Developing Global Priorities for Plant Research

Adapting Agriculture to Climate Variability

October 2020

SoAR FOUNDATION

A report by the Supporters of Agricultural Research (SoAR) Foundation

Developing Global Priorities for Plant Research

Adapting Agriculture to Climate Variability

ABOUT THIS REPORT

This report results from a series of individual interviews with twelve leading plant scientists from Europe, China, and the United States, followed by four virtual meetings held between August 5th and August 12th, 2020. The Supporters of Agricultural Research (SoAR) Foundation sponsored these activities. The dialogue's purpose was to produce a report articulating a plan for implementation of research priorities for the coming decade to inform decision-making of agricultural research funders. This work received support from the U.S. Department of Agriculture's (USDA) National Institute of Food and Agriculture (NIFA), and was conducted in collaboration with Virginia Tech.

In August 2018, SoAR facilitated a workshop in Washington, D.C., to develop a report comprising a concise set of plant-focused research priorities endorsed by leading scientists from Europe, China, and the United States. The priorities identified were envisioned as informing the decision-making of research funders from a variety of international foundations and governmental organizations. A goal of the report was to promote greater coordination among major funders in efforts to support and realize globally impactful innovations within plant research.

This follow-up workshop's goal, focused on three interrelated priority areas identified in the August 2018 report (photosynthesis/water, nitrogen fixation, and plant disease), was to develop research directions, strategies for cooperation and collaboration, and potential funders for the coming decade. Twelve scientists from the United States, Europe, and China participated, working with diverse crop species in the areas of crop phenotyping, plant engineering and breeding, plant-microbe interactions, biotic and abiotic plant stresses, photosynthetic efficiency, and crop management. Seven of the scientists participated in the first workshop and/or its initial interviews. In light of the COVID-19 pandemic, this follow-up workshop was held virtually.

In preparation for the 2020 workshop discussions, SoAR provided the participants with a series of questions covering the current status of their research areas, important research directions for the coming decade, gaps and opportunities, funders, research networks, and opportunities for coordination and collaboration. They were then interviewed individually. The major themes and ideas emerging from the interviews were discussed during the workshop and the outcomes are presented in this report.

Guiding Principles

The research activities proposed in this report are not intended to duplicate or replace ongoing efforts. For example, it will be important to coordinate and cooperate with relevant ongoing initiatives such as:

- EarthBioGenome, a moonshot effort to sequence, catalog and characterize genomes representing all of Earth's diversity over ten years
- The DivSeek International Network, an international coordinated effort to facilitate the generation, integration and sharing of information related to plant genetic resources. CropBooster-P, an EU-funded project, which is drawing up a route map for future-proofing crops,
- EMPHASIS, the European Research Forum on Research Infrastructures (ESFRI) pan-European infrastructure for plant phenotyping will also share related goals.
- Horizon Europe research and its innovation missions in the areas of adaptation to climate change, and soil health and food, which will start in 2021, will be relevant to the strategies proposed here, as well as bioeconomy initiatives that use "whole of cycle" principles to increase efficiencies by recycling resources through diverse products in animal, plant, and microbial systems.
- In the US, relevant new initiatives such as the AI Institute for Next Generation Food Systems (AIFS), are enabling development of the next-generation of food systems through the integration of artificial intelligence at all steps from growing crops through consumption.

The participants view public-private and regional partnerships as essential to maximizing the opportunities to capitalize on the widest possible range of expertise and resources. At the same time, it will be important, whenever possible, to promote the open exchange of data, materials and software code, including the posting of preprints prior to submission to journals (for example, *via* Zenodo, bioRxiv and Addgene), to ensure the broadest possible impact and to enhance international collaborations.

The component activities are envisioned to be inclusive of developing as well as developed world needs with regard to germplasm and traits. Ultimately, this broad scope will be required to address the global needs of farmers for crops that are resilient to environmental stresses (biotic and abiotic) to give yield stability in a changing climate. This would include a diverse funding portfolio that covers crops and stresses relevant to the developing world (e.g. tropical crops and conditions).

