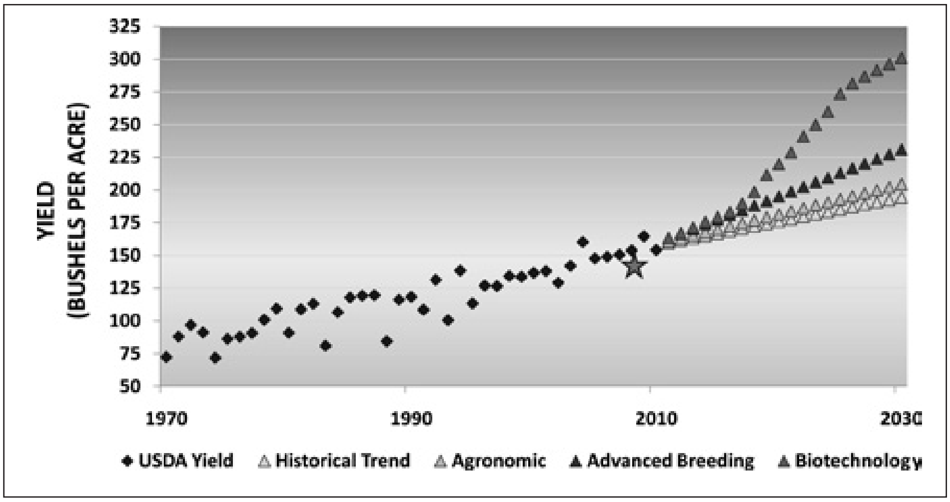

FIGURE 1 Increase in yields since 1970. Doubling yields by 2030 will require advances in biotechnology, breeding, and agronomics.

This commitment is based on the success of the current generation of genetically improved crops that have changed the face of agriculture by increasing yield, reducing yield variability, reducing the use of pesticide and insecticide, and raising the profit per acre for farmers (Park et al., 2011). Approximately 95 percent of soybeans and 75 percent of corn grown in the United States have been improved through biotechnology. More than 95 percent of soy beans in Argentina and 50 percent in Brazil have also been improved.[2]

When given a choice, farmers have consistently adopted biotechnology-improved products because of the advantages listed above. These products, the result of sophisticated technological breakthroughs in genomics, breeding, and agronomy, have changed agricultural practices and expectations. For example, insect-resistant crops have reduced the use of pesticides globally compared with conventional crops (Carpenter, 2010).

Agricultural companies continue to develop seed products with a variety of traits and characteristics adapted to specific environmental regions. The next generation of products promises further improvements in yield and stress traits (e.g., improved drought tolerance), better use of nitrogen fertilizer by the plant, and broader spectrum insect protection. Breakthrough advances in breeding methodologies (e.g., molecular markers and sequencing) promise higher yielding cultivars, and targeting the resultant seed products to optimal management practices promises additional yield gains (Figure 2).

Rapid advances in these complex scientific areas require equally sophisticated information systems. In this article we discuss the changing role of information technology (IT) systems in the evolution of research on seeds and traits as well as on the future of agriculture. We also discuss how systems are evolving to accelerate decisions and opportunities for cross-industry partnerships to develop the next generation of "smart IT" systems in agriculture.

Information, the Heart of Modern Agriculture

Information is essential to modern agriculture, from the creation of new hybrid and varietal products to the placement of products in the correct management zones to capturing value at harvest time. Choosing the correct products for a given farm field requires accurate information about traits in the germplasm, as well as the overall performance of those products. As the combinations of biotechnology traits in products become more complex, companies must provide more information to farmers about traits, product performance, and product fit to agronomic practices.

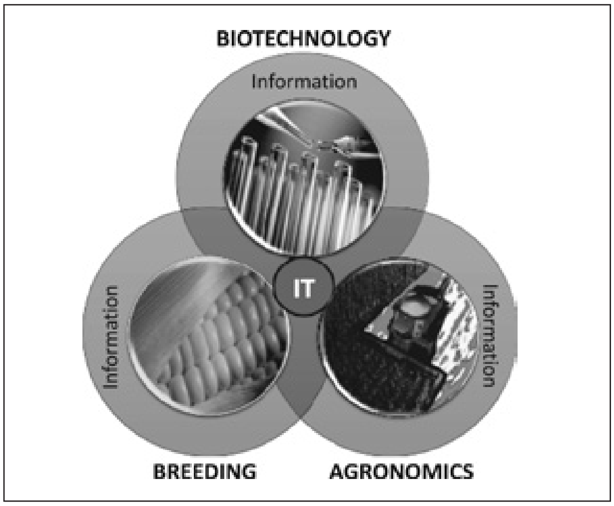

FIGURE 2 Information connects the technologies required to create the next generation of products.

[2] See *http://www.monsanto.com/newsviews/Pages/do-gm-crops-increase-yield.aspx.*

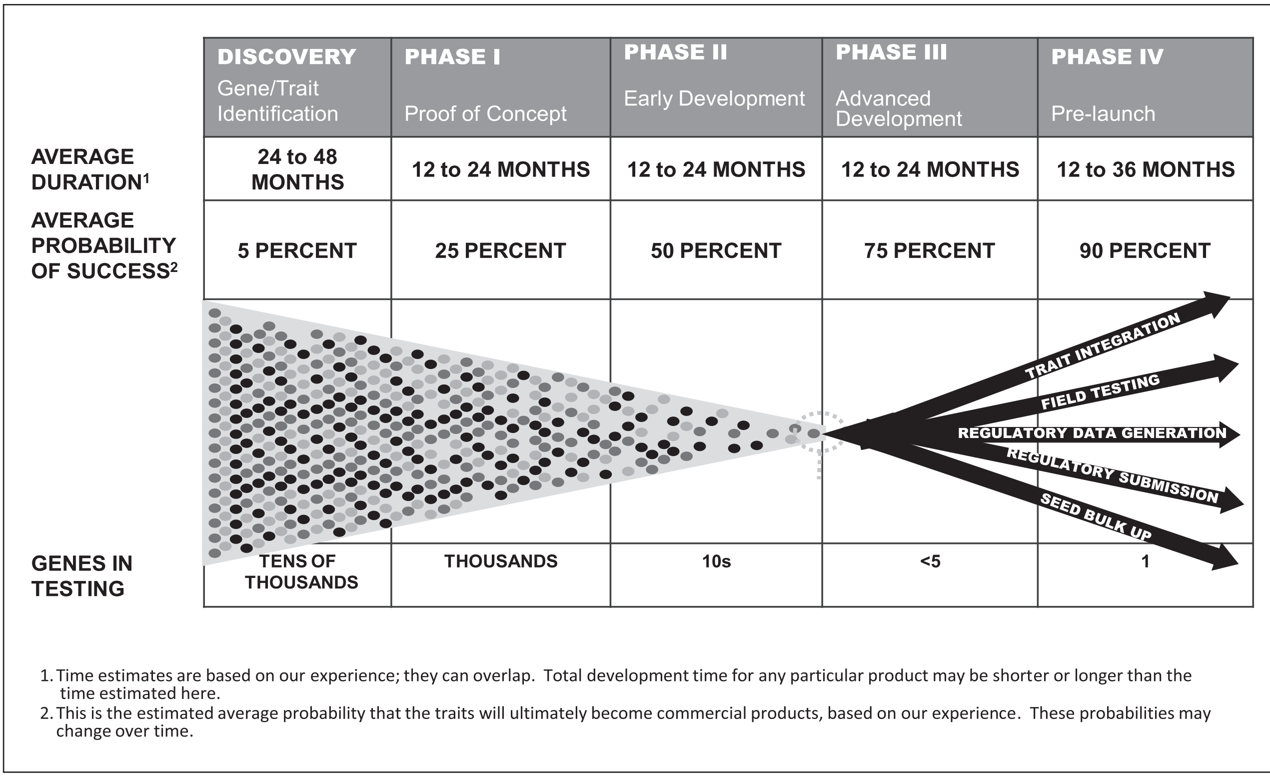

FIGURE 3 Candidate products are culled as they advance through phases in the R&D pipeline. Information must be aggregated and reviewed to make the best possible decisions for each phase.

Recommending the right product for the right management environment or zone involves analyzing many variables (e.g., soil types, drainage patterns, yield in past years, insect pressure, disease pressure). Such analyses require that companies collect information about product performance at refined environmental scales and translate this information into recommendations for farmers. Increasingly, the product is information itself as much as it is seeds and traits.

The development of new products has become a race to integrate and leverage the vast amount of information produced by industrial research and development (R&D) pipelines and industry partners. The increasing complexity of information required for product creation, placement, and value capture requires sophisticated IT systems engineered to handle the scale of information and to interrogate that information to support intelligent decisions.

Success in the marketplace is directly linked to the efficiency and accuracy of translating research information into decisions about products. Thus, IT systems merit significant investment and are considered a key factor in a company's competitive advantage.

Pipelines for Biotechnology and Breeding

Demand for biotechnology traits and locally adapted germplasm has led to the development of agricultural R&D pipelines similar in overall form to those used in the pharmaceutical industry (Figure 3). Product advancement decisions are made in distinct phases. In each phase, candidate products are culled, leaving only the most promising to move on to the next phase. Testing in subsequent phases is increasingly stringent to ensure that the future commercialized product will meet the needs of customers.

Information is generated and consumed by thousands of scientists in high-throughput product development and assessment pipelines. Monsanto has two primary pipelines, one for biotechnology and one for breeding (Figure 4). The biotechnology pipeline identifies new and novel genes for traits, such as insect resistance, herbicide tolerance, and drought tolerance. The breeding pipeline creates germplasms with advantageous native genes that are locally adapted to specific geographic regions across the globe.

Laboratory and field work, each of which contributes to screening and the understanding of novel candidate

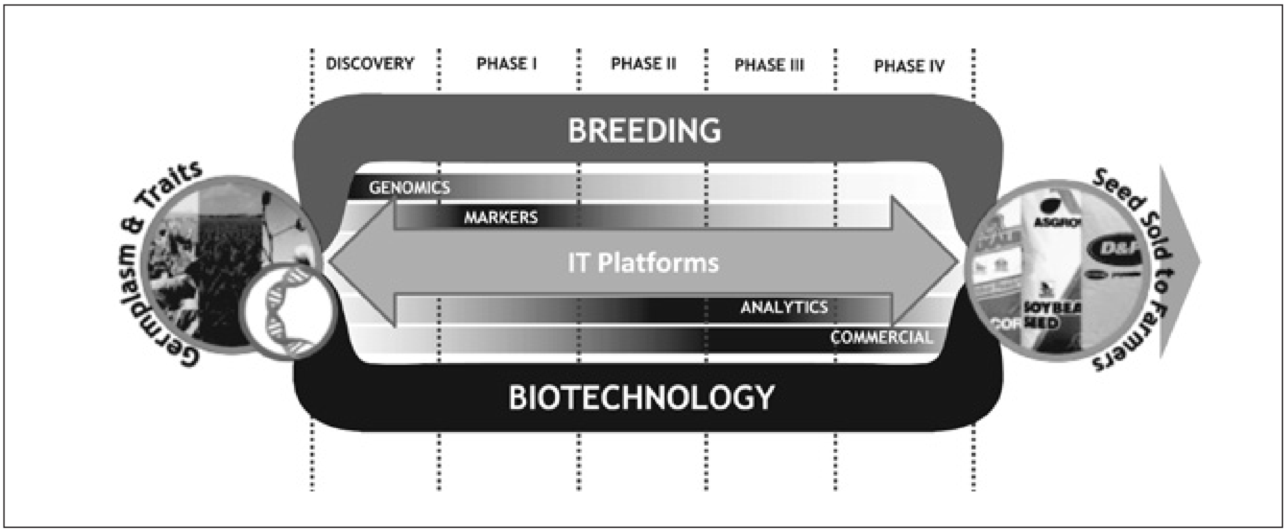

FIGURE 4 Overview of the Monsanto R&D Pipeline. Biotechnology and breeding form parallel R&D pathways, linked by shared tools and technology. IT platforms are major links that support research, product characterization, and product advancement decisions.

genes and germplasm, are integrated in both pipelines. Information collection is industrial in scale and often highly automated.

In the biotechnology pipeline, for example, genomics and molecular biology tools are used to select and characterize thousands of genes every year. The pipeline is organized into a series of steps, including gene nomination, sequencing, cloning, transformation, and greenhouse and field testing. Each step involves integrated laboratory or field processes that together provide a comprehensive view of gene function and quality.

Marker-assisted breeding, a technique in which DNA markers are used to identify individuals with favorable gene combinations, is used in the breeding pipeline. Individual seeds are then "chipped," and the shavings are used to analyze the DNA genotype of each seed (Figure 5). Millions of samples are processed and billions of data points are generated every year.

The chipping, genotyping, and planting of predicted best selections is extremely time sensitive and highly automated. Monsanto runs the largest field testing network in the world. Seeds are planted in millions of field plots every year in thousands of locations around the globe, and information about multiple characteristics of each resulting plant is collected (e.g., yield, moisture content, plant height, disease reactions). Evaluations are conducted in differing geographies many times per year.

The logistical operation of this network involves management of seed inventory, distribution, and experimental design for every plot planted, harvested, and analyzed. Millions of data points are analyzed for the North American harvest alone.

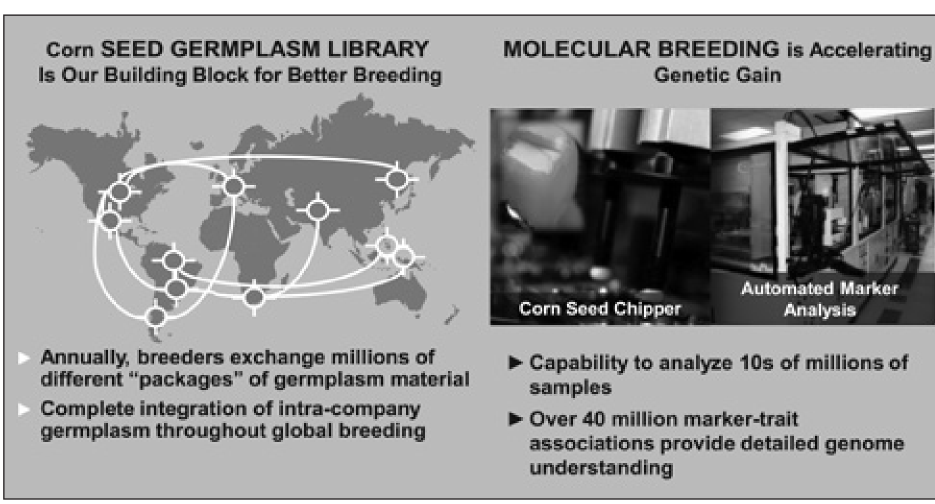

FIGURE 5 Industrial-scale information collection and management for R&D pipelines. IT systems enable global interchange of breeding germplasm. Automation and technological advancements, such as seed chippers and molecular markers for genotyping, require IT systems for managing analysis and interpretation.

Finally, the products advanced through both the biotechnology and breeding pipelines are integrated (again using genetic crosses, field plot evaluations, and molecular markers) to create superior products with the new genes of interest in the best locally adapted germplasm. Creating novel biotechnology products and assessing product performance on this massive scale can only be done with advanced IT systems.

The IT Pipeline

It can take 10 to 15 years to discover and commercialize new genetically enhanced products. The process requires standardized procedures and regulated testing to verify trait expression and farm value. To orchestrate this multistep, multistage, multiyear, interdependent evaluation process, IT systems must model the pipeline so candidate products can be tracked and capacity optimized, results analyzed and interpreted, and compliance ensured throughout. In other words, it takes an IT pipeline to manage an R&D pipeline.

IT systems are a core component in the transition from breakthrough science to industrial-scale implementation.

For example, managing a global-scale plant biotechnology pipeline requires an IT workflow system that connects laboratory assessment points (gene nomination, gene construction, transformation) seamlessly to track detailed information to understand and evaluate genes for various traits. The system brings transparency to the pipeline, enables decisions about gene advancements, and eliminates laborious manual tracking.

Science at the Speed of IT

An organization with the ability to quickly leverage new scientific breakthroughs on a massive scale has a substantial competitive advantage, and IT systems are a core component in the transition from breakthrough science to industrial-scale implementation. For example, breakthroughs more than a decade ago in molecular marker technology, which enabled accurate "tagging" of genes of interest, led to a massive change in the incorporation of novel genes into adapted germplasm. That change could only be made thanks to wholesale innovations in IT systems, which established high-throughput, high-capacity DNA genotyping laboratories, optimized workflows that automatically select plants with the genes of interest in the best backgrounds, and integrated these workflows into the context of an already massive, global breeding pipeline.

Like most companies, Monsanto's R&D pipelines rely on a mix of third-party and highly customized proprietary IT systems that integrate information across workflow steps in each pipeline. These systems make it possible to eliminate many manual steps and replace them with repeatable automation. Having IT systems do much of the work makes it possible for science to be automated and innovations to be leveraged on a massive scale at "the speed of an integrated circuit."

Building such systems at the desired speed and scale requires creating a new type of IT organization that melds scientific expertise in breeding and biotechnology with computer and industrial engineering. Thus, the IT organization is comprised of expert scientists in addition to computer engineers—creating a powerful combination of specialized skills in biotechnology, breeding, genomics, bioinformatics, and computer science in a single organization.

This new model for IT enables a rapid transition from emerging R&D needs and breakthroughs to engineered software solutions that industrialize the application of innovations by standardizing workflow steps, automating information production and analysis, and using standardized algorithms to recommend the best seed placement decisions possible.

In the DNA molecular-marker genotyping example, results from genotyping assays must be scored for each individual seed. With millions of samples, this task cannot be done cost effectively by manual inspection of the scores. Automating the process eliminates a workflow bottleneck and a source of human error.

Another example in the breeding pipeline is the analysis of field-trial information during harvest, when many thousands of designed experiments must be statistically analyzed to determine which candidate products are the best performers in terms of traits of interest, geographies of interest, and years of evaluation. Because every harvest takes a period of weeks and advancement decisions are time sensitive, analyses must be repeated many times as more information is collected from the field. The data are automatically quality checked and analyzed within hours of harvesting as new information becomes available.

Smart R&D Pipelines Rely on Smart IT Systems

To accelerate the creation of the next generation of seed products, the next generation of IT systems must do more than enable decisions and manage complex workflows. These smart IT systems must embody the processes they support, transform scientific intuition into repeatable decisions, and enrich and accelerate resource-constrained pipelines. From the perspective of an R&D pipeline, the focus must change from generating and managing information per se to explicitly defining the decisions made at key points in the pipeline.

The creation of smart IT systems requires a paradigm shift in the role of IT systems in the generation of advanced seed products. Traditionally, IT systems have been considered tools for collecting and managing information used by individuals to make decisions. This mindset focused more on the aggregation of information than on how that information could be used to make optimal decisions and how systems themselves could learn from those decisions in a loop of continuous improvement (Figure 6).

As the volume and variety of information to be aggregated has increased exponentially, decision making based on information aggregation followed by manual decisions by experts has begun to exceed human capacity. For example, selecting a site to conduct a regulated biotechnology field trial seems simple enough until one considers the variety of questions that must be answered to proceed. Do I have the required regulatory permits for the trial? What was grown the previous year in the same field that I should monitor? Are other biotechnology trials nearby? What is the likelihood of the stress of interest occurring (e.g., drought)?

These are just a few of the most straightforward questions that must be answered for any one trial or trait. Now consider testing thousands of genes in multiple backgrounds in thousands of locations each year, globally, in an environment in which product delays can cost hundreds of millions of dollars in lost opportunity.

Designing smart IT systems for decision management has at least three characteristics: capturing the rules and criteria for making a decision; capturing the context in which decisions are made; and capturing the outcome of those decisions so the process can be improved upon. (Figure 6).

