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Special report: The Internet of Things for Precision Agriculture (IoT4Ag)

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ABSTRACT

The National Science Foundation (NSF) Engineering Research Center (ERC) for the Internet of Things for Precision Agriculture (IoT4Ag) was established on September 1, 2020 and launched its collaborative programs across the four NSF ERC pillars of ***convergent research***, ***engineering workforce development***, ***diversity and culture of inclusion***, and ***innovation ecosystem***. IoT4Ag unites an interdisciplinary cadre of faculty and students from the University of Pennsylvania, Purdue University, the University of California-Merced, and the University of Florida, with partners in education, government, industry, and the end-user farming community. The IoT4Ag mission is *to create and translate to practice Internet of Things (IoT) technologies for precision agriculture and to train an educated and diverse workforce that will address the societal grand challenge of food, energy, and water security for decades to come.*

1. Introduction

By 2050, the US population is estimated to grow to 400 million and the world population to 9.7 billion (Food and Agriculture Organization, 2009; Perdue, 2017). Current agricultural practices account for 70% of global water use, energy use is one of the largest costs on a farm, and inefficient use of agrochemicals is altering Earth's ecosystems (Coping with water scarcity in agriculture: a global framework for action in a changing climate, n.d., "Water Scarcity and Agriculture," n.d., "Water withdrawal by sector, around 2010," 2016). With finite arable land, water, and energy resources, ensuring food, energy, and water security will require new technologies to improve the efficiency of food production, create sustainable approaches to supply energy, and prevent water scarcity ("Agriculture Overview," n.d.; Food and Agriculture Organization, 2009; Perdue, 2017; Robert Townsend et al., 2019; Walter et al., 2017).

Monitoring of agricultural crops is still accomplished primarily through the expensive, labor-intensive, and time-consuming process of crop scouting, by manual sampling and documenting the state of the field. Precision agriculture involves the use of technology to acquire and analyze data from the field. However currently technologies such as sensors are limited or non-existent to spatially, temporally, and compositionally monitor the state of the field, data is coarse-grained and siloed in equipment, communications infrastructure is limited or non-existent on the farm, and interventions are reactive and over-provisioned, increasing economic and environmental costs. While the concept of precision agriculture has existed for 30 years, *the exponential growth in information technology and data science and the reduction in their cost is setting the stage for the next revolution in agricultural practices.*

The National Science Foundation (NSF) Engineering Research Center (ERC) for the Internet of Things for Precision Agriculture (IoT4Ag) was established on September 1, 2020 and is a collaboration between faculty and students from the University of Pennsylvania, Purdue University, the University of California-Merced, and the University of Florida, with partners in education, government, industry, and the end-user farming community (Fig. 1). The Center unites a convergence of expertise in agronomy, agricultural engineering and economics, and environmental science and in the science and engineering of physical and cyber systems. IoT4Ag launched its collaborative programs across the four NSF ERC pillars of ***convergent research***, ***engineering workforce development***, ***diversity and culture of inclusion***, and ***innovation ecosystem***.

IoT4Ag ***research*** is creating novel, integrated systems that capture

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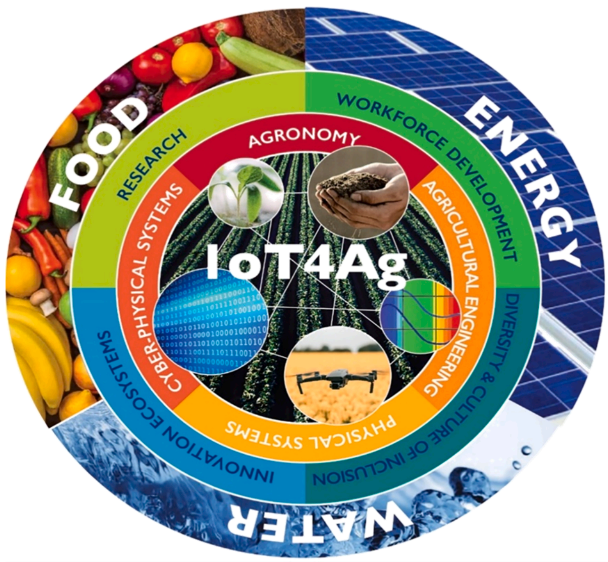

