ILLINOIS
Center for Digital Agriculture

Introduction

Agriculture is entering a transformative age, where technology will change how we support a growing healthy population. The Center for Digital Agriculture at Illinois (the Center) recognizes this transformation and will serve as a catalyst for collaborative research projects across engineering and agricultural disciplines. Increased global productivity and sustainability requires technical innovations that involve the Center's initial themes: automation, data, crops and animals, and people.

The Center will also address the immediate need for a trained workforce. Successful innovations will further increase the need for a workforce skilled in both agriculture and digital technologies, which will lead to new recruitment, training, and retraining challenges for the rural workforce as well as for private sector agricultural concerns.

The Center will leverage the strong tradition of teambuilding for large long-term interdisciplinary research at Illinois, including the National Center for Supercomputer Applications (NCSA) and the Institute for Genomic Biology (IGB). Expertise from these and other centers will advance collaborations between the College of Agricultural, Consumer and Environmental Sciences (ACES) and the Grainger College of Engineering. The Center will enable multidisciplinary research as well as education and outreach involving agricultural, biological, food, consumer, economic, and environmental researchers together with computer science, electrical, civil, mechanical, and other engineering fields.

In partnership with industry, philanthropic organizations, and governmental agencies, the Center will help define policy and address national, global, and industrial priorities. The Center will also launch multiple kinds of partnerships with companies across both agriculture and computing industries, including collaborative research projects, summer internships, scholarship programs, and an industrial affiliates program that will provide companies with preferred recruiting opportunities, priority for collaborative research and consulting, early access to research outcomes, and licensing opportunities for intellectual property.

Vision and Roles for the Center for Digital Agriculture

The University of Illinois is uniquely placed to take the lead in digital agriculture, with departments in ACES and the Grainger College of Engineering that rank in the top tier of *all* of their respective disciplines. The University has taken significant steps towards advancing digital agriculture not only with the Center, but also through the creation of a joint Bachelor of Sciences degree in Computer Sciences + Crop Sciences (CS+CS). Development of a CS + Animal Sciences (CS+ANSC) degree program with the College of ACES is in the approval process.

To achieve collaborative research across these highly diverse disciplines and bring researchers and students from different disciplines together, the Center will organize its research around at least two initial activities: the *Illinois Digital Farm Infrastructure* and the *Digital Agriculture Data Collaboratory*.

- The Illinois Digital Farm Infrastructure will be a flexible and customizable toolkit that simplifies creation of instrumented, networked, semi-automated, and cloud-backed facilities for experimental research and for large-scale on-farm field trials. The infrastructure will enable faculty and students to perform experiments, develop and test equipment, monitor the environment, raise animals and plants for data-intensive experiments, and support large-scale on-farm experimentation. The Digital Farm Infrastructure will provide customizable hardware and software designs that enable extensive use of sensing, wireless communication, edge computing, and automation. As a result, the infrastructure will enable collaborative relationships of engineering researchers interested in developing and evaluating cutting-edge technologies with agriculturalists, food scientists, and biologists interested in exploring novel applications of these technologies.
- The Digital Agriculture Data Collaboratory is a shared space located at NCSA where researchers from all disciplines in the Center will benefit from cutting-edge computer, networking, and visualization equipment, NCSA staff expertise, and synergy with other data-focused research projects. It will enable research in large-scale data storage, data sciences, and data-driven decision making for a wide range of problems. The Digital Collaboratory will bring data science, machine learning, information retrieval, distributed systems, and high-end computing researchers together to explore applications of these technologies in agriculture, food sciences, genomics, and economic modeling and forecasting. It will also contribute to the NCSA Data Analytics service portfolio for its industry partners. The Center for Digital Agriculture will partner closely with NCSA and the NCSA Industry Partners Program in developing the Digital Collaboratory resources and skills.

Funding for the Digital Farm Infrastructure and the Digital Agriculture Data Collaboratory will be obtained from a diverse field of federal, philanthropic, and industry sources.

