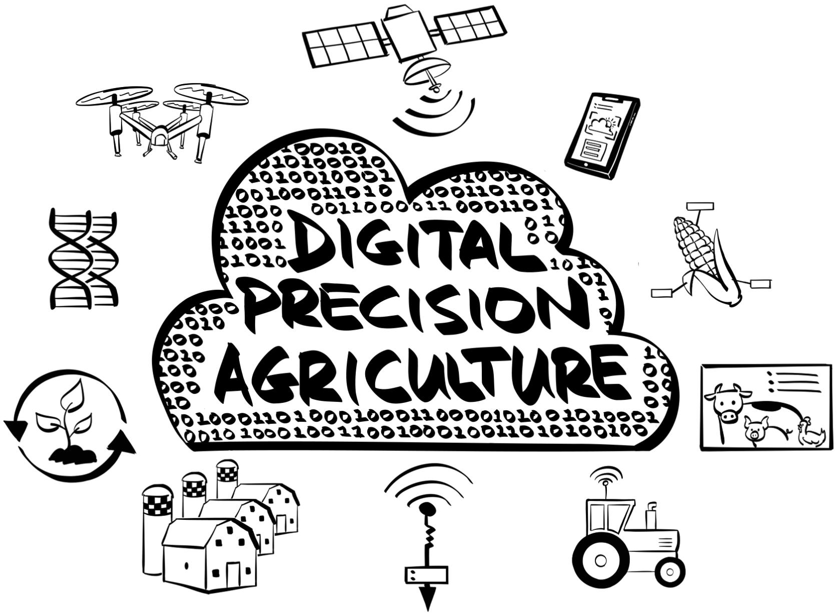
National Science Foundation (NSF) Convergence Accelerator: Digital and Precision Agriculture
Workshop Report



Virtual workshop held May 10, 12, 14, & 21, 2021

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EXECUTIVE SUMMARY

Given the rising world population and the climate crisis, digital and precision agriculture is a significant route forward to feed the world sustainably into the future while protecting the planet. Increasing agronomic and livestock output, with focus on resilience, is a key challenge of the 21st century. Agricultural practices that make use of emerging cutting-edge technologies can lead to improved production with minimal environmental impact. A systems approach should be leveraged to increase overall system efficiency, resilience, and sustainability. Digital and precision agriculture can enable greater productivity by detecting pests and disease, reducing the inputs to the plant while achieving maximum productivity, improving animal welfare, and many other ways.

Massive amounts of data can be analyzed to create algorithms, helping farmers become better informed in their decisions. Additional tools such as computer-aided scouting, and images from satellites/drones/cameras and beyond, can be used to facilitate transformation of the U.S. food production. The latest digital farm management systems offer end-to-end traceability of crops/livestock, making it possible to target consumers who want to buy from producers committed to responsible land use and low emissions. However, to achieve these gains, precise, accurate, and field-deployable sensors/biosensors will be needed across the entire food chain. Furthermore, integrated analytics will be needed to manage the food and agricultural system. To ensure continued improvement in food production/quality, new techniques/systems will be needed to dramatically increase the rate of genetic improvement of livestock and plants. Furthermore, these advances must ensure equity across the ecosystem, so that all stakeholders can benefit from digital and precision agriculture.

The workshop brought together 187 participants to further develop the digital and precision community and to articulate the opportunities for a convergence approach. They discussed the need, barriers to, and what needed to be done to build a convergence pathway. They developed ideas around technologies and data that were needed to make convergence possible in digital and precision agriculture. Ultimately, data standards and databases and integrated systems that are inclusive of the agricultural system are needed if dramatic advances are to be realized. Furthermore, there are wonderful opportunities for interaction with current NSF convergence accelerator tracks, engagement and formal instruction and very importantly in diversity, equity and inclusion. The participants unanimously agreed that digital and precision agriculture is ripe for a convergence accelerator approach and look forward to the opportunity.

A. Introduction

A.1. Grand challenges

The nation is emerging from the pandemic into a very different economy than the one we had a year ago. The pandemic has exposed the intensified need for resilience in the US agricultural sector. The realities of the 21st century – including the needs to sustain environmental quality and operate more efficiently – have resulted in renewed interest in cutting-edge technologies for application in agriculture. There is a large deficit between the amount of food we produce today, and the amount needed to feed everyone in 2050. There are also changes in consumer food preferences creating new demands on food production systems and disrupting the economy of regions where agriculture is a primary industry. Rapid innovation is needed at multiple challenging points, and, because adoption of food production systems is highly interdependent with consumer demands, it will require engagement from food producers and consumers. Investments in digital and precision agriculture present an unprecedented opportunity to advance understanding to resolve scientific and technical gaps of how to support successful integration of agriculture, life sciences, and engineering. It also allows us to explore the connection between technological advances and human behaviors, and the connection of food production systems, societal values, and our relationship with food. Digital and precision agriculture offers huge potential to improve resource-use efficiency, food production and quality, environmental sustainability, and profitability/sustainability of agricultural production. As we optimize, transform, and reimagine what the future could become in the realm of digital and precision agriculture, a big task is determining how this can be accomplished both affordably and intelligently.