Fig. 1. The NSF Engineering Research Center for Internet of Things for Precision Agriculture (**IoT4Ag**) uniting research, education, inclusion, and innovation to build fundamental knowledge, technology, and a diverse workforce to address the global grand challenge of food, energy, and water security.

the microclimate and spatially, temporally, and compositionally map heterogeneous stresses for early detection and intervention to better outcomes in agricultural crop production. The Center is working to realize IoT technologies to optimize practices for every plant; from sensors, robotics, and energy and communication devices to data-driven models informed by plant physiology, soil, weather, management practices, and socio-economics. Diverse participant groups have been and continue to be recruited and are being educated through IoT4Ag ***workforce development*** and ***diversity & culture of inclusion*** programs to have strong science and engineering knowledge to create transformative, socially-just, engineered products and systems. The Center is working to build a workforce able to discover, innovate, translate, and practice precision agriculture solutions. IoT4Ag has established and continues to expand an ***innovation ecosystem*** and network with academic, industry, investment, and government partners and the end-user farming community to collaboratively build the future of precision agriculture. The IoT4Ag ERC is funded for an initial period of 5 years and is renewable for another 5 years of federal support from the NSF, after which the Center plans to be self-sustaining.

The IoT4Ag vision is ***to ensure food, energy, and water security by advancing technology to increase crop production, while minimizing the use of energy and water resources and the impact of agricultural practices on the environment***.

The mission of IoT4Ag is ***to create and translate to practice Internet of Things (IoT) technologies for precision agriculture and to train and educate a diverse workforce that will address the societal grand challenge of food, energy, and water security for decades to come***.

2. Convergent research, workforce development, diversity & culture of inclusion, and innovation ecosystem

2.1. Convergent research

IoT4Ag's research program aims to transform agriculture today and invent integrated systems to realize the farm of the future (Fig. 2). IoT4Ag is working to create next-generation IoT sense-communication-response technologies and establish engineered integrated systems for precision farming of tree crops and row crops, mainstays of the food supply chain. The Center's research is driven by the agricultural-specific use case of IoT, e.g., its scale, the environment, and the socioeconomics. It is pushing the fundamental scientific understanding and bringing together the tools of our disciplines, i.e., the fields of agronomy, agricultural engineering, agricultural economics, environmental science, and of chemistry and chemical engineering, computer science, and electrical, materials, mechanical, and systems engineering. It is propelling us, in partnership with our innovation ecosystem, to create "IoT4Ag breakthrough technologies" in sensors, robotics, and energy and communication devices to inform data-driven models constrained by plant physiology, soil, weather, management practices, and socioeconomics that enable the optimization of farming practices for every plant. Integrated systems engineered from these technologies are being designed to capture the microclimate and spatially, temporally, and compositionally map heterogeneous stresses for early detection and intervention to ensure better outcomes in agricultural crop production.

The Center is structured into three thrusts that vertically integrate fundamental knowledge and technology from different disciplines and that are horizontally integrated to achieve next generation engineered systems for agriculture. The "flow" or "wiring" diagram in Fig. 3 portrays the scientist's or engineer's depiction of the structure and connectivity of the three thrusts to realize the sense-communication-

