CASA-Bio
Catalyzing Across Sectors to Advance the Bioeconomy

AgSystems: Accelerated Breeding for a Resilient Bioeconomy

Integrating advanced plant and animal breeding systems will transform agricultural productivity, sustainability, and climate resilience in the U.S. This proposed initiative will secure food supply chains, drive biotechnological innovation, and foster economic growth in biofuels and bioproducts.

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Executive Summary

The future of the U.S. bioeconomy hinges on bold, strategic investments for agriculture, including cutting-edge technology, resilient infrastructure, and cultivation of a highly skilled bio-workforce. Central to this vision is making sure the enhancement of plant and animal systems becomes a key pillar in fortifying agriculture, promoting sustainability, and driving biotechnological innovation. The advances proposed here are transformative leaps that will secure our supply of food, feed, fuels, and bioproducts to promote economic growth and strengthen the ability of the U.S. to tackle biosecurity threats and global challenges like climate change and resource scarcity. Improving our crops and livestock is not just beneficial, it is imperative to ensure a thriving, competitive, safe, resilient, and sustainable U.S. bioeconomy.

Goal

To transform U.S. agriculture by integrating plant and animal breeding into a unified, collaborative systems-level framework, leveraging new technologies for unprecedented advances in productivity, sustainability, and climate resilience across integrative plant-animal systems.

Justification

The currently fragmented agricultural U.S. model needs to be reimagined by adopting a systems-based strategy that integrates biological building blocks, optimizes shared resources, streamlines operations, and eliminates inefficiencies. Viewing agriculture as an interconnected whole will enable the U.S. to drive transformative progress and ensure a resilient and sustainable global system for food, bioproducts and biofuel production.

Deliverables

Anchored on three deliverables, the vision is for a $1B investment to establish a national, cutting-edge agricultural research network that integrates plant and animal systems to drive productivity and innovation in bioproducts for the bioeconomy while simultaneously strengthening climate resilience and sustainability. By leveraging state-of-the-art technologies such as artificial intelligence, biotechnology, advanced sensor systems, and programmable plants, we will revolutionize breeding to enable the emergence of new agricultural systems, optimize shared resources, and streamline operations. Five Bioeconomy Innovation Centers and associated Climate Resilience Testing Centers located across diverse U.S. regions will foster collaboration among academia, government, NGOs, and industry, while enhancing workforce skills in transdisciplinary science and quantitative systems analysis.

Impact

This holistic, systems-based approach will position the U.S. as the global leader in agriculture, driving innovation and supporting the bioeconomy for the challenges of the 21st century.

Motivation and Justification

Currently, in the U.S., there is no broad-based system that integrates plants, animals, and the environment to holistically address agricultural challenges. Research often shows promise in labs, greenhouses, or small-scale trials but fails to perform as expected on a larger scale and in production systems. Additionally, many scientific breakthroughs do not become commercial products due to the lack of suitable testing environments and streamlined paths to commercialization through public-private partnerships. Establishing a national agriculture network with Bioeconomy Innovation Centers and interconnected Climate Resilience Testing Centers will foster community-level collaboration. By sharing facilities and resources, researchers will be able to align on common goals, address critical challenges, and develop integrated, system-level solutions for plant and animal agriculture, driving progress in sustainable and resilient agricultural practices. Concomitant with this research focus, will be the opportunity to educate and train a new generation of workers, ready to take on the exciting prospects of working in the new agricultural bioeconomy. This approach will enable the translation of basic science into practical applications and promote U.S. leadership in agricultural innovation and advancement.

Whereas innovative breeding methods are revolutionizing crop and livestock development by offering breakthroughs in productivity, sustainability, and the creation of novel bioproducts, gaps in infrastructure and technical challenges in development hinder widespread adoption. To overcome these barriers, this plan introduces a national strategy that integrates three fast-evolving fields essential for maintaining U.S. leadership in agriculture: artificial intelligence (AI), genomics, and biotechnology. The strategy focuses on advancing breeding by using genomic and molecular technologies to boost genetic diversity and developing AI tools that can predict and optimize how that genetic diversity will perform in current and future complex natural systems.

