Feeding the Planet **Sustainably**

A UIDP Bioeconomy Workshop
July 28-29, 2021

UIDP
Strengthening University-Industry Partnerships

Workshop Report

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Contents

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Executive Summary

In the coming decades, agriculture will need major advances to meet the food, feed, fiber, and fuel demands of the growing population while reducing its environmental footprint. Within this context, there is an urgent and critical need to establish an agricultural bioeconomy that is sustainable, productive, and resilient to change. Accordingly, the National Science Foundation (NSF) is making investments to identify needed technological advances and develop partnerships to advance a new agriculture that can sustainably feed the changing planet. This workshop was convened to identify partnership strategies for how use-inspired research can be rapidly translated to innovations that support a new agricultural bioeconomy.

More than 100 participants from academic, industry – (large and small), government, and nonprofit sectors convened virtually for two days to offer a definition of the new agriculture and discuss challenges toward feeding the planet sustainably. The invited scientists and researchers were strategically selected to ensure that diverse perspectives and expertise were represented in the workshop deliberations. Participants envisioned what the new agriculture will look like, using terms such as predictive, sustainable, connected, innovative, collaborative, efficient, and united.

Purpose of the Workshop

Feeding a growing population that inhabits a warming planet is a significant undertaking that will require new strategies powered by technological innovations to improve food production and other agricultural products. The new agriculture should aim to reduce the drivers of climate change while still serving the planet's needs. To achieve this goal, a deep understanding of fundamental biological processes linked to practical innovations will be essential. Conventional approaches must be expanded to include advances in biotechnology, engineering, computation, artificial intelligence (AI), and mathematical modeling, while considering social, economic, and regulatory aspects. Additionally, it is pertinent to identify use-inspired research areas that are most amenable to collaboration and partnerships and where appropriate levels of investment will translate into near-term products, services, and techniques that generate societal benefit.

The workshop's goals were to define the needs for a new agriculture, identify gaps to progress, and articulate near- and long-term goals to achieve successful outcomes. Basic research should be directly connected with and lead to innovations that translate knowledge into practical outcomes. Inherent to success is the essential need for partnerships among all sectors—academic, corporate, government, and non-profit—for achieving these common goals. Industry-academic research consortia are one example of the kind of partnership that will contribute to developing the bioeconomy – both those participating in the research and those investing in it will benefit from collaborative R&D efforts.

Key Findings: The importance of integrating diverse perspectives from different fields remained a consistent theme throughout the workshop. Interdependencies between the bioeconomy, new agriculture, climate change, and social acceptance issues must be recognized and leveraged. Essential elements within such an approach include:

» **Incorporating the needs and wants of consumers and farmers** to deliver appropriate technology and solutions to different regions.

» **Interdisciplinary collaborations** between basic science and high tech and among social sciences, economics, policy, the industrial sector, and other stakeholders.

» **Effective and efficient communication among diverse groups** to foster collaboration and translate the problems, processes, and solutions.

Challenges and Opportunities

While there was overarching agreement about the need to develop approaches incorporating these elements, the participants acknowledged both challenges and opportunities to their development.

Challenges:

- **Contracting and intellectual property management barriers** must be removed to facilitate cross-sector collaborations.
- **Current partnership models do not work well** for developing countries, thus a new, adaptable model for public-private partnerships must be created.
- **Lack of adequate universal data standards**, such as FAIR (Findability, Accessibility, Interoperability, Reusability) standards,[1] capable of accommodating a rapidly developing new agriculture, must be addressed.

Opportunities:

- **The fundamental biology required to solve agricultural problems** is not well understood.
- **There is a knowledge gap between expanding and improving plant transformation technologies**, especially for orphan crops and lesser-studied species.

Recommendations and Next Steps

New agriculture's goal is to accelerate scientific and technological advances to the consumer market. However, the scientific community itself must do its part by instilling a greater sense of urgency, consistently engaging the public, and establishing international standards to catalyze research and commercialization efforts. Toward this goal, public understanding of, and support for, new scientific and technological developments should be improved. Participants recommended the following specific steps for moving forward:

- **Identify actionable steps to enhance capacity** by convening small focus groups of plant transformation specialists from public and private sectors.
- **Invest in a long-term, sustainable solution for computing power** that continually updates and expands as data collection rapidly increases.
- **Establish additional funding programs from federal agencies that are accessible to multiple sectors and that will support research innovation and technology improvement**, thereby advancing existing research tools, such as algorithms and data, from pilot to production so they are more applicable to predictive agriculture.
- **Give special consideration to small-holder farmers** who need key infrastructures, such as seed production and distribution systems, roads, plots, equipment, and other resources.

This report summarizes the key insights and is not intended to be a detailed record of the entire proceedings. We encourage you to share this document with interested parties.

Workshop Findings in Brief

Steps to Address Areas of Concern

- Consider current use of terms that are not socially acceptable, such as "synthetic biology."
- Increase communication highlighting the value proposition for science and tech needed for the new agriculture.
- Expand and consistently apply FAIR data standards and management.
- Define goals for feeding the planet sustainably.

Solutions to Improve Collaboration

- Remove contracting and IP management barriers.
- Increase funding for collaborative efforts that break down boundaries and silos.
- Facilitate opportunities for public-private collaborations.
- Reimagine integrative training and education.
- Build, engage, and retain a diverse and inclusive workforce.
- Communicate effectively and efficiently among diverse groups to foster collaboration and translate processes and solutions.
- Incorporate the needs and wants of consumers and farmers to deliver appropriate technology and solutions.
- Develop a new, adaptable model for public-private partnerships for a new agriculture.

Necessary Technical Advances

- Improve understanding of basic biological and ecological processes.
- Integrate AI, machine-driven, and robotic advances in agriculture.
- Establish foundational infrastructure for advancing synthetic biology.
- Improve plant transformation capability and efficiency.
- Discover and leverage the networks underlying complex biological traits.
- Identify actionable steps to enhance capacity by convening small focus groups of plant transformation specialists from public and private sectors.
- Establish small, cross-sector focus groups of plant transformation specialists to develop actionable recommendations and enhance plant transformation capacity.
- Encourage more multi-sector collaborations, not only between basic science and high tech, but also the industrial sector and other stakeholders.
- Instill a greater sense of urgency, engage the public, and establish international standards to catalyze research and commercialization efforts.
- Translate technological innovation into practical solutions at speed and scale.
- Translate outcomes to diverse and global stakeholders such as end-users, consumers, and those in industry and commodities.

Level-Setting: Challenges and Roadblocks

A pre-event survey (Appendix E) was distributed to participants prior to the workshop to identify key challenges and opportunities in agriculture and biotechnology. Thirty-one participants (26%) responded to the survey and provided consistent responses pertaining to the most impactful challenges and significant roadblocks.

Participants ranked all the current challenges as significantly impactful, with every topic accruing a weighted average above 4 ("Moderate Impact") except for "Integrating artificial intelligence into agricultural systems," which had a weighted average of 3.6 ("Some" to "Moderate Impact"). "Climate resilience" had the highest weighted average of 4.7 ("Moderate" to "High Impact"). These results suggest that there is slightly more emphasis on sustainability, training, and education than on the incorporation of computational technologies. Despite these small differences, the participants identified all components as important, so they should be tackled simultaneously.

Impact of Current Challenges Toward Attaining a Sustainable Agriculture

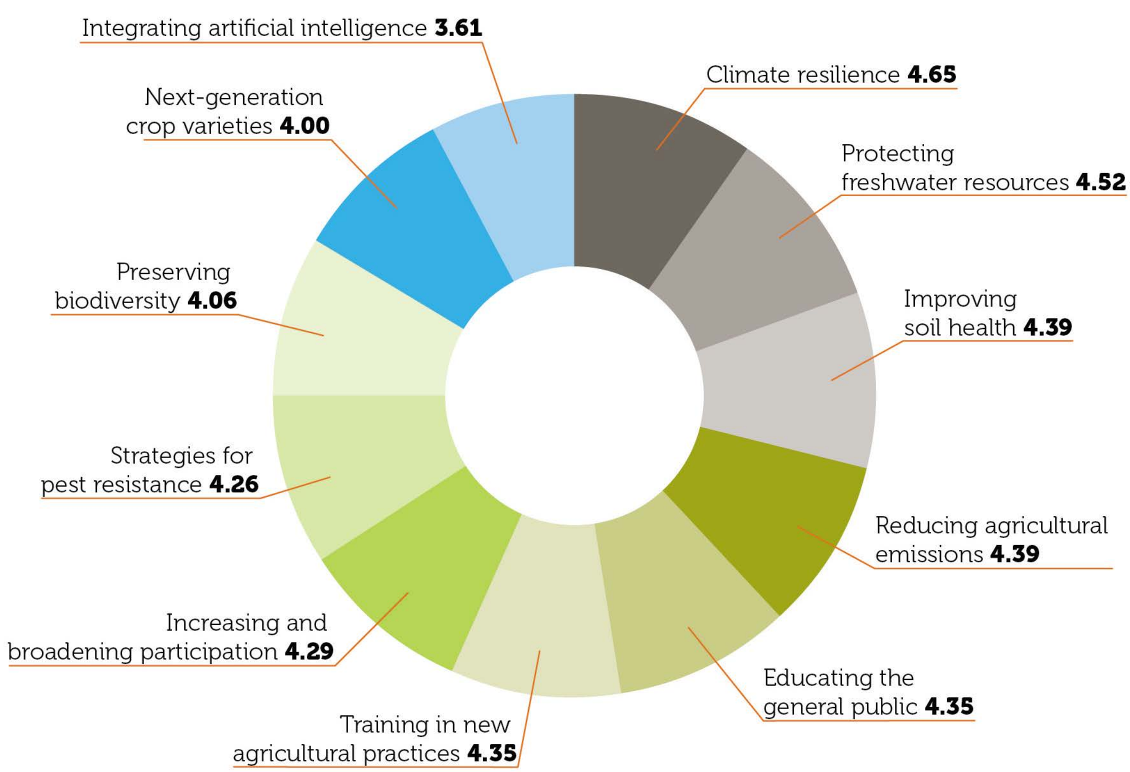


Figure 1 | Survey results on the impact of current challenges in agriculture. Participants scored the impact of these challenges on a scale of 1 ("No Impact") to 5 ("High Impact"). Numbers above represent the weighted average across *n*=31 survey respondents. Refer to Appendix E for survey questions and impact scale.