Defining and Capturing Decisions

The first step in developing a "smart system" is to expose and capture the "decision" itself. The key is to identify decisions in the pipeline that are repeatable and that can be understood as a system of rules that can be applied to similar information repeatedly

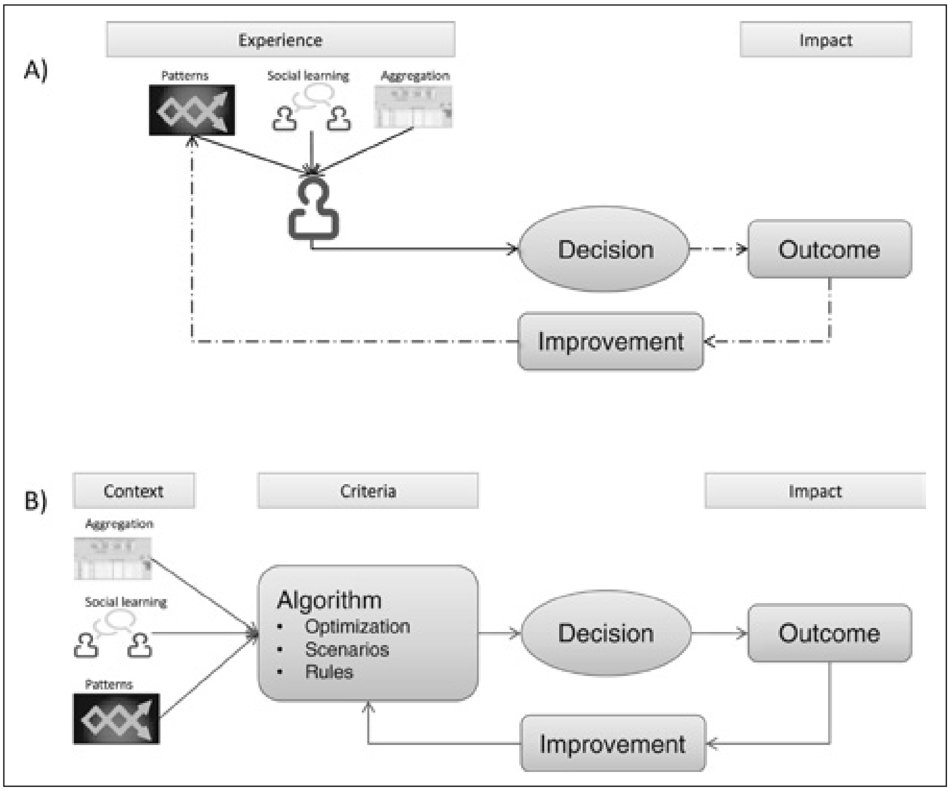

FIGURE 6 Building intelligence into a machine requires smart IT systems. A. Traditionally, experts depended on their experience to make the best decisions possible, and their knowledge of the rules and criteria for those decisions, as well as any learning, remained with the individual. Thus developing feedback loops could take years, making the accumulation of knowledge a slow process. B. By building intelligence into IT systems, rules and criteria can be turned into corporate assets that can be optimized and improved upon.

(Taylor and Raden, 2007). Exposing these rules and criteria requires detailed knowledge about the purpose of experiments and their role in the R&D pipeline.

Capturing Decision Context

A smart IT system must do more than enumerate and apply a list of rules that lead to a decision. It must also capture the context—a snapshot of temporally relevant information—in which the decision is made. Capturing the context is important for learning which information is relevant and how it can be optimally weighted.

Historical context can be provided by information warehouses that store not only what decisions were made but also the exact information that was used to make them at the time they were made. In this way, a record can be built of specific information used for a decision, which, over time, can be leveraged to reconstruct the decision process. Over time, a system "memory" is created that can be used to improve and refine future iterations of that decision.

Capturing Decision Outcomes

A smart IT system must also be able to evaluate and "learn" from the outcome of a decision. What was the impact of the decision? Did the products that advanced at one stage continue to advance? Did this candidate product actually perform better, as predicted, when a certain agronomic practice was used?

A smart IT system must be able to evaluate and "learn" from the outcome of a decision.

Humans learn, at least in part, from the consequences of actions, and a smart IT system must learn in a similar way. By capturing outcomes, the decision model can be benchmarked and improved upon, thus transforming expert decisions into corporate assets that can be learned from, measured, modeled, and subsequently improved upon again by the next generation of scientists.

Partnerships across Industry

Supporting the generation of information from high-throughput pipelines and integrating that information to enable smart IT systems are both massive tasks in terms of scope and scale. Take, for example, the scale of DNA sequencing, which can generate terabytes of information every day. In addition, projections call for exponential growth every 2 to 3 years (Kahn, 2011). Turning these data into information requires analyzing complex DNA sequences and combining that information with other information on gene function to identify new markers and genes.

Facing these challenges and others will require optimized infrastructure, including specialized computing platforms (Schadt et al., 2010), optimized data storage, and networks that support global operations. Designing and implementing these capabilities will be beyond the capacity of a single entity and will require partnerships among public and private institutions that specialize in each of these areas and have experience in applying industry-standard technologies at scale.

Building partnerships with IT providers that have demonstrated expertise in a given computing domain will enable new systems to leverage industry-standard solutions. Partnerships in highly technical areas (e.g., sequence assembly optimization) will also enable the development of sophisticated or custom solutions. Monsanto, for example, has partnered with sequencing equipment manufacturers, universities, specialized hardware manufacturers, and large IT companies to tackle the production and analysis of sequencing information to enable delivery of continually improving seed.

Information, the Next Agriculture Frontier

Agriculture is on the threshold of realizing an exciting and dynamic opportunity to apply and benefit from innovation in IT. The next generation of seed innovations, which will be necessary to double yields by 2030, will depend on how effectively the industry can collect, analyze, and use the explosion of new information to make decisions for the R&D pipeline and the farm. As products become more complex and their selection is driven by more detailed characteristics of local management zones, companies will have to provide more specific on-farm product information. In fact, this information will be as essential as the product itself (i.e., seeds and traits) to realizing maximal yields and economic benefit.

Realizing the goal of doubling agricultural yields by 2030 will require that product performance both improve and become more predictable as multiple traits are targeted to specific stresses and management zones. Optimization of agricultural inputs will become more feasible with the next generation of biotechnology and breeding traits, which will reduce the environmental impact of agriculture by reducing the use of herbicides, insecticides, fungicides, and fertilizers. Combined with advances in farm machinery and precision agriculture, farmers will be able to cultivate the same or more acres more profitably.

These advances mean that agriculture will also become increasingly technology driven, and this "technification" will depend on how we use information. Advances in the extraction and use of information from genomics and molecular breeding will create opportunities for identifying new genes for biotechnology traits. Advances in how we use information to define and use management zones will lead to optimization of product use and seed performance. Advances in information about weather and potential insect infestations will create opportunities to manage risk.

All phases of the agricultural pipeline will be transformed and will require innovations in IT systems to realize the full potential of the seed products under development and to achieve the goal of doubling yields by 2030. Success will be linked to the "intelligence" of smart IT systems, because time-to-market for new products will be linked, in turn, to how quickly and effectively information can be transformed into decisions. Realizing this vision will require new partnerships among seed companies, IT providers, and other key players in the agricultural industry to bring cutting-edge IT to the product development pipeline as well as to the farm.

References

Carpenter, J.E. 2010. Peer-reviewed surveys indicate positive impact of commercialized GM crops. Nature Biotechnology 28(4): 319–321.

Hallauer, A.R., W.A. Russell, and K.R. Lamkey. 1988. Corn Breeding. Pp. 463–554 in Corn and Corn Improvement, 3 ed., Agronomy Monograph 18, edited by G.F. Sprague and J.W. Dudley. Madison, Wisc.: American Society of AGRONOMY.

Kahn, S.D. 2011. On the future of genomic data. Science 331(6018): 728–729.

Park, J.R., I. McFarlane, R.H. Phipps, and G. Ceddia. 2011. The role of transgenic crops in sustainable development. Plant Biotechnology Journal 9: 2–21.

Schadt, E.E., M.D. Linderman, J. Sorenson, L. Lee, and G.P. Nolan. 2010. Computational solutions to large-scale data management and analysis. Nature Reviews Genetics 11: 647–657.

Taylor, J., and N. Raden. 2007. Smart (Enough) Systems: How to Deliver Competitive Advantage by Automating Hidden Decisions. Boston, Mass.: Prentice Hall.

In the future, agricultural machines will become data-rich sensing and monitoring systems.

The Impact of Mechanization on Agriculture

John F. Reid is director, Product Technology and Innovation, John Deere Moline Technology Innovation Center.

John F. Reid

Significant challenges will have to be overcome to achieve the level of agricultural productivity necessary to meet the predicted world demand for food, fiber, and fuel in 2050. Although agriculture has met significant challenges in the past, targeted increases in productivity by 2050 will have to be made in the face of stringent constraints—including limited resources, less skilled labor, and a limited amount of arable land, among others.

The metric used to measure such progress is total factor productivity (TFP)—the output per unit of total resources used in production. According to some predictions, agricultural output will have to double by 2050 (GHI, 2011), with simultaneous management of sustainability. This will require increasing TFP from the current level of 1.4 for agricultural production systems to a consistent level of 1.75 or higher. To reach that goal, we will need significant achievements in all of the factors that impact TFP.

Mechanization is one factor that has had a significant effect on TFP since the beginning of modern agriculture. Mechanized harvesting, for example, was a key factor in increasing cotton production in the last century (Figure 1). In the future, mechanization will also have to contribute to better management of inputs, which will be critical to increasing TFP in global production systems that vary widely among crop types and regional economic status.

For example, a scarce, basic resource that will have to be managed much better is water, a critical input in agricultural production. Both the

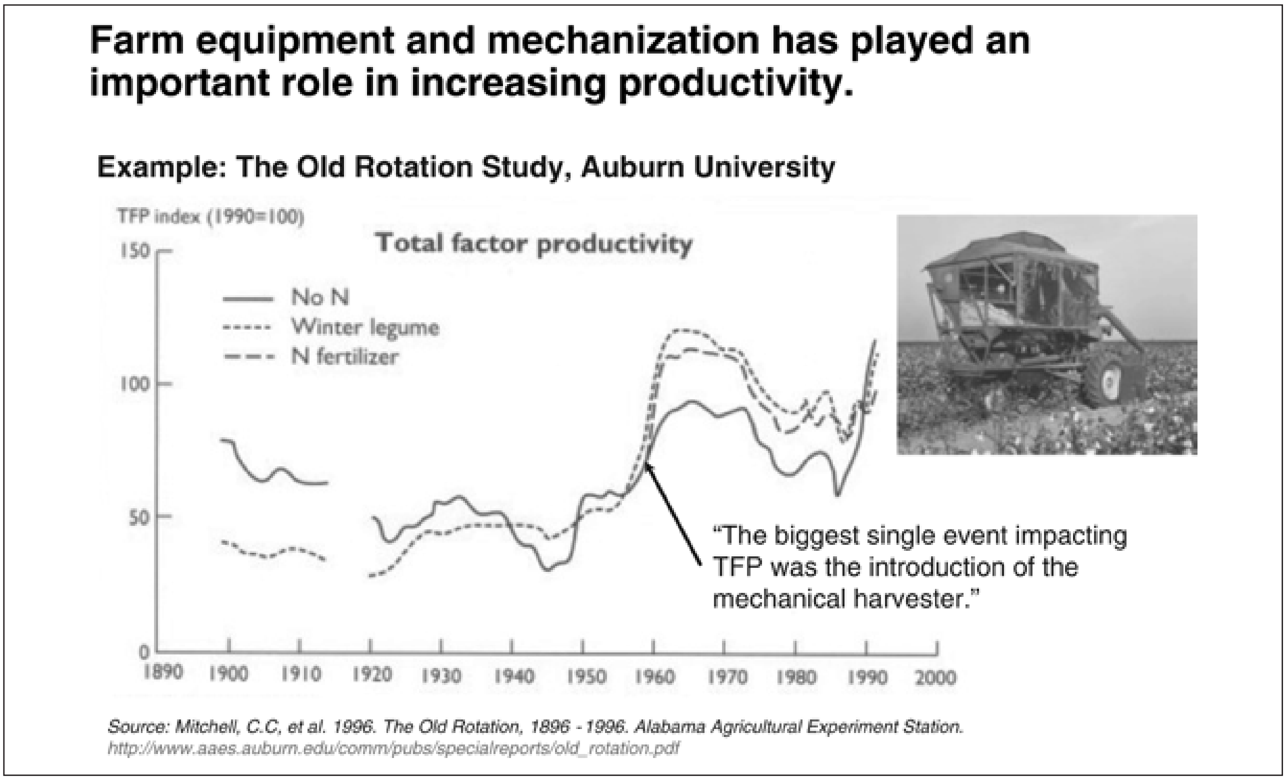

FIGURE 1 Improved farm equipment and mechanization has been essential to increasing total factor productivity (TFP) as illustrated in this example of the Old Rotation Study for cotton production.

efficiency and effectiveness of water use will have to improve dramatically.

Today, approximately 70 percent of withdrawals of fresh water are used for agriculture (Postel et al., 1996). By 2025, 1.8 billion people are expected to be living in areas with absolute water scarcity (UN FAO, 2007), and two-thirds of the world population will live in water-stressed areas. Improving water management will have to be achieved by more efficient irrigation technology and higher efficiencies in whatever technologies farmers are currently using.

In this article, I define the current state of agricultural systems productivity and demonstrate how information and communication technologies (ICT) are being integrated into agricultural systems. I also describe how the integration of ICT will create opportunities for increasing agricultural-system productivity and influencing productivity beyond the agriculture value chain.

The Impact of Mechanization on Productivity

Agricultural mechanization, one of the great achievements of the 20th century (NAE, 2000), was enabled by technologies that created value in agricultural production practices through the more efficient use of labor, the timeliness of operations, and more efficient input management (Table 1) with a focus on sustainable, high-productivity systems. Historically, affordable machinery, which increased capability and standardization and measurably improved productivity, was a key enabler of agricultural mechanization. Figure 2 shows some major developments since the mid-1800s

TABLE 1 Primary Methods for Productivity Enhancement in Agriculture

1. Efficient use of labor by:
   a. removing bottlenecks
   b. making efficient use of time
2. Timeliness of operations by:
   a. hitting optimum agronomic or business windows
   b. reducing spoilage and harvest losses of agricultural products
3. Efficient use of inputs (including water, seeds, nutrients, pesticides, etc.)
4. Enabling sustainable production systems

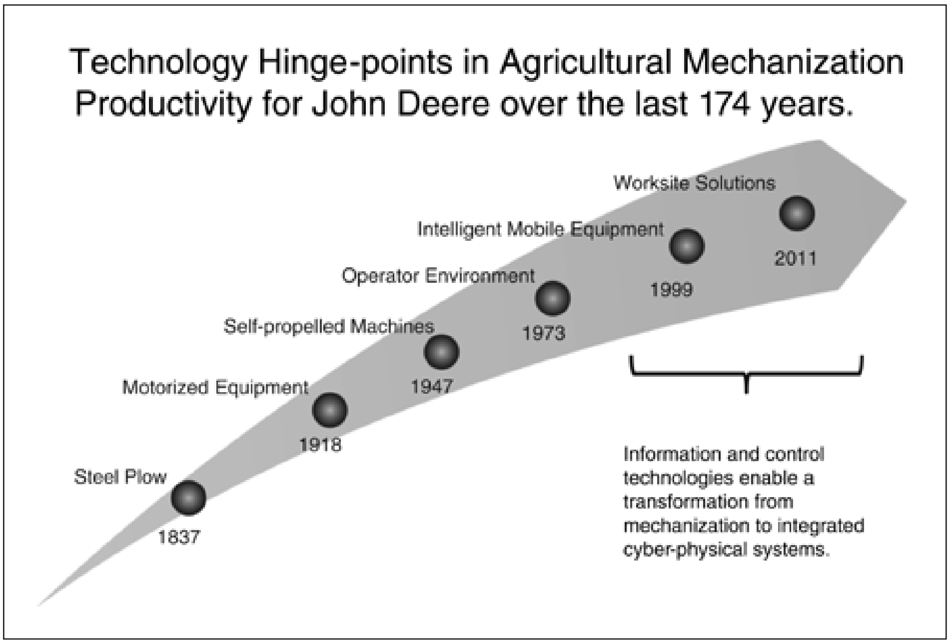

FIGURE 2 A conceptual diagram showing how agricultural mechanization has contributed to increased productivity.

by John Deere, a major innovator and developer of machinery technology.

In the 19th century, as our society matured, a great many innovations transformed the face of American agriculture. Taking advantage of a large labor base and draft animals, farmers had been able to manage reasonable areas of land. This form of agriculture was still practiced in some places until the middle of the 20th century.

Early innovations were implements and tools that increased the productivity of draft animals and assisted farmers in preparing land for cultivation, planting and seeding, and managing and harvesting crops. The origins of the John Deere Company, for example, were based on the steel-surfaced plow developed by its founder. This important innovation increased the productivity of farmers working in the sticky soils of the Midwest.

A major turning point occurred when tractors began to replace draft animals in the early decades of the 20th century. Tractors leveraged a growing oil economy to significantly accelerate agricultural productivity and output. Early harvesting methods had required separate process operations for different implements. With tractors, the number of necessary passes in a field for specific implements was reduced, and eventually, those implements were combined through innovation into the "combination" or combine harvester.

For most of the 20th century, four key factors influenced increases in the rate of crop production: more efficient use of labor; the timeliness of operations; more efficient use of inputs; and more sustainable productions systems (Table 1). These four drivers played out at different rates in different crop production systems, but always led to more efficient systems with lower input costs. Technological innovations generally increased mechanization by integrating functional processes in a machine or crop production system and by making it possible for a farmer to manage increasingly large areas of land.

By the late 20th century, electronically controlled hydraulics and power systems were the enabling technologies for improving machine performance and productivity. With an electronically addressable machine architecture, coupled with public access to global navigation satellite system (GNSS) technology in the mid-1990s, mechanization in the last 20 years has been focused on leveraging information, automation, and communication to advance ongoing trends in the precision control of agricultural production systems.

In general, advances in machine system automation have increased productivity, increased convenience, and reduced skilled labor requirements for complex tasks. Moreover, benefits have been achieved in an economical way and increased overall TFP.

From Mechanization to Cyber-Physical Systems

Today's increasingly automated agricultural production systems depend on the collection, transfer, and management of information by ICT to drive increased productivity. What was once a highly mechanical system is becoming a dynamic cyber-physical system (CPS) that combines the cyber, or digital, domain with the physical domain. The examples of CPS reviewed below suggest the future potential of ICT for achieving the target TFP of 1.75 and beyond.

Precision Agriculture

Precision agriculture, or precision farming, is a systems approach for site-specific management of crop production systems. The foundation of precision farming rests on geospatial data techniques for improving the management of inputs and documenting production outputs.

As the size of farm implements and machines increased, farmers were able to manage larger land areas. At first, these large machines typically used the same control levels across the width of the implement, even though this was not always best for specific portions of the landscape that might have different spatial and other characteristics (Sevila and Blackmore, 2001).

A key technology enabler for precision farming resulted from the public availability of GNSS, a technology that emerged in the mid-1990s. GNSS provided meter, and eventually decimeter, accuracy for mapping yields and moisture content. A number of ICT approaches were enabled by precision agriculture, but generally, its success is attributable to the design of machinery with the capacity for variable-rate applications. Examples include precision planters, sprayers, fertilizer applicators, and tillage instruments.

The predominant control strategies for these systems are based on management maps developed by farmers and their crop consultants. Typically, mapping is done using a geographic information system (GIS), based on characteristics of crops, landscape, and prior harvest operations.

Sources of data for site-specific maps can be satellite imaging, aerial remote sensing, GIS mapping, field mapping, and derivatives of these technologies. Some novel concepts being explored suggest that management strategies can be derived from a combination of geospatial terrain characteristics and sensed information (Hendrickson, 2009). All of these systems are enabled by ICT.

A competitive technology for map-based precision farming is on-the-go sensing systems, based on the concept of machine-based sensing of agronomic properties (plant health, soil properties, presence of disease or weeds, etc). The immediate use of these data drives control systems for variable-rate applications. These sensor capabilities essentially turn the agricultural vehicle into a mobile recording system of crop attributes measured across the landscape. In fact, current production platforms are increasingly becoming tools for value-added applications through ICT.

Precision Guidance

Around the turn of the 21st century, GNSS technology had become so precise and accurate that it had outpaced the requirement for the early phases of precision farming and become commercially viable for enabling a number of automatic-guidance applications (Han et al., 2004). Advances in GNSS technologies include decimeter to centimeter accuracy by using signals from a geospatially known reference point to correct satellite signals. One premium example is a real-time kinematic global positioning system (RTK-GPS) technology (Figure 3a) that reduces fatigue and lowers the skill level required to achieve high-performance accuracy in field operations.