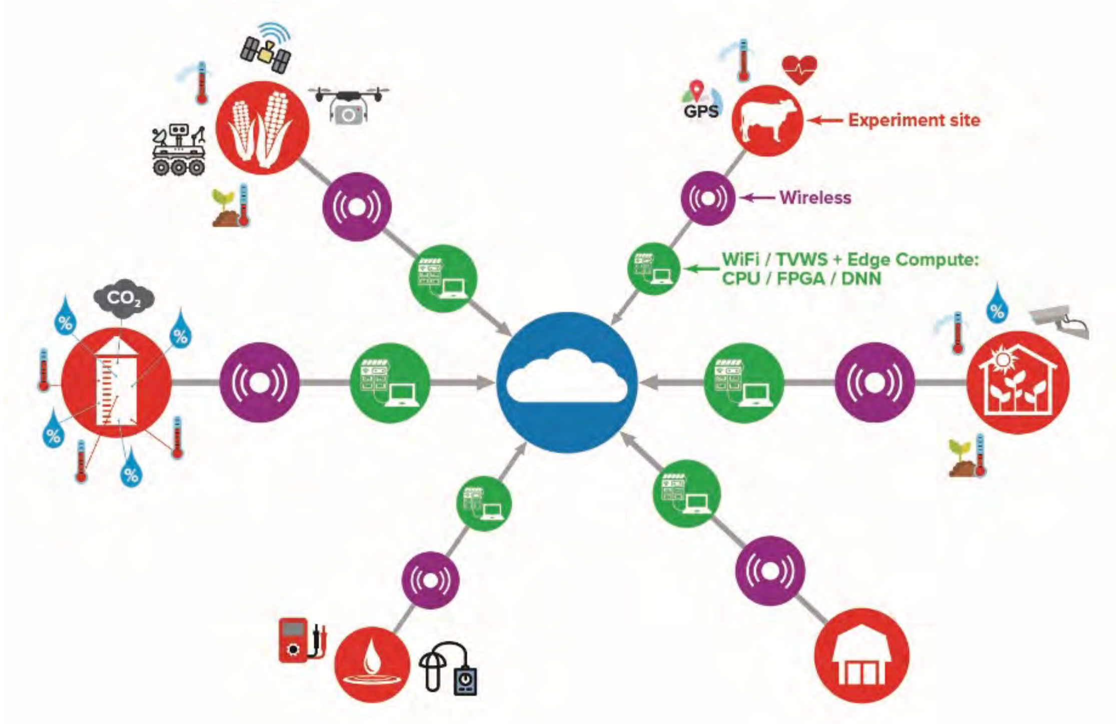

Figure 1 The Internet of Things supports agricultural experiments in diverse, sensor-rich settings (red circles) using short-range wireless networks (purple circle) to connect to edge compute devices (green circle), which transfers processed results to the Cloud.

Another essential factor for the Center is the network of global agricultural, food, and commodity finance companies headquartered in Illinois, many of which have close ties to the University of Illinois. Most, if not all, of these companies currently explore the effect of advanced computing and engineering technologies on their business models. These companies face a profound shortage of skilled personnel at all levels, which impedes their ability to strategically develop and expand their business. Strong collaborative opportunities exist with companies interested in research and development with a medium- and long-term timeframe. Close cooperation of the Center with diverse agricultural and food distribution organizations within Illinois, nationally, and globally will also provide essential guidance to new basic and applied research and its deployment in large-scale production.

Education

The Center for Digital Agriculture is in a position to strengthen opportunities for workforce training at different career stages through newly developed cross-disciplinary undergraduate degrees, advanced degrees, professional online degrees, and community training activities. The Center will also help both students and faculty develop cross-disciplinary research and communication skills, which will advance their ability to perform effectively and efficiently in a dynamic business and academic environment.

The Center will create, foster, and support education and training programs at all levels. Undergraduate degrees already exist or will be launched soon in Computer Sciences + Crop Sciences and Computer Sciences + Animal Sciences. These degree combinations are unique in the United States and include roughly equal numbers of credit hours in Computer Sciences and Crop or Animal Sciences. Additional undergraduate "CS+X" degrees in other agriculture and food-related disciplines are likely to be launched in future. A new Master of Science in Digital Agriculture will include computer science and engineering topics as well as a range of disciplines from the College of ACES. The Center will also reach out to computational and agricultural programs internal and external to the University to increase awareness and penetration of digital agriculture into existing courses. Educating our youth is also a critical element of the Center and outreach to K-12 educational programs, open days, and summer camps will be developed to introduce young students to digital agriculture as a career.