Similar results were obtained for current roadblocks, as participants consistently ranked the roadblocks at a weighted average of 2 or above ("Moderately significant") except for "Challenge of developing effective public-private partnerships" (1.9), "Short supply of trained experts in biotechnology and computation" (1.8), and "Lack of computational experience and cyberinfrastructure to analyze big data" (1.7). The largest roadblock, with a weighted average of 2.5, was "Lack of integration of ideas and approaches across disciplines." This particular result supports the overall purpose of the workshop, which was to bring individuals together to integrate and synthesize ideas from different sectors and disciplines.

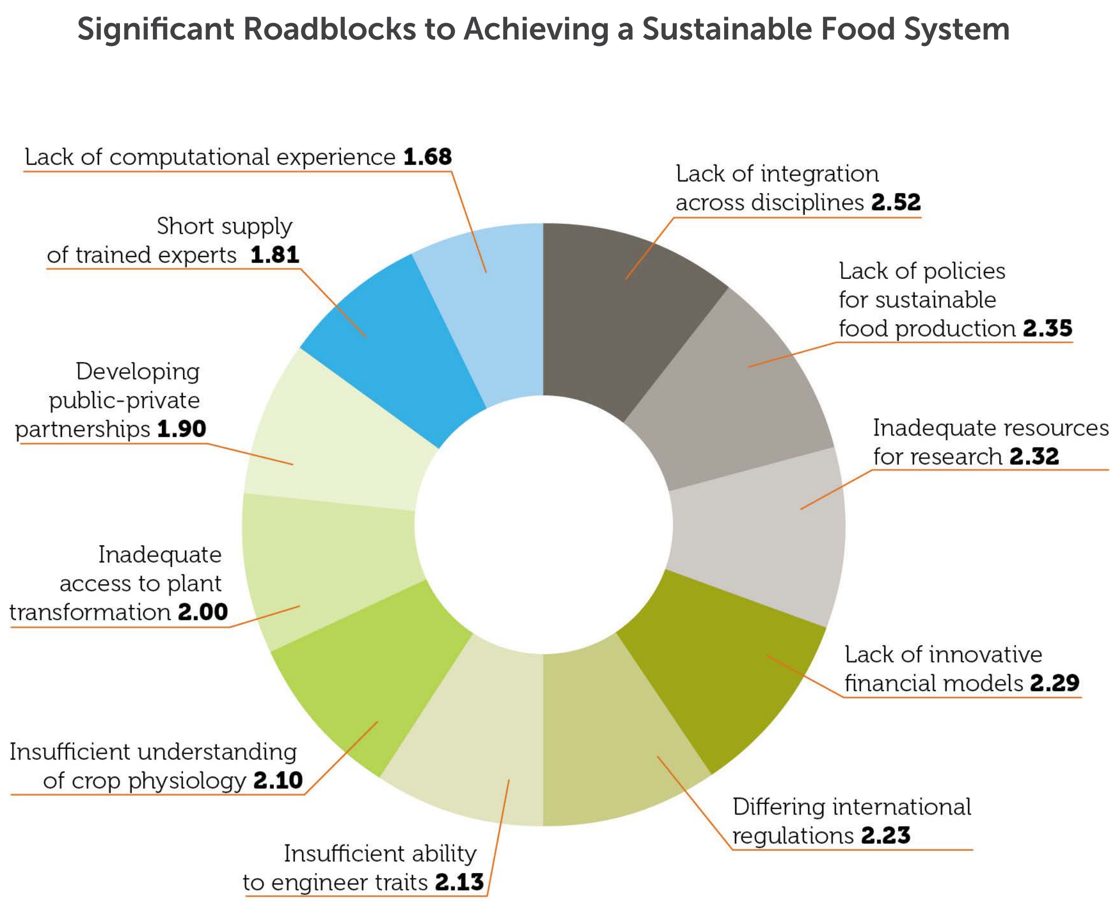


Figure 2 | Survey results on the significant roadblocks to achieving a new agriculture. Participants scored the impact of these roadblocks on a scale of 1 ("Least significant roadblock") to 3 ("Most significant roadblock"). Numbers above represent the weighted average across *n*=31 survey respondents. Refer to Appendix E for survey questions and impact scale.

Conclusions from the Research Landscape

Elsevier research analysts Bamini Jayabalasingham and Celina Sprague presented the results of a review of the global agriculture R&D landscape.[2] Over the past two decades, nearly 400,000 research works have been published on this topic, which includes food security, malnutrition, increasing crop yields, among other concepts. Between 2001 and 2020, global research output on this topic grew at a compound annual growth rate of 9.6%, outpacing the compound annual growth rate of overall global research output by four percentage points. While the United States published the most research, many of the top countries with publications in this area dedicated more of their research portfolio to the topic, with Brazil allocating the greatest national share (2.4% of the country's research portfolio). Among the various sectors that conducted research in this area, academic institutions contributed the most and are represented among authors in approximately 90% of the publications.

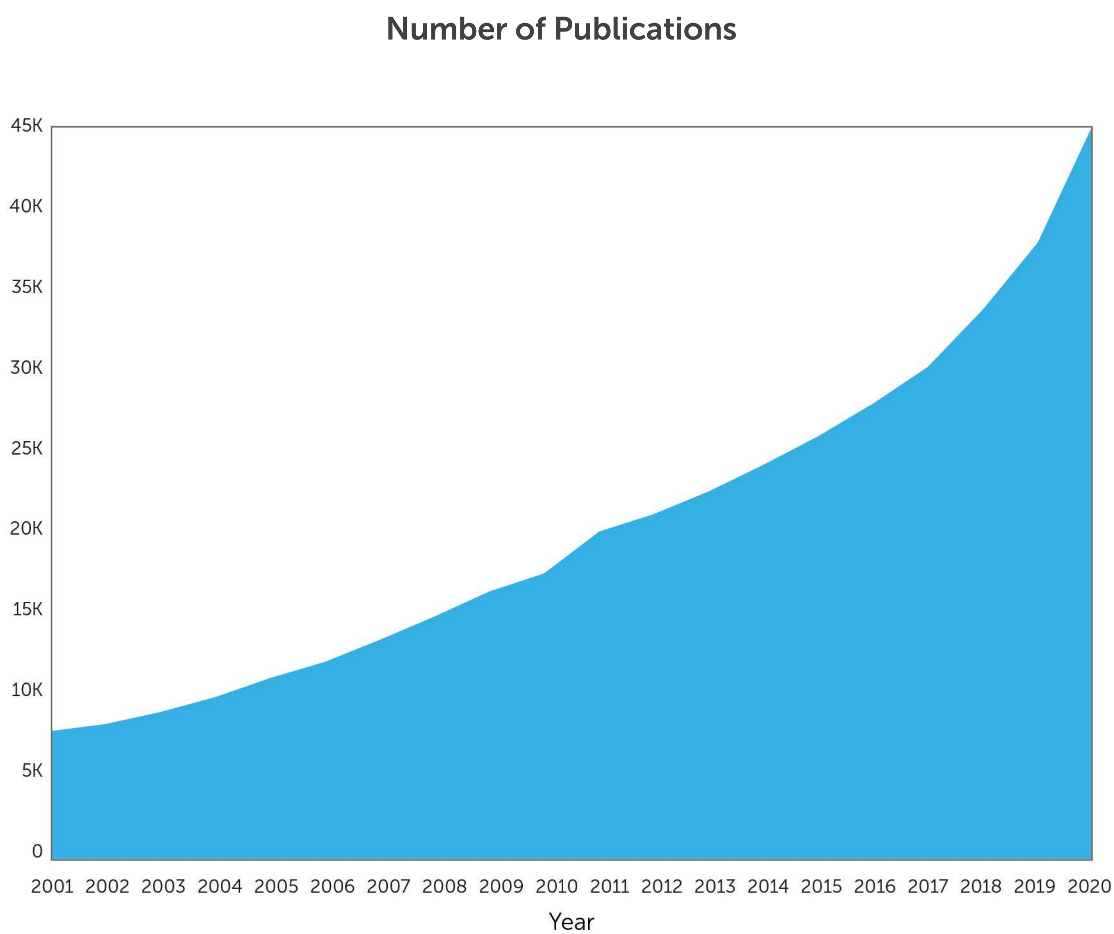


Figure 3 | Publication productivity related to topics within the workshop theme, Feeding the Planet Sustainably, 2001–2020.
Source: Scopus

Globally, biotechnology research is highly represented within the corpus of research on the topic, with computational biotechnology contributing 23%, traditional breeding 12%, and experimental biotechnology 5% of the research published over the past two decades. Traditional breeding and experimental biotechnology maintained their shares of the research over time. In contrast, computational biotechnology research increased representation within the area by 12 percentage points, from 15% of the total in 2001 to 27% of the total in 2020. Overall, biotechnology research stands apart from other research focused on Feeding the Planet Sustainably because a smaller share of biotechnology research was conducted solely by the academic sector, whereas a greater share was led through academic-government collaborations. In terms of citation impact, all biotechnology research has been cited 1.2 to 1.4 times more than the global average. Additionally, both traditional breeding and experimental biotechnology researchers have been cited more commonly in patents. Specifically, 2.5% to 3.5% of the research in these subcategories has been cited in patents, while approximately 1% of the research has been cited in patents for both computational biotechnology research and for this area of research overall. Together, these findings show the integral role that biotechnology research plays toward the thematic goal.