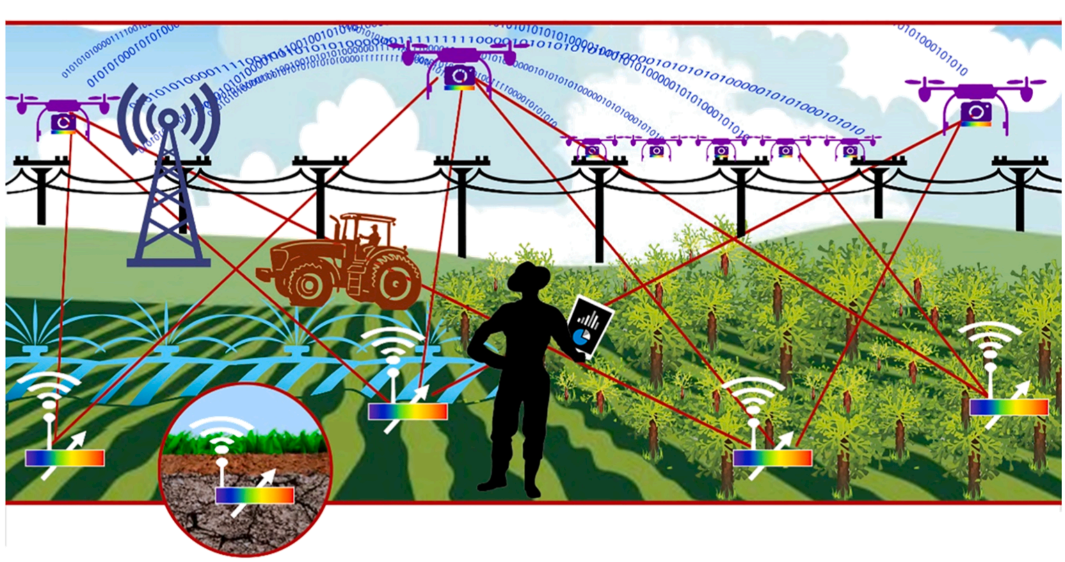

Fig. 2. Schematic of the IoT4Ag "farm of the future" transforming agriculture today.

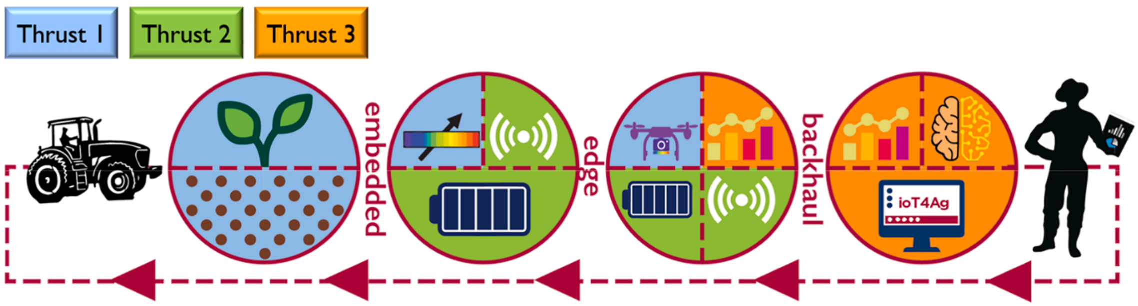

Fig. 3. "Flow" or "Wiring" diagram (from left to right) portraying the IoT4Ag integrated systems in the farm of the future to better manage outcomes in agricultural crop production. manage their fields to ensure crop yield and resiliency in a cost-effective manner.

response integrated systems of the farm of the future to realize better outcomes in agricultural crop production.

IoT4Ag Thrusts:	**Thrust 1 – Agricultural Sensor Systems**
	Thrust 2 – Communication and Energy Systems
	Thrust 3 – Agricultural Response Systems

The diagram also shows the structure and connectivity of IoT4Ag thrusts and the requisite convergence of disciplinary expertise. Plant and environmental scientists are exploring the biotic and abiotic variables that affect crop health and are working together with engineers to design and specify sensors that are *embedded* in the field, to measure these variables from above and below the soil surface. Multi-mode sensors are being co-designed and co-created with energy and communications technologies for the agricultural use case that calls for sensor systems that require zero- or near-zero power, are low cost, can be deployed at large scale, are biocompatible/biodegradable, and can operate below the soil surface and in/below the canopy. Signals are transmitted at the "*edge*" to existing farm machinery or to ground and aerial robots, that are being adopted by the farming community. Robots are being co-designed and equipped with energy and communications technologies to allow autonomous, coordinated multi-robot excursions at the large scale of agricultural fields and to receive and process signals at the edge, directly imaging the field and indirectly imaging sensors from above and below the canopy. A suite of Ag-specific *backhaul* technologies are investigated to transmit signals to the cloud in the characteristically remote and "unconnected" environments of agricultural fields. Multiple instance, multiple resolution sensor fusion techniques are being developed to unite the spatially, temporally, and compositionally heterogeneous sensor data. Models that are data-driven, and yet constrained by the biophysics of plant physiology, the soil, weather, and management practices are being created to "make the invisible visible" and provide "better data". These models are being used to build a decision Ag interface, which coming full circle, allows farmers to intelligently manage their fields to ensure crop yield and resiliency in a cost-effective manner.

