Collaborative Research: AccelNet: International Collaboration to Accelerate Integration of Engineering, Plant Sciences, and Agricultural Research

Project Summary

AccelNet Catalytic Project: Global food production is an enormously complex enterprise crossing every conceivable barrier from geographical borders to scientific disciplines. Challenges to production that threaten our ability to feed the world's growing population are multifactorial and will require the integration of many fields of knowledge and skillsets in order to discover sustainable solutions. It will require the synthesis of discipline-specific theories, protocols, and tools to create new models and a common language to address complicated research questions. The overarching research mission of the Accelerate Integration of Engineering and Agricultural Research using Artificial Intelligence (AI^{2}EAR) Network-of-Networks is to leverage the expanding capabilities in fundamental science, engineering, and modeling to decipher the growing number of agricultural data sets that exist but are not widely available, understood, or actionable. To accomplish this, we will need the efforts of many collaborators with varying expertise and tools spread across the world cooperatively sharing resources. The AI^{2}EAR Network-of-Networks will work to coordinate these experts and their institutions, with the ultimate goal of solving the grand challenge of feeding the world, through convergent research; transparency and open-source practices, education and training.

AccelNet Catalytic Project Intellectual Merit:

The projected global increase to 9.8 billion people by the year 2050 will impose significant challenges on our ability to produce enough food for the world's population. Meeting this demand requires both a 60-90% increase in food production and collaboration among stakeholders all along the supply chain. Key challenges that hinder our ability to meet the world's food security needs, and which this project addresses, include: 1) our inability to sense, quantify, and predict physical and chemical variables in the environment, including the microbiome; 2) the lack of data analytics and models that transform concurrent multi-scale datasets into decision-making strategies for improving crop yield and minimizing crop loss; and 3) the lack of open-source data cyber-infrastructures for accessing, analyzing, and sharing the "insight" extracted from heterogeneous biological, agricultural, and environmental datasets. There are many institutions (public, private, governmental) already working to solve these and other food production challenges, but there is a lack of coordination between them and no standardized lanuage or protocols that allow engineers and computer scientists to communicate effectively with biologists and economists. During the catalytic phase of the AI^{2}EAR Network-of-Networks, we will build a consensus agreement on the mission and specific goals of an international collaboration of networks determining the contribution that each individual network makes and the anticipated results from the larger collaborative. We will advance our understanding of how to build a robust framework that will support the Network-of-Networks and grow collaboration exponentially in order to sustain the AI^{2}EAR and support successful integration of agriculture, life sciences, and engineering to resolve scientific gaps (multiscale sensing, phenotyping, data integration), technical gaps (automation, data access, on-field scalability), and social barriers (economics, risk aversion, social acceptance, grower adoption, privacy) with the overarching goal of ensuring global food security.

AccelNet Catalytic Project Broader Impacts:

AI^{2}EAR will allow participant networks to utilize principles of responsible research and innovation and continuous stakeholder engagement to change, shape, and influence the path of innovation required in 21st-century agriculture. The engineered systems, AI models and platform utilized and developed as part of AI^{2}EAR will promote strategies for fostering innovation to improve yield, reduce crop loss, decrease crop resource demands, and increase food nutrition and quality. All work produced by AI^{2}EAR will be open-sourced and widely disseminated to all stakeholders. The mission is to not only advance knowledge that is usable by other researchers, but that is available and useful to end-user stakeholders such as farmers through the development of user-friendly on-farm decision support tools and solutions and ultimately to benefit to society at large.

Keywords: AI-driven solutions to Ag problems, Ag microbiome, Crop resiliency and nutrition, agro-ecosystem decision support framework

Project Description

I. Network-of-Networks Theme, Vision and Goals

The Network-of-Networks Accelerate Integration of Engineering and Agricultural Research using Artificial Intelligence (AI²EAR) (Table 1) vision is to enable long-term global food security and safety by accelerating collaboration between all the necessary disciplinary thought leaders and provide a framework for sharing of critical resources and information need to drive innovation. Global food production must increase by 60-90% to meet the rising demands of a projected global population of 9.8 billion people by 2050[1.] Significant advances have been achieved with plant breeding[2,3], fertilizers[4,5], genetically modified organisms[6], and precision agricultural services[7–10]. The complexity of food security and safety, however, along with regional and global diversity and the continual pressures of a changing environment, requires the development of AI strategies for improved on-farm decision support and custom solutions. AI²EAR is comprised of an interdisciplinary team of experts with knowledge that is relevant to agriculture.

Table I: Network Name/Home Institution	Locations	Focus	Point of Contact
RiseEnAG, The Engineering Research Center for Rapid Innovation in Systems Engineering and Ag. Sustainability	NC State, USA	Engineering solutions in Agriculture	Williams, Kudenov, Sozzani
ACCESS, Autonomous Cooperative Control of Emergent Systems of Systems	NC A&T State Univ., USA	AI-driven solutions to Agriculture problems	Karimoddini
RP-TDA, Root Phenotyping and Topological Data Analysis	Danforth Plant Science Center, and Wash U.,	Plant imaging for plant resilience	Topp
Sirius, Brazilian Synchrotron Light Lab	Brazil, NC State, USA	Root-soil imaging	Hesterberg
AM RCN, Ag Microbiome	Univ. of Minnesota	Ag microbiome	Kinkel, Dundore-Arias
CCRP, Collaborative Crop Resilience Program, University of Copenhagen, NCSU	Denmark, NC State, USA	Crop resiliency	Grunden, Hestbjerg, Sozzani
PIRE, East Africa Research and Education Partnership: Cassava mosaic disease	NC State, USA Kenya, Africa, Tanzania, Africa	Plant pathogens and emerging pests	Hanley-Bowdoin, Ascencio-Ibanez, Kennedy
FFAR, USDA-ARS, NC State, VIB	NC State, USA, Belgium	Crop resiliency and nutrition	Locke, De Smet, Sozzani
PFR, Plant & Food Research LTD. (a Crown Research Institute)	New Zealand, Kannapolis, USA	Nutrition	Lila, Iorizzo
NU-Tech, Nagoya University	Japan, Research Triangle Park, NC	Agriculture and Biotechnology	Koyama, Maturana
RIKEN, University of Tokyo and RIKEN	Japan, NC State, USA	Plant Live-Holomics	Sugimoto, Higashiyama
ART-21 Arabidopsis Research and Training for the 21st Century	Across the USA.	Bioinformatics, Genomics, Biology, Training	Brady, Friesner
TomorrowNow RCN	NC State, USA	Regional Development	Meentemeyer
BiGG FACTS in One Health, Training Next Generation of Women Bioinformatics, Genetics, & Genome Scientists	Univ. of Tennessee, ORNL, NC State, USA	Bioinformatics, Genetics, and Genomic Sciences in Agriculture	Donaldson

Available sensing and experimental technologies have generated massive, high-dimensional, heterogeneous, and unstructured biological datasets, which are still largely unexplored in a comprehensive way[11]. Modeling, machine learning, and intelligent data analytics approaches have produced promising results in understanding biological processes[12-14], but these approaches fall short of revealing essential "rules" connecting biological discoveries and physical influences on developmental outcomes in crops. Technology companies have coalesced around the integration of heterogeneous datasets to build domain-specific relationships or ontologies that drive advanced data analytics solutions. However, there has been less success in integrating individual yet complementary research networks around a common challenge.

By coordinating existing networks and combining resources, AI²EAR will catalyze the development of next-generation precision-ag solutions that are urgently needed to advance crop performance in a changing environment. Specifically, AI²EAR will accelerate the sharing and early-adoption of strategies and AI models to effectively translate the efficacy of data-driven agriculture solutions. AI²EAR Network-of-Networks activities will be aimed at reducing the barrier to entry into the use of advanced plant analytics and address the emerging "data inequality" threat across agricultural regimes. Increased accessibility and sharing of AI models will enable the application of these engineered platforms to food security problems that arise in developing countries.