A.2. Broader impact

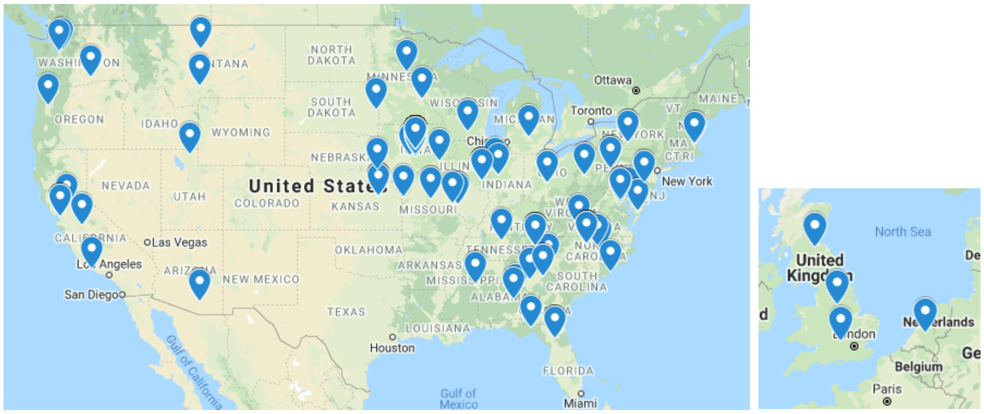
The concept of digital and precision agriculture is predicated on being able to measure something (e.g., nitrogen content of the soil), acting on that information, and responding with a subsequent event (e.g., application of nitrogen when and where needed). The main focus of digital and precision agriculture technology is to increase the accuracy and precision of measurements and predictions, so actions are taken precisely at the optimal timing and at the optimal intensity to generate a desired outcome. Precision livestock farming is the same concept but focused on livestock. For the purpose of this report, "digital and precision agriculture" will refer to both plant and livestock applications.

Digital and precision agriculture platforms can be developed by advancing and integrating remote sensors, artificial intelligence/machine learning algorithms, cloud/edge computing, and mobile apps as customized and data-driven decision-making tools that are scalable across small and large farms. For example, real-time sensing of biotic and abiotic stress in plants offers the possible reduction of chemical application due to residual chemical in the soil from prior crop production as well as season-specific crop response, while in livestock, it may offer possible reduction in antibiotic administration due to disease outbreaks induced by environmental stress. Furthermore, evaluating new application technologies can help farmers use production inputs more efficiently, offer enhanced environmental protection, and increase economic security. In fact, producer participation in local food systems is growing, and the value of local food sales, defined as the sale of food for human consumption through both direct-to-consumer (e.g., farmers' markets) and intermediated marketing channels (e.g., sales to institutions or regional distributors), is an increasing trend. At the same time, there are varying perspectives between small diverse farms typically promoted in agroecology and larger-scale farming that, under current political-economic conditions, can supply more mainstream markets and reach larger, and lower income, populations. Hence, there are gaps in the development of new supply chains from farm to consumer that are not equitably sharing value.

Convergence-based approaches, which frequently draw on large teams of collaborators from multiple disciplines, are critical to solving many of these challenges. The term "convergence" describes a multidisciplinary approach that melds divergent areas of expertise to form conclusions that are inaccessible otherwise. These goals rely deeply on an interdisciplinary environment that encourages fundamental discovery and fosters innovation through acquisition of new technologies. A convergence-based approach involves hybrid systems of people and instruments which address complex structural challenges. In this workshop, we have intentionally brought together intellectually diverse researchers and food production stakeholders to develop effective ways of communicating across disciplines to attempt to adopt common frameworks and a language, which may, in turn, afford solving the problem that engendered the collaboration, developing novel ways of framing research questions, and opening new research vistas. This workshop identified convergent research areas that will improve digital and precision agriculture and offer the potential to overcome social barriers with the overarching goal of ensuring global food security. The outcomes of this workshop will assist in identifying potential deliverables and areas of convergent research that will benefit society by ensuring resilience of the US food chain. The workshop incorporated the synthesis of key convergence research questions, engaging participants from a diversity of perspectives to develop approaches that are best suited to identify a pathway to deliverables and prototypes that will enhance agricultural productivity. This report summarizes the results of the workshop and can be used to identify key institutional practices that could help reframe agricultural infrastructure.

B. Workshop organization

Figure 1. Attendee locations



The workshop was held virtually, with four sessions (two hours each) between May 10th and May 21st, 2021. Registration was by invitation, and there were 187 registrants who participated to varying degrees (**Figure 1**). They represented academia, industry, non-profits, farming/production, and federal agencies (**Table 1**). A concerted effort was made to invite a diverse group of participants. Nineteen attendees were representatives of Historically Black Colleges and Universities.

