Growing Plants, Raising Animals, and Feeding Communities through Connected Agriculture: An IoT Challenge

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Abstract

The Internet of Things is a growing field of design and development in agriculture. In this article, we provide IoT researchers and practitioners a glimpse into the motivations, needs, and challenges faced when designing digital technologies for agriculture. We describe three farming scenarios and offer a vision for the power of IoT in agriculture, followed by a discussion of opportunities for design. We build the argument for why just collecting data isn't enough and suggest target areas for the design of ubiquitous digital technologies for agriculture. Finally, we introduce four communities of practice on IoT for agriculture.

Introduction

Agriculture is core to human survival. Through agriculture we harness the power of nature to grow plants and raise animals to feed, clothe, and fuel our communities. From axe to drone, we have designed and developed technologies to augment our physical and mental faculties in the pursuit of food, and eventually, the practice of cultivation and husbandry. The design of agricultural technologies is not new, but our methodologies, farming practices, communities and values, science, and environment are all changing. Agricultural and technological practice and innovation are deeply intertwined.

The dawn of agriculture is marked by our transition from nomadic to settlement-based societies in the Neolithic period, as we began to domesticate plants and animals. Since then, there have been three technological innovations that have catapulted our agricultural capacity. First was the industrial revolution, spawned by the development of the John Deere steel plow that magnified our ability to break the soil and enable improved seedbeds at that time. Subsequent development of tractors and other machines transformed agricultural operations, making agricultural mechanization one of our top 10 feats of engineering [1]. In the early 1900s came chemical innovations exemplified by the discovery of the Haber-Bosch process: an artificial nitrogen fixation technique use to produce ammonia. Our ability to produce synthetic fertilizers dramatically increased food production. Genetic engineering marks the third wave of technology in agriculture: Norman Borlaug's development of wheat varieties for multiple growing seasons in a year, disease resistance, and, most famously, dwarfism. Along with the continued progress in cultivation methods, these have resulted in the massive expansion of food production throughout southeast Asia, popularly known as the Green Revolution. Each of these periods of technological innovation have had complex ripple effects on human nutrition, environmental conditions, economic prosperity, social justice, and the very nature of agriculture.

We are now well into a new era in agriculture that builds on the knowledge and tools from each of those earlier revolutions: the digital revolution. We design technologies to help us manage complex food logistics and distribute food fairly; improve worker livelihoods, community well being, and equitable money distribution; improve nutritional quality of food, while enabling creativity in cooking; improve animal welfare, soil health, and air and water quality, and create more regenerative agricultural systems. Agricultural technologies are no small matter of programming, and the challenge that lies ahead for the IoT community is a transdisciplinary problem in connecting plants, animals, machines, people, and environments, to support resilience in our food system.

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This has inevitably led to the design of a plethora of networked devices for sensing and actuation, conceptualized as the Internet of Things (IoT), with the promise of technologies to empower us to sense more, act swiftly, and make better decisions. Early visions of IoT for agriculture focused on the augmentation of human senses. Cameras and imaging provide sight at a distance, with computer vision enabling the detection of crop health and tracking of animal movement. Chemical traces can be sniffed out using air quality monitors, allowing for the monitoring of methane emissions by animals in confined environments. Probes allow us to touch soil to sense for moisture, and our hearing is augmented through devices that listen for the presence of predators in our pastures. However, every sensor we introduce runs the risk of inducing sensory overload. An increased interest in sensing farms introduces both opportunities for new agricultural practices but also a cognitive overload on farmers, consumers, and everyone in between, as they are faced with a glut of data. The near-term challenge in agricultural IoT is to consider: How can we empower agricultural stakeholders with high quality and timely data for better decision making?

At minimum, IoT is simply a network of sensors and actuators deployed in a given context [2]. IoT involves machine-to-machine interaction, where each machine may consist of a data acquisition component, a computational and data storage component with networking capabilities, and sometimes, actuators or control logic. Taken to its logical extreme, IoT involves ubiquitous computing, with sensors and actuators embedded in our landscapes, abstracting and automating certain categories of actions (e.g., moving things) and decisions (e.g., when to turn a switch on) without human intervention. It is imperative, therefore, that we consider community values, civil liberties, the future of work, and environmental impacts, among other consequences when designing IoT systems, including IoT for agriculture. Technology is an alloyed good, which combines potential benefits to society and human well being with externalities that may only appear post-deployment.