AI²EAR's research objectives are to develop, share, and adopt tools of discovery via three synergistic research themes: Research Theme 1 - Sensor Science, Engineering, and Integration- will use plant-microbiome data from the CCRP, FFAR, and AMP networks to profile crop, soil, and environmental properties across scale. Research Theme 2 - Data Mining, Machine Learning, Multi-scale Modeling, AI models- will use novel analytical paradigms for processing heterogeneous and unstructured crop, soil, and environmental datasets developed by CCRP, FFAR, ACCESS, and RP-TDA and RiseEnAg networks to provide stakeholders with an agro-ecosystem decision support framework that captures complex interrelationships between crops and the evolving agricultural environment using the decision-making solutions developed by TomorrowNow network. Research Theme 3 - Open-source Data and Network Cyberinfrastructures- will use data and network cyberinfrastructure from CCRP and RiseEnAg networks that support innovations in sensor science and intelligent data mining analytics and will form the foundation of an open-source information sharing platform for real-time querying, systematic organization, and dynamic abstraction of heterogeneous agro-ecological datasets.

Research within AI²EAR will address three of the long-term bold research goals identified by NSF in its "10 Big Ideas for NSF Future Investments". Specifically, AI²EAR will drive fundamental advances in data sciences, developing new tools for data acquisition, data integration, and data mining (Harnessing the Data Revolution). AI²EAR will develop engineering-based systems solutions that will predict the causal relationships across biological and environmental scales that influence performance traits and affect pre-harvest yield and post-harvest loss in crops (Understanding the Rules of Life). AI²EAR identifies a complex grand challenge (food security) and will define the convergent space of research that merges the ideas, approaches, and technologies from engineering and the biological sciences needed to address it (Growing Convergence Research at NSF). The AI²EAR core team has significant NSF funded projects which will be leveraged and supported through this project further advancing NSF's strategic plan and producing value creation and product innovation by accelerating and operationalizing the deployment of AI models that couple multiscale sensing modalities with Ag-Internet-of-Things, edge and cloud computing, data privacy and security, field-scale automation, and data management, and fusion strategies to provide decision support for researchers and ag-stakeholders across the Network-of-Networks.

AI²EAR's context-driven goals are aligned to resolve scientific, technical, and social gaps and barriers that hinder custom decision support for the stakeholder. Goals will be integrated across the 14 initial members of the Network-of-Networks (Table 1) and will facilitate the convergence needed to share common analytical techniques and AI models related to, for example, field-scale automation, edge-based computation, on-farm data fusion, processing, and inference in limited connectivity environments. **Our coordinated global networks will advance understanding of (1)** *how to utilize principles of responsible research and innovation and continual stakeholder engagement to change, shape, and influence the path of innovation[15]*; **(2)** *how to create an incentivized culture of inclusion[16] to integrate ideas from individuals of diverse backgrounds, ethnicities, genders, experiences, and disciplines to enable convergence across engineering and plant/agricultural science to address global food security and safety*; and **(3)** *how to efficiently partner with existing agricultural networks to attract underrepresented minorities (URM) and rural students to foster economic prosperity in rural areas both nationally and internationally*. AI²EAR will be a catalyst for reshaping agricultural research, providing the tools of discovery that will be used for enhancing global food security, improving environmental safety, and improving human health. AI²EAR will effectively and sustainably develop cross-disciplinary, cross-institutional, systems- and innovation-focused initiatives to enable communication and contributions across international community boundaries. Importantly, as detailed in Section "Student and Early-Career Development Plan", AI²EAR's integrative approach to workforce development will integrate hands-on learning, on-farm technology training, transdisciplinary education, and

"soft-skills" development to create a highly trained and diverse workforce, which will be better equipped to address convergent challenges associated with global food security and safety.

AI²EAR comes at a critical time in which AI for agriculture is poised to become a global nexus in engineering Ag sustainability. Activities (e.g. workshops and hands-on research) developed from AI²EAR will bring together diverse groups of major agricultural stakeholders to identify a clear, actionable list of urgent and immediate problems. AI²EAR will work with stakeholders to identify milestones, solutions, and potential pitfalls that must be met or avoided along the way to reach our overall stated goal of accelerating agricultural sustainability through coordinated research and education. These discussions will enable the participants of AI²EAR to further define the research themes to ensure that the science and engineering capabilities can address the research targets of a coordinated global network of scientists, research Universities and Institutions. Our evaluation plan will allow us to monitor, assess, and ultimately quantify the true impact and value of how networks come together within the AI²EAR's Network-of-Networks and research targets.

II.   Network-of-Networks International Collaboration and Contributions

NC State is the ideal institution to serve as the nexus for the AI²EAR network. As an institution, NC State's near term goal is to be a global leader in Plant Sciences, and it is fully vested in supporting interdisciplinary team science. The university has invested tens of millions of dollars in putting interdisciplinary research and education at the forefront of its strategic plan. To date, the Chancellor's Faculty Excellence Program cluster hire program has added more than 75 new faculty members, including Dr. Sozzani, networked into diverse fields to enhance the breadth and depth of interdisciplinary, problem-driven research and innovation to solve societal challenges. NC State has numerous NSF National Research Training Grants, a USDA National Needs Fellowship award, 8 NIH Institutional Training Grants, and it is home to the Foundation for Food and Agriculture Research (FFAR) Fostering our Future grant, which established the FFAR Fellowship Program. FFAR Fellows is a one-of-a-kind graduate program focused equally on research excellence and professional development that works with industry partners to create career-ready graduates. The FFAR Fellows Program has successfully recruited three cohorts of exceptional students, and current linkages with universities and industry across North America make NC State's leadership in AI²EAR network all the more timely. The Executive Director of the FFAR Fellowship Program, Dr. Dunning, will oversee the Student Education and Professional Development aspects for AI²EAR.
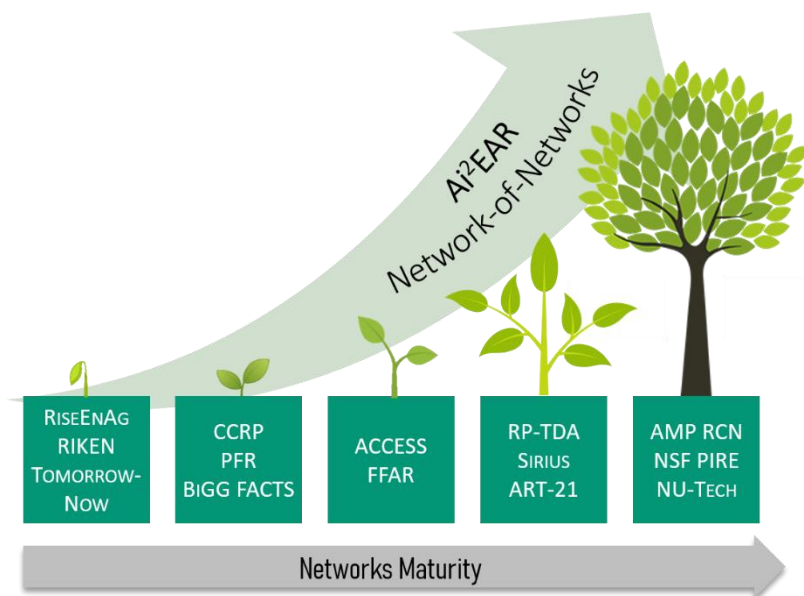

Figure 1 - Representing maturity of various networks

Building on existing collaborations, the AI²EAR network represents an unparalleled opportunity to deeply integrate the research efforts of 14 networks working at the frontier of food safety and security. These collaborations are at different stages of maturity, ranging from years of scientific and educational collaboration with written agreements and protocols to nascent relationships with huge potential. Through the catalytic grant, we will build a road map for all of the networks to mature into a larger, sustainable Network-of-Networks, building strong linkages that will support the overall mission of the entire team. We have identified the following Networks with synergistic strengths to collaborate with NC State and serve as original networks and building blocks for AI²EAR (Fig. 1).

