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Request for Information on the National Digital Twins R&D Strategic Plan

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RFI Response: Digital Twins R&D Plan

The Agroecosystem Sustainability Center (ASC, https://asc.illinois.edu) is an interdisciplinary research center at the Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-Champaign. The ASC is dedicated to advancing agricultural sustainability through cutting-edge research in monitoring and modeling agroecosystems. In alignment with the goals of the National Science Foundation's Networking and Information Technology Research and Development (NITRD) National Coordination Office (NCO), we contribute our insights to the creation of a National Digital Twins R&D Strategic Plan, focusing on **sustaining agricultural production and environmental quality over the broad agricultural landscape**. Our focus is on leveraging digital twin technology to **build resilient agricultural systems and enhance both agricultural productivity and environmental sustainability by empowering adaptive decision-making in managing the broad agricultural landscape**. We envision prototyping and developing the following digital twins will make a profound and transformative impact on U.S. agricultural production and environmental sustainability:

- **Cropland digital twin**: The U.S. croplands are hotspots for human-environment interactions and serve our society by providing food, fiber, fuel, and other ecosystem services. Improving the management of cropland is critical for securing food production, enhancing resource use efficiency, and mitigating climate change. Traditionally, farmers make a series of complex farming decisions mainly based on personal experience and suggestions from peers and trusted advisors to maximize the profitability of crop production. The emerging conservation focus on cropland has the potential to help sustain crop production with less environmental footprints and bring farmers extra revenues from the ecosystem service market, but also further complicates the farming decision-making process due to the complex interactions and tradeoffs among different farming management practices and decisions. Building cropland digital twins can therefore help farmers to streamline and optimize the decision-making process.
- **Pastureland digital twin**: Grazing lands occupy an estimated 3.4 billion hectares (ha; 40%) of the global land surface and provide a suite of ecosystem services including livestock production, wildlife habitat, and many others. Grazing lands function as a key

element in livestock production and support rural and pastoral communities and livelihoods. With a growing population and burgeoning middle class worldwide, the demand for animal-sourced foods is anticipated to increase substantially. Meeting this demand presents several challenges for grazing land ranchers in the US who are already operating under the constraints of natural resource availability, climate change, and the complex demands of ensuring food security and environmental sustainability. Climate change, in particular, imposes substantial challenges for adaptive rangeland management with increased climate variability and frequency of extreme events, such as drought. Ranchers who currently rely on conventional practices and experiential knowledge may not be able to adapt to the changing climate and will require innovative decision-support tools to make their operations more sustainable, resilient, and climate-smart. Building a pastureland digital twin can therefore inform adaptive decisions on pastureland management. We envision a grazing land digital twin can (1) characterize different aspects of grazing land, including forage, animals, economics, and ecosystem services; (2) integrate diverse streams of data as inputs to the digital twin; (3) simulate scenarios and their corresponding impacts to support adaptive decision-making; and (4) generate quantifiable outcomes of different ecosystem services resulting from adaptive decision-making.

- **Watershed digital twin**: Watersheds are complex systems and watershed functions are arguably "emergent processes" – the net outcome from a watershed cannot be well-predicted based on just aggregating information at the sub-watershed scale. Instead, the interactions of hydrological, biogeochemical, and anthropogenic processes across multiple spatial and temporal scales within the watershed must be understood and captured for accurate prediction and interpretation of watershed responses. Climate change and human activities are affecting the quantity, quality, and spatiotemporal distribution of water resources at a watershed scale. Anthropogenic losses of nitrogen and phosphorus from agricultural land not only lower fertilizer nutrient use efficiency, but also lead to eutrophication and harmful algae blooms in streams, rivers, and inland water bodies as well as hypoxia in coastal areas. Building watershed digital twins can help optimize different water resource management scenarios and make more informed decisions related to sustainable water resource management at watershed scales. Watershed-scale digital twins can also help conservationists and landscape resource managers optimize different conservation strategies to improve both water quantity and quality.