Figure 2 Components of the Center for Digital Agriculture

Extension activities will ensure that rural locations, a highly dispersed workforce, and variable local conditions do not limit, but actually enhance and can benefit from the impact of digital technologies. Essential coordination with private sector organizations will build on the existing extensive investment in automation, data analysis, and computing.

Structure and Themes

Faculty from the Colleges of ACES and Engineering will lead the effort to advance the Center for Digital Agriculture. The four initial themes of the Center are:

- **Automation:** technologies that reduce and augment human labor and achieve more effective agricultural outcomes through improved scalability, accuracy, and precision
- **Data:** all aspects of data collection, security, privacy, analysis, storage, processing, transfer and decision making, related to agriculture and food
- **Animals and Crops:** research to improve animal and crop genetics, production practices, and sustainability using digital technologies
- **People in Agriculture:** use of digital technologies in the social and economic aspects of agriculture, food, nutrition and rural communities

Identifying interdisciplinary collaborative projects within and across these four themes will enable effective interaction between engineers and agriculturists, which is an organizing principle and key goal for the Center. For example, collaborative efforts between ACES and COE will drive development of new autonomous capabilities to improve field data gathering and analysis. All four themes will use both the Illinois Digital Farm Infrastructure and the Digital Collaboratory. This collaborative effort will also create new data analysis algorithms to enable more effective animal production practices. Such advances are destined to drive meaningful gains in agriculture, food, and sustainability.

These four themes will help define the initial efforts of the Center. However, members of the Center anticipate and encourage both cross-theme collaborations and the potential addition of new themes.

Within these very broad themes, the Center has identified several focus areas and others will emerge as substantial academic fields in their own right while spanning a wide range of research fields. The Center aims to attract wide faculty participation to encourage collaboration among research groups across the focus areas and themes.

Automation

The advent of large agricultural machines in combination with highly effective seeds, fertilizers, pesticides, and herbicides for row-crops such corn, soybean, wheat, barley, and sorghum has led to a high degree of success for food production in the United States. Many of these systems are now highly automated and can provide timely and actionable information via broadband wireless or satellite connections. These data provide an opportunity to improve crop yields and reduce the excessive use of chemicals, which contributes to herbicide-resistant weeds and nutrient runoff into waterways and oceans. Digital agriculture practices can provide the data to create high-resolution models of farm-environment interaction, which can inform growers on precise prescriptive chemical application.

While agricultural equipment is increasingly automated, the potential of robotics in agriculture has been explored to a very limited extent. For example, teams of dexterous robots could enable entirely new kinds of production agriculture systems ranging from high-throughput phenotyping and monitoring to production farm management to addressing labor shortages. Likewise, sensing and digital imaging could provide data on plant disease and drought stress susceptibility, chlorophyll content, nutrient concentrations, growth rates, and yield potential as well as food production challenges such as uninterrupted monitoring of temperature and pH. Computer vision can aid in phenotyping, animal monitoring, disease detection, sowing, weeding, picking, sorting, grading, and packaging. Low-energy edge computing can make all these uses of sensors more effective through analysis and decision making in near-real-time at the edge of the network. Collaborative efforts with researchers in the data, animals and crops, and people focus areas will identify and investigate suitable applications for these technologies and the new capabilities that can be achieved through orders-of-magnitude improvements in the energy, compute, and memory requirements of the underlying systems.