RiseEnAg Network: Rapid Innovations in SystEms Engineering and Agricultural Sustainability (RiseEnAg) Network, North Carolina State University, USA. The RiseEnAg Network, directed by Dr. Williams, is a research consortium whose vision is to enable personalized crop system solutions through innovations in sensor science, multiscale modeling, and data analytics. These solutions will allow stakeholders, at various economic and agricultural levels, to respond and adapt to the environmental, ecological, and biological variability seen and expected in 21st-century agriculture. RiseEnAg is comprised of an interdisciplinary team of experts from NC State, UC Davis, Univ. of Florida, NC A&T State Univ., UC Santa Barbara, and Univ. of Maryland Baltimore County. RiseEnAg's goal is to drive fundamental advances in data sciences, developing new tools for data acquisition, data integration, and data mining. Currently, two RiseEnAg workshops have been organized with the objectives to: 1) Explore and identify unique and common challenges across all stakeholders that, if addressed, accelerate us toward the common goal of agricultural sustainability; and 2) Identify novel areas of engineering that can contribute to addressing these problems and the potential roadblocks where innovation is needed. Although RiseEnAg provides an example of a unifying network centered around the common goal of diverse stakeholders, the AI^{2}EAR Network-of-Networks provides the resources needed to bring different and more parties together in an effort to identify actionable outcomes that will ultimately benefit all involved. RiseEnAg, within AI^{2}EAR, will function as a catalyst for reshaping agricultural research, providing the tools of discovery that will be used for enhancing global food security, improving environmental safety, and improving human health.

ACCESS Network: Autonomous Cooperative Control of Emergent Systems of Systems (ACCESS), NC A&T State University, USA. ACCESS Network, directed by Dr. Ali Karimoddini, aims to address fundamental problems in modeling, analysis, control, and improvement of complex systems. The approach of researchers at ACCESS to systematically develop tools and techniques for analysis and synthesis of complex systems. ACCESS formulates such complex systems as "Systems of Systems," which are composed of a collection of (many) task-oriented components that together to create a new and more complex system that offers more functionality and performance through sharing the resources and capabilities. Relevant to AI^{2}EAR Network-of-Networks, ACCESS research includes "Cyber-physical systems," "Cooperative and distributed control of multi-agent systems," "Testing, evaluation, analysis, control, and decision making for large-scale complex systems." The research at ACCESS has been funded over $15M by government agencies (NSF, DOD, AFRL, ARO, AFRL, DOT) and industry (GM, Intel, LM, FCA, GD) on different applications of autonomous vehicles. For example, ACCESS has been investigating the application of autonomous vehicles and sensor networks in agricultural problems. In a recent project, funded by NSF, ACCESS is investigating the use of multiple UAVs to form a distributed sensing network to survey a farm and detect problem spots in a farm. To explore the application of robotic systems and AI-driven solutions to agricultural problems, ACCESS has expanded the collaborations within NCA&T (the nation's largest HBCU) and has created a network of researchers from NC State to take a multidisciplinary approach to agricultural problems. As part of AI^{2}EAR, ACCESS will further expand the network of collaborations with other universities and international groups. Throughout these collaborations, a Network-of-Networks of researchers will provide resources that will make teams more capable to target larger problems in order to respond to new (funding) opportunities, helping the overall network to fill the gaps and grow in long-term and impactful research directions.

RP-TDA Network: Root Phenotyping and Topological Data Analysis Network, Donald Danforth Plant Science Center (DDPSC), Saint Louis University (SLU), and Washington University in Saint Louis (WUSTL). As the interface with soil, and the conduit for all water and nutrient resources, root systems are the foundation of plant health and productivity. Yet due to their complexity and difficulty of observation, roots have been largely ignored and arguably compromised during plant domestication and improvement, especially during and since the Green Revolution. New breeding and biotechnology-enabled breeding strategies that incorporate whole-plant structure and physiology are warranted across the spectrum of agricultural crops to simultaneously maximize resource use efficiency and yield. Under an NSF-funded proposal, a team of plant geneticists, physiologists, computer vision and AI experts, and applied mathematicians, led by Dr. Topp, have been working on X-ray based imaging and analysis of thousands of maize and sorghum root systems grown at multiple field sites over multiple years, and from temporally-resolved imaging in controlled environments. Deep Learning algorithms have been developed and employed to segment roots from the soil in 3D volumes. Major challenges are the lack of an open-source cyberinfrastructure capable of transmitting, processing, and storing very large datasets as well as linking

our work to larger phenotyping efforts in these key crops to gain a comprehensive view of plant structure and function. In joining AI^{2}EAR, RT-TDA will be able to share lessons learned from interdisciplinary research, share our data and models and thus increase the impact of our efforts, and in return link up with a large collaborative network where existing solutions can be found and new ones developed. Furthermore, the impact on career development and the opportunity of our team members to be greatly enhanced.

Sirius Network: Brazilian Synchrotron Light Lab Network. To address challenges in areas such as energy, health, and the environment, the new Sirius synchrotron in Brazil hosts a network of scientists conducting basic and applied research in agriculture, biology, geosciences, physics, materials science, and engineering. A network encompassing researchers at the National Center for Research in Energy and Materials (CNPEM) in Campinas, together with agricultural scientists at leading agricultural universities throughout Brazil, including the Federal University of Viçosa, Federal University of Lavras, the University of Saõ Paulo, Saõ Paulo State University, the Federal University Rural of Pernambuco, and the Federal University of Paraná use a variety of techniques, including 3-D chemical imaging of nutrient transport at the root-soil interface and through plants as well as nanometric coherent diffraction imaging of biogeochemical matrices and cellular substructures important for plant health and productivity. Dr. Hesterberg, crop and soil scientist at NC State, is part of the Sirius Network. Because Brazil is a leading producer and exporter of a wide variety of agricultural crops; including sugar cane, soybeans, coffee, oranges, and maize; agriculture is considered a critical scientific research area at Sirius. With a strong foundation of applied research to support the economically important agricultural sector, the network of scientists that are forming around Sirius will create mechanistic knowledge needed to solve some of Brazil's most vexing agricultural problems that are common in tropical regions globally. A key strength of the Brazilian Sirius network for AI^{2}EAR is its combination of strong applied science coupled with emerging basic science conducted at one of the most advanced scientific facilities in the world. This expertise will contribute toward ensuring that the AI approaches used to bridge the essential, but diverse Network-of-Networks within AI^{2}EAR is done in a quantitative and scientifically meaningful way.

CCRP Network: Collaborative Crop Resilience Program. The grand challenge of providing food security for an ever-growing population can be addressed in part by harnessing interactions of plants, soil, and microbes for enhancing crop resilience. Recently researchers from the University of Copenhagen, Aarhus University, the Technical University of Denmark and NC State have been funded by the Novo Nordisk Foundation to help close the knowledge gaps of plant-microbe interactions to the degree that we could accurately and predictively model and manage plant-microbe communities to enhance crop resiliency and productivity in the face of increasingly challenging environmental stresses while reducing chemical and water inputs at the same time. CCRP research will build a robust agri-omics pipeline that supports meaningful network analyses and enables across-project comparisons as well as providing a state-of-the-art platform that can be leveraged by other groups to even further inform our understanding of critical plant-microbe interactions for enhanced plant resilience on a truly global scale, and as such would benefit from serving as a network hub. Specifically, interaction through the AI^{2}EAR would afford the opportunity for NNF students, postdocs, and faculty to engage in collaborative research and training visitations across the networks and more effectively engage stakeholder partners (e.g. NC Small Grain Growers Association, NC Soybean Producers Association), outreach partners (e.g. Natural History Museum of Denmark, NC Natural History Museum), and industry partners (e.g. Novozymes, Chr. Hansen).