In the coming decade, the challenge will be to consider: How can we harness the power of digital agricultural technologies to improve, sustain, and grow with care? Innovations in this space have applications throughout our food system, from agriculture, to production, transportation, processing, marketing, consumption, all the way to waste management. The thoughtful implementation of IoT in agriculture offers the radical opportunity to improve resilience in our food system and enable data-driven regenerative agriculture.

Valley Farms is a 7,000 acre farm located in the Wabash heartland, Indiana. Primary commodities include corn and soybeans, with some land in winter wheat. The land has been farmed continuously for 4 generations with Paul and daughter Laura shepherding the farm into the digital era. Farm goals include:

- To improve coordination and collaboration among the staff.
- Maximize productivity through optimizing machinery and labor decisions.
- To use precision agriculture tools to optimize input efficiency and yield productivity.
- Maintain digital farm records to improve potential of using cutting edge analytics.

UAV Scouting	Put on your VR glasses and I will show you some anomalies in your fields tagged from UAV imagery.
Machinery Maintenance	It is just 10% early, but you may want to do your regular machine maintenance Thursday and Friday while the fields are too wet for work; if you do not, you risk having to do it a holiday weekend.
Variable Rate Tech	Optimal spraying rates, with maximum benefits, require high quality image data within the next few days. I suggest you send the UAVs to Ross 2N, 4S, and 7W today since those fields had excessive foreign material (likely weed seeds) last harvest.
Soil Health Monitor	The latest tillage passes through your fields have been analyzed and lime needs, tallied. Would you like to spend down some of this year's profits to treat fields that could wait until next year? The MyFields app has prioritized, by yield impact fields to treat; select fields and order lime automatically.
Farm Management	You have 63% of your land planted, Because of recent weather, you may have labor capacity to check seed and chemical inventories to be sure the projections get us to the end of planting season correctly. Jack and Jill did this last year, so you may want to have them do it again.
Labor Coordination	The planter and sprayer parts needs are tallied in Trello; consider having Julio take one of the farm trucks home this evening so he can get those items before coming to the office tomorrow. The dealership site shows these in stock and the store is only 3 miles from his home.
Machinery coordination	According to the data in the CONTxT application which is tracking season progress, the 555 acres of the Hill and Vale farms have yet to be planted. According to last week's actual field capacities, you can take advantage of the recent weather pattern to get equipment to that neighborhood to finish that region this week. The plot plans in MyFields generate load lists for seeds and chemicals.

FIGURE 1. Valley Farms: A design scenario envisioning IoT in agriculture.

Bluebird Gardens is an employee-owned 50 acre fruit and vegetable farm outside Monterey Bay, California. Primary commodities include leafy greens, brassicas, and seasonal vegetables such as summer tomatoes and fall pumpkins. Harvey and Suraj are the primary farm managers with a staff of 12 people. Crop commodities are sold via an on-farm market stand, a CSA program, and direct to local restaurants. Farm goals include:

- To improve coordination and collaboration among the staff.
- To provide nesting sites for the endangered Least Bell's Vireo.
- To be more market- and environment-responsive.
- Maintain 5 years of records so as to obtain organic certification all fruits and vegetables grown.

Greenhouse Controls	Your arduino controlled temperature and humidity sensors are correctly conditioning the air within the greenhouse based on the current tomato and pepper seedlings and onion sets profile within the greenhouse.
Augmented Machinery	Your transplanter instrumentation suggests the seedling plants are 12.4% higher than the target. You should either dial back the density or order more seedlings unless you changed plot plans.
Soil Monitoring	The soil moisture and pH probes in strategic zones of the vegetables indicate that pH should be adjusted for tomatoes and brassicas may need irrigation <1 day if it doesn't rain as predicted.
Water Quality	Check the chemicals in the washing station pretreatment circuit because pH seems to be a bit off. Well water and irrigation lines are normal.
Nesting Cam	Today is a good day to tweet about your bird nesting site cameras. Based on the egg laying dates, the next three days are peak hatching dates.
Farm Management Software	With a better alignment of supply to demand over time, increased profit potential is on the order of 22% (see sales trend report which includes unsold or discounted sales from last year for improved rotation and quantities).
Greenhouse Controls	Your arduino controlled temperature and humidity sensors are correctly conditioning the air within the greenhouse based on the current tomato and pepper seedlings profile within the greenhouse.

FIGURE 2. Bluebird Gardens: A design scenario envisioning IoT in agriculture.