Development of a Cohesive Strategy

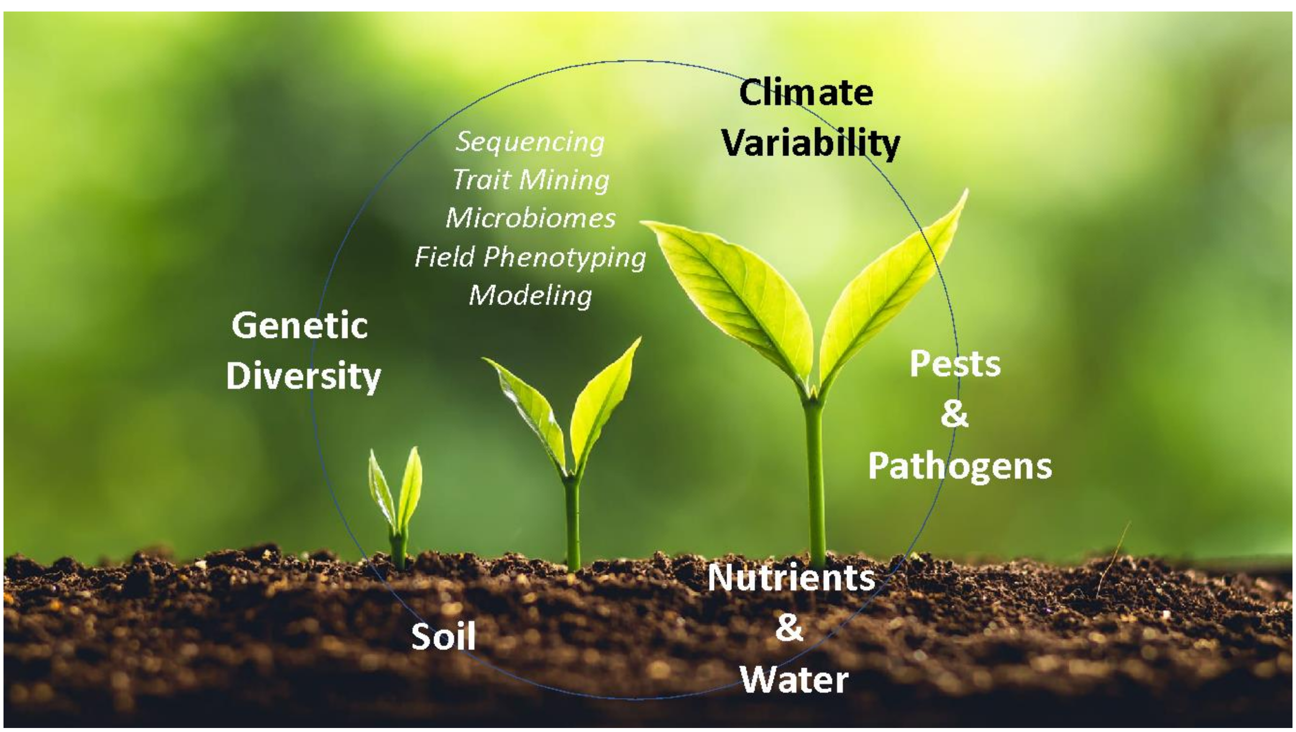
A central theme of the August 2018 report was the recognition that plants in their surrounding environments represent "systems of systems." This concept has been described as the "phytobiome" - the assemblage of plants with their environment and the innumerable organisms with which they interact. The challenges posed by the complexity of plant structures and functions and their environmental plasticity continue to drive research focused on individual plant organs, developmental stages, or processes. However, each of these components are interconnected. A change in one impacts the others and, in turn, the whole plant and its interactions with the environment. Advances in molecular, sensor, and modeling sciences should make it possible to visualize and predict these complex interrelationships and, in allowing the determination of effective research targets, will fundamentally change research and deployment strategies. This principle underpins the research proposed in this report.

While the need for a “system-of-systems” approach remains key, barriers to achieving this goal exist. Simply joining above- and below-ground plant systems to view the performance of the whole plant in field environments is a huge challenge. In addition, plants have intimate relationships with the microbiota in and around them and it is necessary to consider both as part of a single system. These considerations add complexity to the strategies required to collect useful data and develop predictive models.

Interdisciplinary approaches and the use of multiple phytobiomes will be needed along with integration of molecular, ecological, and evolutionary information to obtain meaningful models. The end goal of the report’s strategies is to provide farmers worldwide with increasingly resilient and resource-efficient crop systems with increased yield under optimal conditions and yield stability under stress. This knowledge will enable:

- Adaptation of agriculture to climate change impacts, for example, abiotic stresses (e.g. drought and flooding) and biotic stresses (e.g. pests and diseases).
- Reduction of agricultural inputs for more efficient farming systems with reduced negative environmental impacts.

In total, strategies for developing crops for increased yield and yield stability under stress will need to include advanced knowledge of plant genetic diversity, impacts of climate variability, and environmental impacts. This includes those of soils, nutrients, water, microbial diversity, and microbial interactions. These knowledge goals have been grouped into five overlapping research focus areas that serve as platforms for future research.



Genetic Diversity

Goal: To link plant genetic diversity to performance in the field towards building whole system predictive breeding tools.

Two fundamental questions in agriculture are why do crops perform better in one location than another and how can we better understand that to maximize yield? How does the environment *versus* genotype influence performance and yield? Understanding plant genetic diversity in the context of phytobiomes is key to the answers. We need to invest in capturing the plant's genetic diversity and their associated microbiota and investigate specific and relevant molecular interactions to gain a better understanding of how they perform in different environments and climatic conditions. To achieve this, germplasm representing plant diversity will need to be identified and detailed analyses performed to get to deeper knowledge, mechanisms, and eventually models. A corresponding set of microbiomes will also need to be characterized in detail to understand phytobiome interactions. This knowledge will enable us to make the link between genotype and phenotype to understand current traits, a reflection of what breeders have previously achieved, as well as to develop new trait combinations.