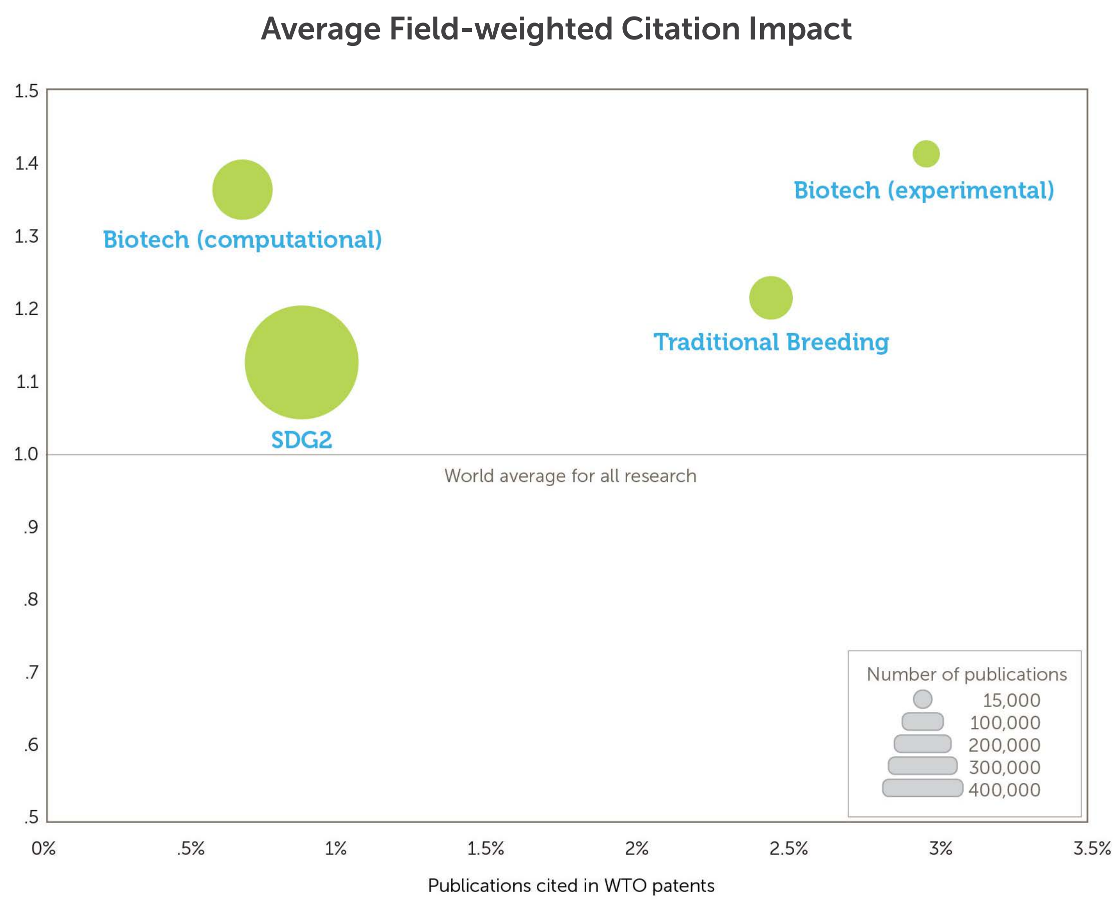


Figure 4 | Average field-weighted citation impact and percent of research cited in World Trade Organization patents for publications from 2001 to 2020 in each subcategory of *Feeding the Planet Sustainably* (SDG2) research. Source: Scopus

Session Highlights from Day 1: Defining the New Agriculture

The first day of the workshop focused on defining the key problems in agriculture, describing the state-of-the-art technologies available, and identifying the remaining gaps in knowledge. After participants discussed the workshop charge, they were placed into six breakout groups and asked to address the following four questions as they related to the group topic.

1. What do we define as a new agriculture, and why do we need it?

2. What research and outcomes are needed to get to a new agriculture?

3. What is the current state of progress toward achieving a new agriculture?

4. What are the current gaps in knowledge?

Facilitated Breakout Sessions

Integration of Biotechnology Applications and Computational Modeling

Current biotechnology approaches generate information-rich data that can expand the repertoire and genetic diversity of crop plants. Integrating these data into computational models can accelerate new discoveries and solutions for a sustainable resilient agriculture.

Key Takeaways

Improve data acquisition and interoperability. Data standards affect environmental, farm, and breeding data capture. Currently, these data are provided in multiple different formats; while FAIR (Findability, Accessibility, Interoperability, Reusability) standards are a good start, they should be expanded, particularly for agricultural data.[3]

Ensure modeling is relatable and predictive. Modeling must be translatable to less understood agricultural problems, such as working with orphan crops, as these challenges require a different mindset. Further, modeling should be standardized with consistent terms adapted across disciplines.

Support inter- and multi-disciplinary training at all educational levels and across sectors. Biologists should be trained in computational techniques, and vice versa. Information should be translated between plant species, i.e., understanding of pan-genomes. Cross-training should be encouraged between breeders and computational scientists and modelers. Finally, farmers and consumers should be included in public engagement.

Using Sensors and Robotics to Measure Key Agricultural Traits

Recently, sensors, advanced robotics, and nanomaterials have been developed for crops, soils, and local environments. Coupled with biotechnology breakthroughs, plants can be designed to adapt to environmental changes.

Key Takeaways

Incorporate the costs of inputs and agricultural impacts of food production into sensor design. The state-of-the-art sensors and their deployment in a field context allows researchers to understand the state of water, nitrogen, and the atmosphere. Use of these data points is most practical in a research context but is currently being explored in production agriculture as well.

Identify the most important intrinsic and extrinsic factors for efficient and sustainable productivity. Important consideration should be given to the development of agricultural infrastructure to improve crop yield in a rapidly changing climate context. Data science approaches are needed to interpret such information and establish models for a predictive framework.

Translate information gathered from basic research studies into different agricultural contexts. In particular, the scalability of sensor and robotics technologies is unclear without investment in research to translate such innovation into practical solutions for farmers.

Targeted Computational Solutions

Designing crop improvement pathways will demand sophisticated methods based on AI systems and machine learning approaches, along with modeling outcomes. Managing and integrating these datasets will be central to solving challenges of the new agriculture.

Key Takeaways

Construct a sustainable and secure agricultural system. This new agriculture incorporates integrated, flexible, and scalable data management, analytics, and visualization systems. Research and development of next generation crops that are resistant to drought, pests, and other stresses should be supported. Understanding the resilience of agricultural systems under the stress of climate change and adjustments in land use is also important.

Shift focus beyond the genotype to phenotype phenomenon. Greater efforts are needed for integrating perspectives from different disciplines to understand how environment and management also contribute to phenotype.

Address several gaps in the current agricultural system. These gaps include data availability and access, good communication among different disciplines and stakeholders, interdisciplinary training, and few visualization systems and translational products. There is also a lack of incentives for researchers, especially those early their careers, to work with an interdisciplinary team – an approach that can take longer to produce tractable results.

Training an Interdisciplinary and Diverse Workforce

Breakthroughs will rely on educating and training a biotechnology-based workforce in new tools and technologies. Training across sectors and disciplines will broaden impact, thereby ensuring that advances in agriculture will align with societal needs.

Key Takeaways

Reimagine graduate training. There should be consideration for changing the current model to one with increased student financial incentives for advanced academic study. Collaborative thinking should be rewarded and incentivized. There should be different considerations for evaluating output beyond publication number and input factors. Inclusive strategies toward research and discovery, involving a diverse population within a new agriculture, is optimal to uncover fresh perspectives.

Change the public opinion of the agriculture workforce. Emphasize the inclusion of new disciplines (e.g., data science, engineering, nutrition, outreach) and partnership opportunities (e.g., farmers, consumers, hobbyists, the general public). This will help to push the science quicker and in a more focused direction and enhance public acceptance.

Ensure the evolution of agriculture maintains a balance between cross-functional thinking and deep knowledge. Improve training about agriculture for those in other fields, balance quick scientific progress with public acceptance, and develop a professional cohort to work collaboratively and focus on team, rather than individual, credit. Convergence of different fields, people, and ideas is a key theme in developing and promoting the new agriculture.

Building the Necessary Transformation Infrastructure

Gene editing and engineering systems are critical tools to advance crop improvement efforts and to allow new crop systems to be endowed with new traits for a sustainable resilient agriculture. Interdisciplinary efforts in this field are needed to improve the robustness and accessibility of these technologies.

Key Takeaways

Improve the accessibility of plant transformation. Transformation should be efficient and allow gene editing for a range of simple to very complex traits in a large array of crops and genotypes.

Greatly increase the efficiency of transformation technology. Current levels of transformation technology limit center and facility approaches. Advancements are needed for both individual- and center-based transformation and editing applications. Significant research investments are needed to achieve near-term improvements in crop transformation and editing.

Incorporate multi-disciplinary approaches in the transformation and editing field. Specifically, transformation- and editing-related translational applications can help ensure social licensing and acceptance of technology for crop improvement.

Big Data for Predictive Agriculture

Large datasets must be translated into measurable outcomes, such as crop yield, soil health, and pest resistance. Collaboration among biologists, engineers, and computational scientists is necessary to develop the agricultural products and solutions to meet emerging needs.

Key Takeaways

Centralize and standardize data management and infrastructure. Focus should be especially placed on imaging data, which is a key component of predictive agriculture. Data should be consistently annotated, and analysis workflows should be maintained in the long term. Cross-disciplinary training in data management and integration is needed.

Shift from data collection to predictive agriculture. There is a need to leverage big data at high-spatial and high-temporal resolutions to develop predictive tools for crop health for real-time decision-making at the local, regional, and national levels. Contributions from the computational field, especially modeling, will be necessary to transition from quantitative measurements to complex biological outcomes.

Encourage equitable data practices across sectors and countries. The availability and restrictions of public-sector data may limit the ability of companies to translate data into products; therefore, a framework for better partnership is needed. Further, scientists and farmers in developing countries need access to infrastructure that leverages big data to implement biotech and production solutions.

Concluding Group Discussion

At the end of Day 1, all members re-convened in a general session to cover the key takeaways from each of the breakout groups and discuss overall conclusions.

Overall Takeaways

- Progress from data collection to predictive agriculture.
- Improve data handling, accessibility, and processing.
- Integrate solutions, converge agriculture with non-agriculture fields, and facilitate new partnerships.
- Reimagine interdisciplinary training and emphasize communication.
- Establish public/private partnerships to advance transformation efficiency and technology.

Gaps and Additional Areas of Concern

- Improve exploration of biological systems.
- Consider current use of terms that are not socially acceptable, such as “synthetic biology.”
- Increase communication of the value of the science and technologies needed for the new agriculture in bioeconomy.
- Increase interdisciplinary approaches and common language.
- Improve consistent application of FAIR data standards and management.

Day 1 Key Takeaways

- Translate technological innovation into practical solutions at speed and scale.
- Improve understanding of basic biological and ecological processes.
- Define goals for feeding our planet sustainably.

Changes to Approaches for Problem-Solving

- Increase collaborative efforts that break down boundaries and silos.
- Facilitate opportunities for public-private collaborations.
- Reimagine integrative training and education.
- Build, engage, and retain a diverse and inclusive workforce.
- Integrate other, relevant disciplines, such as social sciences, economics, and policy.
- Translate outcomes to diverse and global stakeholders, such as those in industry, commodity, end-users, and consumers.

Necessary Technical Advances

- Integrate AI, machine-driven, and robotic advances in agriculture.
- Establish foundational infrastructure for advancing synthetic biology.
- Improve plant transformation capability and efficiency.
- Discover and leverage the networks underlying the complex biological traits.

Session Highlights from Day 2: Integrating Perspectives to Achieve Solutions

The group's conversations and conclusions from Day 1 were translated into how to achieve solutions in Day 2. Toward this goal, the following four questions were posed to attendees, which were then discussed as they relate to broader agriculture issues.