Table 1. Affiliation of workshop participants

Participant Affiliation	Number	Percentage
Academic	145	77.5%
Industry/corporate	21	11.2%
Non-profit	6	3.2%
Farmer/producer	3	1.6%
Federal lab/agency	12	6.4%
Total	**187**	**100%**

The first three sessions of the workshop consisted of a series of small-group discussions in which participants answered questions designed to address how digital and precision technology might transform agriculture and how our current systems, processes, behaviors, and frameworks must adapt in order for the transformation to be most successful. Discussion topics were as follows:

1) To drive collaboration in digital and precision agriculture in the next three years among new and non-obvious collaborators, what are the easiest things we should do, the safe things we could try, the hard things we could explore, and the crazy things that just might work?
2) For digital and precision technology to transform agriculture, our current systems, processes, behaviors, and frameworks must adapt. Capture 10 ways to make the transformation more cost effective, fairer, simpler, faster, or globally beneficial.
3) Remember our future: Imagine it is 2030 and the convergence of digital technologies and agriculture has enabled farmers around the world to feed more people more economically—and with less environmental impact—than ever before. Answer the following questions about what you "remember" about the journey we began in 2021.
    - What was our single most significant milestone?
    - What did we do to get small- and mid-sized farmers on board?
    - How is precision agriculture more accessible today in equitable ways?
    - What was the most difficult challenge we finally figured out?
    - What surprised us the most (and why did it surprise us)?
    - What don't we do anymore that used to seem important?
    - What were the first three things we did in 2021 that set us up for success?
4) To prepare for the future of precision ag, we must first imagine what might happen. Answer the following questions regarding one of five potential futures (disruptive technology, disruptive funding, disruptive regulation, disruptive or unexpected collaboration, or status quo) in the next five years.
    - Tell a story about how this disruption might impact agriculture in the next 5 years.
    - What do we hope will be true in this future?
    - What do we fear will be true in this future?
    - Are there ways we work/operate now that might make it harder for us to be ready for this future?
    - If we're certain that even part of this future will occur, what should we focus our attention on now to be ready?
5) How might the NSF prioritize its investments in precision agriculture–related research in ways that better serve producers, researchers, and the public? What should be explored, tested, or done now?
6) How might we:
    - develop metrics and measures that help us understand if (and how) agriculture is transformed in a positive way?

o incentivize data generation and sharing among established manufacturers, researchers, and entrepreneurs in the next 3-5 years?
o encourage and fund the foundational work of creating standards, ontologies, etc. in the next 3-5 years?
o better connect and engage with small- and medium-sized producers to get them excited about digital and precision ag?
o reimagine high school, trade schools, and colleges to prepare students for a precision agriculture world?
o improve sensor and data interoperability?
o simplify the implementation of novel but complex solutions and adapt them for less privileged and small farmers across the globe?
o identify new “non-ag” technologies early and encourage their developers to explore ag-related uses earlier?

The fourth session was a panel discussion with the goal of identifying why a convergence approach is necessary for digital and precision agriculture, what is needed to build a convergence pathway, and what the community stands to gain from a convergence approach.

C. Why do we need to build a convergence pathway for digital and precision agriculture?

C.1. Incentive to build a convergence pathway

It has been said before: the world is becoming increasingly complex. Rita G. McGrath, Professor at Columbia Business School and one of the world’s leading experts on strategy in uncertain and volatile environments, explains how complicated systems become complex in her article published in the *Harvard Business Review*, “The World Is More Complex than It Used to Be.” She explains that today’s decision makers must take into account numerous environments that used to be isolated from one another but are now “bumping up against each other, often with unexpected results.” It’s been a decade since her article was published, and decision-making has not become any simpler.

Decision-making has become particularly complex when it comes to food production. Changes in consumer preferences; concerns regarding environmental impact, animal welfare, and human health; and social demand for food safety and equitable access are just some of the factors that influence decision-makers associated with plant and animal production. Moreover, decision-makers are becoming increasingly aware of the impact their decisions have upstream and downstream in the food value chain. In a 2016 article published in the journal *Business Strategy and the Environment*, “Cultivating Ecological Knowledge for Corporate Sustainability: Barilla’s Innovative Approach to Sustainable Farming,” authors Stefano Pogutz and Monika Winn describe the multi-year journey taken by pasta-producer Barilla, farmers, and scientists to reduce the environmental impact of cultivating wheat. The article acknowledges the importance of multidisciplinary engagement and suggests the outcome is possible because the scope is a well-defined production system with strongly aligned partners.

A quick review of the history of precision agriculture suffices as a reminder that the origins of precision agriculture are interdisciplinary. Early days of precision agriculture involved soil sampling, geographic positioning systems, and machinery with variable rate application functionality. A similar realization can be derived from precision livestock farming practices that rely on sensors, robotics, microphones, cameras, and informatics infrastructure to manage the life cycle of animals. None of it could be possible today unless there was an interdisciplinary approach, but there is more to a convergence approach than multi-disciplinarity.