In short, in less than 20 years, GPS technology went from being an emergent technology to a robust, mature technology that has optimal capabilities for production agriculture. A number of solutions are emerging today (Figure 3a) for achieving high-precision accuracy through various reference-signal configurations (e.g., RTK-GPS, multiple satellite systems, sensor fusion with complementary sensors, and multiple sources of corrections).

Sensor capabilities turn agricultural vehicles into mobile recording systems of crop attributes.

Operator-guidance aids that provide feedback to the operator about required steering corrections through audio and visual cues were the first systems on the market for precision guidance. This feature allowed a vehicle system to follow paths parallel to prior operations across a field. These types of systems worked well at decimeter accuracy and required no major control-system integration into the vehicle.

The major benefits of these systems were to reduce overlap/underlap in field operations with extremely wide implements, typically for spraying chemicals and fertilizers. The decrease in overlap meant the parsimonious use of resources. The decrease in underlap meant that chemicals and fertilizers were applied to every part of the field.

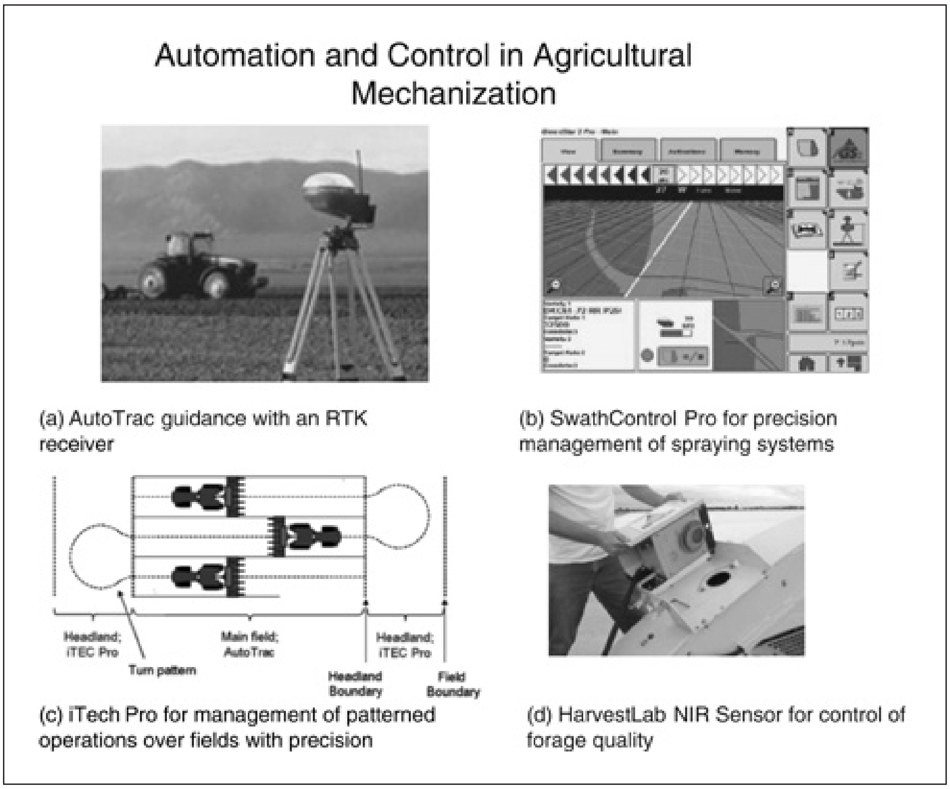

FIGURE 3 Examples of automation in control applied to agricultural mechanization systems: (a) RTK guidance through AutoTrac and a GPS reference station; (b) Swathcontrol Pro; (c) iTech Pro enabling precision patterned guidance across a field; and (d) HarvestLab for sensing crop properties.

On the next level of evolution, automatic guidance systems appeared that managed steering for an operator through automatic control. Automatic guidance systems enabled precision operations depending on the type of GNSS signal and how it was integrated into the requirements of the agricultural operations.

GNSS technology enabled the management of inputs such as seed, pesticides, and fertilizers with precision across the field. For example, the chemical application to buffer zones and grassy waterways was reduced based on sensing of the field location of these features. John Deere's software product, SwathControl Pro (Figure 3b), enabled farmers to manage the definition and execution of this capability.

GNSS technology provided the reference signal that enabled accurate vehicle location at the GNSS sensor, but precision control of the machine required several additions to the system (e.g., attitude correction, inertial sensors, implement control). With these features, a mobile CPS could correct the attitude of the vehicle on uneven terrain and manage the vehicle system path for precision in the execution of complex functions.

The ultimate in unmanned automation is the capability of driving complete field patterns under autonomous management of the tractor-implement functions without frequent operator intervention. Figure 3c shows one commercial example of the execution of this concept. The figure shows a very rudimentary form of path planning, integrated with automatic guidance, that can increase productivity by managing the paths a vehicle must follow. Path management can be programmed to reduce time loss caused by navigation (e.g., turning around) and implement management.

Like precision agriculture, precision guidance creates data from its precision operations that could be used in crop management. Examples of these data include information on the "as-applied" state of operations, vehicle paths, and operational state variables. The data can then be used to meet the needs of other ICT in systems automation and optimization.

System Automation and Control

Until recently, automation has been focused on functions that depend on GNSS or direct sensing. However, processes that lend themselves to control based on the attributes of soil and crop properties are also being investigated. Some initial applications of these, which were coupled with GPS, mapped the yield and moisture of harvested crop operations.

It is also possible to use sensing of soil or crop properties—such as controlling the cut-length of a self-propelled forage harvester (SPFH)—as part of a combination of techniques to increase machine system productivity. In this example, the cut-length is the section length into which a tree, or forage plant, is cut. When an SPFH is operated with static cutting settings, independent of the size of the forage plant, it can consume a significant amount of energy in cutting forage for ensiling (storage in silos).

HarvestLab™, a sensing technology, uses near infrared (NIR) reflectance sensing to detect the moisture content of forage and adjust the cut-length of harvested material (Figure 3d). This control strategy can significantly reduce the energy consumption for harvesting forage with no degradation in the ensiling process. The results are a significant reduction in fuel consumption in the harvest operation and a high-quality cut, which enables proper forage preservation.

NIR sensing has often been used in the laboratory and in grain processing and storage to measure properties (e.g., moisture oil and protein content) of biological materials, which contributes to value-added uses of corn, cereal grains, and forage. As these technologies mature, ICT has the potential to connect information about constituent properties to downstream processes.

Machine Communications

The automation methods described above generate massive amounts of data. However, the data are not limited to on-vehicle storage or even to on-the-go decision making. Inter-machine communication greatly increases the potential of these systems.

In the last few years, the commercial application of telematics devices on machines has been increasing in agriculture, thus empowering a closer connection between farmers and dealers in managing machine uptime and maintenance services. Other applications for machine communication systems include fleet and asset management.

In addition, inter-machine communications are expanding machine system data applications, such as diagnosing and prognosticating machine health. Inter-machine communications can also include implements and tools (e.g., monitoring seeding rate in tractor implement applications). Functionally, a modern, high-end agricultural machine system is effectively a mobile, geospatial data-collection platform with the capacity to receive, use, sense, store, and transmit data as an integral part of its operational performance.

As we strive for higher TFP levels, these high-end applications are moving toward systems with increasingly advanced ICT capabilities, including data communication management from machine to off-machine data stores. Other ICT capabilities under development include vehicle-to-vehicle operations management in the field.

It is clearly within the vision of the industry to develop advanced capabilities (such as those listed below) that leverage these ICT innovations:

- machine knowledge centers that enable improved design, faster problem resolution, and higher system productivity, increased uptime, and lower operating costs
- stores of agronomic knowledge that can lead to optimization of farm-site production systems
- stores of social knowledge related to customer or consumer value-drivers

As ICT continues to penetrate production systems, a massive network is being developed of machine systems that are platforms for value creation—well beyond productivity from agricultural mechanization intended for the farmer or the farm site. These systems are collecting and managing information with potential value in downstream value-chain operations that use crop or drive systems to achieve environmental sustainability.

Worksite and Value Chain Productivity

The next step in automation and control is to move beyond individual vehicle systems to the optimization of production systems and farm worksites. To achieve this goal, we have developed the beginnings of vehicle and machine systems that can both sense and control with precision. These systems can be driven by data from a variety of sources to provide precision control. For example, they are capable of collecting, storing, and transferring information about the crop, field, and machine state at the time of field operation. They can also receive data from public and private data sources.

The next step in automation and control is the optimization of production systems and farm worksites.

Furthermore, data collected by machines can be transferred to farm-management systems as well as to public and private sources that require information about production management for quality, compliance, or value-added purposes. Thus, we are entering an era of emerging field and farm optimization systems that can drive up TFP of the worksite, including machines, geographies, and cropping systems.

As intelligent mobile equipment for worksite solutions has evolved over the last 20 years, agricultural mechanization has also evolved from a bottom-up integration of the foundations of ICT applied to basic mechanization systems required for crop production. The primary machine capabilities of precision sensing, advanced control systems, and communications have created the potential for the emergence of CPS from production agricultural systems.

Although these advanced technologies are not uniformly distributed among platforms and production systems, where they exist, there are opportunities to leverage ICT to increase production systems capabilities. Looking ahead, it is expected that the business value of ICT will expand to additional platforms.

Technologies integrated on vehicles must work seamlessly with other systems. Drawbacks of some initial attempts for ICT capabilities have been the significant time required for setup or management, the lack of a common architecture, the lack of standardization among industries, and the lack of standardization with the farmer in mind as a user of ICT. Recently, several organizations have been working to develop standards, and some improvements have already been developed or are in process (ICT Standards Board, 2006; U.S. Access Board, 2010).[1]

Centers that store machine, agronomic, and social knowledge will aggregate data to provide value-added services for machinery operation and farm management. Some of these data may be collected by farmers, and some will be provided by public and private sources of agricultural information. Some data sources, such as remote sensing, have been mentioned, but a number of others will emerge as the aggregated knowledge in efficient production agriculture increases.

Centers with machine knowledge can help increase equipment uptime and anticipate machine system failures based on vehicle state variables in operation. Machine data that provide a better understanding of machine use can also lead to more efficient system designs that meet the needs of farmers. Agronomic data will create new opportunities for intensive modeling and simulation that can improve production efficiency by anticipating the impact of weather and various production methods.

In the future, ICT will enable the development of new platforms that can provide more support to production agriculture by taking advantage of opportunities to connect farmers, the value chain, and society in ways that are beyond present capabilities. The German-funded iGreen project, for example, is working on location-based services and knowledge-sharing networks for combining distributed, heterogeneous public and private information sources as steps toward future ICT systems (iGreen, 2011). Today, we are extremely close to having true CPS and control systems for measuring the "pulse" of agricultural productivity on planet Earth.

Conclusion

Agricultural mechanization will be a key factor to achieving our TFP goals and feeding a growing planet. Looking ahead, agricultural machines will become data-rich sensing and monitoring systems that can map the performance of both machines and the environment they work on with precision resolution and accuracy, and this capability will unlock levels of information about production agriculture that were heretofore unavailable.

References

GHI (Global Harvest Initiative). 2011. GHI website. Available online at *http://www.globalharvestinitiative.org/*.

Han, S., G. Zhang, B. Ni, and J.F. Reid. 2004. A guidance directrix approach to vision-based vehicle guidance systems. Computers and Electronics in Agriculture 43(3): 179–195.

Hendrickson, L. 2009. Landscape Position Zones and Reference Strips. PowerPoint Presentation. Available online at *http://nue.okstate.edu/Nitrogen_Conference2009/Hendrickson.ppt*.

ICT Standards Board. 2006. . . . to coordinate the standardization activities in the field of Information and Communications Technology. Available online at *http://www.ictsb.org/*.

iGreen. 2011. Welcome to iGreen! Available online at *http://www.igreen-projekt.de/iGreen/*.

National Academy of Engineering (NAE). 2000. Greatest Engineering Achievements of the 20th Century. Available online at *http://www.greatachievements.org/*.

Postel, S.L., G.C. Daily, and P.R. Ehrlich. 1996. Human appropriation of renewable fresh water. Science 271(5250): 785.

[1] See also *http://asabe.org/*, *http://aem.org/*, *http://www.sae.org/*, and *http://www.iso.org/iso/home.html*.

Sevila, F., and S. Blackmore. 2001. Role of ICTs for an Appropriate World Market Development. Presentation at the 12th Members Meeting, Club of Bologna, Bologna, Italy, November 18–19, 2001. Available online at *http://www.clubofbologna.org/ew/documents/Proc2001.pdf*.

UN FAO (United Nations Food and Agriculture Organization). 2007. Coping with Water Scarcity: Challenge of the Twenty-First Century. Available online at *http://www.fao.org/nr/water/docs/escarcity.pdf*.

U.S. Access Board. 2010. Draft Information and Communication Technology (ICT) Standards and Guidelines. Available online at *http://www.access-board.gov/sec508/refresh/draft-rule.htm*.

Requirements for greater transparency about where food comes from and how it is treated along the way are becoming more stringent.

Agriculture and Smarter Food Systems

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Susan Wilkinson

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The growing world population is putting increasing strains on natural resources, including agricultural resources, and recent economic and environmental trends are making the problem even more acute. The unprecedented growth of the global middle class is accelerating demand for foods with higher agricultural footprints, such as meats. At the same time, limited arable land areas, increasing water shortages, rising energy costs, and urgent climate/environmental concerns are creating a desperate need for substantial increases in factor productivities.[1]

In addition, in response to issues related to public health and food supply chains, requirements for greater transparency about where food comes from and how it is treated along the way are becoming more stringent. To meet those requirements, we must find ways to quickly trace the sources of contamination or other health-related issues.

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[1] For example, consider water as one factor in agricultural production. An increase in water productivity implies that the same level of output could be obtained with less water. Other factors could include labor, seeds, fertilizer, types of machinery, etc.

The Transformational Potential of "Physical Meets Digital"

In many domains of human activity today, the infusion of information technology (IT)-enabled "intelligence" capable of driving major improvements in systems-level productivity and performance is accelerating. These improvements will have the most profound impact on "highly physical" domains, that is, domains that involve large-scale infrastructure (e.g., machinery, large vehicles, static structures, and productive land masses) and that are often exposed to natural elements. Examples include traffic systems, utilities management (water or electricity), transportation and shipping, mining, oil and gas, and of course agriculture and the broader food system. In these cases, the use and performance of such infrastructure tend to substantially determine overall system performance.

To varying degrees, many aspects of these kinds of systems have traditionally been resistant to the infusion of intelligence, due largely to the difficulty and cost associated with (1) obtaining detailed, timely data about the system components and surrounding environments and (2) remotely controlling actions based on analyses of those data.

However, manufacturers of heavy equipment are increasingly outfitting their products with deeper levels of instrumentation—various types of transduction capabilities that produce data reflecting the status of the equipment, potentially enabling management or operational changes to be performed remotely. In addition, technologies for generating data that reflect environmental conditions (e.g., in situ sensors, remote sensing satellites, airborne vehicles) are becoming increasingly capable and cost effective. Combined with cost-effective communications and interconnection technologies, comprehensive data reflecting the state of the infrastructure and environment can now be collected with tolerable latencies, enabling effective actions to be executed.

In addition, technology for effectively instrumenting "products," such as food items, pharmaceuticals, and so on, is also becoming more capable and less expensive. Think, for example, of the increased availability of radio-frequency identification and 2D barcode technology, wireless environment/gas sensors in shipping containers, and global positioning system and other location-tracking technologies.

Smarter Agriculture

Broadly speaking, IT is increasingly impacting agriculture and the overall food system in myriad ways throughout the value chain. Impacts range from fundamental inputs, such as genomics and computer modeling that can help drive the next generation of seed and planting technology, to food distribution, such as smarter logistics that can help deliver food more quickly using less fuel and fewer machine resources and with less spoilage en route to the point of consumption.

The clear social need and inevitably growing market demand are driving investment by governments, IT firms, and private equity and venture capital firms. Many venture capital investments have focused on aspects of "physical meets digital," such as traceability, sensing for reducing spoilage, and sensing for agricultural optimization and/or water productivity.

"Agriculture 2.0," which implies decisive shifts in the ways and means of agricultural production, is becoming a term of art in this context. Because venture capital tends to flourish in environments that are experiencing market or business model disruptions, such investments should be watched closely.

Comprehensive data reflecting the state of infrastructure and the environment can now be collected with tolerable latencies.

The present article focuses predominantly on two related areas (see Figure 1) in which "smarter" systems enabled by physical-digital integration can have a positive and global impact: (1) track-and-trace technologies to support food safety and ultimately optimize food supply chains; and (2) increasing farm multifactor productivity by improving water logistics and application, optimizing machine/fleet maintenance, and improving farm operations/processes. Multifactor productivity includes agricultural business optimization as a result of the integration of these approaches with additional downstream business information.

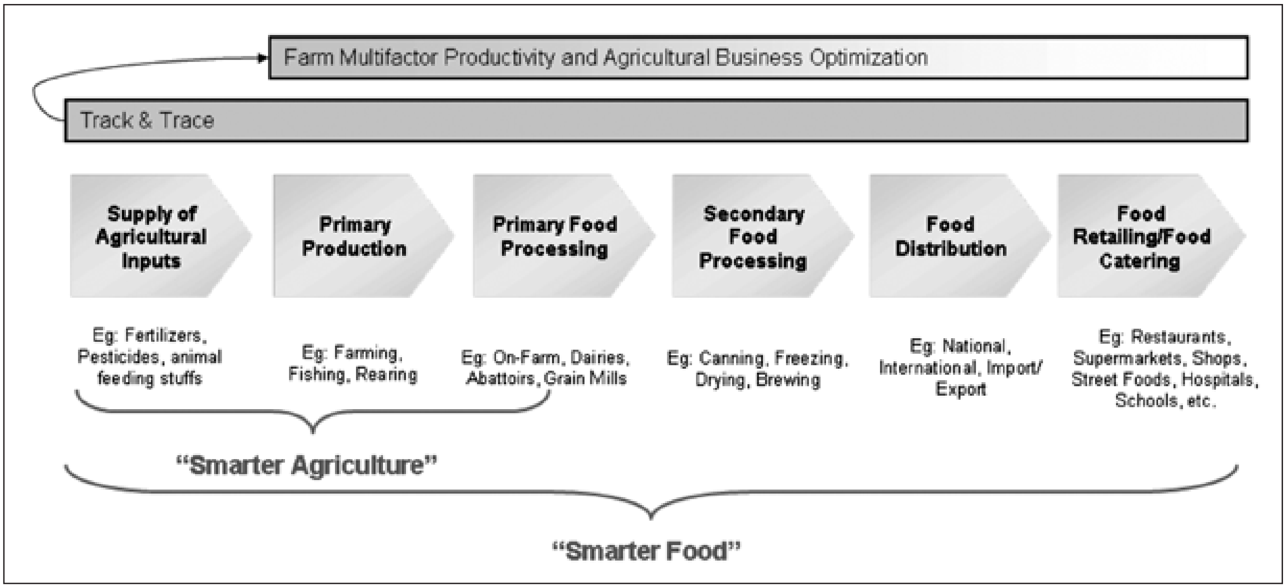


FIGURE 1 Agricultural value chain and topics in this article.

Food Tracking and Tracing

The increasing focus on food safety and security is being driven by a number of factors: (1) the number and/or visibility of food safety-related incidents (Figure 2); (2) the increasing globalization and complexity of the food supply system, which contributes to both higher risks associated with the number and diversity of handling entities and diminishing visibility/transparency. The latter effect produces uneasiness because of uncertainties about where food comes from, which greatly complicates efforts to trace problems back to their sources; and (3) fears of terrorism or other deliberate attempts to damage or contaminate food supplies.

The purpose of food tracking and tracing is to be able to follow food and food components as they flow through and are transformed along various pathways in the value chain, and, when needed, to be able to follow the flow backward to identify the sources and/or conditions to which the food was subjected along the way. The latter capability is a critical component of food safety systems.