Accelerating the rate of breeding progress will rely on preserving and utilizing both the existing genetic diversity in our plant and animal systems and the new diversity created through biotechnology; these are the cornerstones of plant and animal breeding efforts. Moreover, accelerating breeding for all organisms in the agricultural system will require expanding the U.S. national plant and animal germplasm repositories and updating existing infrastructure to manage and utilize rapid increases in genomic and phenotypic data. In addition, the complexity of understanding how plants and animals are impacted by changing and increasingly hard-to-predict environmental conditions will require new and enhanced analytical tools for breeders. Critical innovations in gene editing and, perhaps more importantly, scalable methods for production of successfully gene-edited organisms, are essential for commercial success. The development of standardized protocols for biotechnology products will be a key for efficient testing and commercial deployment of the resulting products. Genetic engineering and genome editing will enhance breeding efficiency, thereby leading to a transformative leap in the speed, precision, innovation, and safety of agricultural breeding.

Agriculture relies on inputs like nitrogen, phosphorus, and water. The need for these inputs puts a strain on agricultural productivity and can result in negative environmental and economic impacts. To address these challenges, a transformative strategy is needed. By developing plant and animal systems that utilize inputs like nitrogen, phosphorus, and water more efficiently, we can cut costs, reduce greenhouse gas emissions, and conserve resources. Resilient crops and animals will ensure stable production despite changing climate and increased frequencies of extreme weather events, fostering a more sustainable and economically viable agricultural system. This strategy includes fostering public-private partnerships,

employing advanced modeling and breeding techniques, deploying cutting-edge evaluation technologies, and training future leaders in agriculture.

Below, we describe three deliverables to address current challenges in agriculture. These deliverables are summarized in Figure 1.