A convergence approach for digital and precision agriculture brings together a diverse set of partners with a strong focus on application-oriented solutions and an emphasis on transitioning inventions into practice. This is necessary because the decisions that impact food production are influenced by stakeholders beyond the academic setting, including citizens, government, industry, advocacy groups, and non-profit organizations, across multiple generations and demographics. More importantly, the transition from research to adoption will depend greatly on how effectively we engage all the critical stakeholders at a time when tensions among stakeholders can be fraught.

C.2. Barriers to building a convergence pathway

Most barriers to building a convergence pathway for agriculture emerge from the diversity of stakeholders engaged directly or indirectly in food production systems. Stakeholders have different roles in food production systems, different incentives, and different lexicons, making it difficult to create convergence pathways, especially that lead from research to commercialization. In addition, the tension between food producers and food consumers has intensified as food is now expected to be all things: tasty, nutritious, affordable, natural, equitable, innocuous, local, and more. Not everyone agrees precisely what each of these criteria mean, as evidenced by the ongoing controversy around food labels and the different regulations that exist on farming and food products worldwide. The onus is often placed on the food producer, who attempts to balance increasing responsibilities to produce food sustainably and profitably. The food producer, in turn, puts pressure on the ag industry input providers to create new products and services that can help them respond to societal demands. They look to government, non-profit organizations, and farmer advocacy groups for representation. The tension is also felt between food producers and academicians who believe they have a proposal for a better solution, but don’t see their ideas implemented at large scale in traditional agricultural systems. These barriers clearly demonstrate that a convergence approach is necessary to accelerate research progress and adoption of digital and precision agriculture technologies.

C.3. What needs to be done to build the convergence pathway?

In the midst of all this, digital and precision agriculture offers a platform to address many of these societal demands on food production. Numerous examples, some theoretical and at small scale, demonstrate that digital and precision agriculture can deliver food that is more nutritious, better for the environment, accounts for animal welfare, and more. Examples exist where digital and precision agriculture can be used to facilitate transparency, allowing consumers to choose food according to production practices that meet their personal preferences. Articles abound that suggest that digital and precision ag can provide farmers with options to achieve sustainability and profitability. A convergence approach that includes a broader range of stakeholders and a focus on real-world challenges should increase the rate of innovation, the scale of implementation, and the magnitude of the impact of digital and precision agriculture.

D. What technologies and data are needed to build a convergence pathway for digital and precision agriculture?

D.1. Technologies

Research is needed to understand the potential of different hardware and software technologies in the context of precision agriculture. Hardware technologies of interest include, but are not limited to: sensors/mobile devices, robotics (ground and aerial), satellites, data centers, next-generation communications networks, and GPS/GNSS; whereas the corresponding software technologies include, but are not limited to: cloud software, Internet of Things (IoT)/edge computing/software including smartphone applications, databases, and AI/ML kernels; and analytics applications (e.g., nitrogen modeling for crops or disease detection in livestock). While most of these technologies have been evaluated in the past in a limited context, further research is required regarding their integration in a goal-oriented fashion in a precision agriculture setting and the corresponding cost-performance analyses. For example, different types of sensors (existing and yet to be developed) on farming equipment can be used to collect data on soil status (temperature, acidity, etc.), hydration conditions, and pests, but how these sensors should communicate with one another (what to communicate, when, and how) to maximize energy efficiency and minimize task execution latency is a critical challenge. Furthermore, data collected from soil and plants via sensors can be combined with remotely sensed data (e.g., coming from drones and satellites), as well as weather prediction statistics, to make predictions about many economically important items, e.g. plant growth, weed control, yield and nutritional value. Similarly, new cyber-physical systems are needed for pen-side diagnosis of disease to mitigate future pandemics in livestock and humans. How such disparate devices can effectively and efficiently communicate with each other remains a very challenging problem, requiring disparate expertise in areas including mechanical engineering, communication engineering, algorithm design, and domain knowledge, along with social sciences and economics to effectively develop solutions that positively impact society. In addition to such “inter-device” problems, we also envision interesting “intra-device'' problems. For example, a robot could monitor animal health while concurrently optimizing environmental conditions to maximize animal well-being. How to implement such multitasking (which is expected to be much more cost/energy efficient compared to employing different robots for different tasks) requires developing novel in-device scheduling algorithms.

Given the recent advancements in self-driving cars and AUVs, one can expect similar achievements (as well as challenging research problems) in self-driving/autonomous tractors and agricultural drones, which would increase production capacity and provide a safer working environment.

Cloud and edge computing are other research areas which can be very beneficial to precision agriculture. Recent advancements in diversifying cloud services have moved the area from conventional Infrastructure-as-a-Service (IaaS) to other general-purpose paradigms such as serverless computing, as well as more specialized services such as Machine-Learning-as-a-Service and Database-as-a-Service. One can envision similar “domain-specific” cloud services in precision agriculture as well, such as plant growth estimation as a service and animal health monitoring as a service. Mobile equipment and smartphones can be connected to such cloud services (possibly diversified in terms of performance-cost ratio) to run necessary analytics tasks, instead of running them on mobile devices or local machines. Such custom services can also be connected to custom databases in the cloud, thereby significantly reducing data movement overhead and costs.