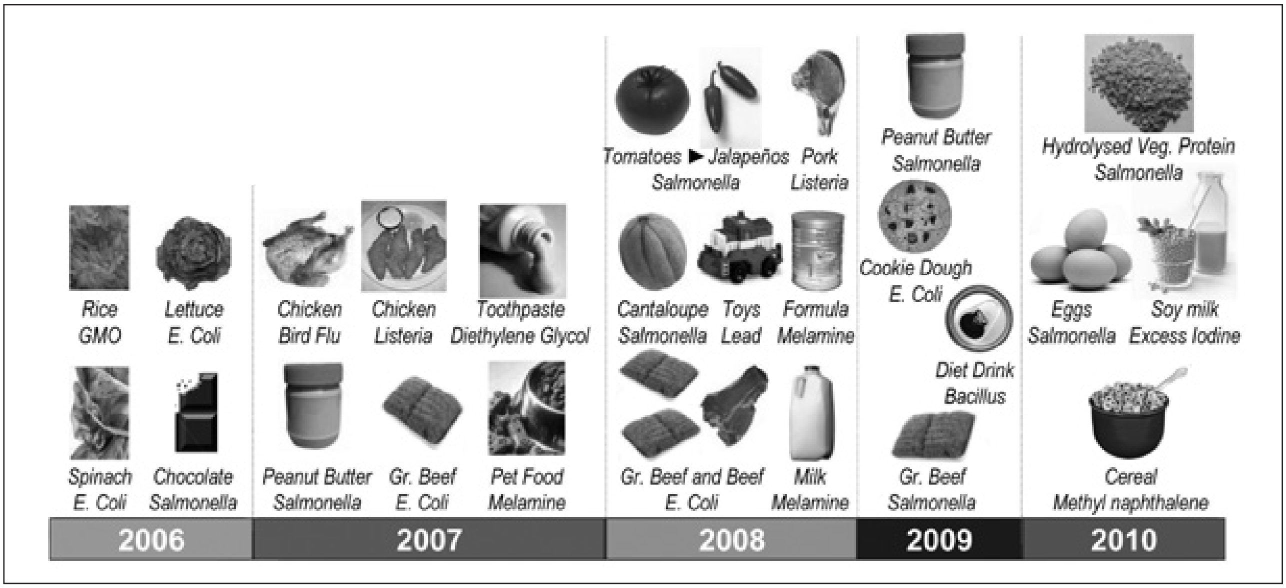


FIGURE 2 A sampling of food contamination and recalls since 2006.

Tracking and tracing capabilities in food systems can be complicated and require coordination among many firms and functions, which may have substantially different business motivations. Broadly speaking, motivation can be compliance driven, that is, dictated by some form of government regulation or customer requirements, or based on business value, that is, focused on branding, overall risk mitigation, or improving value-chain operational performance (e.g., by cross leveraging tracking and tracing capabilities).

One clear benefit of tracking and tracing that applies throughout the value chain is the ability to minimize disruptions caused by a food-safety event. For example, if the cause of the event can be isolated to a particular food from a particular part of a particular farm, the problem can be effectively quarantined, and food sales should return to normal levels as customer confidence recovers. The alternative, which frequently occurs, is that consumers stop buying the type of food (e.g., cucumbers) initially suspected as the cause. Even though the initial suspicion often turns out to be incorrect, sales of many types of food can be adversely impacted as health officials and food-chain participants work to find the culprit.

Even after the culprit is found, it frequently takes a substantial amount of time to identify the location of, and remove the contaminated product from, the market. The longer this takes, the more consumer confidence is eroded, and the longer it takes for sales to return to normal.

Standards and Regulations

Under the Food Safety Modernization Act, signed by President Obama in January 2011, the Food and Drug Administration is required to execute traceability pilot tests and use what they learn to develop new regulations to improve the ability of the food industry to identify the source of food-safety problems and quickly remove contaminated products from the market. For tracking and tracing to succeed, however, there must be a willingness to share information across the supply chain, as well as agreements among trading partners on standardized expressions of key data elements.

GS1 standards could be implemented throughout the food supply chain to enable traceability. GS1 is a not-for-profit organization dedicated to the design and implementation of global standards for identifying goods and services to improve the efficiency and visibility of supply chains. There are GS1 member organizations in 108 countries, and their well-known global trade item numbers (GTINs), including UPC (Universal Product Code), SSCC (Serial Shipping Container Code), and EAN (European/International Article Number), have been used by retailers and suppliers of packaged goods for decades. The adoption of GS1 standards varies by country and sector but has increased significantly every year, and efforts are under way to increase adoption by companies in the upstream supply chain.

GS1 standards for product identification (product type and lot numbers) are the basis of a major initiative undertaken by the produce industry to enable traceability back to the farm. The goal of the initiative, called the "Produce Traceability Initiative" (PTI), is to achieve adoption of electronic traceability throughout the supply chain for every case of produce by 2012. Although participation in PTI is currently voluntary, U.S. food retailers and their major produce suppliers are actively moving toward compliance.

GS1 Standards throughout the food supply chain would make traceability much more feasible.

Execution Issues

Tracking and tracing capability has three major pillars: (1) establishing a premise ID; (2) establishing a product ID; and (3) establishing a means of tracking movements and transformations (Figure 3).

Establishing a premise ID. A unique identifier is required for the source location and for each location an agricultural good passes through on its journey from the farm to the retail outlet. This identifier must be at a level of temporal and spatial granularity appropriate for the purpose and must include the identity of the firm or organization that owns or operates each premise.

On the compliance level, the identifier may, for example, relate to produce from a particular section of a field in a window of several weeks. On the value level, it may include information related to more sustainable or socially responsible practices on the farm, special handling, and so on.

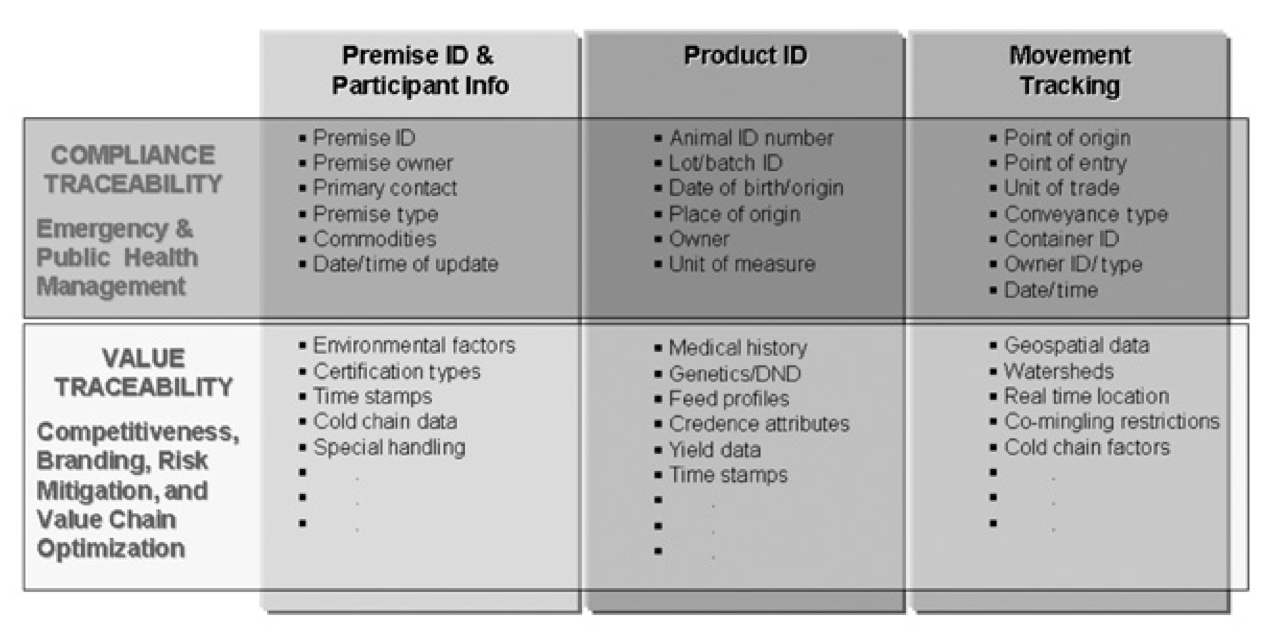


FIGURE 3 Three pillars of food tracking and tracing systems.

Establishing a product ID. The product ID relates to the type and batch of agricultural good produced. On the compliance level, it might relate to a particular type and subtype of vegetable linked to a particular premise, such as a field-packed box of organic iceberg lettuce from a particular section of a particular farm in central California. On the value level, it might include information on the seeds used, irrigation characteristics, and more precise time stamps.

Establishing a means of tracking movements and transformations. As food moves through the value chain, it is physically transported in various types of containers and through various local environments (temperature, humidity, various gas concentrations); it sits for varying periods of time at transition points; and it is transformed in various ways (e.g., blending, canning, freezing, preserving). Thus, maintaining the integrity of the data is a challenge. On the compliance level, it may include tracking points of origin and entry, type and ID of transport, basic information about transformation, and basic information about dates and times. On the value level, it may include environmental characterizations (especially temperature history) and geospatial history.

Implementation Issues

Government regulations and the requirements of business customers will encourage a minimum level (at least) of tracking and tracing capabilities. However, although the deployment of advanced tracking and tracing technology can significantly improve supply chain and other operational efficiencies, adoption has been slow, largely because of the number and complexity of food and food-component pathways and the concomitant need for multiple levels of process alignments and information sharing (including adoption of a consistent semantic model and a system for conveying relevant information and protecting otherwise sensitive information).

In addition, the governance mandate for agriculture and the food supply industries is often split among jurisdictions (e.g., states and provinces) and national bodies. As a result, solutions must support concurrent jurisdictional and national policies.

Therefore, it is essential that all stakeholders be identified, that relative benefits be defined, and that buy-in and cooperation be established. Although all parties will benefit to some degree from risk mitigation and reduced liability, other benefits will vary substantially by stakeholder. Key benefits beyond compliance with regulations may include increased access to global markets, better quality control, improved demand visibility and forecasting, and improved brand image and increased sales.

For incremental adoption, it is important that one define "slices" of a hypothetical comprehensive tracking and tracing system that cover enough space to provide significant benefits to all stakeholders, but are also contained enough to be manageable (and financeable). It is often helpful to define such slices using a so-called "cube model" that has three dimensions: (1) food type; (2) value-chain position; and (3) geographical/regulatory region (e.g., state, province). Manageable slices can often be defined in which one dimension is fixed and the other two vary across the relevant values (e.g., packaged leafy vegetables from all relevant regions from inputs through retail).

Another issue relates to the classic economic "agency problem," that is, that costs and benefits can accrue substantially differently in different areas of the value chain. In practice, costs may be borne disproportionately by food producers/farmers and early processors relative to later processors, distributors, and retailers.

There are signs, however, that the business ecosystem is evolving as third parties increasingly provide technology and process components, such as low-cost labeling technology, tracking-infrastructure-as-a-service, and food environmental monitoring and response capabilities. By leveraging scale and specialization, these changes can lower adoption and management costs.

Country and Regional Issues

Structurally, food systems are globally distributed and integrated in a variety of ways. Different structures reflect economic and policy characteristics associated with the end destination, as well as with characteristics associated with production and distribution points along the way.

For example, food in the United States can come from farms nearly anywhere in the world through a variety of distribution pathways with distinct profiles for risk of contamination, spoilage, and additions to cost. These pathways cross through many different countries and regions, each with potentially different availabilities of relevant technology and deployment capabilities. And the relative economic motivations (e.g., based on labor costs, risk tolerance) for employing necessary processes can vary widely from country to country and even region to region. Nevertheless, companies and policy makers can insist on certain levels of supply chain transparency and can select vendors who can comply.

The food supply for a typical, large, rapidly growing city in a developing country, however, may receive the majority of its food from relatively undeveloped rural farms in remote parts of the country, where the technology for efficient labeling and scanning is either not available or too expensive. In such cases, there may be little or no tracking and tracing, and retailers and consumers may have essentially no insight into where their food comes from or what the safety risks are.

However, as mobile phones and related sensing and communications technologies reach higher levels of penetration and continue to improve in capabilities, they may help make cost-effective, easy-to-use systems available to rural farmers. Mobile phones and so-called "social web" technology also have the potential to convey important, targeted information to rural farmers, directly and through social contexts, that will help them increase output levels and productivity (e.g., Agarwal et al., 2010; Patel et al., 2010; Veeraraghavan et al., 2007).

Enhancing Multifactor Productivity

"Physical meets digital" innovation can help decisively in many respects to increase factor productivity directly on the farm and interactions with early food processors. A few representative examples are described below.

Optimizing Water Logistics and Use

The amount of water used in agriculture is staggering (Table 1). For example, it is estimated that producing 1 kilogram (kg) of wheat requires 500 to 4,000 liters of water, and 1 kg of meat requires 5,000 to 20,000 liters of water (e.g., Lundqvist et al., 2008). Thus it is not surprising that agriculture dominates the human use of water—estimates are in the range of 70 percent.

If, as expected, the global middle class, which eats more meat and delicacies, continues to grow rapidly well into the current century, water requirements will increase much faster than population growth. Around the world today, difficulty obtaining sufficient amounts of clean water for irrigation is already a critical issue.

TABLE 1 Estimated Water Consumption Required to Produce Some Common Foods

Food (1 kg)	Water Required to Produce (liters)
Wheat	500–4,000
Meat	5,000–20,000
Chocolate	24,000

Increasingly, various types of sensor and communications technology are being used to provide data and perform analyses necessary to increase water productivity and reduce irrigation requirements (e.g., Aqueel-ur-Rehman et al., 2011). In dry areas (e.g., North Africa, western Asia), where water is sometimes a more limiting resource than land, farmers may focus more on water productivity than on yield per unit of land (Oweis and Hacham, 2006).

In such areas, deficit irrigation is becoming more prevalent (Geerts and Raes, 2009). This technique involves using measurements and modeling to design and execute strategies for supplying the minimum amount of exogenous water that will support stable and acceptable yields. Successful deficit irrigation requires field instrumentation that provides data reflecting soil conditions, water inputs, evapotranspiration, and spatial crop distribution. Models reflecting such factors as crop stage/type and crop water stress response can then be used to optimize output based on the water restrictions.

It is estimated that spoilage and other waste in the food chain cause about a 30 percent food loss. Therefore, smarter supply chains—both in terms of logistics and the use of environmental monitoring and response systems—can substantially increase the effective "water productivity" of agriculture.

Because of spoilage and other waste in the food chain, about 30 percent of food is lost.

Equipment Health and Fleet-Level Uptime and Maintenance Optimization

Uptime and utilization of heavy equipment in "highly physical" industries, whether on the farm, at a mine site, or on an oil rig, are often key factors in business performance. Fortunately, heavy equipment is increasingly being instrumented with sensors that collect data that can be used to model the health status of the equipment. Combined with other types of inspection data and environmental data, these models may be improved to the point that they ensure the optimization of maintenance of the equipment and maximization of uptime and utilization. Thus leading firms are moving away from "fix on failure" and scheduled-maintenance policies toward condition-based maintenance and ultimately predictive maintenance approaches.

However, these approaches are still in their infancy: accuracy and specificity issues often lead to false positives, as well as a lack of targeted information as to what specifically needs to be fixed/done; and prediction lead times still tend to be too short to take action to optimize maintenance and/or production schedules based on anticipated problems with equipment. Nevertheless, as the volume, diversity, and quality of data improve, and with increasingly creative modeling and analytics, condition-based maintenance and predictive maintenance capabilities are expected to have a major impact on agricultural productivity and cost efficiency in the future.

Biofuels Production for Optimizing the Harvesting and Transport of Highly Perishable Crops

The increasing use of biofuels as an alternative or complement to fossil fuels has had a significant effect on agriculture both in terms of changing demand and production characteristics and in terms of political/social engagement. When traditional food crops such as corn and sugarcane are used as feedstock, upstream biofuels production is similar to food production.[2] Downstream processes, however, resemble more traditional industrial production processes. The need for detailed tracking and tracing of biofuels is generally lower than for other products, but optimizing the process from planting to production can be a priority.

Ethanol production from sugarcane is an illustrative example. Many factors affect the level of sugar in sugarcane (e.g., McLaren, 2009), which is a key factor in the ultimate fuel yield. In addition, because of certain natural biophysical processes, sugar levels tend to decrease rapidly after the sugarcane is harvested. Thus, minimizing the harvest-to-mill time interval is a high priority.

Solutions to this problem include optimizing crop planning and logistics. Using GIS technology and various modeling and analytics approaches to balance water availability, soil characteristics, distance-to-mill, road and weather conditions, traffic, and mill schedules, producers can optimize their planting, harvesting, and transport activities to maximize ethanol yields.

[2] Non-food stocks have many advantages, but this topic is beyond the scope of this article.

End-to-End Operational and Financial Management for Farms

True end-to-end business optimization is often impeded by siloed IT architectures and a lack of timely, reliable information. Typically, different data models are used for different functions. In addition, data are often of varying quality and freshness making it difficult to optimize processes that require trading-off factors associated with different functions/silos in the business.

Nevertheless, cross-functional optimizations, such as aligning harvesting specifics with current market dynamics, can be highly beneficial for agricultural firms. Thus, farms are increasingly instituting capabilities for collecting timely, consistent data about their assets and business processes and using analytics and modeling to enable end-to-end optimization and proactive decision making.

By tracking such factors as per unit costs and revenues, water usage, energy consumption, the health status of equipment, soil characteristics, and crop types/states, and then relating them to yields, metrics of market demand, and current and predicted distribution/logistics characteristics, such optimizations are possible, and managers can have access to decision-support information for balancing business objectives such as cash flow, profit, customer satisfaction, risk levels, and predicted future output capacity.

Conclusions/Action

Information technology will be increasingly important for improving agricultural business productivity and cost efficiency and for providing safe food (and fuel) for a growing and increasingly wealthy and demanding world population. "Physical meets digital" technologies and processes, which are well suited to deployment throughout the food value chain, will have important near-term and longer term impacts. The following priorities are key to making this happen.

Data capture and management policies. Necessary data are becoming increasingly available, but policies and processes to ensure that they are captured and managed electronically in a way that ensures their quality, availability, and integration (especially in federated models) have not been put in place.

Sharing and scale. Useful analytics and modeling often require large amounts of detailed data about many different kinds of assets and processes in the context of actual use. It is in the interest of everyone involved that data be shared as much as possible to accelerate the development of models and analytics that are accurate enough to support critical business decisions. Because important data are generated by many firms and other stakeholders, policies and procedures must engender mutual trust, and security must be provided as needed.

Ecosystem thinking. The kinds of improvements discussed in this paper will require that stakeholders collaborate more closely in mutually beneficial ways based on a sense of shared destiny. Relatively speaking, agricultural and food industry players have tended to be less inclined to adopt this ecosystem mindset.

Tailoring. Approaches and technologies must be adapted for the unique needs and capabilities associated with widely differing sociopolitical and economic development conditions around the world.

Business structure and models. New vendor business models will be needed to enable the widespread adoption by agricultural businesses of necessary technologies and processes. These models should include third-party vendors who can offer key capabilities at lower cost based on scale and specialization. Financing and/or cloud-oriented "as-a-service" models should also be used to reduce adoption and management costs.

References

Agarwal, S.K., K. Dhanesha, A. Jain, A. Kumar, S. Menon, N. Rajput, K. Srivastava, and S. Srivastava. 2010. Organizational, Social and Operational Implications in Delivering ICT Solutions: A Telecom Web Case-study. Paper presented at ICTD2010, London, U.K., December 13–16, 2010.

Aqeel-ur-Rehman, A.Z. Abbasi., N. Islam, and Z.A. Shaikh. 2011. A review of wireless sensors and networks' applications in agriculture. Computer Standards and Interfaces (April). doi:10.1016/j.csi.2011.03.004.

Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management 96(9): 1275–1284.

Lundqvist, J., C. de Fraiture, and D. Molden. 2008. Saving Water: From Field to Fork—Curbing Losses and Wastage in the Food Chain. SIWI Policy Brief. Stockholm: SIWI. Available online at *http://www.siwi.org/documents/Resources/Policy_Briefs/PB_From_Filed_to_Fork_2008.pdf*.

McLaren, J. 2009. Sugarcane as a Feedstock for Biofuels: An Analytical White Paper. NCGA Whitepaper. Available online at *www.ncga.com/files/pdf/SugarcaneWhitePaper 092810.pdf*.

Oweis, T., and A. Hachum. 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agricultural Water Management 80(1-3): 57–73.

Patel, N., D. Chittamuru, A. Jain, P. Dave, and T.S. Parikh. 2010. Avaaj Otalo—A Field Study of an Interactive Voice Forum for Small Farmers in Rural India. Pp. 733–742 in Proceedings of ACM Conference on Human Factors in Computing Systems (CHI 2010). Available online at *http://www.stanford.edu/~neilp/pubs/chi2010_patel.pdf*.