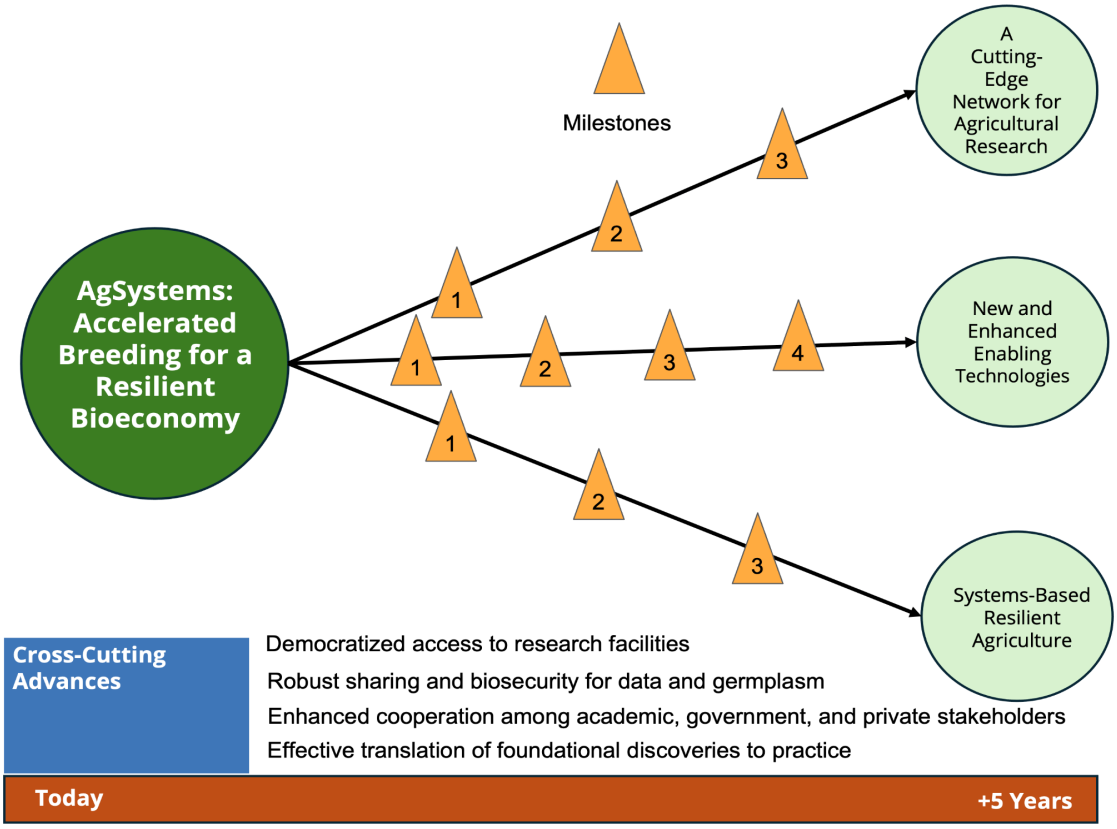

Figure 1: Diagram of the AgSystems initiative, depicting the three deliverables on the right (light green circles), milestones needed to achieve those deliverables (orange triangles), and cross-cutting advances representing some of the expected outcomes.

Deliverable 1: A Cutting-Edge Network for Agricultural Research (suggested investment: $600M)

Aim

Enable the translation of agricultural research into action by testing climate-resilient plant-animal systems for their commercial potential in agriculturally relevant environments, facilitating the application of biological innovations.

Key Milestones

<u>Establish a set of Bioeconomy Innovation Centers to serve as nodes of the network</u>

The network will utilize a centralized hub-and-spoke model and include creation of five advanced breeding coordination hubs (Bioeconomy Innovation Centers) to streamline operations and research

and maximize impact for U.S. agriculture. Strategically located nationwide with, eventually, up to 50 cutting-edge spoke sites (Climate Resilience Testing Centers), the network locations will be selected based on their potential to spur transdisciplinary research and their access to critical resources (e.g., computing, genomic and biotechnology centers) and to existing communities of breeders and transdisciplinary scientists. Spokes would be co-located with proximity to relevant plant and animal farming systems and target environments. Sites will leverage prior federal and state investments, such as centers for agricultural research (for example, land grant universities, USDA-ARS facilities, NSF/USDA AI institutes, NSF Regional Engines, Tech Hubs). Where needed, outdated infrastructure will be modernized with the explicit goal of driving collaboration between academia, the private sector, and government entities to foster development of shared goals and research directions. Key to the success of the Centers will be robust sharing of knowledge and data. To eliminate data silos, the coordination strategy emphasizes establishing large-scale data banks that emphasize Findability, Accessibility, Interoperability, and Reusability (FAIR) principles, and provide publication credits for shared data and sites. This effort will ensure effective dissemination of tools and information to the bio-workforce and retain flexibility for technological advances. Pilot projects will be used to demonstrate the benefits of open data exchange and encourage broad participation as the Network grows. Long-term resources and support for data storage, curation, processing, and public access are also critical.

Update key network biological resources, including national plant and animal germplasm systems and related resources

Existing germplasm repositories and biobank facilities are critical resources and must be updated to grow, propagate, and share germplasm while supporting biosecurity goals. By providing access to existing and new sources of variation, breeders will be able to improve economically important traits like disease resistance, nutrient rich content, productivity, and climate adaptability.

Advance education and training for the next-generation agricultural workforce

There are immense opportunities in agriculture to support meaningful careers and take advantage of the highly skilled STEM trainees and workforce in the U.S. The network will support advancement of these opportunities in three ways: by developing and retaining skilled staff in agricultural research, by strengthening industry collaborations, by fostering attractive employment opportunities at national and regional centers that showcase the intersection of agriculture and technology, and by implementing new hiring and training initiatives. The outcome will be a robust next generation of highly skilled workers for the agricultural bioeconomy.

Deliverable 2. New and Enhanced Enabling Technologies (Suggested investment: $200M)

Aims

- Develop a comprehensive breeders toolbox applicable to economically important U.S. plants and animals.
- Democratize access to technologies and data to improve plant and animal productivity, resilience, quality, diversification, and to create new bioproducts.
- Accelerate development and deployment of artificial intelligence and biotechnology.