In addition, both hardware and software technologies keep evolving, creating a problem of “interoperability,” even across similar devices from the same vendor. One promising direction to explore is standardization of hardware/software interfaces, which can enable plug-and-play type replacement of hardware devices and software components. Possible research directions along this line include developing a “software stack” that enables interoperability of heterogeneous devices (sensors, robots, drones, etc.).

Affordable, high-capacity network connectivity to ag farms is a must for digital and precision agriculture. Yet many farms (especially remote ones) are not connected at all, and 39% of the rural US lacks broadband access. To enable digital and precision ag, we need to develop affordable, high-capacity rural broadband solutions, and the solutions need to support the wide range of communication needs, including but not limited to connecting animal-worn bio-sensors as well as statically-deployed and UAV-mounted high-definition cameras, and providing pervasive, high-throughput wireless connectivity to remote crop farms. To this end, we need to effectively leverage the variety of wireless network architectures and technologies that are suitable for rural deployment, for instance, those featured in the NSF ARA Wireless Living Lab project and including high-capacity, long-range free space optical communications and millimeter-wave wireless backhauls, as well as low-frequency band massive MIMO access networks, among others. In general, rural broadband is quite different from urban broadband, and it requires dedicated research and innovation investment. Furthermore, the need for high-speed internet access will continue post-pandemic, and the equity problem in ensuring the vitality of rural communities will not be solved by new infrastructure alone.

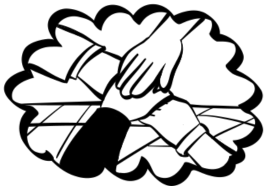
D.2. Data

One of the major concerns in precision agriculture is ensuring accurate and fair evaluation of current practices and the ability to make informed decisions on novel methods. Data can play a critical role in both these activities, as the analysis of data can reveal insights critical for both evaluation and decision-making purposes. There are two important dimensions of data collection and analysis: local (in situ) and cloud-based.

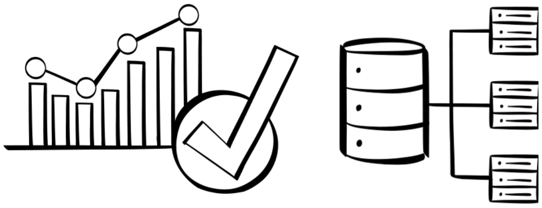
Regarding in situ data collection, current technologies enabled by sensors and the Internet of Things (IoT) allow the extraction of data from plants, animals, soil, and environment, and also allow the monitoring/prediction of plant/animal/soil health as well as fertilizer/feed, sunlight, water, and environmental needs. However, the questions of what data to collect, when to collect, how to collect (e.g., what mix of sensors), and where and how long to store the collected data remain challenging issues and will likely be case-specific. Research is needed to develop intelligent algorithms to answer each of these questions in a wide variety of use cases. Clearly, any such algorithm should be able to make decisions based on a variety of data collected from different sensors, GPS-controlled robots/tractors, drones, and satellites, at different time scales, with potentially different accuracies. The process of integrating such data with different characteristics, i.e., the data fusion problem, is poised to be one of the key research items. Furthermore, in situ data collection should be carried out with resource constraints in mind. In particular, battery-operated data collection devices/sensors have very stringent storage capacity constraints and limited network bandwidth, which make it important to develop data processing algorithms that operate in situ. A promising approach to address power consumption concerns of IoT/edge devices is to employ energy harvesting. Energy-harvesting sensors are in fact an important subclass of IoTs, and many such sensors have already been deployed in various application areas. Important research questions in this context include which energy source to use (e.g., solar, thermal, wind, vibration, RF), how to structure target computation to maximize the use of harvested energy, and how to deal with emergencies that require offloading the data to battery-operated storage media.

Given that on-site data collection and processing/decision-making capabilities will always be limited compared to the growing evaluation/decision-making needs, the use of cloud-based (resource rich) data analytics for precision agriculture seems to be a promising avenue for research. Two important advantages of cloud-based analytics are that data extracted from different locations can be fused/integrated, and sophisticated analytics algorithms can be used since resource constraints will be less of an issue. In particular, cloud-based approaches can implement sophisticated data fusion strategies. Examples include combining sensor-collected and drone-collected data to identify pest damage and integrating data from different sensors/edge devices to predict irrigation needs and plant growth. Further, cloud-hosted analytics systems can employ machine learning (ML)–based algorithms to extract information from data, which is becoming increasingly important given that the amount of heterogeneous, unstructured data is increasing at an exponential rate. It is also important to investigate computation partitioning strategies that divide data analytics tasks between edge/IoT devices and the cloud. Ideally, such algorithms should consider resource constraints of edge/IoT devices, data communication needs/costs, and tolerable decision-making latencies, to identify the best computation-partitioning decisions (an example would be dividing a given data analytics task among sensors, smartphone, and cloud). Orthogonal to such performance/quality of service-related issues are other challenging problems such as minimizing the cost of data collection/processing devices and sensors, data ownership, and security and privacy issues associated with data.