1. What are two to three key goals to achieve feeding our planet sustainably?

2. Which components of these goals have tractable short-term (2 years) versus long-term (5 to 10+ years) solutions?

3. What are specific innovations to solve these goals or their components in the 2-, 5-, 10-year, and longer time frames?

4. What would inspire and enable members of different sectors to work together to achieve these solutions?

CASE STUDY IN TRANSLATION

xarvio > Jeff Spencer, Head of Technology and Data, Digital Farming, BASF

Background

Founded in 2014, xarvio offers digital products that deliver independent, field-zone-specific agronomic advice that enables farmers to produce their crops more efficiently and sustainably. The company operates at the forefront of the digital transformation of agriculture to optimize crop production. With major operations on four continents, xarvio has about 180 employees in technical fields, including agronomy, data science, IT, and engineering, and is a wholly-owned subsidiary of the BASF Group. With about 4 million users worldwide, the company's mission is to improve and automate sustainable crop production.

Current Products

xarvio's products serve both large and small farmers and target multiple segments of the growing community. The company captures data from a range of sources, then feeds the data into an agronomic decision engine to create a customized application or recommendation for the grower/customer. It offers three products:

- **xarvio SCOUTING** is a simple application that farmers can download onto a smartphone. The user takes photographs of an event or problem in the field, from which the app uses computer vision and machine learning to identify a weed, a pest, or other problem and recommend a solution.
- **xarvio FIELD MANAGER** brings more complexity and technology for field and field zone-specific optimization of crop production. It offers support for every step in the growing cycle, from planting to harvest.
- **xarvio HEALTHY FIELDS** builds on the technology components of the other two products and seeks to go beyond a subscription model to contracting with growers to deliver optimal outcomes: disease-free fields.

Commercialization Journey: xarvio FIELD MANAGER

xarvio FIELD MANAGER began with a narrow focus in crop protection. After it was acquired by BASF in 2018, it became clear that the product needed to evolve to optimization across the entire spectrum of grower needs—from seeding to harvest. Innovation and product evolution are enabled by xarvio's status as a small startup operation within the larger company. xarvio has research partners of its own, including a joint venture with Bosch around smart farming for Internet of Things business models within agriculture. This partnership enables xarvio to bring digital or software components as well as digitalized hardware components to a grower.

Jeff Spencer, xarvio's head of technology and data, shared a number of important lessons the company learned over the course of its product development and commercialization journey. These are summarized as follows.

Observational data is in short supply. Data from growers that is accurate and includes important elements for the application to work is in short supply. The reason as to why a farmer made an application or took a particular action is often missing (i.e., pest pressure, crop stage, presence of a disease or weed species).

Low-tech is a high-tech starting point in the eyes of many farmers. This is one impetus for the development of xarvio SCOUTING as a tool to complement xarvio FIELD MANAGER. This fairly low-tech app gives xarvio an opportunity to help people better identify diseases and pests so xarvio FIELD MANAGER can develop mitigation strategies.

Farmers want us to simplify the complexity of farming. Often, we want to hear the agronomics voice of the farmer, but when you speak to the majority of farmers, they really want us to simplify the complexity of the process.

Domain expertise is a limiting factor. While a data-driven approach—AI and machine learning to deliver innovation—is tempting, we are still limited by domain expertise in partnership with data scientists.

Digital is the glue, not the overall solution. Bringing together the right chemistry, the right feed genetic platform, and other domain-specific elements is as important as the digital aspects.

Using these key learnings, Spencer said that xarvio selected five strategic R&D targets to optimize its project pipeline and prioritize future research and partnerships:

- Simplify the complexity of agriculture;
- Innovate around uncertainty (there is much uncertainty within agriculture and our biological systems);
- Automate decision-making;
- Intensify high-resolution data access and creation (including creating synthetic data where there is a missed opportunity to gather observational data); and
- Remain data-driven at our core.

Spencer offered five key takeaways that his company learned in its product journey:

- The digitalization of agriculture is happening and will continue to accelerate, yet many obstacles remain in the last mile.
- Digitalization provides pathways to feed our planet sustainably, and we are seeing many others developing complementary solutions to that of xarvio.
- Closing data feedback loops (such as applied plus observational data) will unlock the full potential to optimize agriculture production.
- There is a talent gap to translate digital capabilities into agriculturally relevant solutions; thus, domain expertise is still needed.
- University-industry research collaboration is essential: "We cannot do this alone; we need partners across industry and academia to succeed."

Facilitated Breakout Sessions

Regional Innovation

Regions are increasingly aware of the tight correlation between innovation and economic health and well-being. There are ripe opportunities for shared regional innovation in biotechnology and the new agriculture.

Key Takeaways

Address climate resiliency across regions. Concerns for annual crops will be different from those regions with longer-term and/or orphan crops. Make use of indigenous knowledge about regional species. Urbanization will continue to happen in developing regions of the world. Food systems will need to be adapted regionally.

Expand crop diversity. Continue supporting germplasm banks. Digitalize genetic information of species that are in danger of extinction. Invasive species will continue to be a concern and may become a bigger issue for biodiversity and habitat restoration.

Share data infrastructure beyond borders. Encourage the delivery of open-source software and open access to information and technology across different regions.

Risk Management

De-risking investments and reducing barriers to success are key components of translational research, especially in the biotechnology industry.

Key Takeaways

Foster collaborations with diverse end users to encourage private investments. Include end users in developing countries early and often in the conversation. Advance and test new technical and biological discoveries accomplished by partnerships between academia, innovative centers, and business schools at regional and global scales.

Unify legislative frameworks. Ideally, new crop products will be generated and aimed at increasing yield, improving nutritional quality, resisting stress, using fewer resources, and/or providing ecological services (carbon fixation, soil conservation). Global legislative regulations are necessary for sharing and adopting new technologies and products.

Change the definition of success. All individual personnel in a multidisciplinary group must be recognized, rather than funding the "lead" individual (i.e., principal investigator). The accomplishments and progress of the entire team should be valued above individual efforts.

High Risk and High Reward Research

Successful translational research requires the right mix of basic, use-inspired, and high-risk research to create a virtuous cycle of discovery and innovation.

Key Takeaways

Establish "systems" agriculture. Integrate computational approaches to interrogate systems and identify optimal combinations of ideas with cyber-physical systems. Establish field experiences to understand crop responses to climate change across regions. Produce large, well-annotated datasets for experts in crop modeling and AI to develop and test new algorithms.

Encourage rapid production and dissemination of results. Outsource more to specialized services, including plant transformation and functional characterization. Include and promote negative results. Learn from industry investments.

Forecast the resiliency of agricultural systems. Crops being developed today will have to grow in the climates of 2040, 2050, and beyond, necessitating changes to agronomic practices, breeding targets, and regional crops. Different data sources, such as weather, soil, ecology, shifting pests/pathogens, and regional economic impacts, should be incorporated into predictive models.

Public Engagement

Public engagement and acceptance are critical to success. Key considerations should be made as to when--and how--to engage the public in new agricultural research and products.

Key Takeaways

Increase effective communication. In an age of widespread misinformation, scientists are not adequately equipped to respond or proactively engage in public discourse. All sectors should support better communication solutions, engaging expertise from the social sciences, farmers and practitioners on the ground, as well as leaders who hold the public trust. Efforts should incorporate benefits to the public, such as sustainability, nutrition, and health.

Engage a larger percentage of the public in science. Incorporate community and citizen science to encourage more direct involvement of the public with plants and agriculture. Establish directed funding for these efforts. Especially, engage youth and underrepresented individuals and promote their retention.

Support public science specialists in different sectors. Establish roles for specialists like agriculture extension agents embedded in university departments. These roles require long-term funding; consider establishing programs that enhance collaborations between biologists and social scientists. Personnel would act as a hub for scientific communication and public engagement, allowing for more effective collaboration with social scientists.

Stakeholders in Public-Private Partnerships

Stakeholders are a key component of public-private partnerships and translational research. There should be a good mix of academic, industry, start-up, and foundation stakeholders from different fields.

Key Takeaways

Create a framework for public/private partnerships. There is a key need for this framework to improve and sustain plant transformation and editing technologies. Formation of plant transformation networks, alliances, and consortiums would be useful for advancing research and enhancing communication.

Establish a licensing and IP pool for new technologies. This would aid in technology research, improvement, and deployment of the technologies. Non-exclusive IP and early access agreements could be part of a useful model. There is a need to create a business model for public/private partnerships where companies are willing to share their IP without competing with their commercial interests.

Encourage alternatives to public/private partnerships in certain situations. Public/private partnerships may work in some cases; otherwise, there is a need to find alternative ways to advance new technological research, such as through increased federal funding sources.

International Regulations

Consensus and international regulations on new biotechnology are necessary to ensure world-wide advances in new agriculture. Considerations must be made for the specific agricultural needs of individual regions and countries.

Key Takeaways

Balance harmonized regulation with individual autonomy. There should be a harmonized regulatory system across countries and regions allowing for sharing and dissemination of new crop varieties and technologies. In addition, autonomy should be established for each country in the sense that each identifies its own needs, builds its own solutions, and makes its own food production decisions for its own culture, agronomy, and climate.

Align on research material movement. In the short term, convene the appropriate stakeholders to begin conversations. In the long term, establish international agreements. Revisit land and data ownership policies that may disenfranchise indigenous populations.

Bring together sectors. Build on successful and sustainable international training programs (e.g., Feed the Future Program). Train students who can go back to their native countries and expand the progress. Establish joint funding opportunities across countries and sectors, including mechanisms to connect researchers with farmers. Bring diverse groups to the table early and often.

Concluding Group Discussion

At the end of Day 2, participants re-convened in a general session to cover the key takeaways from the breakout groups. The results from both days of the workshop were synthesized into overall conclusions and next steps.

Defining the New Agriculture

Participants envisioned the characteristics of the new agriculture using terms like:

Initial Actions and Next Steps

- **Define specific goals** and take inventory of actions to get there.
- **Initiate a model of coordination and collaboration**, perhaps using professional societies, international centers, and funding agencies as catalysts to bring people together.
- **Explore mechanisms to create a pool of existing intellectual property**, particularly of enabling technologies, that can be readily accessible via simple, standardized agreements.
- **Overall goal**: Develop an agricultural system that is sustainable and meets the food, feed, fiber, and fuel needs of the global population.

Address Overarching Areas of Concern

- **Education**. Continue to improve the basic understanding of the fundamental biology needed to solve agricultural problems.
- **Standards**. Expand universal data standards, such as FAIR standards, to better accommodate a rapidly developing new agriculture.
- **Funding**. Create new, additional funding programs between agencies and sectors to provide support for research innovation and technology improvement.
- **Adoption**. Improve public acceptance of and support for new scientific and technological developments.