Key Milestones

Integrate AI, genomics, and biotechnology in plant and animal breeding

Integrating advanced technology with human creativity and innovation is revolutionizing agriculture through AI, robotics, and big data, by automating tasks, optimizing resources, and enhancing decision-making. Machine learning and generative AI will drive breakthroughs in phenotypic and genomic

predictions and genomic design to enable more resilient, productive and novel agricultural systems (e.g., to produce bioproducts and implement biomining of high value minerals). To harness genomic advancements, high-quality reference genomes for additional species are essential. Building agricultural pan-genomes and complete genetic assemblies will further unlock genetic diversity and key traits. Functional annotation and improved data analysis and visualization tools, especially those employing AI and machine learning, will enhance breeding and sustainable practices. The rapid pace of global demands for affordable sustainably produced nutritious food necessitates a revolutionary shift in breeding techniques. An improved understanding of genomes, phenomes, and environmental interactions through AI predictions will allow researchers to better prioritize genome editing targets to make crops and livestock more resilient and able to deliver bioproducts to sustain a vibrant bioeconomy. Tackling challenges in gene editing efficiency and expanding our genetic toolkit will transform agricultural breeding, driving future advances in productivity, the creation of new bioproducts and resilience.

Optimize Germplasm Storage and Utilization

Effective preservation, characterization, and use of germplasm are critical for advancing breeding efforts. Modernizing preservation and characterization methods and implementing digital technologies (e.g., computer vision, remote sensing) will enhance the utility of genetic resources by accelerating the regeneration of strategic germplasm collections and adopting efficient preservation techniques to cut costs and prevent loss. Additionally, developing standardized protocols for collection, storage, and sharing of biotechnology products and establishing centralized repositories will streamline their integration into commercial and research breeding programs.

Reduce generation intervals to accelerate genetic improvement

Reducing generation intervals is essential for accelerating genetic improvements in both plants and animals. Innovative reproductive techniques, such as doubled haploid technology and *in vitro* gametogenesis, can significantly shorten breeding cycles. Integrating these methods with genome biotechnology will maximize their impact, making breeding programs more efficient and responsive.

Enhance data management resources

Robust data management systems are essential for preserving and utilizing the vast amounts of data generated by modern agricultural research. Permanent funding for current infrastructure and the development of improved data management tools will support the utility and advancement of critical databases. Standardizing data collection protocols and integrating various data sources will facilitate new discoveries and accelerate breeding efforts.

Deliverable 3. Systems-Based Resilient Agriculture (Suggested investment: $200M)

Aims

- Develop and apply advanced genetic methods to transform animal-plant systems, reducing agriculture's environmental impact and improving resource input efficiency and output inefficiency.
- Build a reinvigorated agricultural framework that integrates plants, animals, and their environment into a cohesive system.
- Enable adoption of innovative, sustainable, and climate-resilient production systems.

Key Milestones

Focus on developing, field-testing, and deploying new technologies to boost resilience

The integrated network hubs will each have a flexible number of spoke sites (Climate Resilience Testing Centers) for analysis of crop, livestock, and ecosystem performance. These centers will help address the inadequacies of current systems and propose and test innovative breeding solutions to enhance climate adaptability and reduce environmental impact. The network will focus on development as well as deployment of advanced phenotyping tools to measure critical traits like feed efficiency, methane production, and nutrient use efficiency across diverse and future-oriented environments. To overcome current lack of affordable, scalable sensor technologies, these hubs will design and deploy cutting-edge sensors for accurate measurement of environmental and biological variables in agricultural contexts. Significant funding is needed to advance these technologies, as well as shepherd them through the U.S. regulatory framework which can be challenging to navigate. Centralized hubs will help drive public-private partnerships, facilitate genetic and technological advancements, incentivize advances in data sharing and analysis, provide enhanced databases to facilitate regulatory officials in making risk proportionate decisions, and could also provide the opportunity for creation of a centralized resource for advancing publicly funded research solutions to regulatory processes and commercialization through public-private partnerships.

Enhance input efficiency

Current inefficiencies in input utilization by both plants and animals lead to significant nutrient loss, causing ecological problems. Optimizing nitrogen and phosphorus use in livestock production is crucial for reducing agriculture's environmental footprint. At the same time, optimizing nitrogen and phosphorus utilization by plants would reduce massive and highly problematic runoff of these nutrients into U.S. waterways. We propose a national-scale, coordinated evaluation system that identifies high-efficiency animal genotypes and plant varieties. Genetically superior animals will retain more nutrients, minimizing waste and environmental pollution. Enhanced plant varieties will improve nutrient absorption, supporting better animal health and reducing environmental impact. Furthermore, integrating this crop and livestock research and testing will also allow engineered crops (for example, plants with phytase and reduced anti-nutritional factors) to improve phosphorus availability and protein digestion of animal feed, lowering the need for supplements and reducing pollution. The resulting research and development capacity will create more efficient, sustainable, and climate-resilient food production systems.