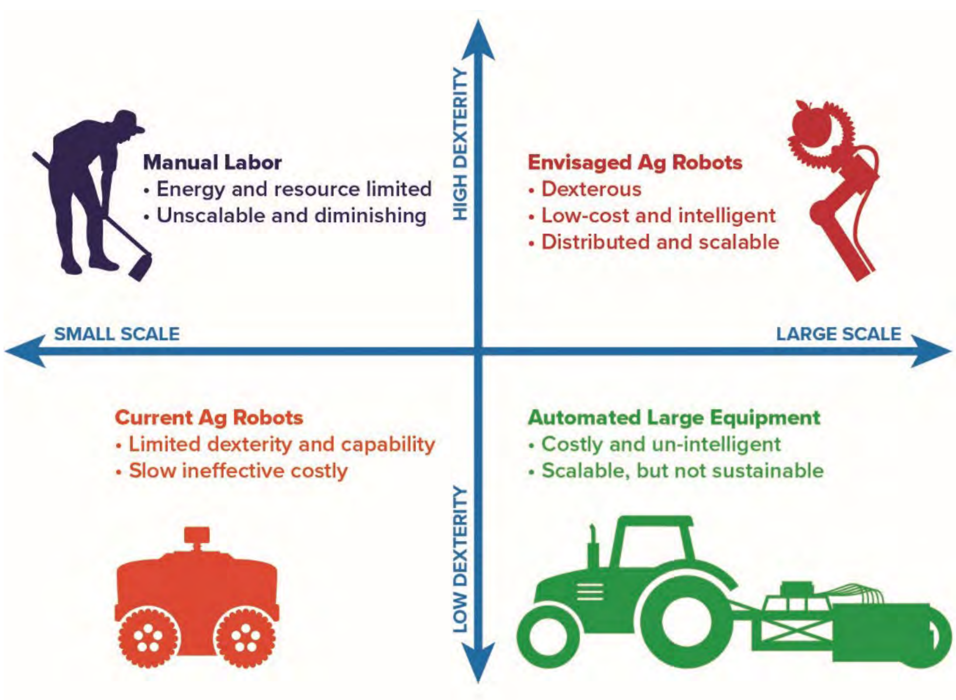

Figure 3 Envisaged Agricultural Robots

Data

Much of our classical understanding of statistical data analysis has been developed for agricultural systems. However, recent advances in mobile technologies, remote sensing, cloud computing, and machine learning has brought unprecedented opportunities to advance precision agriculture, food and financial systems, and new agricultural paradigms. Data-driven approaches will integrate real-time data from farmers, service providers, financial providers, satellites, mobile devices, drones, weather stations, and other digital sensors to support productivity and provide access to services. Digital agriculture has created capabilities in data collection and information extraction on environmental factors and phenotypes that were unimaginable even a decade ago. Using big data analytics, economic modeling and forecasting will investigate the relationship between local and global food security issues and resource management. Importantly, continued success in these areas critically depends on large interdisciplinary research teams, including computer scientists, engineers, and biologists with expertise in crops, animals and microbes, working to combine remote sensing, crowd sourcing, and other novel data collection methods with data sciences and machine learning to generate geographically and temporally detailed data on food production, markets, and food security outcomes. Another emerging element of establishing data provenance, consensus, and immutability is blockchain technology, which uses coding techniques to link timestamp, transaction, and previous block data elements. These properties make blockchain technology especially powerful for tracking detailed information about inputs and production processes through many intermediaries in complex food distribution systems, from farm to table. One significant concern is that the growing use of data-driven technologies in agriculture and the increasing use of Internet-based systems and services raises new security and confidentiality threats. Increased reliance on computer control and digital communications makes agricultural and food systems vulnerable to remote attacks and compromises. Novel algorithmic and computing systems approaches will be needed to address these concerns.

Figure 4 Big Data in Agriculture

Animals and Crops

Improvements in management, crop protection, and plant nutrition enable plant breeders to produce varieties that generate plentiful yields and resist common diseases. The combination of increased pressure on land use, the need to reduce the environmental impact of agriculture, and the increased uncertainty in the environment as a result of climate change increases the threats to global food security. Continued genetic improvement of crops is, therefore, a focus for many researchers in the public and private sectors worldwide. In crop improvement, plant biotechnologists use bioinformatics and modeling to guide crop genome modification for creating new variations while crop breeders use statistical models to guide and predict genetic crop improvement. To increase yields, these models must be sensitive and accurate, which requires a combination of biochemistry, genomics, basic plant biology, algorithms, statistics, environmental monitoring, and rich sensing modalities. Digital methods can greatly enhance the speed and accuracy of these approaches, leading to more rapid gains in genetic improvement in both biotechnology and breeding. For example, automated crop phenotyping can greatly increase the quantity and quality of data on plant growth and development, allowing more accurate and narrow analysis of specific desirable traits, and the screening of larger populations to increase breeding gains per cycle. Real-time on-farm data can facilitate research on field performance and improved cultivation practices.