A Tale of Three Farms

In each of Figs. 1, 2, and 3, we detail a design fiction scenario to offer a sampling of agricultural complexity and decision making. Each scenario is concerned with an archetypal farm and describes a suite of IoT sensing and intelligent decision support that explore the untapped but reachable potential of IoT in agriculture.

Connected Agriculture

We describe five categories of connectedness in agriculture: plants, animals, machines, people, and environments. By breaking down the landscape of agricultural IoT in this manner, we offer a variety of entry points for IoT researchers and practitioners to consider when designing sensors, actuators, micro-computers, and IoT devices for agricultural use cases.

Connected Plants

We grow a very wide diversity of plants as agricultural commodities. Each type of plant has its own unique management challenges, structural properties, tolerances, and components that we care about the most. The efficacy of plant sensing technologies varies widely. Highly standardized plants grown in monocultures offer the least amount of variability and have proven to be a good testbed for many plant sensing technologies. As sensors and our ability to use such data with robotics improves, we are beginning to see more and more design for specialty crops (vegetables, fruits), including interest in design

Luna Dairy is a 300-cow, 400-acre robotic dairy in central Pennsylvania. They market milk to a processor, but regularly entertain schools and other organizations in agri-education. Tricia manages the cropland and machinery and uses mid-level precision technologies because that is all that is available for forage systems. Brian oversees all animal operations. They strive to be exemplars regarding animal well-being, livestock nutrition, and nutrient utilization. They utilize robotic feeders for cows and calves and robotic milkers to improve consistency in feeding and comfort for the livestock. Farm goals include:

- To monitor and improve animal well being and production.
- Educate the public regarding agricultural operations.
- Maximize return on nutrients as well as investment.
- Conserve soil with appropriate forage-based production on the owned land.

Forage Production	The alfalfa growth model, using the near-term forecast for this week and historical trends of the past 8 years for weeks that follow, suggests you commence cutting on May 14 to get all 150 acres harvested near optimally. Even though this may delay corn planting, we are 90% sure you can complete corn planting in time given the day length of silage corn you are planting.
Animal Tracking	Your heifers should be moved from paddock 7 to 8 this afternoon. We could automatically open the gate and mini-swarm UAV operations, but you may want to do this manually and check on #74 while you are there. Her chewing behavior and pasture roaming pattern is atypical for her.
Water Quality	Environmental temperatures have cooled significantly over the past 2 weeks. Generally water intake lowers with temperatures in this range but water intake has steady which indicates your cows are near their optimal comfort level. Milk production and frequency to the milkers is steady.
Feed Management	Usually you rotate from paddock 3 to 10, but given current soil moisture levels, the forecast, and historical records, I am 90% sure that going into paddock 8 first will increase feed production and gain by 7% over the next 30 days.
Environmental Control	The cows spent more time inside over the last three days than is average for this time of year. As a result, your energy consumption is up 16%. Wind, not temperature or humidity, is the cause; if you open 40% of the south curtains and only use fans to control humidity inside, energy consumption can be 15% without affecting comfort.
Robotic Feeding	See the MyFeeder app to see which 8 calves are consuming milk replacer at below threshold (75% of average for calf weight) values. Three of those calves have been treated for scours. Activity and thermal sensors are suggesting the other 5 may be in need of treatment.
Waste Management	Your phosphorus concentration in the manure from the lactating cows is 6% lower than at this time last month. You may be able to use more on your land to lower your nitrogen bill.

FIGURE 3. Luna Dairy: A design scenario envisioning IoT in agriculture.

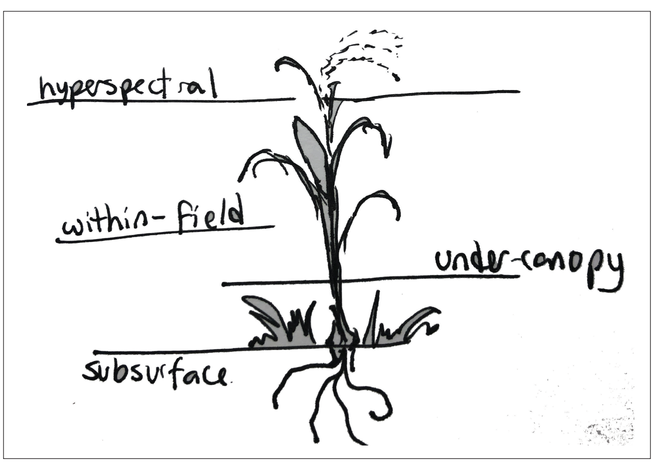

FIGURE 4. Plant sensing

for the management of diverse farming systems.