Reduce output inefficiency and enhance agriculture's role in climate resilience

Methane and nitrous oxide emissions from agriculture contribute to greenhouse gasses that are a significant factor in global climate change, and their reduction would have direct and beneficial impact. As an example, optimizing the feed to support beneficial microbes in the rumen while inhibiting methane emissions, we can reduce methane production by as much as 60%. Another example of output inefficiency is the loss of crop-available nitrogen through soil migration and denitrification. Engineered biological denitrification inhibition in crops can suppress populations of soil microbial denitrifiers responsible for some of this loss resulting in reduced applied nitrogen requirements. Although progress has been made, more research is needed to understand what genetic and physiological components contribute to output inefficiencies, both in livestock and in plants, and new cost-effective measurement methods are needed to dynamically track progress. Additionally, development of an integrated, greenhouse gas traceability system to measure emissions from farm to table would boost the ability to assess benefits of specific interventions. Moreover, this system would enable AI optimization and data-driven decision-making to minimize the environmental footprint of agriculture moving forward and identify opportunities to not only mitigate its impact but also leverage agricultural practices to enhance ecosystem services, such as carbon sequestration, soil health, and biodiversity conservation.

Cross-Cutting Considerations

This initiative focuses on fostering greater collaboration, transdisciplinary science, and progress across sectors. Such broad participation must be accompanied by improved communication, development of a common language, and cooperation among academic institutions, government research bodies, industry and producers; particularly in addressing challenges like data and germplasm sharing. In addition to incentivizing data sharing as a priority, an additional component to this network of facilities will be a dedicated effort by an Advisory Board representing all these sectors to promote trust and spur motivation among stakeholders to adopt effective practices for resource sharing and open access to repositories. Additionally, a harmonized, transparent, and streamlined regulatory approach for biotechnology products is crucial for driving research innovation and commercialization to maintain the U.S.'s leading position in agriculture. At the same time, ensuring robust biosecurity for data repositories and germplasm resources and defending the food system against unexpected threats will be a vital component that spans all aspects of the program.

Expected Outcomes

The key outcome of this initiative will be an integrated network that enables effective translation of foundational discoveries to improve organisms of economic value growing in high-functioning agroecosystems. Such systems will contribute to reducing waste, lowering greenhouse gas emissions, and increasing production of food, fiber, bioproducts, and biofuels required for a vibrant bioeconomy and a secure and stable food supply. Accelerated plant and animal breeding will be enabled by the unprecedented capacity of the integrated Bioeconomy Innovation and Climate Resilience Centers. Collectively, the Centers will transform and engineer plant varieties and animal breeds using genomics and other biotechnologies through use of AI to predict phenotypes from genotypes. In turn, these discoveries will help in design of effective plant-animal-environment systems and management of these systems within real-world agricultural structures.

The initiative will contribute to a national strategy aimed at creating a more integrated and sustainable agricultural system by optimizing synergies between plants, animals, and their environments for development of resilient agricultural production systems that can better withstand climate challenges. Industry will be enabled to capitalize on research breakthroughs, facilitating growth in the bioeconomy, and education and training efforts will ensure that we have a ready agricultural workforce for the future bioeconomy. Moreover, scaling research in agriculturally relevant environments with equitable data sharing will support responsible innovation, balancing sustainability with economic feasibility, and help develop bioeconomies across the agricultural landscape. Finally, enhancing the genetics of agricultural species will ensure the sustainability and security of the overall food system from current and emerging global threats.

Conclusion

The future of the U.S. bioeconomy depends on transformative investments in innovative technologies, integrated agricultural systems, and a skilled agricultural workforce. By uniting and accelerating plant and animal breeding within a collaborative, systems-based framework, this initiative will enhance productivity, sustainability, and climate resilience across the agricultural landscape. With strategic advancements in research, biotechnology, and AI, the U.S. will not only strengthen its agricultural sector but also secure global leadership in tackling climate change and driving the bioeconomy.

Authorship and Acknowledgements

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