The soil is also an increasing focus of cross-disciplinary research. Understanding the association of plant roots with endosymbiotic and soil microorganisms and other soil parameters is an emerging research field entirely dependent on digital information from sensors, sequencers, and other data sources. Sustainable farmland management will be based on collecting and analyzing dense data of soil characteristics along with weather and market variables. Research that advances better decision-making at the producer level will have environmental and productivity benefits. Among these decisions, understand of the adequate use of inputs, such as fertilizers and pesticides, is needed for further integration into agricultural, engineering, and data science efforts.

New sensor technologies, spatial datasets, and analytics platforms are also necessary for agricultural research and outreach in animal agriculture. Critical agricultural microbiome research furthers understanding of livestock nutrition. Research into the gastrointestinal microbiome of animals could have substantial benefits in nutrition, production, animal welfare, and targeted antibiotic use. Precision animal management integrates applied livestock management (e.g., housing, animal behavior, animal health, stress physiology) with cutting-edge techniques in data science (e.g., high throughput phenotyping, data visualization, predictive analytics) to improve welfare and production efficiency of livestock species as well as to maximize environmental stewardship of agricultural operations. New technologies to gather data, such as drones to monitor animal movements, remote sensors for monitoring vital signs, digital video of animal behavior, photo analysis to detect conformation abnormalities, and infrastructure for high throughput phenotyping, are currently under development. This emerging area can provide new means and methods for producers to further optimize resource management, improve animal health and well-being, improve meat quality, and remain productive in a changing climate.

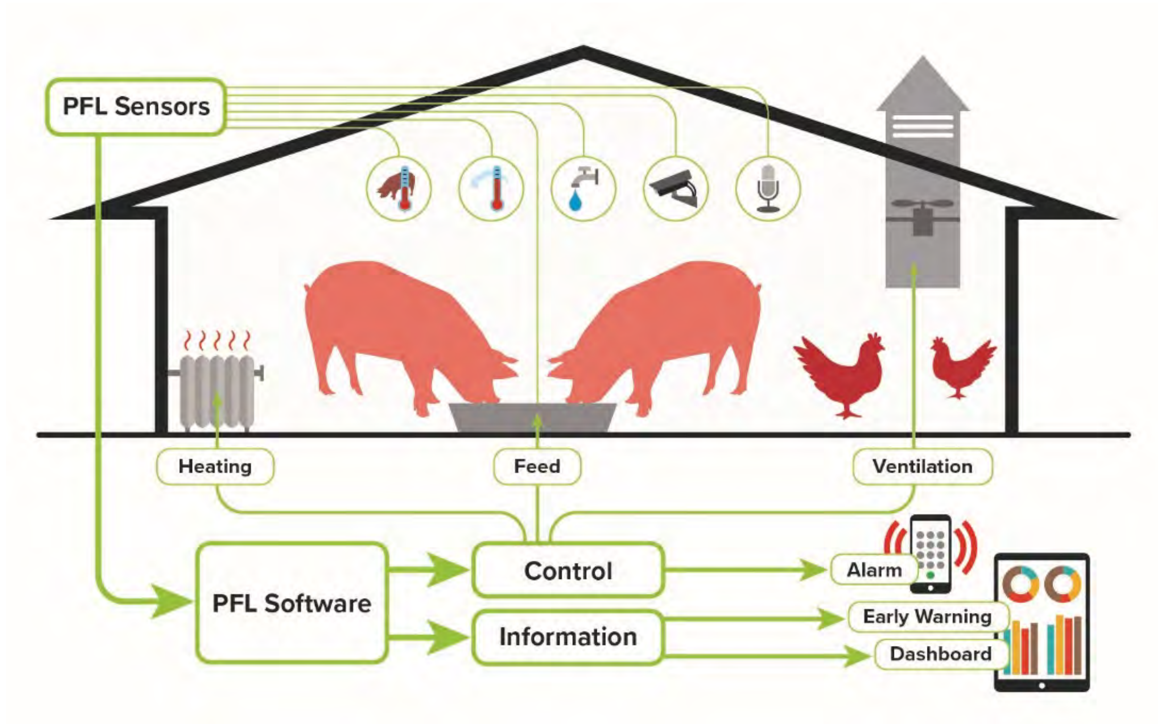

Figure 5 Farm with precision livestock farming technology.