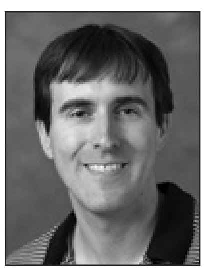
Veeraraghavan, R., N. Yasodhar, and K. Toyama. 2007. Warana Unwired: Replacing PCs with mobile phones in a rural sugarcane cooperative. Presented at the International Conference on Information and Communication Technologies and Development, 2007. ICTD 2007. Available online at *http://people.ischool.berkeley.edu/~rajesh/index_files/WaranaUnwired*.

Models informed largely by sensor-supplied data can provide insights into the role of agriculture in carbon, energy, nutrient, and water cycles.

Multiscale Sensing and Modeling Frameworks
Integrating Field to Continental Scales

Indrejeet Chaubey, Keith Cherkauer, Melba Crawford, and Bernard Engel


Indrejeet Chaubey


Keith Cherkauer


Melba Crawford


Bernard Engel

Agriculture, which has traditionally been considered a source of food, feed, and fiber, is increasingly being identified as a source of energy and ecosystem services, such as biodiversity and climate, water, and pest regulation (MEA, 2005). The growing world population has significantly increased pressure on agriculture in both areas. Historically, agriculture has met societal demands by expanded irrigated and non-irrigated crop-production areas, increased automation, genetic selection and modification of plants, and better management and pest control, among other approaches. Some of these approaches provide few opportunities today for

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increasing agricultural production, but others are in the early stages of development and provide tremendous opportunities for further expansion.

Food production in greenhouses provides a glimpse of the possibilities for meeting increasing demands on agriculture. Modern greenhouse production involves large numbers of sensors and controls, as well as information technologies (IT), to optimize the production of specialty crops, such as fruits and vegetables. Although these specific technologies may not be directly applicable to crop production on a broad scale of watersheds, regions, and even continents, they do provide evidence of the value of sensing and IT in food production. For broader applications, these approaches would have to be greatly expanded and include multiscale sensing.

Computational models and computer-based decision-support systems are increasingly being used to assist with a range of agriculturally related environmental and resource conservation issues. These models rely on data from various sources, including sensors. As ecosystem services provided by agriculture become more important, models and sensor-supplied data in these models that can provide insights into understanding the role of agriculture in carbon, energy, nutrient, and water cycles will also become more important.

Thus, expanding sensing and IT will be critical to meeting the food, feed, and fiber requirements of a growing global population, as well as meeting energy and ecosystem needs.

In this article, we propose a multiscale framework that can meet the need for *in situ* point-scale sensing in continuous time to develop an understanding of fundamental physical and biological processes, spatially continuous sampling over extended areas by remote sensing technologies to represent phenomena at field, watershed, and regional scales, and models of processes that link across these scales and represent associated dynamic processes (Figure 1).

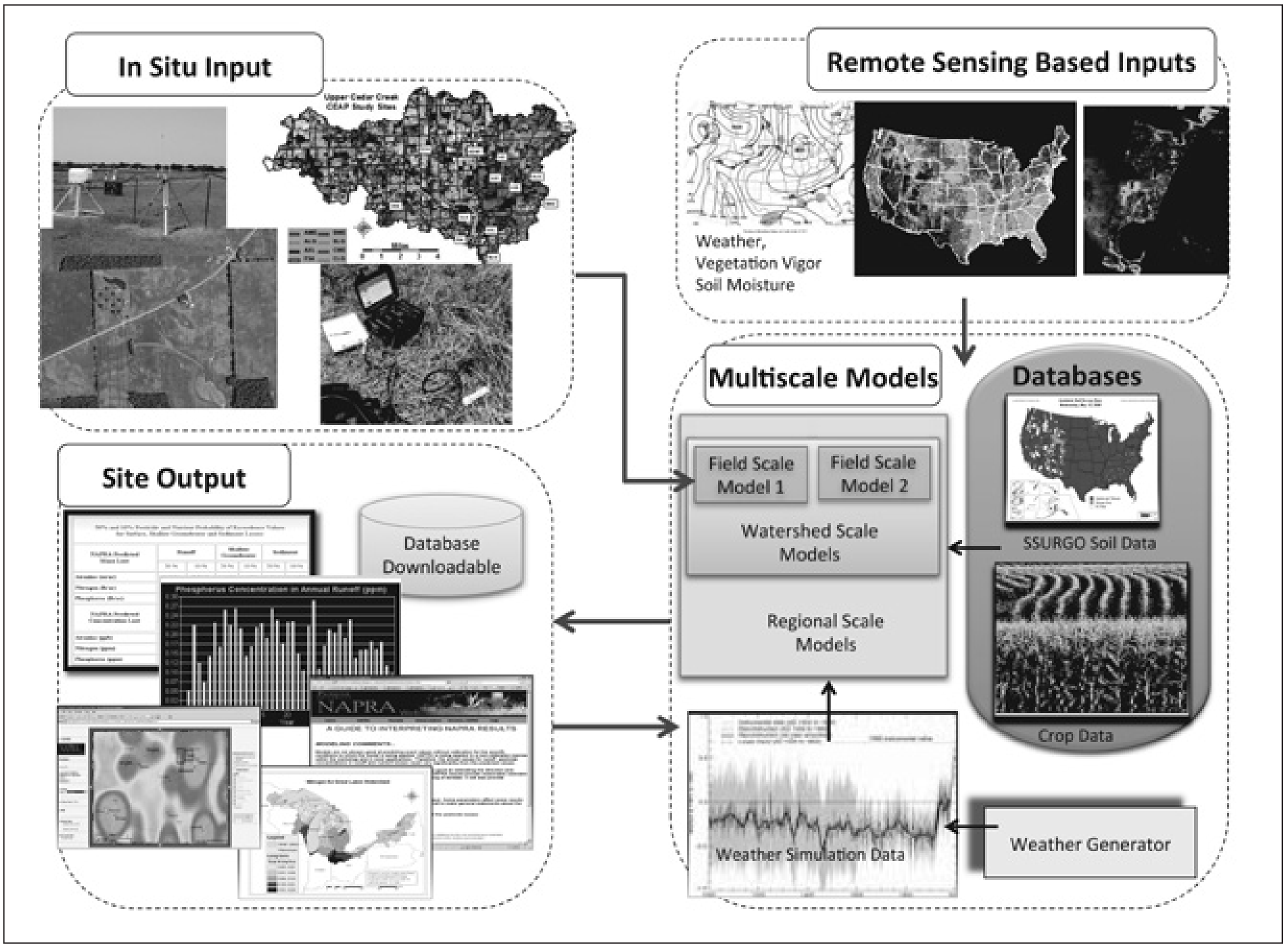

FIGURE 1 Multi-scale framework integrating *in situ* and remote sensing data collection, multi-scale modeling, and process representation to develop agricultural watershed management strategies.

Field-Scale Opportunities: Real-Time Sensing

Soil and climate conditions are key components in growing healthy and productive crops. With advances in precision agriculture, farmers now know more about their soils and crop yields than they have at any time since the mechanization and commercialization of agriculture began in the early 20th century (Lowenberg-DeBoer and Erickson, 2000). For example, yield maps now provide high-resolution information on inter-annual field-scale production variability, enabling farmers to adjust application rates of seed, fertilizer, and pesticides to maximize crop yields.

However, these are static sources of information generated after a crop has been harvested. They cannot provide immediate input about conditions that might lead to reduced productivity, nor can they be used to determine preventive solutions that could increase yield in a given season.

In Situ Technologies

Opportunities and Challenges

Inexpensive sensor technologies and wireless communication are increasingly being used in modern agriculture to provide real-time information on soil and meteorological conditions. Soil temperature and moisture are standard measurements that are important to crop yield. Low temperatures can slow seed germination and cause stress on young plants, thus increasing the likelihood of disease and smaller yields. Late-season planting can avoid cold soil temperatures but also decrease crop yields by delaying growth and development until drier weather later in the summer. Traditionally, soil temperature has been measured at a handful of sites in a state; in recent years daily values have been provided online.

Water stress, induced by limited water availability, is perhaps the biggest factor in reducing crop yield. Soil moisture measurements can provide information on plant water availability, but these data are not regularly collected. However, a growing number of inexpensive soil moisture and temperature sensors are available for use in farm fields to provide information on current conditions, and even to coordinate with irrigation scheduling systems (Oshaughnessy and Evett, 2008; *www.agmoisture.com*).

Measurement of local weather conditions, especially precipitation and air temperature, as well as wind speed, humidity, air pressure, and solar radiation, has been the responsibility of the National Weather Service through the Cooperative Observer Program (COOP), which was launched in 1890. Participants in COOP collect daily precipitation and air temperature measurements, which are distributed through the National Climatic Data Center and many state climatologist offices (*http://dss.ucar.edu/datasets/ds510.0/*).

Much of this information is now available to farmers in near-real time on the Internet, and many weather-related sites provide real-time storm tracking and forecasts ranging from hourly to 10-day blocks. Many commercial organizations have also begun to market meteorological-observation systems, which can be purchased by individuals and installed locally, with direct transmission of data into the corporate system.

These technologies not only provide farmers with site-specific meteorological information, they also contribute to new markets for companies that use these observations to create user-friendly agricultural decision-support products. Examples of such services include forecasts of good weather windows for planting, spraying, or harvesting and site-specific climate information for evaluating crop rotation or pest management strategies.

First-generation biosensors, such as the root oxygen bioavailability sensor, are leaving the laboratory and being used in the real world.

Future Possibilities

Biosensor technology is still in its infancy, but first-generation biosensors are now leaving the laboratory and being used in the real world. One such technology, the root oxygen bioavailability sensor (Liao et al., 2004; Porterfield, 2002), mimics the consumption of oxygen by a root, and therefore the transport of water and nutrients into the plant. Oxygen consumption is as important to crop yield as soil moisture because the rate of consumption is sensitive to both dry and overly wet (oxygen-limited) conditions (Drew and Stoltzy, 1996).

Biosensors have also been developed that are sensitive to nutrients and contaminants of interest in agriculture, including nitrate and phosphate (McLamore et al., 2009). These sensors are currently limited in operational applicability by their short lifespan (days to months) and because they are designed for use in liquid media. However, as scientists merge their knowledge of biosensors with modern manufacturing technologies, such sensors will surely make their way into agricultural applications, including monitoring the distribution of nitrogen and phosphorous across fields and informing next-generation farm equipment about where more fertilizer should be applied to maximize production.

Measurement of carbon storage and fluxes will be important for agricultural systems to offset emissions in other parts of the economy. Current fluxes of carbon from soils are poorly understood, primarily because making accurate measurements is difficult and costly; it requires proper installation of chambers at the soil surface to capture fluxes or micrometeorological stations taking rapid measurements to estimate fluxes just above the soil surface. To be useful for climate-change adaptation and mitigation plans, however, newer, more cost-effective systems that require less operational oversight will be necessary for quantifying carbon fluxes and eventually for monitoring carbon sequestration.

Fluxes of carbon from soils are poorly understood, primarily because making accurate measurements is difficult and costly.

Communications Technologies

Exploiting Multipurpose Communications Systems

The integration of new and existing sensor technologies with wireless communication systems has already begun, and many companies now offer wireless meteorological and soil moisture sensor systems. With these tools, farmers can check the status of their fields before leaving the house.

Connections to cellular phone networks, satellite uplinks, long-distance radio frequency communications, and direct Internet or WiFi connections have all become relatively common and are often options for commercially available sensor systems (e.g., *http://www.campbellsci.com/communications*). However, there are still significant difficulties in initial installation of many of these technologies.

Advancing the State of the Art for Production Agriculture

Self-organizing wireless hardware and software for sensor networks have recently become commercially available (Martinez et al., 2004), making the development and deployment of sensor networks possible. Although these networks have great potential for agricultural applications, integrating communications, data acquisition, and sensor technologies into operational nodes in a stable, functional sensor network requires significant effort and knowledge and will require overcoming major challenges to their deployment.

Agricultural sensor networks must be robust enough to survive environmental extremes including rain, sun, and flooded fields. They must also be minimally intrusive, so they do not hinder access to the field by heavy machinery, and they should be designed to survive inadvertent run-ins with such machinery. In addition, sensor nodes must be designed for easy installation and removal, so nonfunctioning nodes can be easily replaced and all nodes can be removed prior to tillage.

Once these technological problems are resolved, probably in the coming decade, self-organizing networks could be integrated with inexpensive sensor technologies, making it possible for farmers to deploy networks rapidly across their fields and giving them immediate access to spatial and temporal information about field conditions. In addition, it should be possible for sensors to communicate directly with farm equipment and personal electronic devices, such as smart phones.

This would give farmers in the field access to both real-time and archival information about field conditions as they survey or work in their fields. Smart software or links to service providers could provide additional input about potential problem sites, potential ways to resolve those problems, and even suggestions for where to find materials or equipment or bids from other service providers.

Remote Sensing: Technologies for Scaling Information

Current Capabilities for Production Agriculture

"Remote sensing" refers to technologies that can make measurements without being in direct contact with the target of interest. Often characterized not only by the acquisition of a measurement, but also by the spatial and temporal resolution of data, information based on remote sensing provides capabilities for scaling *in situ* measurements and understanding physical and biological processes in systems that operate on watershed, regional, continental, and global scales. These technologies extend spatial coverage, provide information about inaccessible areas, and acquire unique measurements via a variety of sensing modalities.

Remote sensing technologies on tractors and combines and on airborne and space-based platforms are now integral to modern agriculture, with applications ranging from subsistence farms to large-scale mechanized production farms and high-value specialty crops. Remotely sensed precipitation, temperature, and wind speed are incorporated into weather predictions; Global Positioning System (GPS) data are assimilated into guidance systems for field operations; and advanced sensors are incorporated into specialty equipment for use in precision agriculture.

Imaging technologies most commonly used in production agricultural applications flown on satellites, airplanes, and unmanned vehicles record reflected light or energy from land/water surfaces. Multispectral sensors, such as the advanced very-high-resolution radiometer (AVHRR) sensors on NOAA satellites, have provided daily global coverage at kilometer scale for decades, resulting in widespread use of vegetation indices as indictors of crop vigor (Lillesand et al., 2007). In fact, these simple indices, which provide free data globally, are the most widely used inputs for models of agricultural yield and for empirical indicators of crop health.

More advanced products derived from the next generation of these sensors, such as NASA MODIS (*modis-land.gsfc.nasa.gov/*), are slowly being incorporated into models used in agricultural research and applications. Data products derived from the Landsat series of missions (*landsat.usgs.gov*) have also significantly improved a wide range of agricultural applications, although the 16-day repeat cycle is a limiting factor, particularly in cloud-covered regions. The availability of products based on multispectral data acquired by both space-based and airborne platforms has increased dramatically in the past decade, as satellites launched by both governments and the private sector provide capability for timely products to support agricultural applications.

Future Contributions to Agriculture

Imaging technologies can now simultaneously acquire hundreds of measurements in narrow windows (bands) of the electromagnetic spectrum. New active sensing technologies that emit energy in specific wavelengths and measure associated responses are also becoming commonplace. Three technologies that are evolving to operational level on airborne and space-based platforms are particularly promising for advancing the science of agriculture: (1) hyperspectral imaging; (2) active and passive microwave systems; and (3) laser-based systems.

Soil moisture, a critical factor in crop condition, irrigation strategy, and predicting crop yield, cannot be measured directly and is difficult to derive from remote-sensing data.

Coupled with corresponding advances in agricultural modeling and data-delivery systems, these technologies can revolutionize the characterization and prediction of agricultural processes on multiple scales. Like *in situ* sensors, these new remote sensing technologies provide opportunities for entrepreneurs to develop and deliver products to farmers.

Hyperspectral imaging sensors, which mimic laboratory spectrometers that provide chemistry-based information related to reflectance and absorption, provide two-dimensional images in hundreds of narrow bands. These data can advance the science of agriculture in physically based and empirical models to estimate chlorophyll content (Haboudane et al., 2008) and nitrogen content (Chen et al., 2010), monitor water stress, detect invasive species, evaluate water quality, and so on (Thenkabail et al., 2000). Commercially flown airborne hyperspectral sensors monitor high-value agricultural crops, and hyperspectral satellite missions are being developed by the international community for launch in the next decade.

Remote sensing-based soil moisture products are primarily based on **measurements in the microwave region of the spectrum**, where dielectric properties of soils under different conditions can be related to soil moisture. Although soil moisture cannot be measured directly and is difficult to derive from remote sensing data, it is one of the highest priority measurements for agricultural remote sensing. In addition to being a critical factor in crop condition, soil moisture is an important parameter for characterizing atmospheric and land-surface interactions and plays a role in regional and global weather patterns. Soil moisture is also of paramount importance in developing agricultural management strategies (e.g., irrigation) and predicting crop yield, as well as detecting and monitoring drought.

Current operational space-based soil-moisture products have low resolution (tens of km), which is useful for regional and global applications but of limited use for watershed-scale applications (Jackson et al., 2010). However, the upcoming launch of the NASA Soil Moisture Active/Passive (SMAP) mission (*smap.jpl.nasa.gov/Imperative*) is widely anticipated by the agricultural community because it is expected to provide advanced soil moisture products at resolutions that will be useful for watershed management.

Agricultural management decisions are made at field scales, but policy decisions apply on regional, national, or even international scales.

Laser-based systems, such as LIDAR (light-detection and ranging) systems, emit laser pulses of given wavelengths and detect energy that is intercepted and scattered back to the sensor. GPS-derived trajectories and the platform motion are combined with the time to interception of the backscattered energy to derive high-resolution three-dimensional presentations of the landscape (*lidar.cr.usgs.gov/*).

Airborne LIDAR products, which are widely used for floodplain, bathymetric, and urban mapping, are being investigated specifically for agricultural applications. LIDAR provides the most accurate remote sensing-based estimates of topography (and therefore slope and sun exposure), which are relevant to agricultural management decisions related to runoff (e.g., fertilizer application), crop production in high-relief areas, and soil mapping and management. Information related to the vertical structure of vegetation (e.g., height, density) can also be derived from LIDAR, providing a non-intrusive alternative to traditional destructive sampling (Dubayah et al., 2010; Selbeck et al., 2010).

These three advances in sensor technologies provide clear evidence of the potential of new data sources to support research and applications in agriculture in both the developed and developing worlds. Coupled with decision-support models and rapidly evolving communication technologies, these new sources of data have much to contribute to next-generation agriculture.

Closing the Gaps with Models

Enabled by the widespread availability of computational resources, significant advances have been made in agricultural models that can link and integrate across scales and processes. However, major challenges will have to be overcome before we can take advantage of the power of simulation modeling to evaluate agricultural production, its impact on environment and ecosystem services, and the development of sustainable management strategies. A few of these challenges are described briefly below.

Integration of Models at Different Spatial and Temporal Scales

In situ observations have long been used for the development, calibration, and evaluation of models—from field-scale models such as DRAINMOD (Skaggs et al., 1995), which simulates water and nutrient movement through subsurface drainage, to the WEPP model (Laflen et al., 1991), which simulates soil erosion from hillsides, to the soil and water assessment tool (SWAT) (Arnold et al., 1998), one of the most widely used catchment-scale models that can evaluate impacts of agricultural management decisions on crop production, hydrology, and water quality (*swatmodel.tamu.edu*).

Agricultural management decisions are made at field scales, but policy decisions apply on regional, national, or international scales. Currently, simulation models for analyzing the impacts of agriculture on the field to river-basin scale work in isolation from models that work on global scales. To enable agricultural production evaluations in a single modeling environment, these models will have to be integrated.

Remote sensing and sensor networks are two technologies that are helping to bridge the gap by providing spatial observations that can be used to scale processes from the field and watershed to larger scales. For example, large-scale variability in soil moisture is controlled largely by general conditions (e.g., when it last rained and vegetation type), whereas small-scale variability depends much more on local conditions (e.g., Crow and Wood, 1999).

Process Representation to Evaluate Competing Demands

Evaluating competing demands for services from agricultural lands (e.g., biomass production for food and fuel, water-quality improvement, minimum-flow requirements to meet the needs of ecosystems, etc.) will require an integrated modeling framework that includes ecosystem services, production of food and fuel, and the use of water to support agricultural production and ecosystem demands. The development of such models and frameworks will be essential for sustainable agricultural production in the future.