Solutions to Improve Collaboration

- **Synergies**. Leverage interdependencies between the bioeconomy, new agriculture, climate change, social acceptance issues, etc. to promote the necessary investments in new technologies.
- **Contracting/IP**. Remove contracting and intellectual property management barriers to facilitate collaborations.
- **Market Research**. Incorporate the needs and wants of consumers and farmers to deliver the appropriate technology and solutions.
- **Convergence**. Encourage more extensive interdisciplinary collaborations, not only between basic science and high tech, but also by incorporating social sciences, economics, policy, the industrial sector, and other stakeholders.
- **New Models**. Develop a new, adaptable model for public-private partnerships that will be essential to deliver a new agriculture. Current partnership models do not work well for developing countries.

Necessary Technical Advances

- **Plant Transformation Technologies**. Expand and improve plant transformation technologies, especially for orphan crops and lesser studied species.
- **Plant Transformation Capacity**. Establish small focus groups of plant transformation specialists from public and private sectors to develop actionable recommendations and enhance plant transformation capacity.
- **Communications**. Communicate effectively and efficiently among diverse groups to foster collaboration and translate the problems, processes, and solutions.
- **Urgency**. Instill a greater sense of urgency, engage the public, and establish international standards to catalyze research and commercialization efforts.
- **More Tools**. Accelerate existing research tools, such as algorithms and data, from pilot to production so they are more applicable to predictive agriculture.
- **Small Holder Farmers**. Develop seed production and distribution systems for small holder farmers, considering that the infrastructure for these systems (such as roads, plots, equipment, etc.) does not currently exist for all farmers.
- **Computing**. Invest in a long-term, sustainable solution for computing power that continually updates and expands as more data are collected.

Conclusion and Charge for Action

The workshop's goals were to define the needs for a new agriculture, identify gaps to progress, and articulate near- and long-term goals to achieve successful outcomes. In defining the characteristics of the new agriculture, participants united behind a shared vision and direction for future research. Over the course of two days, workshop participants identified a number of actionable recommendations, and we look forward to seeing specific steps taken to adopt many of them.

Core to the workshop findings is that basic research should be directly connected with and lead to innovations that translate knowledge into practical outcomes. Success hinges on developing strong partnerships among the sectors—industry, academia, and government—to achieve mutual goals. Through collaborative, cross-sector R&D, including formal models such as industry-academic research consortia, strong partnerships will contribute to developing the bioeconomy that will benefit both those participating in the research and those investing in it.

Appendix A:
Review of the Global Agriculture R&D Landscape

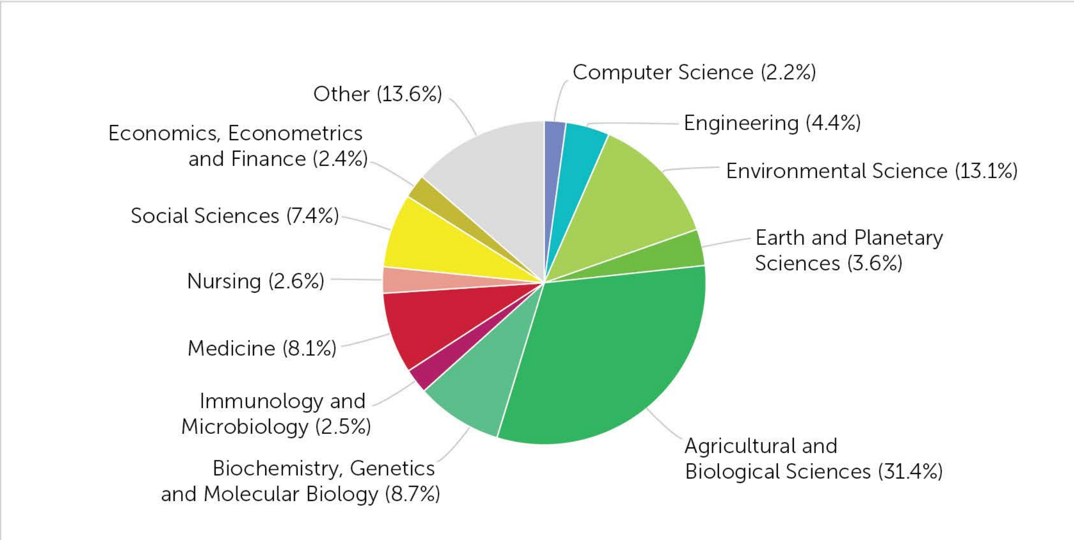
Research that supports the goal of the workshop topic was mapped to the United Nations Sustainable Development Goal (SDG) 2: Zero Hunger – End hunger, achieve food security and improved nutrition and promote sustainable agriculture.[4] The query for defining this research was developed previously and consists of over 1,000 independent queries developed to address the specific targets and indicators related to this goal.[5] Table 1 shows the three research subcategories of interest within SDG 2 and how they were defined using queries.

Subcategory Name	Query Terms
Traditional Breeding Strategies	GWAS OR "Genome Wide Association Study" OR qtl OR "Quantitative Trait Loci" OR haploid OR phenotyp* OR genotyp* OR transgen*
Biotechnology (experimental)	"Synthetic biology" OR "Gene edit" OR engineering OR genomic*
Biotechnology (computational)	robotic* OR sensors OR computation OR "Machine Learning" OR "Artificial Intelligence" OR model* OR predict*

Table 1 | Subcategories of interest and the query terms used to identify the relevant research.

Results: The Research Landscape

Research supporting the goal to feed the planet sustainably spans many concepts. The key phrase Food Security features most prominently in the publication set, while Malnutrition and Agriculture feature as the second and third most highly represented key phrases, respectively. Figure 5 provides insight into the subject areas under which the publications fall and the research Topics[6] most highly represented in the research. These data show that related research falls primarily within the subject areas of agriculture, environmental sciences, and medicine. The largest topics represented within the research are indicated in Figure 5 and Table 2. The co-clustering of terms reveals five major themes in the research, three of which are related to agriculture.



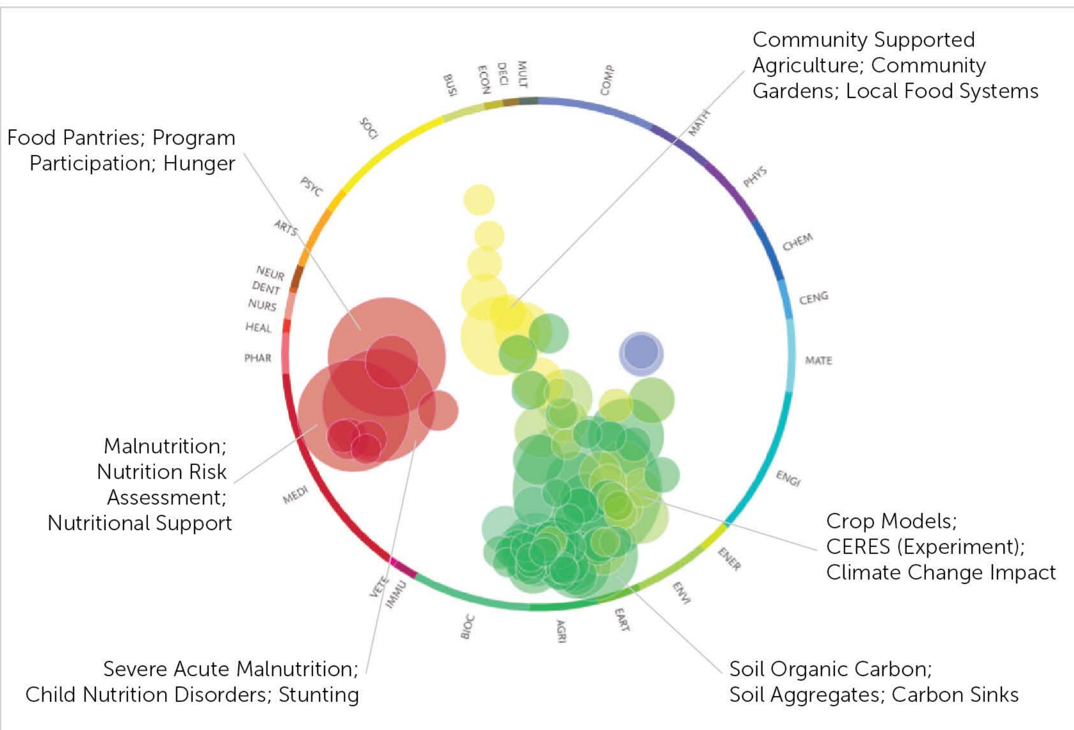


Figure 5 | Top: Distribution of research publications from 2011 to 2020 in the research area "SDG 2: Zero Hunger" across subject areas. Bottom: Distribution of publications within Topics from 2011-2020 in the research area "SDG 2: Zero Hunger." Source: Scopus and SciVal

Topic Name	Scholarly Output	Average Field-weighted Citation Impact	Topic Prominence Percentile
Crop Models, CERES (Experiment); Climate Change Impact	4,760	1.6	99.7
Food Pantries; Program Participation; Hunger	3,040	1.4	99.2
Severe Acute Malnutrition; Child Nutrition Disorders; Stunting	3,108	1.1	99.2
Malnutrition; Nutrition Risk Assessment; Nutritional Support	3,114	1.0	98.9

Table 2 | Largest Topics represented in Feeding the Planet Sustainably research (based on publication count). Topics are ascribed names based on the three most common key phrases found in research titles and abstracts for that topic. Key phrases are generated by matching against a set of thesauri spanning all major disciplines, thus reducing the occurrence of redundant terms (e.g., neoplasm and cancer). Metrics shown are scholarly output (number of publications), average field-weighted citation impact, and topic prominence percentile. Field-weighted citation impact is a field-, age-, and publication-type-normalized indicator providing insight into how often the research has been cited. A value above 1.0 indicates the research is cited more than expected based on global levels. Topic prominence percentile provides insight into the relative momentum around a topic. A value near 100.0 indicates high momentum for the topic. Source: Scopus and SciVal

Research that contributes to a new agriculture has grown markedly over the past two decades, as shown in Figure 6. While in 2001, 0.7% of all research related to the topic, this value has since doubled to 1.4% of all research in 2020. This represents a compound annual growth rate (CAGR) over the past two decades of 9.6%, which is four percentage points higher than the growth rate of research overall (CAGR = 5.6%). From 2001 to 2020, 394,414 publications were published in this research area.