E. What will be delivered to the community by taking a convergence approach?

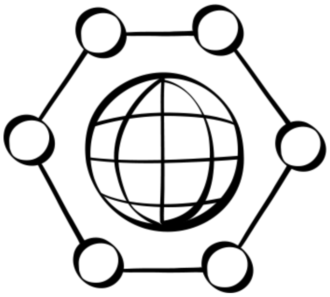


E.1. Data standards and databases



We envision two major data-related outcomes from employing a convergence-based approach to precision agriculture. First, we propose developing a set of standard data formats and associated ontology that can be used for analytics. Currently, agricultural data, when collected, is stored in silos in an isolated manner, and as a result it is not amenable to the application of AI/ML algorithms. Reaching a standard data format or, even better, employing ontologies (detailed characterizations of data vocabularies, their structure, and their relationships) will not only make it easier to share data across research groups but will also enable the development of portable analytics algorithms without worrying about data formats and translation. We want to emphasize that, without standardization/ontology efforts, it will be very difficult, if not impossible, to combine agricultural data coming from multiple disparate sources (different types of sensors, robots, drones, and satellites), and consequently, the data analytics algorithms to be developed will not be as powerful. Secondly, we envision new database systems to hold both collected data and results from analytics. Such databases could store data either in its entirety or in some compressed/summarized form in persistent storage (such as hard disks and solid-state devices) and provide different interfaces of varying sophistication to researchers for querying the database. In particular, we see the funding, organization, and support of a collaborative consortium to develop a comprehensive, searchable, open source, central repository and library of data related to precision and digital agriculture as a priority. The goal of the library would be to provide unrestricted access to data and software that has been obtained primarily from users and research groups from across the globe. The database would be coordinated and supported by a professional team who would provide regular updates to the industry regarding new uploads, and retrieval-analysis systems. Early engagement of a variety of stakeholders collecting, analyzing, and creating digital solutions through a convergence accelerator approach can be critical in determining the long-term viability and economic sustainability of data infrastructure requirements.

E.2. Integrated systems



The commercial release of “micro-computers” in the early 1980s was a turning point in the realization that digital information management was poised to make all sectors of the economy more efficient; agriculture was no exception. Given the amount of digital inputs in today’s society, we can point to multiple instances where agricultural workers have increased, many times over, their information management capacity. Four decades of intensive adoption of digital technology, at ever-increasing rates, has shown that digitalization of production processes facilitates the substitution of energy for information, a great achievement for humanity and a big challenge to make it a more equitable and inclusive process for a diverse segment of society engaged in farm work. In spite of the many challenges, the convergence of precision and digital agriculture presents a unique opportunity to create conditions and outcomes that neither can produce by itself. This is the starting point, a commitment to creative solutions and constructive approaches with global perspectives, without ignoring the unique characteristics of local ag and tech systems. The workshop produced an interesting set of thoughts and perspectives regarding the human interface engaged in agricultural production systems. The outcomes of this four-day exercise captured the multidimensional nature of farm labor issues, but in an effort to write a concise report, we have limited it to discussions that attempted to characterize the current situation, as well as efforts to formulate a more equitable and inclusive future for a diverse segment of society that will fill the jobs created around technologically advanced agriculture. Following is a list of challenge areas documented in the workshop:

i) Global Distribution – Regional Needs. Many of the participants have a multi-national background, and therefore, we observed frequent reference to the contrasting conditions between farm workers in developed vs. less developed economies, and the need to create solutions that fit regionally. In the case of developing countries, access to internet-connected devices is creating digital platforms for development of agricultural systems that benefit all levels in the farming enterprise, including farm workers. On the other hand, the labor dynamics in industrialized countries are more complex, as complex as the diversity of the farming systems in place. To cite an example, corn/soybean farmer operators have access to capital and high-capacity machinery, as well as retaining a family composition with less dependency on hired labor; but specialty crop growers have huge challenges to meet their contract labor requirements for manual work. In both cases, workshop participants identified an emerging trend with a shift in the skills required of farm workers in the future, and it was acknowledged that helping with the transition moving labor towards a higher level of computer literacy will bring significant societal benefits in any region or country. Furthermore, although digital and precision agriculture has the potential to enhance and increase the global food demands, adoption has been slow for smallholder farms compared to large farms. Given that the more than 500 million smallholder farms play important role in agriculture, and also given that the integration of mobile technology, remotely sensed data, and distributed computing and storage capabilities are opening new opportunities for smallholder farmers, innovative models of education and training are needed to enhance their adoption of the increasingly data-driven agriculture. It is also necessary to define accurately the impediments for technology adoption, which a convergence approach is more likely able to detect, because various perspectives are represented.