AM RCN Microbiome Network: The Agricultural Microbiomes Research Coordination Network (RCN) is led by Linda Kinkel (Co-Scientists JP Dundore-Arias, Posy Busby, Jude Maul, Dan Tomso, and Jan Leach). The scientific focus of this RCN is to foster collaborative, synthetic, and cross-disciplinary research and analyses, advance the development of complex data analytics for microbiome research, and accelerate microbiome science and its applications to sustainable global crop production. Through 2020, the RCN will have sponsored or co-sponsored 4 workshops, 9 sessions at national or international meetings, and one 2-day symposium, with 2 years remaining in our funding. Of particular importance, we led the development of a novel hybrid in-person/virtual participation model for a recent microbiome workshop in Alexandria, VA. While funds were available to support in-person attendance of only 60 participants, we managed to attract over 400 participants from N countries through a Zoom/Slack platform that we developed. We created 27 'virtual communities', each consisting of 6-8 virtual participants to facilitate participation. All virtual participants had full access to meeting talks in real-time, and participate in

all small-group breakouts. By using this hybrid model, we were successful in democratizing our meeting, and especially facilitating the participation of early-career participants who may have lacked resources or time to travel to participate in-person. This provided an outstanding means for enhancing the diversity of participants in our workshop, and the deliberate construction of virtual communities to maximize disciplinary diversity generated an extraordinarily rich record of discussions (uploaded to a Slack channel). The RCN hopes to transport this model to the AI[2]EAR Network-of-Networks to enhance participation and to build bridges among scientists from diverse fields. There is substantial value in weaving together the AM RCN with the proposed AI[2]EAR, specifically in facilitating efforts to build publicly-accessible databases, integrating the latest in engineering and AI with microbiome `big data', and building our collective capacity to tackle big challenges. Being part of a larger network will expand our potential for thinking beyond our own discipline or sub-discipline and inspire us to find both the complementarity and common ground needed to create new thinking in agriculture. The network-of-networks will help to build a more expansive research vision while providing critical exposure and training to the next generation of scientists. We welcome the opportunity to bring our Ag Microbiomes research community into this network-of-networks.

PIRE Network: PIRE Sub- Saharan Africa Network: This NSF funded PIRE grant created an international collaboration/network between universities in the US and Sub-saharan Africa. PIRE includes collaborations with institutions in the US that span bioinformatics, virology, entomology, and others. It includes East Carolina State University and North Carolina A&T in the state but also Rutgers University and Auburn University. The collaboration with African Institutions includes the BeCA-ILRI hub and Jomo Kenyatta University of Agriculture and Technology in Kenya and the TARI-Mikocheni and TARI-Selian research centers in Tanzania. The BeCA-ILRI hub is a center that aims to secure food in Africa, does capacity building and empowers African scientists, together with technology and research and product development for advancing agriculture. It is also a networking hub for all of Africa. JKUAT is a University of similar size to NC State sharing many of the mandates and interests. TARI is part of the national network of agriculture research centers in Tanzania and we have direct contact with two of the centers. We work on the diagnostics, control, and evolution of viruses and their vector transmission. PIRE main focus is cassava but expands to other crops and systems. PIRE will bring the experience in international collaboration and student training to the AI[2]EAR network and in return will use the AI[2]EAR to sustain the PIRE initiative and build on its legacy.

FFAR Network: Foundation for Food and Agricultural Research Network. USDA- NC State- VIB (Belgium): Exacerbated weather negatively affects yield and seed nutritional content, making it imperative that researchers determine how to increase crop resilience to climate change. Through a funded project from the Foundation for Food and Agriculture Research, USDA-ARS is partnering with NC State and the Flanders Institute for Biotechnology (VIB) in Ghent, Belgium, to apply advanced machine learning algorithms and leverage the natural genetic diversity of plants and improve the sustainability, nutrition and flavor profiles of crops. To accelerate the translation of basic biological knowledge to applied food crop breeding, the FFAR Network is critically leveraging a network of industry and nonprofit partners, including Benson Hill, BASF, and the North Carolina Soybean Producers Association. Collaborative learning experiences, including joint hands-on learning, on-farm technology training, cooperative extension, and international visitation for students and postdoctoral scholars involved in AI[2]EAR will provide unparalleled collaborative experience and cross-disciplinary training. In turn, the FFAR Network, capitalizing on USDA-ARS itself as a nationwide network of research scientists, will provide unique insights and lessons learned from their academic-industry-nonprofit relationships that will be shared during the AI[2]EAR proposed activities.

PFR Network: Plant & Food Research (PFR) Ltd., New Zealand- USA: NC State collaborations with PFR institutes located in Palmerston North, Mt Albert, and Lincoln, NZ are primarily in the arena of functional foods, genomics, and metabolomics of health-protective foods, food strategies to i) combat escalating incidence of metabolic diseases; and ii) stabilization of the bioactive properties of food components to permit delivery to rural communities. Dr. Lila has collaborated on new food concepts and prototypes as well as technologies and formulations that deliver health benefits. Currently, the PER network research capitalizes on a recently-awarded on *Vaccinium* genotypes, which are critical to the agroindustries in both countries (USDA SCRI CAP grant led by NCSU). We are excited to engage with the AI[2]EAR Network as we believe it will afford us the PFR Network a wider audience, valuable scientific collaborations, and potential for more robust training opportunities for our students. In return, we look forward to sharing

our robust scientific resources on the development of functional ingredients and edible plant proteins, including phytoactive plant flavonoids.

NU Tech Network: Nagoya AgBiotech Network. Nagoya University (NU) is an educational hub in central Japan that, in 2007, founded the Technology Partnership of Nagoya University, Inc. (NU-Tech), a non-profit organization, located in the Research Triangle Park (RTP) of North Carolina. NU Tech promotes technology transfer between NU and US companies primarily in the life sciences as well as it facilitates researcher exchange and collaborations between NU and North Carolina universities. Nu-Tech has recruited US students at NU, and vice versa. In addition, NU Tech organizes annual technology roundtable in RTP by partnering with NC State, UNC-Chapel Hill and Duke University as a venue to share research innovations in agriculture and biotechnology areas. NU Tech, Nagoya University and their new partner, Gifu University, are interested in expanding collaborative opportunities beyond the RTP. Via mutually beneficial research collaborations and roundtable-workshop coordination within the AI^{2}EAR Network-of-Networks, the NU Tech-Gifu Network will leverage our network-of-networks to indeed look beyond just NC State and UNC partnerships but to welcome additional corporate, institutional, and academic partners thus creating new models and a common language to address complicated research questions to accelerate development and commercialization of technologies. The NU Tech will continue to offer a variety of short-term and long-term programs to which AI^{2}EAR students and postdoc will have access to, thus strengthening networks and relations among university researchers and transferring cutting edge technologies from Nagoya University, and Gifu in the USA.

RIKEN-Tokyo Network: Rikagaku Kenkyūjo (RIKEN) is a designated National Research and Development Institute with seven campuses and roughly 3000 scientists. Multiple ongoing collaborations between RIKEN investigators, including Drs. Sugimoto and Sozzani, have benefitted from NSF East Asia and Pacific Summer Institute (EAPSI) fellowships to graduate students and have promoted knowledge transfer and skill sharing. The strong plant molecular and plant-pathogen expertise at RIKEN is well suited to the AI^{2}EAR interdisciplinary focus on applying engineering, AI, and data analytics to improve plant science. By coordinating new training and collaborations via the AI^{2}EAR Network-of-Networks cutting-edge techniques such as those developed in the Higashiyama ITbM Live-Holonics Institute (soon moving to U. of Tokyo) will be shared with and applied by the greater scientific community at an efficient and widespread level. Correspondingly, RIKEN-Tokyo plant research groups will benefit from reciprocal knowledge sharing with other AI^{2}EAR networks.