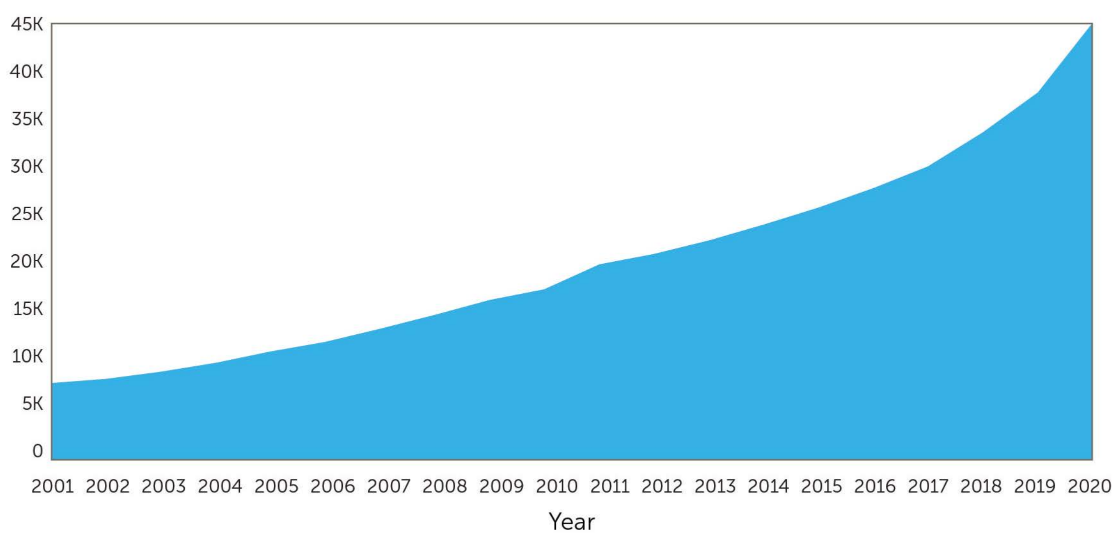


Figure 6 | Publication productivity related to topics within the workshop theme, Feeding the Planet Sustainably, 2001–2020. Source: Scopus

Figure 7 shows the top 15 regions contributing to the research. The United States leads in this respect, having contributed to 89,945 publications over the past two decades. China follows with contributions to 47,365 publications. Beyond absolute publication count, the percentage of all research focused on this research goal provides clues about regional prioritization strategies. These data show that although the United States contributed to the highest number of publications, Brazil, India, and Australia dedicated more of their overall research efforts in this area, which represents 2.4%, 1.7%, and 1.5% of their research output, respectively. In contrast, 0.9% of the United States research output related to the research theme.

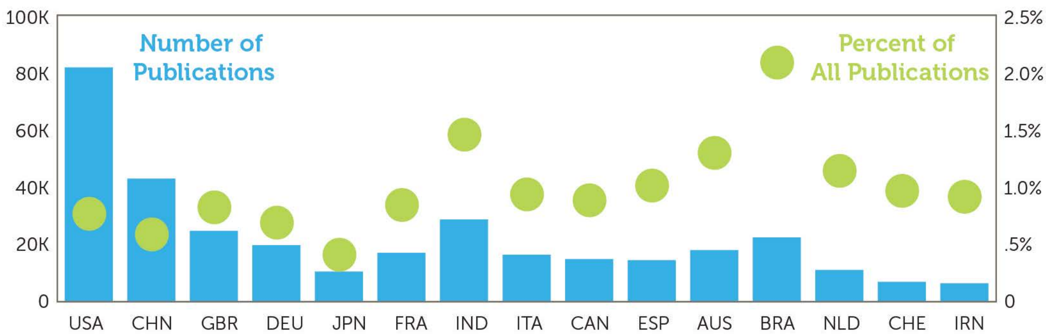


Figure 7 | Number of Feeding the Planet Sustainably research publications from each region and percent of the research portfolio represented by Feeding the Planet Sustainably research published 2001–2020. Source: Scopus

Table 3 shows the contribution to research publications over the last five years (2016–2020) disaggregated by cross-sectoral collaboration type. The data show that 89% (164,845) of all publications involved some contribution from academic institutions, with 29% of those publications resulting from collaboration with a government entity, 27% resulting from collaboration with a non-governmental organization (NGO), and 2% resulting from collaboration with a corporate entity.

Collaboration Type	Scholarly Output	Collaboration Type	Scholarly Output
Academic	85,287	Academic-Corporate-NGO	748
Academic-Government	33,082	Academic-Corporate-Government	731
Academic-NGO	29,532	All Sectors	648
Academic-Government-NGO	14,210	Corporate	318
Government	6,632	Corporate-NGO	204
NGO	6,021	Corporate-Government	112
Government-NGO	2,324	Corporate-Government-NGO	69
Academic-Corporate	1,255		

Table 3 | *Feeding the Planet Sustainably* research publications from 2016–2020 categorized according to the sectors represented in the author byline. Source: Scopus

Biotechnology Research

Figure 8 shows that biotechnology research contributes greatly to the topic, with research using the approaches of computational biotechnology, traditional breeding, and experimental biotechnology representing 23%, 12%, and 5% of the globally published research, respectively. In the United States, these subcategories represent a slightly higher percentage of this research portfolio, with 28% of U.S. research using a computational biotechnology approach, 13% of U.S. research employing a traditional breeding approach, and 6% of U.S. research employing an experimental biotechnology approach. The percentages of research falling within biotechnology areas has been consistent over the last two decades (2001 to 2020) both globally and in the United States, with a few exceptions. Globally, research employing computational biotechnology approaches has gained higher representation; it now represents 27% of research on the topic, up from 15% in 2001. In the United States, research employing computational biotechnology approaches represented 19% of *Feeding the Planet Sustainably* research in 2001; this value has increased by 13 percentage points over two decades, to 32% in 2020.

In general, the distribution of collaboration types within biotechnology subcategories is similar to that observed for the topic overall, as shown in Figure 9; the academic sector contributes to the most research while the corporate sector contributes to the least. It is notable that within the traditional breeding and experimental biotechnology subcategories, less of the research is done solely by the academic sector and a greater share of the research is a result of academic-government collaboration and academic-government-NGO collaboration.

Research uptake into other research and innovations is indicated by metrics such as citations in research publications and patents. Figure 10 shows that 2.5% to 3.5% of publications in traditional breeding and experimental biotechnology are cited in patents, while less than 1% of publications in computational biotechnology is cited in patents. The biotechnology subcategories have a field-weighted citation impact that is 1.2 to 1.4 times more than the global average, indicating the research is highly cited and has a high uptake in other research.

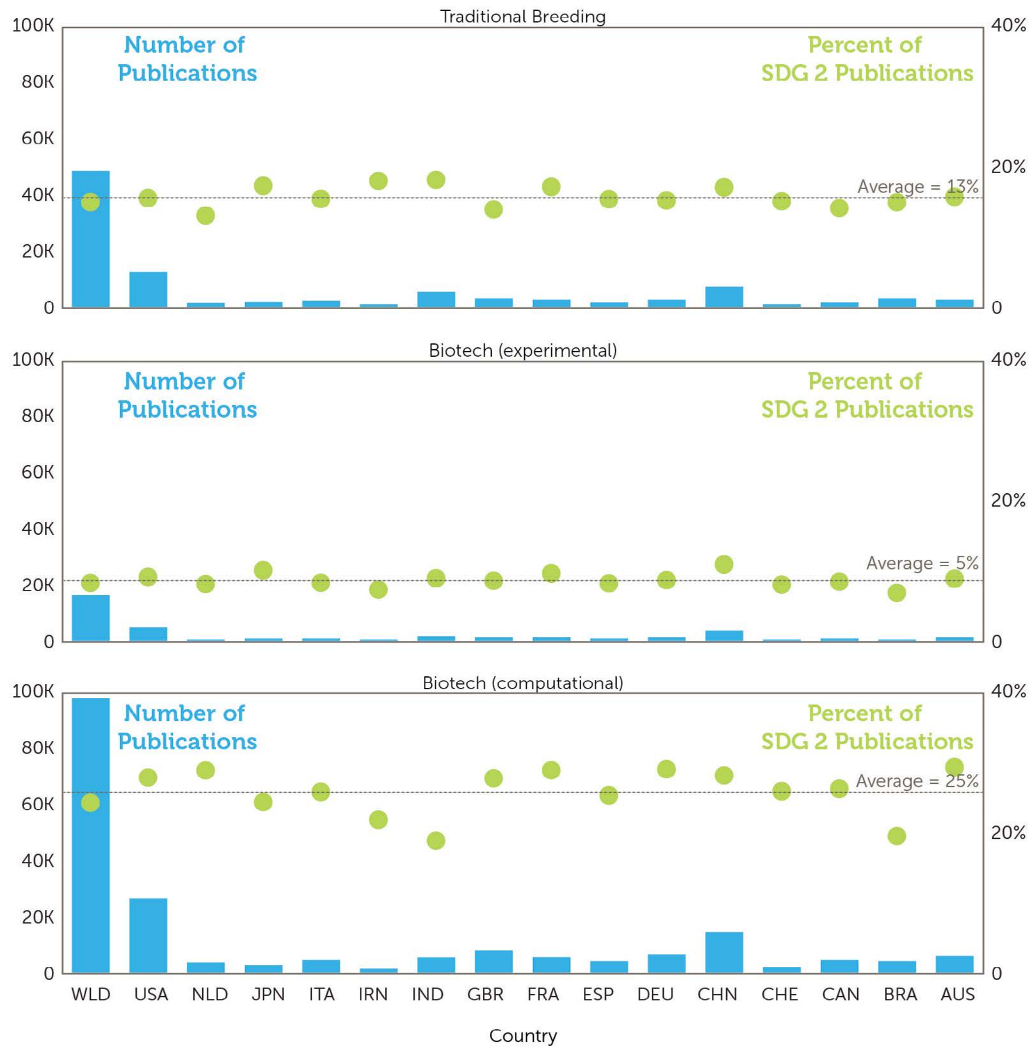


Figure 8 | Number of research publications in biotechnology subcategories of Feeding the Planet Sustainably research by region and percentage representation within the research portfolio (2001 to 2020). Source: Scopus