2.1.1. *Thrust 1 – Agricultural sensor systems*

Thrust 1 research is in the design and manufacture of resilient, networked, intelligent sensor-robotic systems that monitor the state of plant and soil health over extended areas. Thrust 1 is addressing fundamental scientific questions to uncover how the complex system of abiotic and biotic variables affect crop yield and resilience, and with this knowledge is designing technologies and systems that will be deployed with the spatial, temporal, and compositional resolution needed to capture the state of the field. Thrust 1 unites faculty research groups from eight departments across all four partner universities with expertise in plant and environmental science and in sensors, robotics, and mapping of agricultural fields.

IoT4Ag Thrust 1 Breakthrough Technologies

- Multi-mode, low-cost, distributable, environmental and soil sensor technologies
- Autonomous aerial and ground-based robots

2.1.2. *Thrust 2 – Communication and energy systems*

Thrust 2 research is in enabling advanced approaches for powering IoT devices and robots in the field and for data communication from heterogeneous platforms of sensors, robots, and farming equipment. Thrust 2 is working to establish the knowledge and technologies specifically needed in agriculture, from powering devices and communicating from below the soil surface to deploying technologies at field scales. Thrust 2 is composed of faculty groups from four departments and three of our universities with expertise in IoT sensor and robotic power and in edge and backhaul communication.

IoT4Ag Thrust 2 Breakthrough Technologies

- Energy storage and delivery technologies for field-scale operation
- Ag-specific edge and backhaul communications

2.1.3. *Thrust 3 – Agricultural response systems*

Thrust 3 research is in building and deploying smart response systems that are driven by machine learning and decision-based models for precision agriculture. Thrust 3 is creating techniques to manage uncertainty and fuse the spatially, temporally, and compositionally heterogeneous data from the field to collect not just more, but better data. The thrust is building models, constrained by the biophysics of plants in agricultural fields, to establish a decision-Ag interface for growers to intelligently manage their fields in a cost-effective manner. Thrust 3 is brings together faculty groups from seven departments and our four universities with expertise in machine learning and sensor fusion and in controls and decision agriculture architectures.

IoT4Ag Thrust 3 Breakthrough Technologies

- Biophysically-constrained data-driven models for field analytics
- Decision-Ag interface for field management and improved outcomes in agricultural fields

Fig. 4 is a Milestone Chart describing the work of the thrusts to deliver IoT4Ag technologies and to increase their complexity and scale over the lifetime of the Center to realize the two IoT4Ag testbeds, i.e., 1) Integrated Systems for Precision Farming of Row Crops and 2) Integrated Systems for Precision Farming of Tree Crops. In Year 1, 28 multi-institutional, multi-disciplinary, multi-thrust research projects vertically integrating the ERC 3-planes of fundamental knowledge, enabling technologies, and integrated systems across three horizontally integrated research thrusts were launched. A number of projects are