Pertaining to the above digital twins, we provide our insights on the following topics:

Artificial Intelligence (AI): Leveraging artificial intelligence in building agricultural digital twins may significantly improve the efficiency and accuracy of prediction. As an example, researchers at the ASC are using knowledge-guided machine learning (KGML) to improve the quantification and prediction of both crop production and environmental footprints (such as greenhouse gas emissions and nitrogen leaching). Researchers at ASC are also coupling existing physical plant models with advanced computer vision techniques to generate 3D crop geometric models for major crops, such as corn and soybean. Given better geometric accuracy produced by these models, physical simulations on aggregated crop canopy digital twins closely mirror real system behaviors.

Data: Proper data collection and management is a cornerstone of digital twin implementation. ASC researchers are building integrated monitoring systems that use a combination of observational techniques to speed up data collection with less cost, including internet of things (IoT) sensor networks and cross-scale sensing (ground, airborne, and satellite remote sensing). We aim to continue and expand these methods to enable comprehensive monitoring and analysis of agroecosystems to inform digital twin models. With proper data quality control, multi-source observational data can serve as a multi-angle lens to depict the dynamics of complex real-world agroecosystems.

Ecosystem: A collaborative ecosystem across agencies and disciplines is crucial to advance the development of agricultural digital twins. Interdisciplinary research including agricultural science, geospatial science, environment science, and computational modeling can bridge potential research gaps. Collaboration across national agencies such as the National Science Foundation (NSF), the United States Department of Agriculture (USDA), or the National Aeronautics and Space Administration (NASA) would create a robust ecosystem for development.

Sustainability: Considerations of sustainability are at the forefront of agricultural digital twin development. Agricultural digital twins may inform humans to adopt sustainable agriculture practices, such as optimizing resource use or adopting smarter farming practices. With a combination of real-time observational data and predictive models, digital twin platforms enable us to make informed decisions to maintain ecosystem productivity while striving for increased sustainability. Enhancing real-time monitoring increases our ability to intervene swiftly. Predictive modeling helps to understand the interactions and trade-offs among different management practices on both ecosystem productivity and environmental sustainability, thus building up the foundation for supporting various decision-making.

VVUQ: To ensure the reliability of agricultural digital twin systems, rigorous methods of verification, validation, and uncertainty quantification should be included in each part of the digital twin architecture. Beginning from collecting and curating data used to empower the system, measurements of observational uncertainty should be collected. Supersites and experimental watersheds should be established to collect gold-standard validation tests. When leveraging artificial intelligence solutions for prediction or simulation, outputs should be associated with accuracies or representations of model confidence. All model predictions, no matter from process-based, AI-based, or hybrid models, should be validated using real-world data to verify model accuracy. Embedding VVUQ into agricultural digital twin architecture improves confidence from a scientific perspective and comforts users who are willing to consider decision-making recommendations from the digital twins.

Workforce: Developing a diversely skilled workforce is particularly important for the advancement of agricultural digital twins. Training programs integrating skills across academic disciplines (agricultural science, environmental science, geospatial science, computer science, engineering, and socioeconomics) would best prepare a workforce to develop agricultural digital twins. Additionally, cross-disciplinary STEM education ensures a broad range of perspectives in R&D efforts related to digital twins.

Concluding Remarks

With the insights above in mind, we currently imagine applications of agricultural digital twins in three broad use cases: cropland, pastureland, and agricultural watersheds. Cropland digital twins focus on complex cropland landscapes, including components such as crops, soil, water resources, climate, and human management to provide insights enhancing productivity and sustainability. Pastureland digital twins focus on the management of grazing lands, monitoring livestock health, and simulating livestock behaviors to predict grazing patterns and optimize productivity and sustainability of grazing land. Watershed digital twins integrate all natural and anthropogenic processes from headwaters to downstreams and from terrestrial to aquatic environments to predict water quantity and quality and also support watershed conservation planning efforts. Across various scales and systems, ASC highlights the potential impact of agricultural digital twins on improving agricultural productivity and environmental sustainability.

In summary, incorporating agricultural digital twins in the National Digital Twins R&D Strategic Plan enables advancement in adopting sustainable agricultural practices and addressing agricultural challenges. The ASC stands ready and excited for the development of a comprehensive strategic plan, including continued collaboration for the future development of agricultural digital twins.