ART-21. The ART-21 Research Coordination Network is a mature network administered by present and former elected members of the North American Arabidopsis Steering Committee (NAASC). The project had several main goals including: 1) Identify emerging technologies where using Arabidopsis as a model organism will provide fundamental discoveries and enable translational research in crop species; 2) Enhance interdisciplinary training of scientists for academic and extra-academic careers; 3) Increase the diversity of research scientists using targeted mechanisms. Progress toward each of these goals involve community workshops and/or course at our international annual meeting, targeted focus groups and production of commentary papers regarding our findings and recommendations, as well as providing funding and career development activities for early career researchers and under-represented minorities. The ART-21 Steering Committee and project focus groups include relevant international partners and networks to provide a more global perspective. ART-21 will provide expertise and perspective into several critical areas underpinning the proposed AccelNetl Collaboration: execution of activities with a large group of members; insights into the best means and mechanisms to create meaningful scientific communication; and efforts to increase diversity and impact within larger communities. The AI^{2}EAR Network-of-Networks will help disseminate ART-21 results and ensure that activities will continue to have a broad impact.

TomorrowNow, RCN Urbanization Network: TomorrowNow is a collaborative project led by four universities in North Carolina focused on developing a serious game that can help a greater number, and a greater diversity of people affect decisions that impact the places where they live and work. TomorrowNow is using real spatial data and developing interactive technologies that can help build a common understanding of challenges in the Triangle, and figure out how to address them. This RCN Network unites government officials, academic researchers, industry leaders and members of community groups and other organizations to co-develop a serious game that will tackle challenges related to rapid urbanization and

stormwater management in the Triangle region of North Carolina. As part of AI²EAR Network-of-Networks, TomorrowNow will gather all the needed information to start assessing how people affect decisions that impact agriculture and will transfer aspects of food production, supply chain movement and transportation to participating networks.

BiGG FACTS Networks: Training the Next Generation of Women Bioinformatics, Genetics, & Genome Scientists: The BiGG FACTS program is a network of researchers who provide research and Extension training in big data analysis for undergraduates in agriculture or allied disciplines. The goal is to prepare women for the workforce and academic challenges in agricultural careers. Research teams, composed of students and faculty mentors, focus on: 1) Plant and animal sectors of One Health; and 2) Analysis and interpretation of big data. BiGG FACTS is an important educational network that will provide lessons learned to inform the preparation of underrepresented audiences in engineering, AI, and data analytics.

Network-of-Networks Foundation: The initial networks represent varying levels of sophistication and resources but all have leaders committed to AI²EAR and are devoted to engaging in team science and resolving all the inherent difficulties (e.g., interdependence, joint ownership, collective responsibility) because they understand it presents our best, if not only, opportunity to solve the grand challenges facing our society and world. The foundation building for the individual networks outlined above to come together as the larger AI²EAR Network-of-Networks is already taking place ensuring that if this catalytic award is funded there will be a smooth and speedy launch of the project. The NC State CCRP Network team members already traveled to Denmark for kick-off meetings where synergies with AI²EAR were discussed and core international team members identified. In addition, the NU Tech Network and NC State are organizing, Fall of 2020, a workshop in Nagoya. AI²EAR Drs Sozzani and Maturana (NU University, see letter) applied for funding to the Academic Consortium for the 21st Century (AC21), an international network comprising 18 institutions, including educational, research and industrial organizations throughout the world. The AC21 Special Project Fund will help finance the proposed NU Tech-NC State workshop. During this workshop, we will invite members of Gifu and Kasetsart Universities with the goal of encouraging and introducing new research opportunities, exchange, and networking for academics of agricultural-focused universities in the neighborhood of Nagoya University.

AI²EAR team members who have not already done so, and eventually Fellows, will be asked to read the NIH Field Guide to Collaboration and Team Science prior to the first Annual workshop so everybody comes in with a common language and base knowledge as we draft the roadmap for AI²EAR.

III.   Results from Previous NSF Support

NSF Early CAREER -MCB-1453130: Modeling emergent behavior of gene networks controlling plant stem cells (4/01/15-3/30/220, $740,965, PI Sozzani). Accomplishments-Intellectual Merit: The research goal of this CAREER proposal is to experimentally identify the essential features that govern regulatory networks and develop accurate mathematical models that describe their molecular dynamics. Emergent behaviors of stem cell networks is investigated by integrating genome-wide approaches with cutting-edge imaging technologies and mathematical modeling. Accomplishments-Broader Impacts: The outreach goal is to develop a platform for effective interdisciplinary education by proposing an individualized educational program. A plant systems biology course integrating biological (gene expression, genome data, signaling data, modules/gene to function, and interaction between modules) and mathematical (data-driven modeling, structural identifiability and estimation, dynamics, and computational tools) approach has been developed and offered the past five years (2014-2019). Publications: To date, there have been 16 publications from this support (Nature Com[17], PNAS[18], eLife[19], Dev Bio[20], Nature[21], Plant J[22], Dev[23], Curr Bio[24], Mol Cell[25], Methods in Mol Bio[26–28], J Exp Bot[29], Plant Phys[30], Plant Biotech J[31], Curr Opinion in Plant Bio[32]).

NSF DEB-1714276: AgMicrobiomes: An interdisciplinary research network to advance microbiome science in agriculture (10/1/17-9/30-21; $499,998, PI Kinkel). Accomplishments- Intellectual Merit: The overarching goal of this project is to develop a coordinated global network of scientists, research sites, and model cropping and plant systems focused on agricultural plant and soil microbes. *In 2018, we sponsored 2 workshops for 150 participants, supported sessions at 2 international meetings, and established a project*

website and database of microbiome researchers. In 2019, we sponsored a third workshop and scientific sessions at 2 national meetings. In 2020, we have events planned at 5 national or international meetings. Accomplishments- Broader impacts: The project targets 4 key areas: i) increasing diversity in agricultural microbiome research, via active recruitment of and targeted scholarships provided to diverse participants; ii) aggressive inclusion of young investigators; iii) development of open channels of communication and collaboration targeting especially under-represented geographic regions; and iv) increasing agricultural microbiomes eduction. Publications: Phytobiomes Journal[33].

NSF Bilateral BBSRC NSF/ Bio – 1517058: Modelling Cellular Differentiation in Plants (08/01/15 - 07/31/18, $513,651, PI Long, co-PI Sozzani). Accomplishments-Intellectual Merit: The goal of this project is to identify and mathematically characterize emergent behaviors of gene regulatory networks during the ontogenic development of differentiated phloem cells and use this information to generate computational models that predict how regulatory signals regulate this process in the face of changing environmental conditions. Accomplishments-Broader Impact. This project is supporting 1 graduate student and has supported 1 postdoc, and 2 undergraduate students from local MRIs who presented her work at the Annual Shaw University Student Research Symposium, NCSU Summer Undergraduate Research Spring Symposium, Annual Biomedical Research Conference for Minority Students (ABRCMS). Publications: To date, there have been 6 publications from this support: Front Plant Sci[34,35], Nature[21], PNAS[18], Dev Bio[20], Curr Bio[24]

NSF EEC 1840440: Planning Grant: Engineering Research Center for Rapid Innovations in SystEms Engineering and Agricultural Sustainability (RiseEnAg) – (09/01/2018 – 08/31/2020, $99,940, PI Williams, co-PI Sozzani, Kudenov, Oralkan, Ogan). We propose a vision for RiseEnAg to advance discovery, innovation, and education for next-generation sustainable agricultural technology solutions. Accomplishments-Intellectual Merit: Through this planning grant, we will crystallize our vision by: 1) defining specific problems that will yield significant societal impact; 2) defining a convergent space of research, along with appropriate personnel, that are able to address the scientific and technical gaps; 3) engaging with the Ag-producer, Ag-grower and the Ag-Biotech community to assess how emerging technology can be used to increase value to their industry; and 4) identifying opportunities for team formation and engagement in leadership and management training. Accomplishments-Broader Impact. Thus far, we have several meetings, including a two-day stakeholder engagement workshop where day 1 was focused on identifying the problems important to agricultural growers and producers and day 2 was focused on identifying opportunities to provide value to the ag-biotech industry within a precompetitive space. Both days were well attended with 24 attendees on day 1 and 39 attendees on day 2 across 3 universities, 10 ag-biotech companies, a non-profit, and a commodity group. The data obtained from the discussions were coded, synthesized, and analyzed for emergent themes across these stakeholders. Interactions that have emerged from this planning grant have led to the submission of multiple federal grants totaling $10.6M.