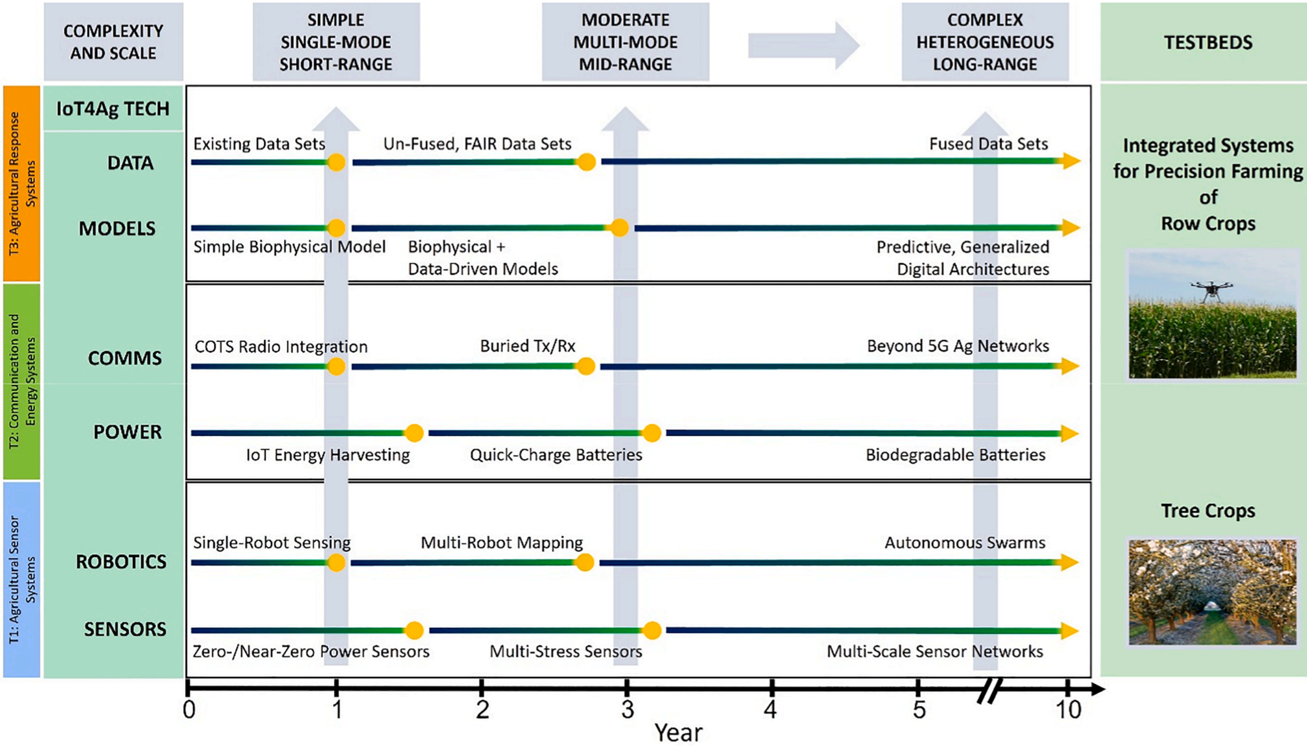

Fig. 4. IoT4Ag 10-Year Milestone Chart.

operating within the IoT4Ag testbeds.

The fundamental knowledge and enabling technologies are intimately connected. For example, IoT4Ag is working to probe the theoretical limits of electromagnetics, important to understanding signals in the soil, canopy occlusion, and signal interference; to create of a suite of Ag-specific communication technologies that connect sensors located in remote and obstructed agricultural environments to the cloud. The Center is advancing materials properties and processes, e.g., from host-guest chemistry to low-cost processable, biodegradable, and biocompatible materials, to realize sensors, that measure variables of interest, and energy devices, that operate in the soil, and allow agricultural field scale measurements. IoT4Ag is developing machine learning approaches to deliver robust predictive models that effectively capture site-to-site variability due to environmental changes and decision science to synthesize Decision Ag interventions that are interpretable, risk-based, and economically feasible. Finally, and coming full circle, IoT4Ag 'sense-communication-response' technologies are impacting agronomy, addressing fundamental scientific questions such as understanding how abiotic and biotic variables affect crop yield and resilience.

2.2. Workforce development

The Center is educating diverse groups of students and professionals to build and practice precision agricultural science, IoT technologies, and systems. IoT4Ag is engaging K-12 and community college students; through exhibits, kits, and lessons/labs with our partner schools, museums, and organizations; high-school students and teachers and community college and undergraduate students in research experiences; PhD and postdoctoral fellows in interdisciplinary research and intra-Center and international exchange; and agricultural professionals and growers through IoT4Ag Ag-extension programs.

2.3. Diversity & culture of inclusion

IoT4Ag is committed to creating, sustaining, and promoting a diverse community by developing and delivering programs, based on good practices, to create transformative changes in engagement, equity, and inclusion of diverse groups in science and engineering and in the practice of agriculture that creates a lasting sense of belonging for Center members and a positive, productive, collaborative climate. The IoT4Ag ERC provides a platform of disciplinary, institutional, and demographic diversity amongst the core institutions and its partners in ***research***, ***workforce development***, and ***innovation ecosystem*** to unite and include diverse groups as they educate each other and work collaboratively to achieve the common goal of realizing food, energy, and water security to benefit society through the development of transformative, socially just engineered products. Diversity & Culture of Inclusion educational programs foster critical reflection about issues that intersect innovation and equity, such as facilitating technological access in underserved communities, ethics in agriculture, data governance, and algorithmic and implicit bias.