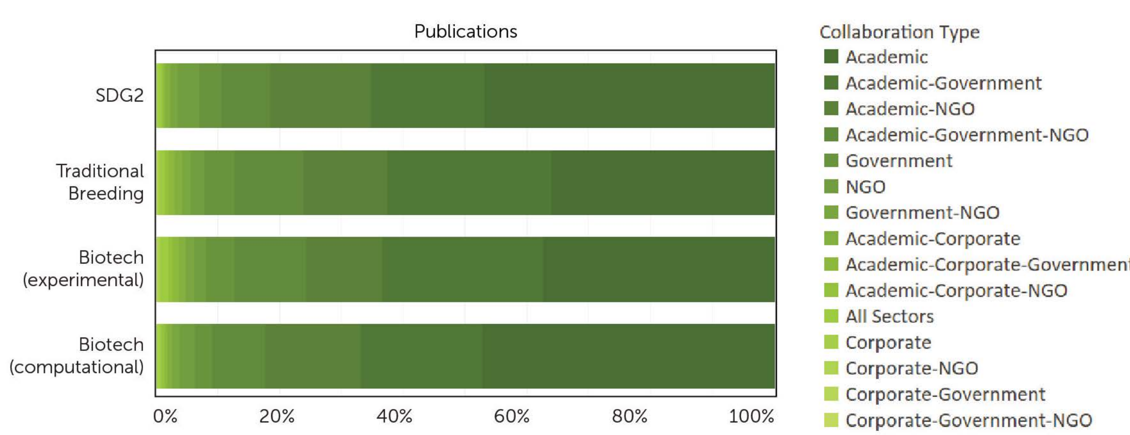


Figure 9 | Feeding the Planet Sustainably (SDG2) and biotechnology subcategory research publications from 2016 to 2020 categorized according to the sectors represented in the author byline. Source: Scopus

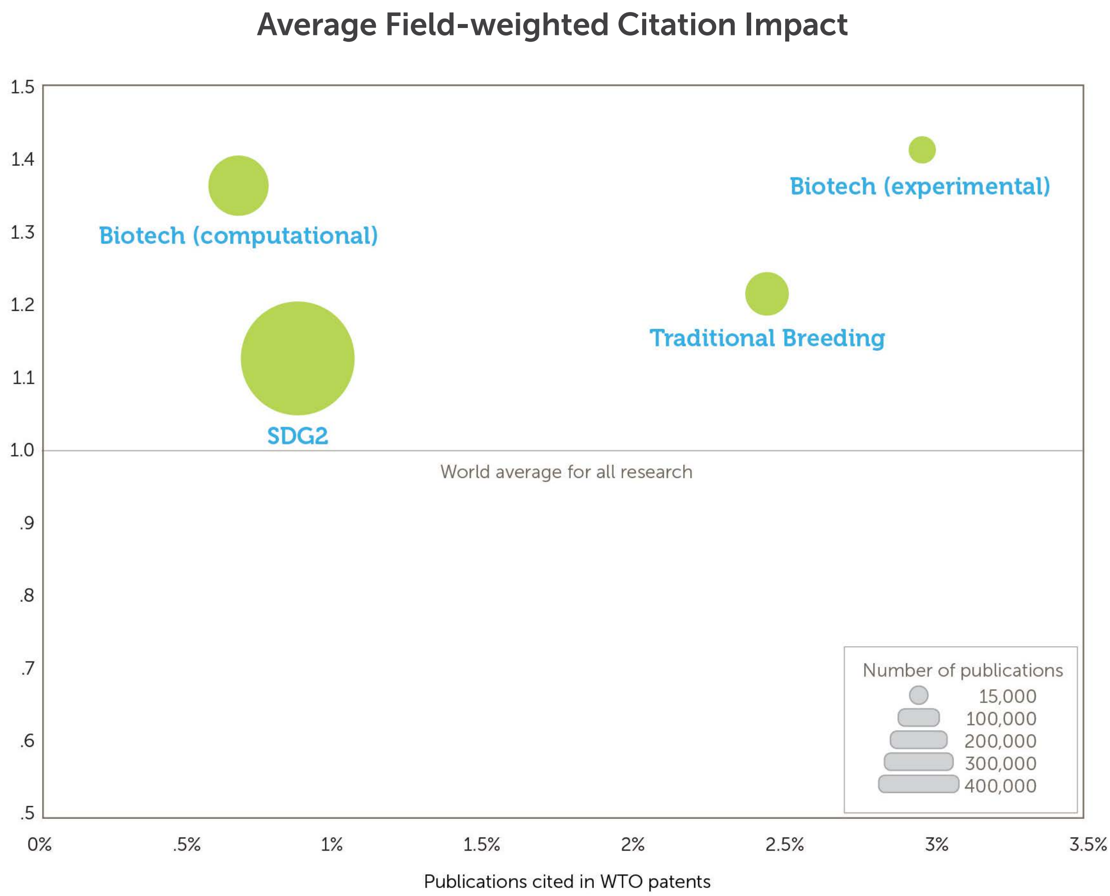


Figure 10 | Average field-weighted citation impact and percent of research cited in World Trade Organization patents for publications from 2001 to 2020 in each subcategory of Feeding the Planet Sustainably (SDG2) research. Source: Scopus

	Top 20 institutions publishing research within topical subcategories		
	Traditional Breeding	**Biotech (Experimental)**	**Biotech (Computational)**
1	Cornell University (991)	Cornell University (451)	University of Florida (978)
2	University of Minnesota Twin Cities (639)	University of Minnesota Twin Cities (265)	Cornell University (901)
3	University of Wisconsin-Madison (451)	University of Wisconsin-Madison (185)	University of Minnesota Twin Cities (773)
4	University of Florida (426)	University of Florida (177)	Harvard University (709)
5	Ohio State University (303)	Ohio State University (136)	University of Wisconsin-Madison (668)
6	Pennsylvania State University (220)	University of California at Berkeley (100)	Ohio State University (526)
7	University of California at Berkeley (150)	Pennsylvania State University (87)	University of California at Berkeley (518)
8	Harvard University (107)	Harvard University (74)	Pennsylvania State University (489)
9	National Institutes of Health (84)	Stanford University (53)	Johns Hopkins University (449)
10	Duke University (68)	National Institutes of Health (52)	Columbia University (439)
11	University of Washington (66)	University of Washington (48)	University of Washington (397)
12	Stanford University (58)	University of California at Los Angeles (43)	Stanford University (357)
13	University of California at Los Angeles (52)	Massachusetts Institute of Technology (43)	University of Michigan, Ann Arbor (350)
14	Johns Hopkins University (49)	Duke University (32)	University of California at Los Angeles (327)
15	The University of Chicago (48)	University of California at San Diego (31)	Duke University (256)
16	University of California at San Diego (42)	The University of Chicago (29)	The University of Chicago (185)
17	University of Michigan, Ann Arbor (38)	Johns Hopkins University (28)	Massachusetts Institute of Technology (182)
18	University of Pennsylvania (35)	University of Michigan, Ann Arbor (23)	University of Pennsylvania (169)
19	Massachusetts Institute of Technology (33)	Columbia University (21)	National Institutes of Health (153)
20	Columbia University (30)	University of Pennsylvania (17)	University of California at SanDiego (140)

Table 4 | Top 20 institutions publishing research within each subcategory of Feeding the Planet Sustainably research, ranked by publication output during the period 2001–2020, indicated in parentheses. Source: Scopus

Appendix B: Feeding the Planet Workshop Agenda

Wednesday, July 28, 2021

11 – 11:10 a.m.	**Workshop Introduction** Tony Boccanfuso, UIDP Theresa Good, NSF Welcome and workshop overview by the National Science Foundation (NSF) and UIDP.
11:10 – 11:30 a.m.	**Opening General Framing Session** Todd Jones, Corteva Agriscience Jan Leach, Colorado State University Wayne Parrott, University of Georgia Charge to participants, workshop rules and goals. Organizers will introduce the main theme of Day 1, which is how we can integrate the four key themes toward a new agriculture.
11:30 a.m. to 12:30 p.m.	**Review of the Current R&D Landscape** Natalie Clark, Iowa State University Bamini Jayabalasingham, Elsevier Todd Jones, Corteva Agriscience Wayne Parrott, University of Georgia Elsevier will provide findings from their review of the nation's current sustainable agriculture capabilities and benchmark against global activities.
1 – 2:15 p.m.	**Concurrent Breakout Sessions: Key Workshop Themes** Participants will be assigned to groups prior to workshop. Groups will be interdisciplinary and from different industries. Each group will determine the state-of-the-art methods in each field, discuss limitations/gaps, and determine how to integrate biological and computational methods toward desired outcomes.
1 – 2:15 p.m.	**Integration of Biotechnology Applications and Computational Modeling** Alexander Bucksch, University of Georgia Current biotechnology approaches generate information-rich data that can expand the repertoire and genetic diversity of crop plants. Integrating these data into computational models can accelerate new discoveries and solutions for a sustainable resilient agriculture.
1 – 2:15 p.m.	**Using Sensors and Robotics to Measure Key Agricultural Traits** Molly Hanlon, Penn State University New crop systems and sensors for plants, soils and local environments, advanced robotics, and nanomaterials. Coupled with biotechnology breakthroughs, plants can be designed to adapt to environmental change.

Wednesday, July 28, 2021

1 – 2:15 p.m.	**Targeted Computational Solutions** Eric Lyons, University of Arizona Leverage data-rich outcomes of biotech and engineering advances. Designing plant improvement pathways will demand sophisticated methods based on AI systems and machine learning approaches, along with modeling outcomes. Managing and integrating these data sets will be central to solving challenges of the new agriculture.
1 – 2:15 p.m.	**Training an Interdisciplinary and Diverse Workforce** Jennifer Nemhauser, University of Washington Breakthroughs will rely on educating and training a biotechnology-based workforce in new tools and technologies. Training across sectors and disciplines will broaden impact, thereby ensuring that advances in agriculture will align with societal needs.
1 – 2:15 p.m.	**Building the Necessary Transformation Infrastructure** Kan Wang, Iowa State University Gene editing and engineering systems are critical tools to advance crop improvement efforts and allow new crop systems to be endowed with new traits for a sustainable resilient agriculture. Interdisciplinary efforts in this field are needed to improve the robustness and accessibility of these technologies.
1 – 2:15 p.m.	**Big Data for Predictive Agriculture** John Cushman, University of Nevada Large datasets need to translate into measurable outcomes such as crop yield, soil health, and pest resistance. Groups of biologists, engineers, and computational scientists need to collaborate to develop the agricultural products and solutions to meet emerging needs.
2:45-3:45 p.m.	**Report Outs** The facilitator and note-taker from each break-out group will present each group’s answers to the four key questions that were asked.
4-5 p.m.	**Concluding Group Discussion** Tony Boccanfuso, UIDP Natalie Clark, Iowa State University Todd Jones, Corteva Agriscience Jan Leach, Colorado State University Wayne Parrott, University of Georgia Come together as a group to summarize answers from each of the six topics and identify key takeaways from Day 1.