Figure 4 overviews the different "levels" at which we sense plants. Each of these types of sensor data, when coupled with an actuator, may be used for a variety of strategic and tactical decisions in a field. Some examples include:

- Subsurface: Sensing root architecture can inform our assumption about nutrient uptake, and thus determine nutrient management and tillage remediation.
- Under-canopy: By counting plant stems in a row, we can determine yield potential and gain an understanding of how plant density affects plant growth or planter settings affect germination.
- Plant-level: Genomics data and within plant sensing via, for instance, hyperspectral imaging and high throughput phenotyping offer insights into the interplay between genetics and environment.
- Overhead: Machine or unmanned aerial vehicle (UAV) mounted sensors can be used to determine weed-crop competition or disease manifestation, providing farmers with a map of crop health to inform field management.
- Extraterrestrial: Remote sensing can be used reasonably effectively to estimate biomass or ground cover and subsequently crop effects on the landscape.

Connected Animals

Livestock introduce many levels of complexity when thinking about IoT for agriculture. While raising animals for food, there is a delicate balance between managing their diet, environment, and other factors to result in high-quality meat. There is also a need to care for their well being and quality of life. Animal needs vary widely; to date, IoT for livestock has focused on support for beef and dairy cows.

- Individual (external). A common practice, whether animals are kept indoors or outdoors, in water or on land, is tagging. Tags have evolved from brands to clips on ears, to RFID tags that allowed for tracking of animal movement, and more recently are beginning to include a variety of sensors. For example, accelerometers placed on ear tags can provide researchers with valuable data on animal behavior, allowing early detection of stress, sickness, estrus, or pregnancy.
- Individual (internal). More recently, experimental technologies are being developed to provide livestock managers with insights into individual animals' internal health as well. This includes, for instance, the placement of small devices inside the rumen of a cow to monitor their digestive activity to determine animal health and feed efficiency and to anticipate effects on the resulting meat or milk.
- Groups. Herd tracking is also a growing area of interest, with explorations in the use of drones to track, guide, and potentially deliver medicines to animals that roam in pastures. The idea behind these systems is to minimize human

intervention in the life of the animals, conceivably reducing stress and allowing for increased independence of grazing herds.

Connected Machines

Given early visions of IoT as simply machine-to-machine interaction, it makes sense that agricultural machines were some of the first things to be networked. Early digital agriculture took the form of precision agriculture, which primarily involved automation of farm activities typically conducted by machinery. The introduction of drive-by-wire meant that tractors, harvesters, combines, and other large farm vehicles were the perfect testbed for early IoT (with much of their data flowing in standard controller area networks, CANs [3]). Variable rate technologies exemplify early success in closing the sense-decide-act loop in agriculture [4]. For example, variable rate planting technologies can utilize a soil map (generated with remotely sensed images and/or machine data that is augmented with ground truth data collected by field scouts) to plant different crop varieties in different soil types. Subsequently, a variable rate applicator could, using a projected yield map based on historical data, apply fertilizer in a more optimal manner. While such technologies have been relatively widely adopted, variable rate technologies and other precision machinery have typically been used in the realm of fairly large-scale, wide-acre monoculture cropping systems.

There is also growing interest in creating IoT systems for indoor livestock agriculture, where animals are able to interact with a variety of machinery from weighing scales, feeding stations, to milking devices. Here, dairy cow operations have received the most attention with dramatic impacts on the landscape of dairy, particularly in the United States. An instrumental approach has been robotic milking and robotic feeding.

Connected Environments

Weather, soil, air, and water quality monitoring, for both indoor and outdoor agriculture, are increasingly important as our environmental conditions become more volatile. Some of the first forms of sensing to be streamed from farms include rainfall, humidity, temperature, and other data from weather stations located on farms across the world. At times, these are farmer-owned and operated, while in other cases a weather station may be part of, for instance, the National Weather Service network. Land and water on farms are typically sampled periodically, sent to laboratories where they are tested, for example, for microbial, chemical, and nutrient composition. More recently, soil and water sensors have been developed to, for example, detect soil moisture, pH, and nutrients. Such sensors are increasingly connected to networked computers that provide access to real-time environmental data at specific locations on farms. Such data are crucial components of agricultural IoT as they provide critical site conditions that often determine the constraints and conditions for various agricultural activities to be conducted (e.g., smart irrigation).