People in Agriculture

People are a crucial part of the agricultural system, both as stewards and as beneficiaries of the multitude of outputs produced from food, fiber, and fuel products to environmental services or disamenities. Understanding the interaction between agriculture and people requires modeling the interplay between human and natural systems. For example, predicting how a new seed technology will alter land and other input use and resulting environmental outcomes necessitates understanding how farmers will change their behavior. Or, one might want to predict how climate change will affect trade patterns and change farmer profits, food accessibility, composition, and nutritional outcomes. Answering these questions requires detailed data on farm production, environment, human behavior, markets and nutrition as well as the ability to combine the data to understand the agricultural and food system as a whole.

Novel data from sensors, remote sensing, retailers, and cellular phones provide potential for improving our understanding of the various components of the agricultural and food system. Combining these data into models of how humans interact with their environment requires flexibility not only in the models of natural systems to capture thresholds and heterogeneity, but also in the ability to combine those estimates with socioeconomic models that allow for complex human behavior. Currently, models of coupled human-natural systems are often "clunky" and are either painfully simplified natural or socioeconomic models or have little detailed connection between models and suffer from computational constraints. Machine learning approaches afford the potential to build complex coupled models of social and natural systems due to their flexibility and frequent parallelization.

These approaches can be used to understand the agricultural supply chain by predicting supply shortfalls and resulting price spikes, climate vulnerabilities, or transportation bottlenecks. Rapid improvements are being made on estimating crop type and yield from satellite data. Combining these data with geocoded information on local prices and transportation infrastructure will allow researchers to better model both the supply and flow of agricultural commodities. Advances in the analysis of high-frequency trading data combined with text analytics further facilitate analysis of market information and infrastructure on price outcomes. In combination, these models will allow us to identify vulnerabilities and target areas for efficiency gains. Another area in which vast quantities of data are produced is in host-microbiome research. Quantitative and computational tools to analyze, visualize, and interpret large and complex datasets from host-microbiome research are inadequate or do not exist. To address this issue, research is focusing on development and deployment of multiple capabilities. For example, novel bioinformatics software programs are needed to translate complex microbial datasets into integrative and predictive models of host-microbe interactions that will bridge the gap in our understanding of the role and function of the microbiome in the host. Another example involves novel visualization tools to advance conceptual understanding of host-microbe interactions within the context of large-scale organizational systems.

Figure 6 *Activities in the food system include the production of raw food materials, transforming raw materials into retail products, marketing those products to buyers and product consumption. Transportation, storage, and waste disposal play a role in each activity*

Likewise, more research is needed in agricultural environments to increase the effectiveness of agricultural practices, food processing and food safety, nutritional quality of products, and product shelf life while minimizing food/animal waste, carbon emissions, and air/and water pollution. Research teams will strive to increase our understanding of the food supply chain processes from the farm to the table that affects and improves the quality of the environment while sustaining the agricultural environment and preserving it for future generations. Technological advances can potentially modify and improve every step of the food supply chain. In addition, the complexity of the current challenges will require an understanding of the economic drivers of production practices.

Conclusion

Optimizing the global agricultural system requires data associated with the people, crops, animals and activities involved in producing, transporting, trading, storing, processing, packaging, wholesaling, retailing, consuming and disposing of food, fuel, fiber, and feed. Research is needed across this spectrum to understand everything from the nature of the data itself, its storage, transmission and optimal analysis, to how it might be used to optimize areas from precision agriculture to food manufacturing to water use and treatment.

The University of Illinois at Urbana-Champaign has recognized this need for transdisciplinary research and education in founding the Center for Digital Agriculture. The Center will serve as a hub for collaborative research across a broad spectrum of engineering and agricultural disciplines not only within the university, but also with industry, government, and academic collaborators across the globe. Existing and future research, education, and extension projects will advance Illinois expertise and position the Center for Digital Agriculture as a major center of innovation and scholarship that will impact agriculture and food systems research and practice worldwide.