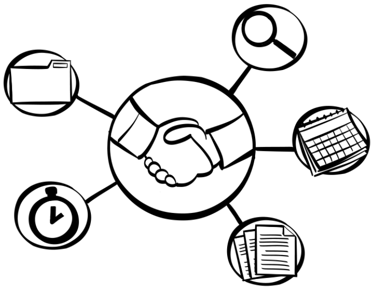
ii) Identification of People Groups. There is a long history in the role farm labor has played in the development of farming systems. Undoubtedly, farm labor is at a low position within the farm structure, and dominated by migrant workers and other less-represented demographics. It was generally accepted that the current system has not avoided the creation of underserved, misrepresented, and ignored people groups. Training programs with digital content are educational opportunities with high potential. The educational background of many individuals in the above groups places them at a point in the response curve where the returns per unit input increase at a high rate.

iii) Understanding the Role of Automation. The experts in the workshop frequently mentioned that technological advances in robotics in agriculture are directly linked to the uncertainty in the supply of labor. There is no doubt these two phenomena are connected; some workshop participants expressed that automation is the solution to labor dependency. But further discussions arrived at presenting the relationship between automation and labor not in the form of substitution, but rather in the form of parallel development. Convergence of digital and precision agriculture creates incentives for technology R&D, coupled with the need to have specialized labor to deploy/service/repair the automated equipment operating in the field. The forward-looking position of workshop participants advocating for workforce development was in the direction where automation and farm labor will achieve a complementary relationship where one makes the other stronger.

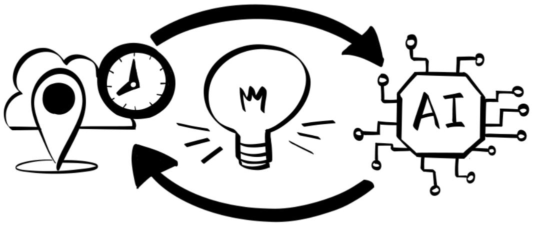
iv) Workforce Training. The overall reception of the concept of investment in workforce training was very positive among the workshop participants. Many points were brought up to identify some of the specific issues and solutions. Those points included: a) Training oriented towards gaining proficiency in the use of electronic field equipment already commercially available, and very specific to the digital hardware and operations already adopted by local growers; b) Provision for basic level of computer literacy and addressing language barriers; c) Training supported and organized through the Extension platform of Land Grant institutions with the option of granting agricultural worker certification; and d) Participation of the private sector through financial support, access to hardware, software upgrades, etc.

v) Farm Worker Mobility. Formal econometrics studies have documented a trend in the reduction of Mexican labor migration serving in US agriculture. The case of Mexico-US relationships is only used here as a starting point to support the argument that a modern system of multinational labor supply is a desirable condition for the future. Moreover, the creation of labor pools with digitally-trained workers will promote further convergence of digital and precision agriculture and foster technological development with equity and inclusion of individuals engaged in this trade. A thought outside the box is to visualize a modern labor pool of young professionals trained domestically and in other countries with agricultural digital technology curricula.

F. What opportunities exist for education/outreach and diversity, equity, and inclusion?

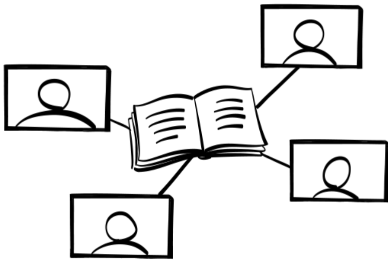


F.1. Cross-interaction with current NSF Convergence Accelerator tracks



Various aspects of the research items outlined in this report have cross-interactions with existing NSF Convergence Accelerator program tracks, such as Track A: Harnessing the Data Revolution and Track D: AI-Driven Innovation via Data and Model Sharing. In particular, as explained above, one of the important research directions in precision agriculture is data storage, modeling, and sharing, which can directly benefit from both data-centric and model-centric AI approaches to data, which are currently being explored in Track D. In turn, precision agriculture can provide domain-specific (agricultural) temporal and spatial data to Track D, which can lead to exploration of new machine-learning algorithms to extract insights from data. Similarly, precision agriculture can provide input for knowledge networks (Track A) by bringing together different types of domain-specific information, and it can benefit from Track A by employing some of the AI-based techniques developed there to enrich agricultural data.

F.2. Engagement and formal instruction



As articulated in the workshop on “Global Perspectives in Convergence Education” Sponsored by the National Science Foundation (NSF); the Organization for Economic Co-operation and Development (OECD); the US National Academy of Sciences, Engineering, and Medicine (NASEM); and the University of Southern California (USC), there is a need to “prepare society for the disappearance of old jobs and the arrival of new ones.” Today, most students and consumers do not have a direct connection to the farm, but digital and precision agriculture offer opportunities to attract and retain tech-savvy STEM talent to address societal issues such as climate change, sustainability, and food security. Furthermore, there are new and advanced career opportunities that require a diverse pool of talent. Technological advancements may serve as incentives for sustained investment and engagement in agriculture and related industries. The engagement and preparation of all citizens is essential to the utilization, adoption, growth, and innovation of digital and precision agriculture. These technologies will enhance accessibility and will benefit veterans, the disabled, socially disadvantaged farmers, and any stakeholders interested in retooling or engagement in the industry. Existing infrastructure will have to adapt, and resource allocation decisions will need to be made by institutional leaders to build curriculum and models for instruction. Intentional efforts must be made to be inclusive in planning and fostering collaboration and funding in support of innovations in teaching, development of novel pedagogies, and educational research focusing on integration of digital and precision agriculture–related science and technology. Further inclusion of contextual and culturally relevant scenarios is needed in the classroom. A systems approach for the integration of digital and precision ag knowledge into education programs K-16 and beyond is needed. This will aid in early exposure and an informed citizenry for use and adoption and for innovation in a collaborative ecosystem.