A systems approach to connected agriculture is currently best exemplified by vertical agriculture. Crops are grown in carefully controlled greenhouses, with nutrients delivered through a network of pipes and filters, controlled lighting and air conditions, and constant streams of data about plant and growth chamber properties available to farm managers via a suite of dashboards.

Connected People

Most farmers and farm workers in the United States are already connected via smartphones. Currently, there are many applications to allow people to track their work, but also coordinate and collaborate on farm activities. Some applications provide real-time streaming data collected by sensors (e.g., weather station apps), while others provide real-time location of tagged livestock. In many ways, the current state of IoT means that for each type of thing connected in a farm, there is likely a standalone web or mobile application that people must use to interact with the data. However, there is significant untapped potential for wearable technologies that are enabled with voice input and smart algorithms to provide hands-free, and ideally automatic, data collection, manipulation, and visualization of agricultural data.

Infrastructural Limits

It is critical to note that there are two fundamental hardware limitations to current efforts in IoT for agriculture. First are power limitations. The lifetime of a battery is particularly important as the frequency of change must be considered. In the case of large-scale agriculture, IoT sensors may be deployed across vast spaces. As the distances between plants, animals, machines, and people are great, the frequency of battery change as a result of battery life is particularly problematic. A farmer does not want to chase down a cow to replace its ear-tracker battery or have to visit each sensor; this would introduce an entire layer of maintenance due to IoT device density. Since plugging in an IoT device is not always an option in agriculture, many devices are designed to include, for instance, small photovoltaic systems to produce their own power. However, limitations on panel size and efficiencies constrain the computational capacity of such devices.

Second is Internet connectivity in rural spaces. Agricultural landscapes are less sparsely populated than urban areas. For too long, this has been the rationale used to excuse limited to no availability of broadband Internet in rural communities [5]. The promise of IoT in agriculture to provide decision support based on real-time site-specific conditions is hampered by our ability to transmit data on farms: from big data (e.g., drone-captured imaging of vast grazing lands), to distributed data (e.g., location and other data from hives located on orchards across a region), and dense data (e.g., multiple, by minute measurements of water quality in aquaponics farms). While there is growing support for increased access to rural broadband, we argue that edge computing, mesh networking, and continued reduction in cost and size of micro-computers can still allow for IoT innovation in agriculture. Furthermore, new technologies and approaches for connectivity, sometimes with delay or low bandwidth, solve some of these problems.

Opportunities for Design

In the last decade, there have been some key technological developments that improve our ability to realize IoT for improved resilience in food systems and enable data-driven regenerative agriculture. There has been a steep decline in the cost of sensors, micro-computers, actuators, and other IoT components, along with a growing interest in developing environmental sensing technologies for smart and connected cities, ecologies, and agriculture. In turn, this has led to research efforts in data science, machine learning, ontologies, and decision support to take advantage of increased availability of agricultural data. An increasing interest in open source technologies, as well as demand for access and agency to one's data, further has the potential for innovation in agricultural IoT. Opportunities and challenges for design are driven by urgent issues faced in agriculture due to climate change, support for rural communities, increasing inequality, and public values and interest in the provenance of food.

The reality and future of IoT in agriculture will unfold soon. We offer eight opportunities in design for improved research and innovation in IoT for agriculture.

Design for Sustainability: We have previously issued a call to action, bringing together through human-computer interaction (HCI) researchers, designers, and practitioners to critically engage in the design of technologies for a more sustainable food system [6]. We argue that human-centered, community-oriented, and environmentally sensitive approaches to research and development are critical for IoT adoption in agriculture.

Design for Rural Communities: The increasing presence of connected devices in our homes and workplaces will also be matched with increasing familiarity and comfort with such technologies in general, which may influence adoption of agricultural IoT. In the case of agriculture, the digital divide remains within countries including the United States, where there is a gap in access, availability, and education regarding digital technologies between urban and rural communities [7]. We have previously described infrastructural challenges in agricultural landscapes. Digital transformation must also be paired with access to employment and education opportunities for workforce development and modernization. If the future of agriculture is digital, we must prepare for the shift in skills required for the future of work.