2.4. Innovation ecosystem

The IoT4Ag ***innovation ecosystem*** is structured with two bodies: the ERC industrial/practitioner advisory board (IPAB) of industry, venture, government, non-profit, and innovation partners; and unique to IoT4Ag, an Ag-systems advisory board (ASAB) comprised of the end-use grower community. The two-bodies balance "tech push" vs. "industry pull" and guide the direction of Center research, workforce development, and diversity and culture of inclusion activities. This ecosystem ensures transfer of knowledge, technology, and a workforce from IoT4Ag university labs to application through entrepreneurship and commercialization by industry partners and adoption by growers. Engagement with our IPAB and ASAB partners throughout the life cycle of IoT4Ag research, from problem definition to evaluation and deployment of our systems to technology transfer, is essential to maximize impact of the Center and ensure IoT4Ag pursues research that has a clear value proposition for industry and that is well-suited for commercialization and adoption by the farming community, including small farms and under-served regions.

Through the Center integration across all four ERC pillars, "***IoT4Ag***

will deliver more crop for every drop of water and Joule of energy to ensure a food, energy, and water secure future."

3. Limitations and pitfalls

The Center aims to develop next-generation technologies to realize IoT-enabled precision agriculture. IoT4Ag research efforts will lead to systems that combine state-of-the-art sensors, robotics, communications, and data science approaches for monitoring the state of a field of crops with high spatial and temporal resolution and making decisions on this data using biophysically informed models. Even with successful achievement of the IoT4Ag mission to create and translate these precision agriculture technologies and systems, a mission which is necessary to realize the overarching vision of improved crop yields with less water, energy, and fertilizer use as outlined in Section I, it may not be sufficient. Technical and non-technical challenges that are outside the scope of the Center could limit the impact of IoT4Ag technologies and systems and prevent the vision from being achieved. Three primary risks are briefly discussed here.

First, the Center will have highest impact if *local* interventions can be made quickly and cost effectively based on the data and insight provided by IoT4Ag integrated systems. The development of intervention approaches is not within the scope of IoT4Ag's work, so these technologies must be developed by other researchers and companies. If approaches for *local* interventions do not advance quickly enough, IoT4Ag systems may have less impact than anticipated. To mitigate this risk, we are creating systems designed to work with both existing and more nascent local interventions. Furthermore, we are continually keeping track of the state of intervention technologies, in part through connections with industry members and end-users in the Center, and will adjust our technology roadmap based on internal and external advances.

Second, IoT4Ag systems are being developed to take advantage of data from multiple sources, this includes our own sensors, commercial sensors and agricultural equipment, and public and private sources. Standards and policies for accessing, sharing, and using data from a number of these sources is quite variable and also evolving as precision agriculture technologies develop. We are working to mitigate this risk by engaging stakeholders, including end-users and agricultural companies, through the Center to understand perceptions and expectations regarding data privacy and accessibility. As we develop decision systems in Thrust 3, issues related to data standards and access are actively being addressed in our projects.

Finally, IoT4Ag systems will only have impact if the technologies are adopted by end users. Adoption is not guaranteed even if the systems are engineered to meet performance targets and economic constraints. Adoption will also require education of end users on the benefits and implementation of IoT systems which are different from existing management practices. To mitigate this risk, we are and will engage with members of IoT4Ag's ASAB and agricultural professionals, including crop consultants, through our research on adoption and our professional education activities as part of our workforce development, to identify routes and broadly disseminate information about IoT4Ag systems.

4. Discussion

The IoT4Ag logic model for the Center convergent research pillar is shown in Fig. 5. The model highlights the convergence of institutionally, disciplinarily, and demographically diverse IoT4Ag faculty and students from academia with partners in education, government, industry, and the end-user farming community. These groups bring together their expertise, tools, and infrastructure in a research program supported by the NSF to create and translate to practice precision agriculture technologies and systems. The Center activities are positioned to deliver outputs in agricultural-specific IoT sensor, robotics, energy, communication, and data science technologies and their integrated systems, that are responsive to the scale, environment, and socioeconomics of farming. The research program outcomes are structured to build needed fundamental knowledge, technologies, and systems with increasing complexity and scale over time and to establish trusted relationships between researchers and stakeholders to realize precision agriculture systems that contribute to a food, energy, and water secure future.