Thursday, July 29, 2021

11 a.m. to 12 p.m.	**Welcome and Day 1 Recap** Tony Boccanfuso, UIDP Natalie Clark, Iowa State University Todd Jones, Corteva Agriscience Jan Leach, Colorado State University Wayne Parrott, University of Georgia Leaders will summarize the key points from Day 1 and discuss the focus for Day 2: how to accelerate the needed research and get it to market.
12-12:30 p.m.	**Translational Case Study: Xarvio** Jeff Spencer, BASF Mike Nuccio, Inari
1 – 2:15 p.m.	**Concurrent Breakout Sessions:** **Integrating Perspectives to Achieve Solutions** Participants will be assigned to groups prior to workshop. Groups will be interdisciplinary and from different industries. Each group will focus on answering the question is assigned to them.
1 – 2:15 p.m.	**Regional Innovation** Rodrigo Sarria, AgBiome Regions are increasingly seeking to promote their economic development through supporting innovation. There are ripe opportunities for shared regional innovation in biotechnology and the new agriculture.
1 – 2:15 p.m.	**Risk Management** Paul Chomet, NRGene Derisking investments and reducing barriers to success are key components of translational research, especially in the biotechnology industry.
1 – 2:15 p.m.	**High Risk and High Reward Research** Jan Leach, Colorado State University Successful translational research requires the right mix of basic, use-inspired, and high-risk research to create a virtuous cycle of discovery and innovation.
1 – 2:15 p.m.	**Public Engagement** Dave Jackson, Cold Spring Harbor We will need to engage the public and ensure their acceptance: this could be early in the research process or right before product launch.

Thursday, July 29, 2021

1 – 2:15 p.m.	**Stakeholders in Public-Private Partnerships** Jeff Rosichan, Foundation for Food & Agriculture Research Stakeholders are a key component of public-private partnerships and translational research. There should be a good mix of academic, industry, start-up, and foundation stakeholders from different fields.
1 – 2:15 p.m.	**International Regulations** George Kantor, Carnegie Mellon University Consensus, international regulations on new biotechnology are necessary to ensure world-wide advances in new agriculture.
2:45-3:45 p.m.	**Report Outs and Discussion** The facilitator and note-taker from each break-out group will present each group's answers to the four key questions that were asked.
4-5 p.m.	**Concluding Group Discussion** Come together as a group to summarize answers from each of the six topics and identify key takeaways from Day 2.

Appendix C: Participant List

Robyn Allscheid, National Corn Growers Association

Georges Backoulou, Langston University

Pooja Bhatnagar- Mathur, International Crops Research Institute for Semi Arid Tropics (ICRISAT)- CGIAR

Adam Bogdanove, Cornell University

Natalie Breakfield, NewLeaf Symbiotics

Nicki Briggs, Perfect Day

Richard Broglie, Pivot Bio

Alexander Bucksch, University of Georgia

Wolfgang Busch, Salk Institute for Biological Studies

Trevor Charles, University of Waterloo

Paul Chomet, Agriculture Consultant

Fan-Li Chou, American Seed Trade Association

Natalie Clark, Iowa State University

Kate Creasey Krainer, Grow More Foundation

Nik Cunniffe, University of Cambridge

John Cushman, University of Nevada

John de la Parra, The Rockefeller Foundation

Natalia de Leon, University of Wisconsin, Madison

Jose Dinneny, Stanford University

Cassie Edgar, McKee Voorhees & Sease PLC

C. Eduardo Vallejos, University of Florida

Mario Fenech, North Carolina State University

Bob Furbank, Centre of Excellence for Translational Photosynthesis ANU

Eduardo Ganem Cuenca, McGill University

Bill Gordon-Kamm, Corteva Agriscience

Louis Gross, University of Tennessee, Knoxville

Frederic Hamelin, Institut Agro

Molly Hanlon, Pennsylvania State University

Roger Innes, Indiana University

David Jackson, Cold Spring Harbor Lab

Scott Jackson, Bayer

Bamini Jayabalasingham, Elsevier

James Jones, University of Florida

Jennifer Jones, SmithBucklin, primary contractor to United Soybean Board

Todd Jones, Corteva Agriscience

Heidi Kaeppler, University of Wisconsin

Sophien Kamoun, The Sainsbury Laboratory

George Kantor, Carnegie Mellon University

Paul Kersey, Royal Botanic Gardens, Kew

Catherine Kistner, DFG - German Research Foundation

Evangelia Kougioumoutzi, UKRI-BBSRC

Renee Lafitte, Bill and Melinda Gates Foundation

Jan Leach, Colorado State University

Andrew Leakey, University of Illinois at Urbana Champaign

Stephen Long, University of Illinois

Argelia Lorence, Arkansas State University

Eric Lyons, University of Arizona

Charlie Messina, Corteva Agriscience

Blake Meyers, Donald Danforth Plant Science Center

Allison Miller, Saint Louis University/Danforth Plant Science Center

Matthew Moscou, The Sainsbury Laboratory

Kusum Naithani, University of Arkansas-Fayetteville

Cristina Negri, Argonne National Laboratory

Jennifer Nemhauser, University of Washington

Michael Nuccio, Inari Agriculture, Inc.

Wayne Parrott, University of Georgia

Zhaohua Peng, Mississippi State University

Kirstin Petersen, Cornell University

Vijaya Raghavan, McGill University

Sally Rockey, Foundation for Food and Agriculture Research

Pam Ronald, UC Davis

Jeff Rosichan, Foundation for Food & Agriculture Research

Rodrigo Sarria, AgBiome, Inc.

James Schnable, University of Nebraska-Lincoln

Norman Scott, Cornell University

Heike Sederoff. North Carolina State University

Mark Settles, NASA Ames Research Center

Patrick Shih, UC Davis

Ray Shillito, BASF

Sauleh Siddiqui, American University

Jane Silverthorne, Supporters of Agricultural Research (SoAR) Foundation

Erin Sparks, University of Delaware

David Stern, Boyce Thompson Institute

Shangpeng Sun, McGill University

Nigel Taylor, Donald Danforth Plant Science Center

Phil Taylor, Bayer

David Tricoli, UC Davis

Joyce Van Eck, Boyce Thompson Institute

John Verboncoeur, Michigan State University

Dan Voytas, University of Minnesota

Ruth Wagner, Bayer

Guo-Liang Wang, The Ohio State University

Kan Wang, Iowa State University

Paul Westerhoff, Arizona State University

Brigitte Weston, Gates Ag One

Philip Wigge, Leibniz IGZ

Cranos Williams, North Carolina State University

Bing Yang. University of Missouri

Appendix D: Workshop Observers

Senay Agca, National Science Foundation

Andrea Belz, National Science Foundation

David B. Berkowitz, National Science Foundation

Lura Chase, National Science Foundation

Parag Chitnis, USDA/NIFA

Walter R. Cleaveland II, National Science Foundation

Karen C. Cone, National Science Foundation

Jared Dashoff, National Science Foundation

Richard B. Dickinson, National Science Foundation

Cassandra M. Dudka, National Science Foundation

John Erickson, USDA-NIFA

Victoria Finkenstadt, USDA National Institute for Food and Agriculture (NIFA)

Theresa Good, National Science Foundation

Courtney E. Jahn, National Science Foundation

Nora Lapitan, USAID

Ann Lichens-Park, USDA's National Institute of Food and Agriculture

Gail McLean, U.S. Department of Energy

Michael L. Mishkind, National Science Foundation

Diane Okamuro, National Science Foundation

Jack Okamuro, USDA Agricultural Research Service

Appendix E:
Pre-Event Survey

In the coming decades, agriculture must be both sustainable and productive as it meets the needs of a growing population while facing a changing climate and resource limitations. Please indicate how impactful each of the following challenges are for sustainable agriculture.

	No Impact	Little Impact	Some Impact	Moderate Impact	High Impact
Improving soil health	◯	◯	◯	◯	◯
Climate resilience	◯	◯	◯	◯	◯
Next-generation varieties of crops	◯	◯	◯	◯	◯
Integrating artificial intelligence into agricultural systems	◯	◯	◯	◯	◯
Protecting and ensuring an adequate supply of freshwater resources	◯	◯	◯	◯	◯
Strategies for pest resistance, especially newly emerging pests	◯	◯	◯	◯	◯
Reducing agricultural greenhouse gas emissions	◯	◯	◯	◯	◯
Preserving biodiversity, including agricultural diversity	◯	◯	◯	◯	◯
Educating growers, consumers, stakeholders, and policy makers on new technologies and solutions	◯	◯	◯	◯	◯
Training and educating the current and next generation in new agricultural practices	◯	◯	◯	◯	◯
Increasing and broadening participation across all peoples, places, and sectors	◯	◯	◯	◯	◯

Which of the following represent the most significant roadblocks or bottlenecks to achieving a sustainable food system?

	Least significant roadblock/bottleneck	Moderately significant	Most significant roadblock/bottleneck
Differing international regulations on genome-edited crops			
Insufficient understanding of important physiological processes in crops			
Insufficient ability to breed and engineer complex traits in crop			
Inadequate resources for fundamental research in sustainable agriculture			
Lack of innovative financial models for monetizing conservation measures			
Challenge of developing effective public-private partnerships			
Lack of clear, cohesive strategies and policies for sustainable food production			
Inadequate access to new technologies or facilities for plant transformation			
Lack of computational experience and cyberinfrastructure to analyze big data			
Short supply of trained experts in biotechnology and computation			
Lack of integration of ideas and approaches across disciplines			

What is the most significant gap in knowledge, technology, or training that needs to be addressed in order to ensure a sustainable agriculture for the future?

References

[1] See The FAIR guiding principles for data stewardship: fair enough? | European Journal of Human Genetics (nature.com)

[2] See Appendix 1 for an expanded review of the research landscape. The full research report is available at uidp.org.

[3] See The FAIR guiding principles for data stewardship: fair enough? | European Journal of Human Genetics (nature.com)

[4] The full research report is available at uidp.org.

[5] Methodology and the full query for SDG 2 research can be accessed at: https://data.mendeley.com/datasets/9sxdykm8s4/3.

[6] Topics refers to publication sets created using citation patterns of Scopus-indexed publications. The methodology for using citation patterns to define research Topics was developed through an Elsevier collaboration with research partners (Klavans, R., & Boyack, K. W. 2017. Research portfolio analysis and Topic prominence. Journal of Informetrics, 11, 1158–1174.). The advantage of taking a citation-based approach to identify research Topic is that one need not rely on identifying all the relevant keywords to define a research area. Rather, the research area is delineated by citation patterns in the Topic, whereby research that appears in the same citation network is clustered together in the same Topic. This approach provides a more nuanced definition of the research Topic.

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