Design for Data Sovereignty: Pursuant to achieving its technical potential, IoT can be thought of as ubiquitous computing, with sensors integrated throughout our landscapes. However, monitoring without agency or control is simply surveillance. Digital agricultural technologies must consider the data rights of farmers while offering consumers and other farm stakeholders appropriate insights into the provenance of food. To achieve this, we must negotiate the balance between transparency and accountability with privacy. This is further complicated as networked landscapes inevitably introduce security threats into otherwise isolated systems. We argue that successful IoT for agriculture must begin with transparency in data use, a focus on the ethical implications of monitoring and control, and consideration of data sovereignty of food system stakeholders to be a primary requirement.

Design for Agricultural Diversity: Agricultural systems are extremely diverse, as are the factors of inspiration and drive toward IoT implementation for different crops, animals, practices, and places, where initially, IoT systems were not commonly available for small-scale agricultural systems; nor were they particularly affordable. However, the increasing proliferation of low-cost sensors and microcontrollers, matched by consumer appetites for understanding the provenance of their food, has led to an explosion of interest in digital technologies across systems and scales [8].

Design for Trust and Accountability: We have previously called for the design technology to increase trust and accountability in our food system [6]. IoT, in particular, offers the capacity to ground-truth agricultural practices, by allowing for provenance data to truly begin within the farm itself. Indeed, there are several current efforts in research and practice proposing the harmonization of farm sensor and/or sample data, and farm management information, in the context of environmental conditions to provide verifiable evidence of sustainability claims. Indeed, IoT in agriculture is a foundational component of improving traceability in the supply chain, particularly given the current trend of utilizing blockchain technologies for supply chain verification.

Design for Agricultural Practice and Decision Support: Effective IoT for agriculture demands the closing of the sense-decide-act loop. Achieving dramatic improvements (true loop closing) will require interoperability unlike ever seen before in agricultural contexts. Data from machinery, sensors in soil, products, bins, sensors on animals, data regarding workers, weather, imagery, audio traces, and video need to first be interoperable and machine readable; then true fusion can occur. Researchers wrangle data (and do it in post-processing mode) in order to test hypotheses and develop models, but practitioners certainly do not have the time or generally the skill set to gather, reformat, align, visualize, and analyze data.

Given our silo-ized sensor-driven approach to IoT, to date we have typically only been able to offer decision support for the optimization or management of single variables (e.g., yield optimization, irrigation timing, weather reporting). Early developments in one-dimensional data-driven approaches in agriculture were technologies for soil characterization, crop health, yield maps, and livestock feed management. Some popular "full-stack" technologies include variable rate applicators for more efficient input use (e.g., water, pesticides, fertilizer) in large-scale row cropping systems and, more recently, robotic milkers and feeders that allow many cows and calves to find their own milking rhythm and schedule. The next level of decision support must have larger reach.

In addition to the often one-dimensional approach, current commercial IoT and analytic platforms largely focus on strategic decisions. A couple of exceptions would be controls for irrigation, grain bin aeration/drying, and greenhouse conditions. Because of this, there has been little need for real-time data flow (or maybe it is that the lack of real-time connectivity has resulted in the delay-tolerant focus). With a dramatic improvement in interoperability and connectivity, there is great potential to also improve tactical decisions. The current state of delayed access to data for insights, however, often results in poor or missing data [9]. Such poor and occasionally sparse data leaves lots of potential for improving decision making. If we can achieve connectedness and interoperability, the state of the firm/farm/operations can be known, so managers can better make the "best next" decision. In cropping systems, this might entail knowing moisture content of soils in all fields and stage of growth of crops in all fields. In livestock systems, this might be knowing daily rate of gain and daily feed intake per animal. In logistics, it could be up-to-date knowledge of queues and at-the-moment capacities.

We look forward to a near-term day when economic and environmental sustainability (and also logistics when it comes down to details) and optimal nutrient management in cropping systems can be accomplished using relevant data. That may include public data (topography, soil type), non-IoT data (soil sample results), and sensor data to improve related decisions. By integrating georeferenced yield data (i.e., "fused" analysis from sensors for location, speed, width, crop flow, crop moisture), electron conductivity of soil, and UAV imagery, which can indicate plant health and nutrient concentrations, we will be able to improve strategic decisions within the context of an entire season. We will also influence tactical decisions and implementation over time with people and machines, through optimization (even by simplifying constraints or using simplified objective functions).