Sensors and Networks for Monitoring Water Quality

Monitoring water quality is very expensive and time consuming. This is the primary reason for the limited availability of global water-quality data products. In addition, *in situ* and remote sensing technologies for monitoring water quality can only evaluate a limited number of indicators. For the next generation of water-quality models, we will need sensors that can easily and inexpensively monitor parameters such as nitrogen and phosphorus concentrations, pathogens, and sediment in real or near-real time.

New Applications for Modern Communication Devices

Applications to support daily decisions (e.g., the location of the nearest gas station) on mobile communication devices have increased dramatically in the last few years, and the agricultural community also has access to some real-time data (e.g., crop yield). However, we need applications that can be used to evaluate the impacts of agricultural production on hydrology, water quality, and ecosystem services. The development of such applications will facilitate education and decision making for sustainable agricultural production and environmental quality.

Looking to the Future

Although the hurdles described above will be difficult to surmount, attention is now focused on advanced sensing, data storage and retrieval, communication capabilities, modeling, and advanced applications in the agricultural community. Coupled with the increasingly interdisciplinary nature of agricultural education, research, and commercial activities, the future looks promising for the development of new capabilities for meeting both growing demands for food, feed, and fiber, and for diverse ecosystem services in a rapidly evolving world.

References

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment–Part 1: Model development. Journal of the American Water Resources Association 34(1): 73–89.

Chen, P., D. Haboudae, N. Tremblay, J. Wang, P. Vigneault, and B. Li. 2010. New spectral indicator assessing the efficiency of crop nitrogen treatment in corn and wheat. Remote Sensing of Environment 114: 1987–1997.

Crow, W.T., and E.F. Wood. 1999. Multi-scale dynamics of soil moisture variability observed during SGP'97. Geophysical Research Letters 26: 3485–3488.

Drew, M.C., and L.H. Stoltzy. 1996. Growth under Oxygen Stress. Pp. 845–858 in Plant Roots: The Hidden Half, edited by Y. Waisel, A. Eshel, T. Beeckman, and U. Kafkafi. New York: Marcel Decker.

Dubayah, R.O., S.L. Sheldon, D.B. Clark, M.A. Hofton, J.B. Blair, G.C. Hurtt, and R.L. Chazdon. 2010. Estimation of tropical forest height and biomass dynamics using LiDAR remote sensing at La Selva, Costa Rica. Journal of Geophysical Research 115(3): 1–17.

Haboudane, D., N. Tremblay, J.R. Miller, and P. Vin Vigneault. 2008. Remote estimation of crop chlorophyll content using spectral indices derived from hyperspectral data. IEEE Transactions on Geoscience and Remote Sensing 46: 423–437.

Jackson, T.J., M.H. Cosh, R. Bindlish, P.J. Starks, D.D. Bosch, M. Seyfried, D.C. Goodrich, M.S. Moran, and J. Du. 2010. Validation of Advanced Microwave Scanning Radiometer soil moisture products. IEEE Transactions on Geoscience and Remote Sensing 48: 4256–4272.

Joseph, A.T., R.van der Velde, P.E. O'Neill, R.H. Lang, and T. Gish. 2008. Soil moisture retrieval during a corn growth cycle using L-Band (1.6 GHz) radar observations. IEEE Transactions on Geoscience and Remote Sensing 46: 2365–2374.

Laflen, J.M., L.J. Lane, and G.R. Foster. 1991. WEPP: A new generation of erosion prediction technology. Journal of Soil and Water Conservation 46(1): 34–38.

Liao, J., G. Liu, O. Monje, G.W. Stutte, and D.M. Porterfield. 2004. Induction of hypoxic root metabolism results from physical limitations in O_2 bioavailability in microgravity. Advances in Space Research 34(7): 1579–1584.

Lillesand, T.M., R.W. Kiefer, and J. Chipman. 2007. Remote Sensing and Image Interpretation, 6th ed. New York, N.Y.: John Wiley and Sons.

Lowenberg-DeBoer, J., and K. Erickson, eds. 2000. Precision Farming Profitability. West Lafayette, Ind.: Purdue University Press.

Martinez, K., J.K. Hart, and R. Ong. 2004. Environmental sensor networks. IEEE Computer 37(8): 50–56.

McLamore, E.R., D.M. Porterfield, and M.K. Banks. 2009. Non-invasive self-referencing electrochemical sensors for quantifying real time biophysical flux in biofilms. Biotechnology and Bioengineering 102: 791–799.

MEA (Millennium Environment Assessment). 2005. Ecosystem and Human Well-Being: Synthesis. Washington, D.C.: Island Press. Available online at *http://www.millenniumassessment.org/en/Products.aspx?*.

Oshaughnessy, S.A., and S.R. Evett. 2008. Integration of wireless sensor networks into moving irrigation systems for automatic irrigation scheduling. Paper No. 083452. Proceedings of the American Society of Agricultural and Biological Engineers International (ASABE), Providence, Rhode Island, June 29–July 2, 2008.

Porterfield, D.M. 2002. Use of microsensors for studying the physiological activity of plant roots. Pp. 503–527 in Plant Roots: The Hidden Half, edited by Y. Waisel, A. Eshel, T. Beeckman, and U. Kafkafi. New York: Marcel Decker.

Selbeck, J., V. Dworak, and D. Ehlert. 2010. Testing a vehicle based scanning lidar sensor for crop detection. Canadian Journal of Remote Sensing 36: 25–34.

Skaggs, R.W., M.A. Breve, A.T. Mohammad, J.E. Parsons, and J.W. Gillliam. 1995. Simulation of drainage water quality with DRAINMOD. Irrigation and Drainage Systems 9(3): 257–277. doi:10.1007/BF00880867.

Thenkabail, P.S., R.B. Smith, and E. DePauw. 2000. Hyperspectral vegetation indices and their relationships with agricultural characteristics. Remote Sensing of Environment 71: 158–182.

NAE News and Notes

NAE Newsmakers

Fourteen NAE members and one foreign associate have been **elected to the American Academy of Arts and Sciences**. Induction of the new class is scheduled for October 1, 2011, at the academy's headquarters in Cambridge, Massachusetts.

Paul G. Allen, chairman, Vulcan Inc.

Frances H. Arnold, Dick and Barbara Dickinson Professor of Chemical Engineering, Bioengineering and Biochemistry, Division of Chemistry and Chemical Engineering, California Institute of Technology

Wanda M. Austin, president and chief executive officer, The Aerospace Corporation

Marsha J. Berger, professor, Courant Institute, New York University

Edmund M. Clarke, FORE Systems University Professor of Computer Science, Carnegie Mellon University

Glenn H. Fredrickson, professor of chemical engineering and materials and director of Mitsubishi Chemical Center for Advanced Materials, University of California, Santa Barbara

Leah H. Jamieson, Ransburg Distinguished Professor of Electrical and Computer Engineering and John A. Edwardson Dean of Engineering, Purdue University

Michael I. Jordan, Pehong Chen Distinguished Professor, University of California, Berkeley

Linda P.B. Katehi, chancellor, University of California, Davis

L. Gary Leal, Warren B. and Katharine S. Schlinger Distinguished Professor of Chemical Engineering, University of California, Santa Barbara

Chad A. Mirkin, director, International Institute for Nanotechnology and Rathmann Professor of Chemistry, Northwestern University

Alan R. Mulally, president and CEO, Ford Motor Company

Shree K. Nayar, T.C. Chang Professor of Computer Science, Columbia University

Patricia G. Selinger, retired vice president, Data Management, Architecture and Technology, IBM Silicon Valley Laboratory

Howard A. Stone, professor, Department of Mechanical and Aerospace Engineering, Princeton University

NAE Foreign Associate **Raghunath A. Mashelkar**, CSIR Bhatnagar Fellow, National Chemical Laboratory, India

Isamu Akasaki, professor, Meijo University, received the **IEEE 2011 Edison Medal.** Professor Akasaki was honored for his "pioneering contributions to the development of nitride-based semiconductor materials and optoelectronic devices, including visible wavelength LEDs and lasers."

Norman R. Augustine, retired chairman and CEO, Lockheed Martin Corporation, will be honored by the Wings Club with the **2011 Distinguished Achievement Award,** which is given in recognition of outstanding accomplishments in the field of aviation. The award will be presented on October 21, 2011, at the club's 69th annual dinner-dance at the Waldorf Astoria Hotel in New York City.

John Werner Cahn, Department of Physics, University of Washington, was awarded the **2011 Kyoto Prize** by the Inamori Foundation for his "outstanding contribution to alloy materials engineering by the establishment of spinodal decomposition theory." The highest private award given in Japan, the Kyoto Prize is bestowed on an individual whose achievements have had global reach and have contributed to the betterment of society. The prize includes a diploma, the Kyoto Prize medal, and a cash gift of $625,000.

Frans Kaashoek, professor, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, has been chosen to receive the **2010 ACM (Association for Computing Machinery)-Infosys Foundation Award in the Computing Sciences** for his contributions to the structuring, robustness, scalability, and security of software systems underlying many applications. Dr. Kaashoek's use of information-flow control techniques to address a major security challenge in widely used commercial systems has led to efficient, portable, and highly distributed applications of software systems and wider use of portable embedded and distributed systems. The prize includes a $150,000 award.

The Association for Computing Machinery (ACM) has named **Takeo Kanade**, U.A. and Helen Whitaker University Professor of Computer Science and Robotics, Carnegie Mellon University, the winner of the **2010 ACM/AAAI Allen Newell Award** for contributions to research in computer vision and robotics. The Newell Award is given in honor of career contributions that have contributed to computer science as a whole or that bridge computer science and other disciplines. The award includes a $10,000 prize and is supported by the Association for the Advancement of Artificial Intelligence (AAAI) and individual contributors. Dr. Kanade received the award on June 4 at the ACM Awards Banquet in San Jose, California.

Alfred E. Mann, USC Board of Trustees, USC-AMI Chairman, and chairman and CEO, MannKind Corporation, was awarded the **Medical Design Excellence Awards (MDEA) Lifetime Achievement Award** presented by UBM Canon. The award is given to an individual whose contributions during a long career have had a demonstrable impact on technological, business, and cultural advancements in medical devices.

IEEE has awarded **H. Vincent Poor**, dean of engineering and applied science and Michael Henry Strater University Professor, Princeton University, the **2011 IEEE Eric E. Sumner Award**. Sponsored by Alcatel-Lucent Bell Labs, the award was given in recognition of Dr. Poor's pioneering contributions to multiple access communications. Dr. Poor received the award on June 7 at the IEEE International Conference on Communications in Kyoto, Japan.

Priyaranjan Prasad, retired technical fellow, Safety Research and Development, Ford Research Laboratory, received the SAE International **Arnold W. Siegel International Transportation Safety Award** during the SAE 2011 World Congress. The winner of the award is chosen for his or her outstanding international research, innovation, and contributions to crash injury protection, crash injury biomechanics, and crash injury design for all kinds of vehicles.

John Rogers, Lee J. Flory-Founder Chair in Engineering, University of Illinois, has been awarded the **Lemelson-MIT Prize**. Rogers' research has resulted in the creation of revolutionary products integral to human health, fiber optics, semiconductor manufacturing, and solar power. The prize is bestowed on an outstanding mid-career inventor dedicated to improving our world through technological invention and innovation. The prize includes a $500,000 cash award.

Bruce E. Rittmann, Regents' Professor of Environmental Engineering and director, Swette Center for Environmental Biotechnology, Arizona State University, was selected to receive the **Environmental Engineering Excellence Award** from the American Association of Environmental Engineers. The organization presented the award to Dr. Rittmann on May 4 at the National Press Club in Washington, D.C. Dr. Rittman was honored for creating new technology that removes dangerous contaminants from water.

The IEEE Computer Society and Association for Computing Machinery presented **Gurindar Sohi**, John P. Morgridge Professor and E. David Cronon Professor of Computer Sciences, University of Wisconsin-Madison, with the **Eckert-Mauchly Award** on June 7 in San Jose, California. Dr. Sohi was honored "for pioneering widely used micro-architectural techniques for instruction-level parallelism."

Rao R. Tummala, Joseph M. Pettit Chair in Electronics Packaging and director of NSF-ERC in SOP Technology, Georgia Institute of Technology, is the recipient of the **2011 IEEE Field Award in Components, Packaging and Manufacturing Technologies,** which is sponsored by the IEEE Components, Packaging and Manufacturing Technology Society. Dr. Tummala was honored for pioneering and innovative contributions to package integration research, cross-disciplinary education, and globalization of electronic packaging. The award was presented on June 2 at the IEEE Electronic Components and Technology Conference in Lake Buena Vista, Florida.

Amnon Yariv, Martin and Eileen Summerfield Professor of Applied Physics and professor of electrical engineering, California Institute of Technology, was named the recipient of the **2011 IEEE Photonics Award**. The award, sponsored by IEEE Photonics Society, was presented to Dr. Yariv on May 4 at the Conference on Lasers and Electro-Optics in Baltimore, Maryland, for fundamental contributions to photonics science, engineering, and education that have broadly impacted quantum electronics and light-wave communications.

2011 Japan-America Frontiers of Engineering Symposium Held in Osaka, Japan

JAFOE participants discuss their research during the poster session.

On June 6–8, 2011, the tenth Japan-America Frontiers of Engineering (JAFOE) Symposium was held at the RIHGA Royal Nakanoshima Center Building in Osaka, Japan. The event, which was organized by NAE and the Engineering Academy of Japan, was originally scheduled to be held in Tsukuba. However, after the March earthquake, tsunami, and Fukushima Daiichi nuclear disasters, the venue was changed to the Kansai area, which was not subject to risks associated with the events in March.

Sixty up-and-coming engineering leaders—30 from each country—attended this very productive meeting. The four sessions for this year were on massive data management, the Smart Grid, bio-inspired materials, and robotics. Presentations on cutting-edge research in each subject area by two Japanese and two Americans included: large-scale spatial simulation design and analysis; smart grid cyber-security; construction of advanced materials from injectable gels to nanoparticle arrays; and human-like assembly robots in factories.

On the first evening, Dr. Masato Sagawa, president of Intermetallics Co. Inc., gave an informative and welcoming dinner speech. Dr. Sagawa had led research on the development of the neodymium magnet, the strongest type of permanent magnet. Other highlights of the symposium were a poster session on the first afternoon that provided an opportunity for each participant to describe his or her technical work or research, a walking tour of major attractions in Osaka, such as Osaka Castle, and a river cruise with a "Rakugo" storytelling guide.

The symposium and organizing committee were co-chaired by **Katharine Frase**, vice president of industry solutions and emerging business at IBM, and Ichiro Kanaya, associate professor in the Graduate School of Engineering at Osaka University. The next JAFOE symposium will be held in late fall 2012 in the United States.

Funding for the symposium was provided by the Japan Science and Technology Agency, The Grainger Foundation, the Precise Measurement Technology Promotion Foundation, The Watanabe Memorial Foundation for the Advancement of Technology, and the National Science Foundation.

The goals of FOE symposia, which bring together outstanding mid-career engineers (ages 30 to 45) from industry, academia, and government to learn about developments and approaches in a variety of areas of research, are to support and encourage interdisciplinary exploration and to facilitate contacts and collaboration among the next generation of engineering leaders.

For more information about a symposium series, visit *www.naefrontiers.org*. To nominate an outstanding engineer to participate in a future Frontiers meeting, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or *jhunziker@nae.edu*.

Second China-America Frontiers of Engineering Symposium

The second China-America Frontiers of Engineering (CAFOE) Symposium, hosted by Qualcomm at its headquarters in San Diego, was held on March 28–30. The Chinese Academy of Engineering was a partner with NAE in organizing the event, which was supported by The Grainger Foundation. NAE member **Zhigang Suo**, Allen E. and Marilyn M. Puckett Professor of Mechanics and Materials at Harvard University, was U.S. co-chair. Zhihua Zhong, president of Hunan University, was Chinese co-chair.

Consistent with other bilateral FOE symposia, this meeting brought together approximately 60 engineers, ages 30 to 45, from U.S. and Chinese universities, companies, and government laboratories for a 2-1/2–day meeting to learn about leading-edge developments in four fields of engineering: ocean engineering, wireless communication, bio-inspired engineering, and advanced vehicles and mobility.

The ocean engineering session was focused on ocean resource exploitation and hydrodynamics. Two of the talks were on the recent Deepwater Horizon disaster, particularly technology drivers for deepwater drilling. The other two speakers described their work on experimental and computational hydrodynamics, which are essential tools for working in the harsh marine environment.

The four speakers in the session on wireless communication highlighted recent advances and research approaches to improving the capabilities and efficiency of wireless communication systems and enabling new applications. The topics included (1) wireless circuit and silicon evolution and the latest research on exploiting higher radio frequencies to achieve very high speed, point-to-point communications; (2) cognitive radio; (3) integrated systems design and recent approaches to leveraging body-area networks and processing sensor data for preventive health applications; and (4) efforts to improve power efficiency across networks to meet users' needs for higher data rates.

Presentations in the third session, on bio-inspired engineering, highlighted intricate natural design principles and precision engineering that are inspiring new engineering applications from the molecular level to the tissue level. The first speaker explained the principles of molecular assembly and described how they are being used to assemble synthetic materials. This next talk was on molecular "reprogramming" approaches to regulating the behavior of stem cells. The third presentation was on "lab-on-a-chip" micro-devices that integrate living cells as intelligent components. The final speaker described tissue-engineering methods that mimic natural tissue and organ development processes.

The emphasis in the last session, on advanced vehicles and mobility, was on green and intelligent vehicle technologies being developed in response to shrinking supplies of fossil fuels and increasingly complex and congested urban driving environments. Topics included (1) technical breakthroughs for autonomous driving systems achieved by Carnegie Mellon's Tartan Racing, which won the DARPA Urban Challenge; (2) Edison2's design and development of the Very Light Car, which gets more than 100 miles per gallon equivalent (MPGe) and won the Automotive X Prize; (3) a new approach to designing forward collision-warning systems that would improve vehicle safety; and (4) a new routing protocol called Ubiquitous Query for Travel Information (UQTI) to facilitate access to information and improve mobility.

A poster session on the first afternoon was both an icebreaker and an opportunity for participants to share information about their research and technical work. That evening, a dinner address was given by **Irwin M. Jacobs**, NAE chair and co-founder and director of Qualcomm, on the history of Qualcomm, including the development of CDMA and its contributions to telecommunications and areas for continuing innovation. On the second afternoon, participants visited: the Qualcomm Museum which brought to life the company's history and impact; the Qualcomm Research Center, where new technologies are being developed; and the manufacturing floor, where prototypes for in-house use are produced.

The next CAFOE Symposium will be held in China in March 2013. For more information about a symposium series or to nominate an outstanding engineer to participate in a future Frontiers meeting, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

Penn Engineering and NAE Explore "Engineered Networks" at NAE Regional Meeting and Symposium

Eduardo D. Glandt, dean, School of Engineering and Applied Science, welcoming meeting participants.

NAE President Charles M. Vest addressing the audience.

NAE and Penn Engineering hosted a regional meeting and symposium on April 26, 2011, at the University of Pennsylvania (UPenn) to investigate the surge of research interest in the science and engineering of complex, networked dynamic systems. Advances in net-centric technology and autonomous systems promise unprecedented levels of performance, robustness, and efficiency. The symposium, Engineered Networks, focused on two areas in which network science and networked systems have led to spectacular advances: (1) the study of collective behavior in networked, multi-robot systems and (2) the analysis of aggregation and strategic interaction in social and economic networks.

Eduardo D. Glandt, dean of the School of Engineering and Applied Science at UPenn, NAE member, and chair of the symposium, welcomed more than 100 students, faculty, industry partners, and NAE members to the event. NAE President **Charles M. Vest** then delivered his opening remarks and provided an overview of NAE activities.

Session I: Robotic Networks

In the first session, three speakers detailed recent advances and future directions in collective robotics. The session was introduced by Kostas Daniilidis, professor of computer and information science and director, General Robotics, Automation, Sensing and Perception (GRASP) Laboratory at UPenn, who summarized the history of coordination among robotic vehicles and cooperation between manipulators, as well as work inspired by analogous swarms of organisms in biology.