AI²EAR Executive Committee (EC)
Ross Sozzani, NC State, Lead PI
Linda Kinkle, AMP RCN Network
Cranos Williams, RiseEnAg Network
Rebecca Dunning, FFAR Fellows Network
Terri Long, Braodening Partecipation
Christopher Top, RP-TDA Network
Ali Karimoddini, ACCESS Network
Amy Grunden, CCRP Network
Anna Locke, FFAR Belgium Network
Mary Ann Lila, PFR Network
Koyama, NU Tech Network
Sugimoto, RIKEN Network
Siobhan Brady, ART-21 Network
Joseph Donaldson, BIGG FACTS Network
AI²EAR Project Coordinator, TBN

TABLE 2: Members of Executive Committee

IV. Network-of-Networks Coordination Plan

In a broad international Network-of-Networks model, coordination will be key to success. Through the catalytic phase, we will hire a Project Coordinator who will be based in NC State's College of Agriculture's (CALS) International Programs as part of the team of Dr. Cisneros, Director of International Programs (see letter). The Project Coordinator will manage the administration and day-to-day activities of AI²EAR, as well as planning a kick-off meeting and three annual workshops. The Project Coordinator will work with the AI²EAR Executive Committee (EC) (Table 2) on project administration and management as well as student and faculty exchanges and serve as the connector among AI²EAR network partners. The Project Coordinator will coordinate network communication and work with IT staff in CALS International Programs and other team members to design and develop an AI²EAR website and to ensure appropriate

protocols are followed to ensure the success of student exchanges. Likewise, the Project Coordinator will work with the EC to ensure protocols for coordination and communication are adopted and following throughout the catalytic phase.

AI²EAR Network-of-Networks proposal provides a unifying theme centered around the common goal of creating and bringing together diverse international networks and stakeholders. <u>Each member network will engage fully in all activities of AI²EAR including attending, in person or virtually, the kick-off and annual meetings, sharing facilities, equipment and resources and recruiting, mentoring, hosting, and cross-training AI²EAR Fellows and visiting scholars.</u>

Post-award, the first task of the EC will be to hire a Project Coordinator. During the winter of 2020, the Project Coordinator along with senior personnel, Dr. Tucker, will do a comprehensive evaluation of available/widely used international communication tools and software and data sharing tools and repositories in addition to surveying networks to understand was is currently in use and available to them. Recommendations for communication protocols will be decided at the Kick-off meeting.

The primary purpose of the kick-off meeting is to bring together key representatives of the initial AI²EAR networks, who will constitute the AI²EAR EC. Even prior to the kick-off meeting, the team will be working to broaden AI²EAR to fill gaps in expertise, diversity, etc. Additional institutions will be invited to join AI²EAR and participate in the kick-off meeting. <u>The format for the Kick-off Meeting, and Annual Workshops that follow, will be hybrid, a combination of in-person as well as virtual.</u> The goal is to create an interactive environment where barriers to travel such as time and money are eliminated. The meeting and sub-working group breakout sessions will be managed using an integrated Zoom/Slack platform, to include open and sub-working group-specific Slack channels, which will be made available on the AI²EAR website for later reference or viewing. Each participating network or institution will designate one senior postdoc, or someone in a comparable position, to serve as the communication coordinator to oversee an online platform such as Zoom, in order for as many people as possible to participate. In addition, non-affiliated scientists will be able to view all presentations and discussion summaries through Zoom, as well as engage with the meeting participants via Slack channels. Social media will also be leveraged to reach as broad an audience as possible, e.g., Twitter and Instagram. During the initial kick-off meeting we introduce all of the networks and their core team members, engage professionally as well as socially, and take a comprehensive inventory of each network's assets including but not limited to human resources, relevant research strengths, data sets, unique equipment, specialized facilities, and specialized training programs, and existing linkages with other institutions that can be leveraged for AI²EAR. In addition, participants will have the opportunity to take part in sub-working group meetings based on their interest and expertise. Breakout sessions will focus on tasks such as developing the criteria and selection process for AI²EAR Fellows (*see Student and Early-Career Developmental Plan*), identifying gaps in the expertise needed to address overarching research goals, drafting AI²EAR mission, goals, objectives, etc. These efforts will be facilitated by Drs. Sozzani, Kinkel and Keyton. We will invite experts in the "science of team science" to address the group and separately conduct a facilitated SWOT Analysis including an open discussion to identify likely institutional barriers to AI²EAR's success such as IP, requirements around student and faculty exchanges, publishing, etc, In addition, the team will address logistical and intrapersonal barriers such as communication across time zones, funding, complacency, ensuring mutually beneficial relationships, etc. The goal will be to have as many people speak, lead, and present as possible in order to build camaraderie and trust among team members and magnify as many different perspectives as possible. All presentations and discussions will be recorded and materials copied and made available on the AI²EAR website.

Following the kick-off meeting, the largest meetings of AI²EAR, will be an annual workshop every fall. The plan is to hold workshops in conjunction with established, widely attended, Professional Society meetings in order to spread the word about AI²EAR and leverage the networking and exchange of scientific ideas inherent at such events. The exact purpose (goals, objectives, outcomes) of the three annual workshops will be decided as part of the catalytic process of growing AI²EAR. Each will be preceded by a 3 day AI²EAR Fellows (student and postdoc) professional development training, as explained in the "Student and Early-Career Development Plan". By holding these events back to back annually, the intent is to converge PIs and stakeholders from all of the networks and encourage collaboration amongst students, postdocs and PIs within AI²EAR. The two-day annual workshops will consist of presentations, roundtables and breakout

sessions with the exact content & agenda being decided by the Network over time. These workshops will allow for the sharing of best practices, new technologies, and data management in relation to accelerating the integration of engineering and agricultural research using artificial intelligence, as well as planning the next steps in network building.

In Fall 2021, the first annual AI²EAR workshop will be held in conjunction with the annual NU Technology Roundtable in Research Triangle Park (RTP), located close to NC State. We will use this opportunity to focus on refining the general strategies associated with each research theme, orienting participants towards the short- and long-term goals of the AI²EAR. As with the Kick-off meeting, participants will be able to participate in person or virtually. By this time we will be one year into the project, have conducted the initial Kick-off meeting and feel confident we will have established protocols and tools to provide our entire network a virtual community of practice. The AEC and Project Coordinator will report on the outcomes of the Kick-off workshop and activities that took place since, including but not limited to an overview of the AI²EAR Network Asset Inventory, selection of the initial cohort of AI²EAR Fellows. Each Network will also report out any information relevant to the growth or status of their individual Network and progress made building linkages within AI²EAR. New partners will be introduced and given an opportunity to present on the topic of their choice to the group. The Research Mini-Grant Award Program will be introduced and a sub-working group will finalize the guidelines for the program. The goal is to have the first grants awarded by early Spring 2022. Evaluation Coordinator, Dr. Shaun Kellogg, will also report on the status of his project evaluation and what has been learned so far. During this session, he will receive feedback from team members as well (*see Evaluation*).