Design for Ubiquity: As we are beginning to think about sensor consolidation to offer multi-sensed models of farms and critically consider the diversity of commodities in agricultural systems, we are able to design for agricultural diversity. Effective IoT in agriculture requires intelligently deployed sensing, which also captures structured metadata (i.e., full context) in machine readable formats with the potential for human comprehension.

If agricultural data streams and sets really met the FAIR (findable, accessible, interoperable, and reusable) principles (even in a private context), tactical decisions could be facilitated with microservices and apps that merge data and models. The three farming scenarios depicted earlier in this article hint at some of these possibilities. Consider, for example, that if soil type, soil cover, weather, and topography were known, and soil moisture and growing degree days (GDD) could be computed, visualized, and analyzed. This could positively influence decisions regarding sequencing of spring work in fields; if planting date and variety (GDD to maturity) were automatically recorded, GDD tracking could provide an approximate status of each field going into each next "phase" of the growing season (scouting, spraying, harvesting). Combined with aerial imagery or sensor data that kept these models on target, a farmer would have decent assurance of near optimal logistics.

Design for Interoperability: Digital agriculture is in its infancy and currently involves a fragmented landscape of data, models, tools, and communities. Several efforts exist to introduce conceptual and practical interoperability to enable seamless IoT-based systems. For instance, the Open Technology Ecosystem for Adaptive Management [10] effort around interoperability in field-level measurement techniques aims at a connected user experience through an ecosystem of tools and a data sharing community for the enablement of soil health research.

Such efforts require ontologies, application programming interface (API) frameworks, and standards as fundamental building blocks for interoperability for use in communities of practice that include farmers, researchers, and developers alike. For example, the Open Ag Data Alliance [11] is an open source extension of the REST framework designed for agricultural data interoperability. OADA provides a "standard API framework for automated data exchange" with an immediate focus on knitting together disparate machine data streams.

The harmonization of sensor data requires an ontological consistency among farm models and software. We have previously developed the Modeling Sustainable Systems (MoSS) framework for modeling complex adaptive systems for modeling farms [12]. The goal was to provide an information model of an agricultural system that used a coherent vocabulary and syntax, mapped onto farmers' mental farm models, and enabled the spatio-temporal representation of heterogeneous farm data to enable design for decision support. Our current work includes the extension of MoSS as a means to harmonize sensor data across scales.

Open Source for IoT in Agriculture

An open source approach to software development democratizes innovation, removes barriers to collaboration, increases markets, and improves the talent pipeline [13]. A functioning and interoperable middle layer — between the raw sensor data and insight to users, or better yet automated controls — can only be achieved via open source development where standards naturally emerge due to success in achieving the goal [2]. This same open source culture speeds innovation because there is less reinventing of interfaces, conversion utilities, and algorithms. It results in more productive development due to a talent pool knowledgeable in how to FIND solutions to seemingly new problems from other fields.

We invite the IoT community to four communities of practice on agricultural technology. We introduce these communities simply as an entry point for IoT researchers. As we are founding members of the groups listed in this section, we describe this selection as we can offer a point of entry for IoT researchers and practitioners looking to engage in IoT development for agricultural use cases.

The Gathering for Open Agricultural Technologies (GOAT): A grassroots, online, open source community, the GOAT forum and instant messaging channels offer an easy place to begin: http://forum.goatech.org. GOAT was initially founded to bring together farmers, researchers, and technologists interested in coordinating open source development of digital technologies for agriculture, including IoT [14].

The Open Agricultural Technology & Systems Center (OATS): Researchers at the Purdue OATS are focused around a suite of topics including sensor development and harmonization, machine automation, data interoperability, human centered design, and agricultural modeling and simulation, detailed at http://oatscenter.org. OATS faculty argue that IoT for agriculture requires coordination across each of these fronts, across government, industry, and research through an open source development paradigm.

Precision Sustainable Agriculture (PSA): For IoT researchers particularly interested in technology targeted at large-scale sustainable agriculture research and practice, including farming techniques such as cover cropping, visit http://www.precisionsustainableag.org. Researchers are particularly interested in the integration of sensing techniques across scale via the consolidation of sensor data from probes, drones, and satellites.

Open Technology Ecosystem for Adaptive Management (openTEAM): A collaborative community of farms, research labs, non-profit organizations, food companies, and food system stakeholders. Members are dedicated to the development of critical technologies to improve our understanding of regenerative agricultural practices, particularly in service of adaptive soil health management. Working groups, ways to get involved, and more information can be found at http://openteam.community.

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