The first talk, "Networks of Aerial Robots," was by Vijay Kumar, UPS Professor of Mechanical Engineering and Applied Mechanics and deputy dean for education at Penn Engineering. He described recent advances that have enabled a new generation of small aerial vehicles and explained the principles and methodologies used to create small, agile micro vehicles capable of navigating complex indoor environments. He also described the theory and framework for using cooperating vehicles to transport large payloads, perform some kinds of construction tasks, and so on.

The presentation by Daniel E. Koditschek, Alfred Fitler Moore Professor and chair of the Department of Electrical and Systems Engineering at UPenn, "Interior Networks of Control and Coordination," included a review of a long-term research agenda seeking to confer dynamical dexterity on increasingly utilitarian robots, with a focus on the key problem of limb coordination. He described the conceptual interplay between robotics and neuromechanics, as well as between applied mathematical theory and empirical engineering design.

The third presentation was by keynote speaker Naomi Leonard, Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering at Princeton University. Her talk, "Collective Motion and Ocean Sampling Networks," focused on the design and control of optimum trajectories for self-directed underwater gliders. She described the significant potential social impact of her research, the underlying theory, and the daunting technical problems she faces in designing control strategies and implementing mobile sensor networks comprising an autonomous ocean observing and prediction system. She also reviewed the practical experience her group had accrued with a fleet of autonomous vehicles that tracked optimally planned paths over a period of many days in support of studies of Monterey Bay by environmental scientists.

Session II: Social and Economic Networks

The second session was introduced by George Pappas, Joseph Moore Professor of Electrical and Systems Engineering and deputy dean for research at Penn Engineering. He highlighted emerging intellectual connections between the fields of networked robots and the networked economy. These connections, he explained, are the foundation for a new network science.

The first speaker in this session, Ali Jadbabaie, Skirkanich Associate Professor of Innovation in the Department of Electrical and Systems Engineering, focused on information aggregation and social learning. In his talk, "Aggregation in Complex Networks," Dr. Jadbabaie presented and then analyzed a non-Bayesian model of information aggregation and social learning that shows how individuals in a social network might reach consensus and rationally aggregate information at the same time.

The final speaker—and second keynote speaker—Amin Saberi, Department of Management Science and Engineering at Stanford University, turned his attention to issues related to "Internet Monetization." Saberi explained how recent advances in algorithmic game theory and mechanism design have led to the development of novel algorithms for computing equilibria in online and sponsored search auctions. He then presented a novel approach to algorithmic game theory and mechanism design.

Dean Glandt brought the symposium to a close with some brief remarks and invited all participants to continue the lively discourse at the reception. For more information about Penn Engineering and the symposium, visit *www.seas.upenn.edu*.

New Study on Integrated STEM Education

In collaboration with the National Research Council (NRC) Board on Science Education, NAE has launched a new study to explore the potential and challenges of integrated K–12 STEM (science, technology, engineering, mathematics) education. Over a period of many years, considerable investments have been made in research to improve K–12 STEM teaching and learning. Most of this research has focused on single subjects in the STEM quartet, most often science or mathematics. This orientation is important, not only because it is consistent with the way education is delivered in this country, but also because of the complexity and lack of understanding of how students acquire knowledge and skills in each of the STEM disciplines.

One aspect of STEM education that has received relatively little attention is how and to what degree the four subject areas are, or might be, integrated in primary and secondary curricula and the potential impact of integration on learning. Connections among STEM subjects are commonplace in the world we live in but are largely absent in K–12 classrooms. Advocates of STEM integration argue that STEM subjects would be more relevant to students and teachers, would enhance motivation for learning, would improve student achievement, would address calls for students with better workplace and college-readiness skills, and would increase the number of students who might consider careers in STEM-related fields.

The goal of the 36-month NAE/NRC study is to develop a research agenda for determining the value—in terms of student achievement, motivation, career aspirations, and other factors—of integrated K–12 STEM education in the United States. Margaret Honey, president and CEO of the New York Hall of Science, is chair of the 15-person study committee. The project is funded by the S.D. Bechtel, Jr. Foundation, the National Science Foundation, the Samueli Foundation, and PTC, Inc.

EngineerGirl! Essay Contest Winners

Melissa Meng

Ming Li Wu

Samantha Harris

The National Academy of Engineering *EngineerGirl!* (*www.engineergirl.org*) website announced the winners of its 2011 Essay Contest, "Engineering and Human Service—Relief from a Disaster." This year, students in grades 3 through 12 were asked to describe an item used for disaster relief and explain the engineering behind its design. Older students were also challenged to suggest potential changes that might be made to the item for use in a different disaster relief scenario.

This year NAE received more than 960 entries from students all over the country. The essays were judged based on creativity and originality, design potential and feasibility, and communication. Contestants were encouraged to find unique items for disaster relief and to thoroughly explain their design and, for the older contestants, to think carefully about how to improve upon them.

Prizes were awarded to winners in three categories: elementary school (grades 3 through 5), middle school (grades 6 through 8), and high school (grades 9 through 12). Prizes ranged from $500 for first place to certificates for honorable mention.

First place for grades 3 through 5 was awarded to Melissa Meng, a third-grader from Gilbert Linkous Elementary School in Blacksburg, Virginia, for her description of the capsule designed to rescue the Chilean miners trapped underground last year. In her essay, she explains the symbolism of the capsule's design, as well as its technical specifications.

For grades 6 through 8, the first-place winner was Ming Li Wu, a sixth grader from North Alabama Friends School in Huntsville, Alabama. She described a solar-powered refrigerator created by students for an engineering competition in a story-like narrative that showed imagination and creativity.

The winner of first prize for grades 9 through 12 was Samantha Harris, a 10th-grader from Charleston Catholic High School in Charleston, West Virginia. The subject of her essay was special chambers in underground mines that provide emergency shelter for miners. Harris' essay provides an in-depth look at advances in engineering technology that have made it possible to create underground chambers with controlled levels of oxygen and carbon monoxide.

Second place winners were: Sophia Giovanis, Grade 2, Long Lake, Minnesota; Haylie Thomas, Grade 8, Littleton, Colorado; Leighton Suen, Grade 12, Staten Island, New York. Third-place winners included: Michelle Zhu, Grade 3, Cupertino, California; Olivia Reynolds, Grade 7, Baltimore, Maryland; and Megan Pence, Grade 12, Ponte Vedra, Florida. Winners of Honorable Mention included: Anna Eichelberger, Grade 4, Long Lake, Minnesota; Doina Ghegeliu, Grade 7, Astoria, New York; Landis Bing, Grade 8, Land O'Lakes, Florida; Naina Iyengar, Grade 11, Monmouth Junction, New Jersey; and Zachary Tucker, Grade 12, Lima, Ohio. All of the winning essays have been posted on the *EngineerGirl!* website.

EngineerGirl!, NAE's innovative website, is a general reference point for young women considering careers in engineering, a field in which they have been, and continue to be, underrepresented. *EngineerGirl!* provides career guidance for students and parents, links to other sites, games, and interesting facts about engineering and the history of women in engineering. Portions of the site have been translated into Spanish to meet the needs of the Latino community.

The 2011 *EngineerGirl!* Essay Contest was made possible by the generous sponsorship of Energy Solutions and Bechtel. For more information about *EngineerGirl!*, see *www.engineergirl.org* or e-mail *engineergirl@nae.org*. A companion website, *www.EngineerYourLife.org*, is geared for academically prepared high school girls.

Projects by the Center for the Advancement of Scholarship on Engineering Education (CASEE)

The third **Frontiers of Engineering Education (FOEE) Symposium**, sponsored by the O'Donnell Foundation, will be held in November. All attendees are early-career engineering faculty who have introduced innovative educational projects in their classrooms. The attendees are selected from individuals nominated by engineering deans and NAE members based on the novelty and potential impact of their educational innovations. The 2011 symposium is organized around three dimensions of pedagogy: (1) expertise in teaching students cutting-edge engineering knowledge and skills; (2) project-based learning; and (3) active and self-directed learning.

CASEE recently received a grant from Advanced Micro Devices Inc. (AMD) to create a **Guide to Infusing Real-World Experiences into Engineering Education**. For this project, CASEE will ask engineering deans and faculty to submit descriptions of successful models of real-world engineering education to a committee of industry and academic experts, who will select the most exemplary models to highlight in the printed guide. In addition to publishing the guide, NAE will host a workshop for engineering deans to identify impediments to adapting these models at their institutions and discuss ways of overcoming them.

CASEE recently developed a website, **Principal Investigators Garnering Useful Instruction on Developing [Project] Effectiveness (PI GUIDE)**, for online mentoring in educational project management and change leadership (*http://govpiguide.org*). The site includes video scenarios drawn from actual situations and discussions by experienced PIs about how to manage the situations they depict. In addition, the site supports a peer-mentoring network for novice PIs. In the future, the site will also include videos of PIs from Advanced Technological Education (ATE), Transforming Undergraduate Education in STEM (TUES), Research on Gender in Science and Engineering (GSE), and the Robert J. Noyce Scholarship Programs.

CASEE and the American Society for Engineering Education (ASEE) conducted a **pilot survey** of engineering and engineering technology students in 2- and 4-year institutions. The survey of 8 community colleges and 17 four-year engineering colleges took place during the spring 2011 semester. In June 2011, NAE hosted a policy summit, with representatives of all participating institutions and individuals from federal agencies and education-related associations. Discussions centered on the survey data per se, policy implications for student transitions, and the impacts of data collection on institutional resources. Data analysis is ongoing, and we hope to broaden the institutional sample in future projects.

Finally, CASEE provides research-to-practice summaries for promoting gender equity and improving teaching based on research on engineering education, social science, and educational psychology (*www.nae.edu/casee* and *www.nae.edu/casee-equity*). CASEE also recently developed a website that provides short inspirational videos that can be used as **recruitment tools** by institutions or individuals. This website highlights individuals with engineering degrees who have interesting jobs and provides links to websites that describe engineering and pathways to earning engineering degrees (*http://engineeringaworldofdifference.org* or *http://eemawod.org*).

Presentations at the Directors' Guild of America

NAE worked with the Science and Entertainment Exchange and IEEE to organize three presentations at the Directors' Guild of America on June 9. Sponsored by IEEE, the event brought together NAE member **Frances Arnold** of Caltech, Maja Mataric of USC, and Randii Wessen of NASA JPL to discuss cutting-edge research in directed evolution, robotics, and space exploration, respectively. Approximately 80 members of the entertainment industry hoping to be inspired and to get story ideas attended the event.

The session was moderated by Jon Spaihts, a science-fiction screenwriter. Spaihts noted, "There is a two-sided exchange going on here. Obviously, the more that filmmakers like myself learn from scientists, the more stories we find. I hope this auditorium is filled with storytellers whose imaginations are magnified by what they hear tonight and think about things like chemistry and robots in ways they never have before. I know that these sorts of fertile conversations have directly influenced my own storytelling."

At the conclusion of the event, Frances Arnold added, "Science is a limitless source of ideas, and engineering is both cool and fun. Filmmakers like those here tonight need to spread the word to young people that engineering gives you the tools to change the world."

NAE-IOM "Go Viral" Challenge

A team of college students from Cooper Union for the Advancement of Science and Art, New York University (NYU), and Northwestern University won the top prize in the National Academy of Engineering–Institute of Medicine (NAE-IOM) "Go Viral to Improve Health: IOM-NAE Health Data Collegiate Challenge."

SleepBot, an app that charts users' sleep habits and benchmarks them against potential threats associated with sleep deprivation, was selected as the first-prize winner from submissions by 15 teams in response to the challenge, which was issued by IOM and NAE as part of the Health 2.0 Developer Challenge. The challenge to university undergraduate and graduate students was to work in interdisciplinary teams to develop a Web-based or mobile product that tackles a health issue in a creative way and encourages community interaction. The developers of SleepBot are Edison Wang and Kevin Tulod, Cooper Union; Jane Zhu, NYU; and William Qiao, Northwestern.

A team from Arizona State University (ASU) claimed second prize with Freebee, an app that spreads awareness on college campuses about health risks from alcoholism, smoking, unsafe sex, drug use, and unsafe campus behavior. Freebee developers are Jennifer Burkmier, Ramya Baratam, Louis Tse, Chris Workman, and Jane Lacson. Details about Freebee are available at *http://www.youtube.com/watch?v=yd-qKqIjCT0*.

Another ASU team took third place with IMPAct, a Web-based, interactive planner that enables individuals and families to keep track of medical appointments. IMPAct team members are Tania Lyon, Taylor Barker, Edgar Sanchez, Eric Kern, and Jennifer Jost.

The first-place team received a $3,000 prize and an opportunity to demonstrate SleepBot during the plenary session, on June 9, of the Health Data Initiative Forum, a gathering of health leaders, software engineers, and IT developers working to accelerate the public use of health data and spur innovation to improve individual and community health.

The Freebee and IMPAct teams received $2,000 and $1,000, respectively, and displayed their winning technologies in the exhibit hall at the forum. Hosted by IOM and the U.S. Department of Health and Human Services, the purpose of the forum was to promote interaction among health and data experts and explore topics related to applications of health information. Several companies and organizations announced new challenges and other initiatives during the event.

New Volume of *Memorial Tributes* Available

Volume 14 of *Memorial Tributes*, a series honoring deceased members and foreign associates, is now available. Each volume is a collection of articles, mostly by friends or business associates of the deceased, highlighting his or her contributions to engineering that have benefited humankind. NAE members or foreign associates who wish to receive copies of Volume 14 or a previous volume should contact the NAE Membership Office at (202) 334-2198. Copies are available to nonmembers from the National Academies Press, (202) 334-3313.

Tributes to the following individuals are included in Volume 14:

Paul A. Beck
Gary L. Borman
Joseph E. Burke
Spencer H. Bush
L.G. (Gary) Byrd
Benjamin A. Cosgrove
Alan G. Davenport
H. Ted Davis
Victor Froiland Bachmann De Mello
Michael L. Dertouzos
Coleman Dupont Donaldson
Jackson Leland Durkee
Gunnar Fant
Irene K. Fischer
Patrick F. Flynn
John W. Fondahl
Gerard F. Fox
John L. Gidley
John J. Gilman
Earl E. Gossard
Serge Gratch
William A. Griffith
William T. Hamilton
Howard L. Hartman
Martin C. Hemsworth
Kenneth J. Ives
Joseph M. Juran
Roger P. Kambour
Raphael Katzen
Ken Kennedy
Jack D. Kuehler
Ralph Landau
Kurt H. Lange
Craig Marks
Albert R. Marschall
Thomas L. Martin Jr.
David Middleton
Joseph Miller
William W. Moore
Morris Muskat
Phillip S. Myers
Robert E. Newnham
James Y. Oldshue
Ralph B. Peck
Theodore H.H. Pian
William Hayward Pickering
Nathan E. Promisel
Robert O. Reid
Allen F. Rhodes
Jacob T. Schwartz
William Rees Sears
Franklin F. Snyder
George E. Solomon
Morgan Sparks
John E. Steiner
Olin J. Stephens II
Thomas G. Stockham Jr.
Bruno Thürlimann
Rong-yu Wan
Charles M. Wolfe
A. Tobey Yu

Calendar of Upcoming Events

September 19–21	U.S. Frontiers of Engineering Symposium Mountain View, California
October 14–15	NAE Council Meeting
October 15	NAE Peer Committee Meetings
October 16–17	NAE Annual Meeting
November 3–5	EU-U.S. Frontiers of Engineering Symposium Irvine, California
November 8–9	NRC Governing Board Meeting
December 2–3	Committee on Membership Meeting Irvine, California

All events are held in Washington, D.C., unless otherwise noted.

NAE Annual Meeting, October 16–17, 2011

The 2011 NAE Annual Meeting will be held October 16–17 at the JW Marriott Hotel and the Keck Center of the National Academies in Washington, D.C. Members of the NAE Class of 2011 will meet on Saturday, October 15, for an orientation. That evening the new members and foreign associates will attend a black tie dinner in their honor hosted by the NAE Council.

The induction ceremony for the Class of 2011 will be held at noon on Sunday, October 16. An awards program will follow.

On Monday morning, October 17, there will be a Business Session for members and foreign associates, followed by the annual Forum "Making Things: 21st Century Manufacturing and Design." In the afternoon, section meetings will be held at the Keck Center and the JW Marriott. The Annual Meeting will conclude that evening with an optional dinner dance at the JW Marriott.

The flyer for the NAE 2011 Annual Meeting is available on the NAE website. Go to *www.nae.edu* to register online.

In Memoriam

PAUL M. ANDERSON, 85, president, Power Math Associates, died on April 26, 2011. Dr. Anderson was elected to NAE in 2009 "for contributions that have advanced the analysis and control of electric power systems worldwide."

IRVING L. ASHKENAS, 94, retired chairman of the board, Systems Technology Inc., died on April 10, 2011. Mr. Ashkenas was elected to NAE in 1992 "for leadership in flying qualities theory and practice, and for contributions to flight control systems and aerospace vehicle system design."

ROBERT R. BEEBE, 83, independent consultant, died on June 11, 2011. Mr. Beebe was elected to NAE in 1990 "for notable contributions to the mining industry in the area of mineral processing and materials handling."

DONALD J. BLICKWEDE, 90, retired vice president, research, Bethlehem Steel Corporation, died on April 24, 2011. Dr. Blickwede was elected to NAE in 1976 "for leadership in engineering advancement in the steel industry."

HARRY E. BOVAY JR., 96, president, Mid-South Telecommunications Company, died on May 24, 2011. Mr. Bovay was elected to NAE in 1978 "for contributions to expansion of knowledge in the energy field including power generation and utilization, and leadership in petrochemical plant development."

WILLARD S. BOYLE, 86, retired executive director, Communications Research Division, AT&T Bell Laboratories, died on May 7, 2011. Dr. Boyle was elected to NAE in 1974 "for contributions to solid-state electronics including the solid-state laser and charge-coupled devices."

CYRIL M. HARRIS, 93, Charles Batchelor Professor Emeritus of Electrical Engineering and Professor Emeritus of Architecture, Columbia University, died on January 4, 2011. Dr. Harris was elected to NAE in 1975 "for contributions to the field of acoustical engineering through engineering practice, research and the engineering literature."

DANIEL D. JOSEPH, 82, Regents Professor Emeritus and Russell J. Penrose Professor Emeritus, University of Minnesota, and Distinguished Emeritus Professor of Mechanical Engineering, University of California, Irvine, died on May 24, 2011. Dr. Daniel was elected to NAE in 1990 "for development of ingenious analytical tools and laboratory experiments used in the discovery and elucidation of novel fluid-mechanic phenomena."

ROBERT G. KOUYOUMJIAN, 87, Professor Emeritus of Electrical Engineering, Ohio State University, died on January 3, 2011. Dr. Kouyoumjian was elected to NAE in 1995 "for contributions to the development of the uniform geometric theory of diffraction and the analysis and design of antennas and scatterers."

MAX V. MATHEWS, 84, Professor (Research) of Music, Emeritus, CCRMA/Music Department, Stanford University, died on April 21, 2011. Dr. Mathews was elected to NAE in 1979 "for contributions to computer generation and analysis of meaningful sounds."

UN-CHUL PAEK, 76, Professor Emeritus, Department of Information and Communications, Gwangju Institute of Science and Technology, died on May 3, 2011. Dr. Paek was elected to NAE in 1998 "for the practical production of optical fibers."

ROBERT J. PARKS, 89, retired deputy director, Jet Propulsion Laboratory, died on June 3, 2011. Mr. Parks was elected to NAE in 1973 "for contributions in radio-inertial guidance, communications methods, systems engineering, and project management of spacecraft and missiles."

WARREN M. ROHSENOW, 90, Professor Emeritus, Massachusetts Institute of Technology, died on June 3, 2011. Dr. Rohsenow was elected to NAE in 1975 "for contributions to boiling and condensing liquid-heat transfer and the teaching of the concepts of heat and mass transfer."

JOHN H. SINFELT, 80, Emeritus Senior Scientific Advisor, Exxon Research and Engineering Company, died on May 28, 2011. Dr. Sinfelt was elected to NAE in 1975 "for contributions in catalysis by metals and bifunctional catalysis, and especially for the concept of 'polymetallic cluster' catalysts."

ROBERT C. STEMPEL, 77, chairman and CEO, Energy Conversion Devices Inc., died on May 7, 2011. Mr. Stempel was elected to NAE in 1990 "for outstanding contributions to automotive emission control, fuel economy, and safety engineering and for leading the integration of such developments."