A collaborative ecosystem should include access to centralized data repositories and tool kits for teaching and development of curricula and research experiences supported by core facilities or centralized hubs. Sharing of best practices, innovations, and technological resources via extension activities, museums, or displays in departments should be encouraged. National SEED Project money could be used for building strategic collaborations with cybersecurity programs to develop relevant curricula (e.g., seed money for collaborative efforts, such as between animal science and electrical engineering using Afimilk sensors on dairy cows for undergraduate and graduate research). At the K-12 level, ag discovery programs, 4-H, the National FFA Organization, and partnerships with ag-education teachers can be used to increase awareness of digital and precision ag. Experiential opportunities should be encouraged, such as science fairs and research experiences for students in STEM programs in middle school, traditional high school, and early college programs. Furthermore, digital and precision ag training of ag education and STEM teachers will build partnerships to implement convergence education. Taking an "Understanding by Design" approach will help to determine the educational needs to tackle complex problems. At the undergraduate level, professional development and collaborative research in digital and precision ag will provide a strong foundation for the development of curricula and convergence pedagogy. Such engagement will need support from institutional leadership and merit and engagement policies; therefore, outreach and training of institutional leadership is needed. Digital and precision ag researchers can contribute to high-impact practices in undergraduate education. These include internships, summer undergraduate research experiences, and course-based undergraduate research. The latter can impact a larger number of students and offers an opportunity for diverse thought, inclusive scientific discourse, and communication regarding digital and precision agriculture. The National Science Foundation’s Innovation Corps (I-Corps) can be used to provide experiential learning opportunities. Emphasis should be placed on the engagement of STEM talent within public institutions and on convergence on culturally responsive student mentoring for careers and innovation. Collaborations with farmers and funding from industry, foundations, government, academia, industry, and community sources may help in the creation of digital and precision agriculture training centers. Students can assist with preparing resources to disseminate complex information among stakeholders (producers, researchers, and the public). There is a need for graduate-level curricula and new or reorganized graduate programs. Convergent efforts focusing on education in ag and environmental systems developed through inter-institutional and interdisciplinary collaborations in areas such as data analytics and sensor technology for diverse ag systems (integrated efforts in soil, air, plant, animal, etc.) in collaboration with ag education may enable research and development of pedagogies to allow convergent thinking and discourse while including the development of soft skills such as leadership communication ethics around the use and applications of digital and precision agriculture. Professional training, such as engagement in entrepreneurship training through the NSF I-Corps, may help researchers gain valuable insight into entrepreneurship and innovation in this area and should be introduced early in all institutions. The NSF, in partnership with the USDA, could develop a postdoctoral scientist and teacher training track that focuses on preparation of future scholars targeting convergence education in this area.

F.3. Diversity, equity, and inclusion

The need for diversity, equity, and inclusion in agriculture has been well established. Engaging equitably with a diverse and inclusive set of stakeholders in agriculture offers the opportunity for a stronger, more creative, and more innovative industry. It creates an environment ripe for the inclusion and incorporation of the ideas, innovations, and voices of stakeholders from all genders, backgrounds, races, ethnicities, etc. Workshop participants collectively affirmed that emphasizing equality with a diverse and inclusive set of stakeholders “makes better science sense” by creating an environment with more perspectives and richer and more creative insights. It was also noted that engaging limited-resource, smallholder farmers in the digital and precision agriculture enterprise is not only an educational imperative but also vital to enhancing diversity, equity, and inclusion. One recommendation is the development of pilot grants designed for researchers to partner with K-12 educational programs and limited-resource farmers to integrate the disciplines and fill the gaps between education, research, and outreach while including close contact with farmers. Providing a multidisciplinary educational experience (computer science, environmental science, plant science, data science) allows for the demonstration of real-world applications of STEM education in food production and environmental sustainability. These partnerships will provide opportunities for middle school, high school, or early college students to learn how to conduct research and develop data science skills and should provide funding for limited-resource farmers to adopt precision agricultural tools.

The underrepresentation of many groups, including women, underrepresented minorities, and persons with disabilities, in research, education, and the workforce in the integrated areas of digital and precision agriculture deprives large segments of the population of the opportunity to be creators of technology and not only consumers. Addressing the challenges of diversity, equity, and inclusion will require collaborative and translative programs and activities as well as cultural change across all sectors of the community.

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