During this catalytic phase of development, the specific objectives of the annual workshops will be to: 1) Define the independent and interdependent goals of each network to outline specific goals for a globally coordinated network; 2) Identify AI²EAR common strategies, and goals to improve yield, reduce crop loss, decrease crop resource demands, and increase food nutrition; 3) Explore and identify unique and common challenges across all networks that, if addressed, accelerate us toward the common goal of agricultural sustainability; 4) Identify best tools for network to network communication, data sharing, and data management, including how to best structure an open-source platform for accessing, analyzing, storing all the data sets that will be important to AI²EAR Network-of-Networks research; 5) Utilize principles of responsible research and innovation and continuous stakeholder engagement to change, shape, and influence the path of innovation; and 6) Identify novel areas of engineering that can contribute to addressing these problems and the potential roadblocks where innovation is needed.

The second annual AI²EAR workshop will be held in coordination with a professional society focused on the life and plant sciences, e.g American Society of Plant Biology. By holding the meeting in conjunction with a respected Professional Society meeting we will reach a large number of people working in fields synergistic to AI²EAR and hopefully expand the Network significantly. The third and final AI²EAR workshop will also be held in conjunction with a large Professional Society meeting, but one focused on engineering, e.g Society of Engineering Sciences. The goals once again to make our peers aware of the opportunities afforded by AI²EAR and expand the Network.

V.   Timeline & Sustainability

The current AI²EAR Networks are all in their own right established entities with institutional support, funding, facilities, and resources. They are all committed to leveraging these resources throughout the catalyst project and beyond as AI2EAR grows and matures by dedicating time and resources. The Executive Committee will ensure that AI²EAR "sustainability" beyond the catalyst and eventually full implementation phase is embedded in the mission and goals of AI²EAR. See the timeline (Table 3) for an overview of major activities and milestones of the planned catalytic phase.

Table 3. Accelerate Integration of Engineering and Agricultural Research using Artificial Intelligence (AI²EAR) Network-of-Networks

Task	Fall 2020	Winter 2020	Spring 2021	Summer 2021	Fall 2021	Winter 2021	Spring 2022	Summer 2022	Fall 2022	Winter 2022	Spring 2023	Summer 2023	Fall 2023
Year 1													
Quarterly Executive Committee Zoom Meeting	X	X	X	X	X	X	X	X	X	X	X	X	X
Hire Project Manager	X	•											
Inventory of Network members current communication, document sharing resources & tools	X	X											
Website development	X	X	X										
Planning for Spring Kick-off meeting	X	X											
Spring Kick -Off Meeting			•										
AI2EAR Evaluation			X	X	X	X	X	X	X	X	X	X	X
Website Live				•									
Selection of 1st cohort of AI2AIR Fellows				•									
First Annual Fellows Professional Development Symposium					•								
First Annual AI2EAR Annual Meeting					•								
Year 2													
Applications for Fellows Research Mini-grant due					X								
Selection of 1st cohort of AI2AIR Fellows Mini Grant recipients						•							
Selection of 2nd cohort of AI2EAR Fellows						X	X						
First Cohort of Mini-grant recipients participate in travel & research							X						
Second Annual AI2EAR Fellows Symposia and Newark Annual Meeting								X					
Year 3													
Applications for Fellows Research Mini-Grants due									X				
Selection of 2nd cohort of AI2EAR Fellows Mini-Grant recipients										X			
Selection of 3nd cohort of AI2EAR Fellows										X	X		
2nd Cohort of Mini-Grant recipients participate in travel and research											X		
Final Fellows Professional Development Symposium and Network to Network Annual Meeting													X

• **Milestones**

VI.   Network-of-Networks Communication Plan

To expand our reach with free worldwide access, the Project Coordinator, staff within CALS International Programs, and designated postdocs or comparable person at each Network will be tasked with developing communication protocols for large scale group interaction (eg., annual workshop) as well as day-to-day inter, intra-team conversations, using communication tools such as Zoom, Slack and Twitter. Following formally scheduled meetings, and importantly, after each workshop, AI²EAR facilitating team, and appointed or emergent science teams, will be required to respond to a 1-minute video, phone and/ or slack chat survey. *Each attendee will be asked:* 1) "What did you learn in this meeting?", 2) "What is unclear to you from this workshop?", and 3) "Did you speak in this workshop?" These three questions allow meeting analysis regarding collaboration and the spread of information across the networks. *Post-meeting analysis will focus on:* 1) "Were the in-person attendees the right people at the workshop?", 2) "Were the general presentations and breakout sessions used for discussion and problem-solving, appointment of tasks, conflict management, and/or decision making", and 3) "Did the workshop conclude with clear articulation and documented next steps?". These questions engage members and provide information about their self-assessment of identity and engagement as an AI²EAR team member.

AI²EAR will also employ analytical tools such as DIRECT[36] and VOS Viewer[37], and Cognitive Work Analysis[38–40] to: 1) conduct a socio-organizational analysis to identify strategies for effective communication during planning meetings and discussions; 2) identify team member competencies and match them based on AI²EAR needs; 3) establish cultural and expertise heterogeneity across networks to mitigate geographic location, disciplines, and/ or cultural challenges. These data will be used to develop communication networks among AI²EAR members. Semi-annually, a *here's where we are* memo will be distributed among all individuals working on or funded by the grant.

An inward-facing AI²EAR website will serve as a repository of all project reports, including workshop documents, project schedules, and access to AI²EAR's project goals and goal accomplishment timeline. This website will also include an email link enabling any project member to request information or assistance from the team science expert. The website will include Q&A sessions where AI²EAR students and postdocs answer questions about specific computational tools, experimental designs. Based on

feedback from these channels, teamwork assessments or training will be developed and scheduled for a specific individual, a specific team, or for a general AI²EAR audience.

VII.   Network-of-Networks Student and Early-Career Developmental (S&ECD) Plan

The mission of the AI²EAR S&ECD plan is to develop highly trained researchers with the leadership, teamwork, and management skills needed to work cooperatively with others to address the challenge of achieving global food security and safety. The professional development training and peer relationship-building will complement the students' technical training, increasing the likelihood of linkages among the network participants and setting the stage for enlarging the network and magnifying its outcomes as these young researchers establish their own careers.

The professional development training is modeled on the successful Foundation for Food and Agriculture Fellows Program. The FFAR Fellows Program, designed and managed by NC State, engages cohorts of 16-20 Ph.D. students in the agricultural and life sciences from 18+ universities across the U.S. and Canada. Using face-to-face and virtual formats, students train to become better communicators, better leaders, and better team members. Students draw on program coaches and their assigned mentors in industry, academia, and government to develop and adhere to annual Professional Development Plans. We will establish an AI²EAR Fellow Program, in which graduate students or postdoctoral researchers (postdocs) from AI²EAR participating networks and selected by the AEC will meet face-to-face for 3-days of professional development activities annually during the three-year program. Initially, selected annually by each of the participating networks, 14 AI²EAR Fellows -one for each network- will participate in programming tested and refined by this existing initiative. Special consideration will be given to identify and incentivize participation by URM students. Training will focus on three primary topics: communications, both interpersonal (one-to-one, small and large group; cross-cultural) and presentation (to scientific and non-scientific audiences); self-awareness and self-management (identification of strengths, inventory of emotional intelligence, communication/work styles, cultural intelligence); and project design and management for international collaborations. These meetings will be held in conjunction with the AI²EAR's annual workshops, with formal networking activities incorporated to give AI²EAR Fellows exposure to researchers at each member network. AI²EAR Fellows meetings will also be hybrid, meaning while students will be strongly encouraged to attend in person, an option for virtual participation will be made available and the entire event will be recorded and posted on the AI²EAR website.

Mentorship is a key component of the program. AI²EAR Fellows will create annual Professional Development Plans, drawing on advice from a set of 3-4 mentors from within the network. Fellows will also belong to a 4-member peer mentor group, with peers from other network members. These peer mentor groups meet during the three annual workshops and engage in two calls annually, facilitated by the Executive Director of FFAR Fellows program, Dr. Dunning. These networked program structures are designed to create opportunities for Fellows to practice their developing professional skills and to co-create a productive, synergistic, and expanding 'digital agriculture' network.