Author statement

Cherie R. Kagan, David P. Arnold, David J. Cappelleri, Catherine M. Keske, and Kevin T. Turner worked collaboratively to acquire funding for the IoT4Ag Center and to write and edit the manuscript.

INPUTS & RESOURCES	ACTIVITIES	OUTPUTS	OUTCOMES		
			SHORT-TERM	MEDIUM-TERM	LONG-TERM
•NSF funding and ERC program resources •Excellent faculty; undergraduate, graduate, and postdoctoral Fellows; and staff •State-of-the-art PI research laboratories and shared experimental and cloud and edge computing facilities •Existing and innovative science and technologies; data; and tools, and methods from different disciplines •Agricultural extension campuses with row and tree crop control, plots, and field and orchard-scale instrumented testing facilities, representing the diversity of crops and agricultural environments in the US •Scientific advisory board members •Existing and new relationships with industry members, government and innovation partners, and the end-user community of growers joining our industry practitioner and Ag-systems advisory boards	•Use current and create new IoT sensors for high-resolution, multi-mode sensing of plant and environmental targets •Construct an autonomous robotic fleet to map targets in unstructured fields at scale •Design, fab and test bio-degradable IoT battery, antenna •Optimize waveforms for rural and agricultural communication networks •Investigate rapid recharging of and high-power density batteries •Generate robust, interpretable, interoperable analysis for data with different spatial and temporal resolutions •Implement active learning for uncertainty reduction in agricultural situational awareness •Use biophysical models to constrain and train machine learning models •Integrate all thrust technologies in a system •Evaluate technologies in control, plot, and field testbeds and with industry and grower groups	•Reliable, accurate, multi-mode sensor systems distributable at field scales for early detection of biotic/abiotic targets affecting crop yield and resiliency •Hardware-software tools for mapping and fusing chemical and physical data on targets above and below the soil surface •Ag-specific edge and backhaul communication technologies •Powers sources for field-scale deployment of IoT sensors and robot fleets •Data sets and software for use in research and adaptable to production for model development, training, calibration, or decision making •Data-driven decision and control systems for agricultural response •Control, plot, and field testbed protocols for system evaluation •Cost-effective, integrated Ag sense-communication-response systems •Studies of the socio-economic benefit of precision Ag	•Knowledge of technology requirements through guidance from our stakeholders composed of industry members, government and innovation partners, and growers •Disciplinarily diverse experts create new research and development opportunities •Advances in knowledge of plant, environmental, device, and data science and engineering •Creates innovative sensor, robotic, power, and communication technologies and new biophysically-constrained models, controls, and software interfaces to advance Ag practices •Produces publications, patent applications, copyrights, and new industry collaborations •Recognized as a global leader in sense-communication-response systems for agriculture, and commercial innovation through technology transfer	•Academia – government – industry partnership shortens the cycle to define-develop-deploy IoT4Ag systems •Increased number and types of measurable and interpretable plant and environmental targets, and increased areas and resolution in mapping •Higher data rate and longer-range communications with more coordinated robotic and farm machinery platforms; Ag-use case included in future communication standards •Better quality data for precision and scalable analytics and risk-aware interventions •Increased crop yield and quality from deployment of IoT4Ag systems, benchmarked against current industry methods •IoT4Ag builds on knowledge and technologies to receive additional funding from federal, state, philanthropic, or industry sources •Research yields new educational resources and tools	•Multidisciplinary Ag–Tech research is sustainable and growing, and broadens the impact of IoT in other sectors •Known best practice example of convergent research driving new knowledge and innovative technologies and systems for the benefit of society •Help realize the "NSF 10 Big Ideas" in Understanding the Rules of Life, Harnessing the Data Revolution, Mid-scale Research Infrastructure, and Growing Convergence Research •Deployed automated, integrated systems for early detection and intervention that transform agricultural practices •Increased efficiency of energy, water, and agrochemical use in farming establishing sustainable agricultural processes •Increased production of high-quality crops for greater US and global food security and higher profitability of farms •US is the global leader in precision agriculture

Fig. 5. IoT4Ag logic model for convergent research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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