JOHN A. TILLINGHAST, 84, independent consultant, died on May 7, 2011. Mr. Tillinghast was elected to NAE in 1974 "for leadership in the development and utilization of advanced systems of generation and transmission."

J. ERNEST WILKINS JR., 87, Distinguished Professor of Applied Mathematics and Mathematical Physics, Emeritus, Clark Atlanta University, died on May 1, 2011. Dr. Wilkins was elected to NAE in 1976 "for peaceful application of atomic energy through contributions to the design and development of nuclear reactors."

JACK KEIL WOLF, 76, Stephen O. Rice Professor, University of California, San Diego, Center for Magnetic Recording, died on May 12, 2011. Dr. Wolf was elected to NAE in 1993 "for contributions to information theory, communication theory, magnetic recording, and engineering education."

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at *http://www.nap.edu* or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads. For the United States to maintain its global leadership and competitiveness in science and technology, we must invest in research, encourage innovation, and educate a strong, talented, diverse science and technology workforce. According to the authoring committee of this report, the U.S. labor market is projected to grow faster in science and engineering than in any other sectors in the coming years, making minority participation in science, technology, engineering, and medicine (STEM) on all educational levels a national priority. The study committee analyzes the rate of change and challenges to diversity, especially because minorities, which are the fastest growing segment of the population, are severely underrepresented in science and engineering. The committee argues that the federal government, industry, and post-secondary institutions must work with K–12 schools and school systems to increase minority access to and demand for post-secondary STEM education and technical training. To that end, the committee identifies best practices and provides a comprehensive road map for increasing the involvement of underrepresented minorities in STEM education and improving the quality of their education in general. Recommendations focus on academic and social support, institutional roles, teacher preparation, affordability, and program development.

NAE members on the study committee were **Wesley L. Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics and associate provost, Massachusetts Institute of Technology; **John B. Slaughter**, professor of education and engineering, University of Southern California; and **Richard A. Tapia**, University Professor and Maxfield-Oshman Professor of Engineering, Rice University. Paper, $40.00.

The Future of Computing Performance: Game Over or Next Level? With the end of dramatic exponential growth in single-processor performance, the era of sequential computing must give way to a new era of parallelism. Because the change will mean overcoming significant scientific and engineering challenges, this is an opportune time for innovation in programming systems and computing architectures. Despite increasing diversity in computer designs to optimize for power and throughput, the next generation of discoveries is likely to require advances in both hardware and software. In addition, there is no guarantee that parallel computing will be as common and easy to use as sequential single-processor computer systems are now. Nevertheless, unless we aggressively follow the recommendations in this report, it will be "game over" for improvements in computing performance. Unless parallel programming and related software developments are widely adopted, the development of new applications, which have always driven the computer industry, will stall, and many other parts of the economy are likely to follow. The authoring committee of this report describes the limits of single processors based on complementary metal oxide semiconductor (CMOS) technology and the challenges inherent in parallel computing and architecture, including increased power consumption and escalating requirements for dissipating heat. The committee also provides a research, practice, and educational agenda for overcoming these challenges.

NAE members on the study committee were **Samuel H. Fuller** (chair), chief technology officer and vice president of research and development, Analog Devices Inc.; **Robert P. Colwell**, consultant, R & E Colwell & Associates, and retired fellow, Intel Corporation; **William J. Dally**, Willard R. and Inez Kerr Bell Professor of Computer Science, Stanford

University; **Daniel W. Dobberpuhl**, vice-president, Apple; **Mark A. Horowitz**, chair, Department of Electrical Engineering, Stanford University; and **David B. Kirk**, fellow, NVIDIA. Paper, $36.00.

Blue Water Navy Vietnam Veterans and Agent Orange Exposure. The U.S. Department of Veterans Affairs (VA) has established that Vietnam veterans who develop diseases associated with exposure to Agent Orange are automatically eligible for disability benefits—with the exception of veterans who served on deep-sea vessels. These "Blue Water Navy" veterans must prove they were exposed to Agent Orange before they can claim benefits. At the request of the VA, the Institute of Medicine conducted a study on whether Blue Water Navy veterans were subject to exposures to Agent Orange similar to the exposures of other Vietnam veterans.

NAE member **Menachem Elimelech**, Roberto C. Goizueta Professor, Environmental Engineering Program, Yale University, was a member of the study committee. Paper, $37.50.

How Communities Can Use Risk Assessment Results: Making Ends Meet: A Summary of the June 3, 2010 Workshop of the Disasters Roundtable. During and after a disaster, text messages, Tweets, Smartphone apps, and social networks, along with 24-hour cable news and other media, can deliver relevant information to emergency responders, decision makers, and the general public. Participants in the workshop summarized in this volume identified ways to use these technologies to communicate risks associated with an emergency or disaster, identify and assess real-time conditions in impacted areas, and inform decisions by responders. This workshop was one session in a World Bank conference, "Understanding Risk: Innovation in Disaster Risk Assessment." Workshop participants emphasized three messages: (1) the need to integrate bottom-up communications from citizens to keep emergency responders and managers informed of changing conditions; (2) the need to prepare people for disaster and emergency situations by anticipating emotional reactions, developing and practicing emergency plans, and improving communications and preparedness; and (3) understanding how virtual and personal social networks contribute to resilience and how access to technological risk assessments can increase resilience.

NAE member **Gerald E. Galloway Jr.**, Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park, was a member of the roundtable. Free PDF.

America's Climate Choices. The study committee argues that environmental, economic, and humanitarian risks posed by climate change indicate a pressing need for taking action now to limit the magnitude of climate change and prepare for adapting to its impacts. Despite some uncertainty about future risk, acting now will reduce whatever risks there are and reduce the need for larger, more rapid, and potentially more expensive actions to reduce risks later. Reducing vulnerabilities to the impacts of climate change requires mostly common sense investments that would also protect against natural climate variations and extreme events. In addition, crucial decisions about investing in equipment and infrastructure now, which can "lock us in" to commitments to continuing greenhouse gas emissions for decades, should be revisited. Finally, although it may be possible to scale back or reverse responses to climate change, it is difficult or impossible to "undo" climate change itself. Therefore, although efforts by local, state, and private-sector actors are important, they are likely to be less successful than efforts based on strong federal policies establishing coherent national goals and incentives and promoting U.S. engagement in responses on an international level. The inherent complexities and uncertainties of climate change can best be met by: iterative risk management and efforts to significantly reduce greenhouse gas emissions; preparations for adapting to impacts; investments in scientific research, technology development, and information systems; and collaboration by scientific and technical experts and other stakeholders involved in climate choices.

NAE members on the study committee were **Albert Carnesale** (chair), Chancellor Emeritus and professor, University of California, Los Angeles, and **Charles O. Holliday Jr.**, retired chairman of the board and CEO, DuPont. Paper, $29.95.

Assessment of Fuel Economy Technologies for Light Duty Vehicles. Various combinations of commercially available technologies could greatly reduce fuel consumption in passenger cars, sport-utility vehicles, minivans, and other light-duty vehicles without compromising vehicle performance or safety. This National Research Council report provides estimates of potential fuel savings and costs to consumers for available technologies for three types of engines: spark-ignition gasoline engines; compression-ignition diesel engines; and hybrid engines. Because energy savings are directly related to the amount of fuel used, the focus is on fuel consumption (i.e., the amount of fuel consumed in a given driving distance). Savings can be measured by money saved on purchases of fuel and decreases in emissions of carbon dioxide. By contrast, fuel economy, the usual information given on vehicle stickers, is a measure of how far a vehicle can travel on one gallon of fuel. The study committee concludes that vehicle stickers that provide information about both fuel consumption and fuel economy would be most helpful to consumers.

NAE members on the study committee were **Trevor O. Jones** (chair), chairman and chief executive officer, ElectroSonics Medical Inc.; **Thomas W. Asmus**, retired senior research executive, DaimlerChrysler Corp.; **Rodica A. Baranescu**, manager, Fuels and Lubricants Engine Group, Navistar Inc.; **Linos J. Jacovides**, president, Paphos Consulting, and retired director, Delphi Research Labs; **John G. Kassakian**; professor of electrical engineering and computer science, Massachusetts Institute of Technology; and **Robert F. Sawyer**, Professor Emeritus, Department of Mechanical Engineering, University of California. Paper, $60.00.

Change and the 2020 Census: Not Whether But How. In this interim report, a panel of experts, formed by the National Research Council at the request of the U.S. Census Bureau (USCB), suggests general research priorities for the 2020 census. The panel suggests that USCB take an assertive, proactive approach to planning for 2020 and makes three core recommendations. First, the panel identifies four broad topic areas for research early in the decade. Second, USCB should adopt an aggressive, assertive posture toward research in these priority areas. Third, USCB should set bold goals to underscore the need for reengineering and building a commitment to change.

NAE members on the study committee were **Thomas M. Cook** (chair), former president, T.C.I., and **Arthur M. Geoffrion**, James A. Collins Chair in Management Emeritus, UCLA Anderson School of Management. Paper, $21.00.

Transforming Combustion Research through Cyberinfrastructure. Even in the face of climate change and the increasing availability of alternative energy sources, fossil fuels will continue to be used for many decades. However, they are likely to become increasingly expensive as pressure to minimize the by-products of combustion (pollutants) also increases. The Multi-Agency Coordinating Committee on Combustion Research requested that the National Research Council conduct a study of the structure and use of a cyber infrastructure (CI) for research on improved combustion systems. The committee was asked to explore the potential benefits of CI for research and future applications; evaluate accessibility, sustainability, and economic models; identify CI necessary for education in combustion science and engineering; and identify human, cultural, institutional, and policy challenges and describe how they are being addressed in other fields. The committee also estimates the resources necessary to provide stable, long-term CI for research in combustion.

NAE members on the study committee were **Chung K. Law**, Robert H. Goddard Professor of Mechanical and Aerospace Engineering, Princeton University, and **Mark S. Lundstrom**, Don and Carol Scifres Distinguished Professor of Electrical and Computer Engineering, Purdue University. Paper, $30.25.

Assessment of Approaches for Using Process Safety Metrics at the Blue Grass and Pueblo Chemical Agent Destruction Pilot Plants. The U.S. Department of Defense, through the Assembled Chemical Weapons Alternatives Program, is constructing two full-scale pilot plants at the Pueblo Chemical Depot in Colorado and the Blue Grass Army Depot in Kentucky for the purpose of destroying the last two remaining inventories of chemical weapons in the U.S. stockpile. Together, these two storage sites account for about 10 percent of the original U.S. chemical agent stockpile, which is being destroyed in accordance with the international Chemical Weapons Convention Treaty. The facilities at the Pueblo and Blue Grass sites will use neutralization technologies, which will require specially designed equipment, to destroy chemical agents in rockets, projectiles, and mortar rounds. The Program Manager for Assembled Chemical Weapons Alternatives, which is responsible for safe operation of the facilities, asked the National Research Council to conduct a study on the efficacy of using process safety metrics at these two sites. Process safety is a framework of design principles, engineering, and operating practices for managing the integrity of operating systems, processes, and personnel handling hazardous substances. The authoring committee discusses the pros and cons of using leading and lagging process safety metrics to provide feedback on the effectiveness of controls for mitigating risks and minimizing the consequences of incidents and offers recommendations for facilitating the development and application of process safety metrics at both sites.

NAE member **Mauricio Futran**, consultant, Westfield, New Jersey, was a member of the study committee. Paper, $21.00.

New Worlds, New Horizons in Astronomy and Astrophysics: Panel Reports. Every 10 years the National Research Council releases a survey of astronomy and astrophysics, outlines priorities for the coming decade, and recommends overall priorities for the field as a whole. This volume is a collection of panel reports on key sub-areas: cosmology and fundamental physics; galaxies across cosmic time; the galactic neighborhood; stars and stellar evolution; planetary systems and star formation; electromagnetic observations from space; optical and infrared astronomy from the ground; particle astrophysics and gravitation; and radio, millimeter, and submillimeter astronomy from the ground. This companion volume to *New Worlds, New Horizons: A Decadal Survey of Astronomy and Astrophysics* will be useful to managers of research programs in astronomy and astrophysics, congressional committees with jurisdiction over agencies that support this research, the scientific community, and the public.

NAE member **A. Thomas Young**, retired vice president, Lockheed Martin Corporation, was a member of the study committee. Paper, $55.00.

Federal Funding of Transportation Improvements in BRAC Cases. In a study by the Transportation Research Board on improving Defense Base Closure and Realignment Commission (BRAC) decisions, the study committee concludes that traffic delays resulting from current BRAC decisions and short timelines for implementing those decisions impose substantial costs on surrounding communities and may even be harmful to the military. The report offers recommendations for mitigating the adverse effects of BRAC decisions for the near, short, and long term. Among its recommendations, the committee calls on Congress to consider a special appropriation or the allocation of uncommitted Stimulus funds to address severe transportation problems caused by increases in military traffic. The purpose of these funds would be to initiate projects as soon as possible to reduce congestion within three years.

NAE member **Thomas B. Deen**, retired executive director, Transportation Research Board, National Research Council, was a member of the study committee. Free PDF.

Review of the Scientific Approaches Used During the FBI's Investigation of the Anthrax Letters. Less than a month after September 11, 2001, letters containing anthrax spores (*Bacillus anthracis*, or *B. anthracis*) were sent through the U.S. mail. Between October 4 and November 20, 2001, 22 individuals developed anthrax; 5 cases were fatal. During the subsequent investigation, the FBI worked with other federal agencies to coordinate and conduct scientific analyses of spore powders from the letters, environmental samples, clinical samples, and samples collected from laboratories that were possible sources of the spores. The agency also called in external experts, including some who had previously developed tests to differentiate among strains of *B. anthracis*. In 2008, seven years into the investigation, the FBI asked the National Research Council to conduct an independent review of the scientific approaches used during the investigation to determine (1) if they met appropriate standards for scientific reliability and for use in forensic validation and (2) whether the FBI reached appropriate scientific conclusions.

NAE members on the study committee were **Alice P. Gast** (chair), president, Lehigh University, and **David R. Walt**, Robinson Professor of Chemistry, Tufts University. Paper, $49.00.

National Security Implications of Climate Change for U.S. Naval Forces. In response to a request from the Chief of Naval Operations, the National Research Council appointed a committee, under the auspices of the Naval Studies Board, to study the national security implications of climate change for U.S. naval forces. The committee concluded that if even the most moderate current trends in climate continue, they will present new security challenges for the U.S. Navy, Marine Corps, and Coast Guard. Although the timing, degree, and consequences of future climate change remain uncertain, changes are already under way in regions around the world, such as the Arctic, that call for a naval response. The report addresses both near- and long-term implications for U.S. naval forces and provides corresponding findings and recommendations. Because the terms of reference for the study directed that it be based on scenarios developed by the Intergovernmental Panel on Climate Change and other peer-reviewed assessments, the committee did not address the science of climate change itself or challenge the scenarios on which its findings and recommendations are based.

NAE members on the study committee were **Frank L. Bowman** (chair), president, Strategic Decisions LLC, and U.S. Navy (retired); **Arthur B. Baggeroer**, Ford Professor of Engineering, Secretary of the Navy/Chief of Naval Operations Chair in Oceanographic Science, Departments of Mechanical Engineering and EECS, Massachusetts Institute of Technology; **David J. Nash**, chairman and CEO, Dave Nash & Associates International LLC; and **David A. Whelan**, vice president, Strategic Innovation Phantom Works, and chief scientist, Boeing Defense, Space, and Security, The Boeing Company. Paper, $43.00.

A Risk-Characterization Framework for Decision-Making at the Food and Drug Administration. Every day, the Food and Drug Administration (FDA), which is responsible for ensuring the safety of food, drugs, and other products, must make decisions, often based on incomplete information, that have public-health consequences. FDA recognizes that systematically collecting and evaluating information on the risks posed by regulated products would improve its decision-making processes. Consequently, FDA and the U.S. Department of Health and Human Services asked the National Research Council to develop a conceptual model for evaluating products or product categories and to provide information on associated potential health consequences. This report describes a proposed risk-characterization framework for evaluating, comparing, and communicating the public-health consequences of decisions about a wide variety of products. The framework is intended to complement, not replace, other risk-based approaches that are already in use or are under development at FDA. The proposed framework provides a common language for describing potential public-health consequences of decisions, is applicable for all FDA centers, and draws extensively on the scientific literature to define relevant health dimensions for FDA decision making. In addition to conclusions and recommendations, the committee provides case studies of how the framework can be used.

NAE member **John T. Watson**, University of California, San Diego, was a member of the study committee. Paper. $45.75.

Seeing the Future with Imaging Science: Interdisciplinary Research Team Summaries. Imaging science has the power to illuminate regions as remote as distant galaxies and as close to home as our own bodies. Although many disciplines that can benefit from imaging have common technical problems, researchers often develop ad hoc methods for performing individual tasks rather than building frameworks that could address these problems. At the 2010 National Academies Keck Futures Initiative (NAKFI) Conference on Imaging Science, researchers from academia, industry, and government formed 14 interdisciplinary teams to find a common language and structure for developing new technologies, processing and recovering images, mining imaging data, and visualizing data effectively. The teams spent nine hours over a period of two days exploring challenges at the interface of science, engineering, and medicine. This volume provides summaries written by each team describing a challenge and outlining an approach to solving it. The summaries also include research areas that should be explored to clarify the fundamental science behind the challenge, a plan for engineering the application, an explanation of the reasoning behind the approach, and a description of the benefits to society of solving the problem.

NAE members on the steering committee were **Farouk El-Baz**, research professor and director, Center for Remote Sensing, Boston University, and **Charles Elachi**, director, Jet Propulsion Laboratory. Paper, $34.75.

Forging the Future of Space Science: The Next 50 Years. From September 2007 to June 2008, the Space Studies Board conducted a monthly seminar series, with each talk highlighting a different topic in space and Earth science. This volume includes the principal lectures from the series on subjects ranging from global climate change to the cosmic origins of life, exploration of the Moon and Mars, and scientific research to support human spaceflight. The prevailing messages throughout the seminars are: how much we have accomplished over the past 50 years; how profound our discoveries have been;

how much contributions from the space program have affected our daily lives; and yet how much remains to be done.

NAE members on the study board were **A. Thomas Young** (vice chair), Lockheed Martin Corporation (retired); **Daniel N. Baker**, director, Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder; **Yvonne C. Brill**, aerospace consultant, Skillman, New Jersey; **Saroosh Sarooshian**, UCI Distinguished Professor and director, Center for Hydrometeorology and Remote Sensing, University of California, Irvine; and **Warren M. Washington**, senior scientist, Climate Change Research Section, Climate and Global Dynamics Division, National Center for Atmospheric Research. Paper, $39.25.

Materials Needs and Research and Development Strategy for Future Military Aerospace Propulsion Systems. The ongoing development of military aerospace platforms requires continuous advances in technology. However, significant advances in the performance and efficiency of jet and rocket propulsion systems strongly depend on the development of lighter, more durable high-temperature materials to reduce engine weight without reducing thrust. Unfortunately, materials development has been significantly cut back since the early 1990s, when the United States led the world in propulsion technology. This study provides an overview of current and planned efforts to meet U.S. military needs, considers mechanisms for the timely insertion of materials in propulsion systems and how these mechanisms might be improved, and describes general research and development strategies for developing materials for future military aerospace propulsion systems. The conclusions and recommendations point the way to improving the efficiency, level of effort, and impact of materials development by the military.

NAE members on the study committee were **Wesley L. Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics and associate provost, Massachusetts Institute of Technology, and **William L. Johnson**, Ruben and Donna Mettler Professor of Materials Science, Engineering and Applied Science, California Institute of Technology. Paper, $47.00.

Protecting the Frontline in Biodefense Research: The Special Immunizations Program. The U.S. Army's Special Immunizations Program is an important component of its overall biosafety program for laboratory workers at risk of exposure to hazardous pathogens. The program provides immunizations for scientists, laboratory technicians, and other support staff who work with certain hazardous pathogens and toxins. Although the program was established to serve military personnel, it was expanded through a cost-sharing agreement in 2004 to include other government and civilian workers, reflecting the expansion of biodefense research in recent years. This report focuses on issues related to the expansion of the program, such as regulatory frameworks under which vaccines are administered, the addition of new vaccines, and factors that might influence the development and manufacture of vaccines for the program.

NAE member **Stephen W. Drew**, Drew Solutions LLC, and Merck & Co. Inc. (retired), was a member of the study committee. Paper, $43.50.

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