AI²EAR will use an activities-based logic model to define specific S&ECD activities, establish quantifiable metrics, and specify desired short- and long-term outcomes. This will be developed in coordination with the Friday Institute for Educational Innovation at NC State (*as detailed in the Evaluation Section*). The catalytic phase of AI²EAR will be used to set the stage for the development of the following initiatives: cross-institutional programming such as minors, certificates, or degree programs; project-based, innovation-focused courses for convergent education; short courses for both network and non-network students and other stakeholders that bridge engineering, data sciences, and life sciences; and innovation and collaboration-focused incentives that involve students and postdocs, including travel grants and internships.

During the catalytic phase, we will develop a Research Mini-Grant Award Program, to provide funding for selected students and postdocs to travel to and work in a Network member's labs for 3 months each summer. The program will be open to all students enrolled in accredited graduate programs with priority given to URM students and those from AI²EAR Network members. The AEC will be responsible for reviewing applications and matching the best applicants with host sites.

VIII.   Network-of-Networks Broadening Participation Plan

Once fully implemented, AI²EAR's international Network-of-Networks will provide unique learning experiences ideal for cross-training a diverse and interdisciplinary population of students and postdocs in convergence science. Our objectives for broadening participation are to i) train talented and diverse students and postdocs and ii) create thriving inclusive research, and mentoring environment for diverse students, faculty and staff.

During the catalytic phase and specifically at the kick-off meeting and Fall 2021 workshop, we will identify effective programs that support a sustained culture of inclusivity including recruitment, attrition and retention programs. Across AI²EAR, we anticipate many successful programs and models that can be incorporated into our overall plans for broadening participation. These efforts will be led and advanced by the Broadening Participation Director, Dr. Terri Long. AI²EAR will actively connect to and engage talented URM students, as well as students from rural areas, community colleges, veterans, low-income and first-generation college students from Minority Serving Institution (MSIs) and community colleges by leveraging existing relationships of each member network. For example, AI²EAR will include the ACCESS Network: Autonomous Cooperative Control of Emergent Systems of Systems (ACCESS) Laboratory, NC A&T State University, and MSI and AI²EAR networks. Another example, AI²EAR will actively engage the NC State's Military and Veterans Services and North Carolina's Community College System, as well as nearby MSIs to ensure their faculty and students' awareness of research and recruiting opportunities available through AI²EAR. We will collaborate with similar programs at other AI²EAR institutions such as The Summer School program at Sirius, which is aimed at university students from Latin America and the Caribbean, and the Community of Scholars Program at the University of Minnesota (AMP RCN), which provides Native American graduate students and other URM students with travel grants, workshops, writing initiatives, and community events.

Effective mentoring is essential for the success of students from URM groups. AI²EAR graduate students and postdocs, especially those from URM groups and veterans, will be paired with at least one faculty mentor from a network outside of their home institution network. This faculty mentor, who will video chat with the student at least once a semester, can act as a career coach and advocate for the overall success of the student outside of their graduate committee. Additionally, during the catalytic phase of our network-of-networks, we will explore starting an AI²EAR Graduate Bridge Program. Network partners will work together to explore establishing a 6-week summer research program that will be organized in collaboration with the NC State's LSAMP Bridge to the Doctorate Program model in which students are welcomed to campus with summer orientation, which addresses the transition from undergraduate to graduate education and builds a community with other minority graduate student organizations. This program gives students, particularly those coming from MSIs and community colleges an early start on research, thus accelerate the sharing of strategies and AI models.

Faculty, postdocs and students, particularly those from URM groups, of AI²EAR will present their research at meetings of societies that support URM groups such as ABRCMS, SACNAS, and MANRRS. At these meetings, participants of AI²EAR network to networks will share results from workshops and surveys about the need for a common language or protocols that allow engineers and computer scientists to communicate effectively with the biologist and economist. To continue building relationships and recruitment networks we will also organize MSI Undergraduate Institution Seminar Series in which AI²EAR graduate students and postdocs will give seminars and panels at MSIs that neighbors their home institutions to discuss their research and personal experiences of graduate school. In exchange Faculty and postdocs from these MSIs will also be invited to give AI²EAR research seminars. Students, postdocs, faculty and staff located at NC State will also participate in the annual NCSU Diversity in STEM Symposium, research and mentoring symposium focused on diversity in STEM, and paralogous programs run at AI²EAR networks. In addition, as part of the AI²EAR research seminar series, the NCSU Office for Institutional Equity and Diversity (OIED) will provide a Broadening Participation Workshop each year designed to build relationships through understanding, as well as in-person and online training options for conducting equitable and inclusive hiring processes at all levels. All of these will available by webinar, recorded and made available afterward.

IX.   Network-of-Networks Evaluation

During the catalytic phase, we will develop an extensive evaluation program to assess the effectiveness of overall education as well as the diversity and inclusion programs using tools developed through NSF's Alliance for Graduation Education and the Professoriate (AGEP) program. The Student Assessment of their Learning Gains (SALG) instrument[41] will be used to evaluate the AI^{2}EAR Fellow Program. Formative and summative assessments will be conducted under the leadership of Drs. Long and Donaldson, including assessment of design, development, and implementation of surveys/workshops; assessment of mentoring, retention and engagement activities for URM students in the education pipeline; review of data reflecting the number of URM faculty and students participating in AI^{2}EAR; and assessment of effective incentives and engagement programs that lead to diverse and international research, mentoring, and training opportunities.

Overall progress towards a fully integrated network-of-network model will be assessed by an independent evaluator, Dr. Shaun Kellogg, at the Friday Institute for Educational Innovation. Thorough evaluations of the creation and implementation of workshops, student exchanges, and website creation, as well as of formative feedback on and documentation of the project team process will help to ensure that the project activities are completed and project goals achieved. The detailed plan as it relates to process and outcomes evaluation is described below.

Evaluation of the Project Process: In order to gauge the extent that project components have been implemented as intended, Dr. Kellogg will attend the kick-off meeting as well as each of the 3 annual workshops and provide assistance to the project team in the development and administration of participant surveys for workshops, student-student exchanges, and formally scheduled meetings. He will use the survey data to provide feedback to the project PIs about how well the project process is working. Dr. Kellogg will also provide feedback on the website development and collection of site analytics, including recommendations for improving user engagement. Dr. Kellogg will report to members of the EC on a quarterly basis.

Evaluation of Project Outcomes: Dr. Kellogg will help guide the development of an activities-based logic model that defines specific activities, establish quantifiable metrics, and specify desired short- and long-term outcomes. Dr. Kellogg will assist in the creation of appropriate instruments and protocols for the collection of data associated with short- and long-term outcomes and conduct external review analyses. As one of the primary goals of this project is to facilitate and grow a "Network-of-Networks," social network analysis will play an important role in determining the extent to which implementation efforts were successful in developing connections between members of various networks, including the quality and quantity of their engagement. It is anticipated that data for network analyses will come from the following sources: questionnaires, website analytics, and research publications. Questionnaires will be used to solicit details from participants about the quality and quantity of involvement (e.g. communication, collaboration, advice-seeking) with members of other networks. Trace data from website log files including user contributions (e.g. discussion posts, shared files, etc) and members' interactions with and across networks will be used to gauge the extent to which the website has served as a useful medium for connecting members of each network. Finally, bibliometric networks constructed based on co-citation or co-authorship relations will be used to gauge the success of the initiative in facilitating research partnerships among network members. Data from these three sources will be used to calculate network-of-networks statistics and graphs for assessing the development over time. The evaluation of both the process and outcomes and the evolution of AI^{2}EAR will help to ensure that we meet the goals of the project in the time allotted for the grant.

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