Sequencing

Goal: To establish a public collaborative program to sequence germplasm representing the genetic diversity available in international seed banks.

The first step to capturing the genetic diversity within and across crop species is to sequence their genomes. Advances in sequencing technology have led to a reduction in cost of an assembled 1Gb genome to the ~$2,500 range, and resequencing a plant genome to about $5/Gb. A public collaborative program should be initiated to sequence germplasm representing the genetic diversity available in seed banks. Sequencing targets should comprise representatives from across plant phylogeny, including crops, wild crop relatives, and potential crops. The germplasm selected should include diverse annual and perennial crop types (e.g. root and tuber crops), since root crops have different carbon allocation from shoot crops. A lot of carbon is transferred to roots and tubers and these are used for food and feed. However, we still do not understand how the shoot communicates with the roots in carbon allocation or for seed filling. These and other plant genetic diversity gaps should be identified that can translate into breeding opportunities so that there will be more material to work with in the future.

Cooperation with DivSeek International would enable selection of sequencing targets with maximal potential impact and avoid duplication with other efforts. Some germplasm diversity selected should align with the 30% of the EarthBioGenome roadmap represented by plants. It would benefit from the broader scope of diversity under study in this initiative, which aims to determine how to mine global diversity to learn how a million species have adapted to a changing environment.

There are estimated to be approximately seven million crop accessions conserved in gene bank collections worldwide.[1] The CGIAR germplasm collections represent a rich resource for genetic diversity of regional importance to developing world farmers, although they only represent

[1] http://www.fao.org/3/i1500e/i1500e00.htm

about 10% of the worldwide gene bank collections. The USDA ARS genetic resource collections include the U.S. National Plant Germplasm System, as well as animal and microbe collections, and data and resources are accessible through the new GRIN Global portal. The China National Crop Germplasm Gene Bank at the Chinese Academy of Agricultural Sciences (CAAS) in Beijing holds over 400,000 crop accessions, over 65% of which were land races and varieties collected from China. The China National Gene Bank (CNGB) in Shenzhen also serves as an integrated repository for data and plant, animal and microbial resources of importance to agriculture. A noteworthy feature of CNGB is its integration in one place of the germplasm and one of the largest sequencing output capacities in the world (about 24 Pb/year).

Potential sequencing partners would include the U.S. Department of Agriculture's Agricultural Research Service and National Institute for Food and Agriculture, as well as the U.S. Department of Energy Joint Genome Institute and CNGB. Genetic information on germplasm collections is an area where there could eventually be public-private partnerships that take the public base information to investigate interactions with climate, microbes, and nutrients of potential downstream utility. The data to be generated would be a public good and should be publicly available and tied to germplasm that is also accessible to the public.

Trait Mining

Goal: To establish a public-private partnership to use machine learning to develop low-cost trait mining tools for global agriculture.

Trait mining is currently a far more expensive and challenging step than obtaining sequence information and achieving high throughput will require artificial intelligence-based approaches, like machine learning. Machine learning tools are evolving quickly, primarily for non-agricultural applications in the private sector. Rather than duplicating these tools, it would make sense to catalyze their application to agricultural datasets in the public sector. This approach is likely to be especially effective in plants because there are more than 300,000 species adapted to numerous environments. Through public-private partnerships, machine learning strategies could be developed to mine sequence data for key traits at a reasonable cost. Important target traits would include:

- Photosynthesis under diverse environments
- Disease resistance
- Nutrient and water sensing and response in plants
- Thermotolerance
- Protein folding and novel biochemical pathway reconstruction

Potential partners for this strategy include:

- Google, which has an agricultural focus area
- Facebook AI Research (FAIR), which has been working with biomedical groups but could potentially apply its tools to agricultural problems
- The Peng Cheng Laboratory in Shenzhen, China, a newly-established research center of excellence in AI, space networking, and their applications.

There are opportunities here to leverage existing tools to accelerate progress on plant traits.

Microbiomes

Goal: To establish coordinated public efforts to sequence, spatially map and functionally characterize plant-associated microbiomes across diverse species.

The plant microbiome comprises all micro- and macro-organisms living in, on, or around the plant, including bacteria, archaea, fungi, and protists. In order to understand phytobiomes, it will be necessary to fully sequence a subset of plant-associated microbial communities, including closely associated microbes (e.g. fungal symbionts (mycorrhizal fungi) and fungal endophytes), some of which can transfer phosphorus and other nutrients to the plant. Specific molecular interactions would then be investigated to gain a mechanistic understanding of key developmental and agronomic properties of the association. Specific goals are to:

- Sequence plant-associated microbiomes at key developmental stages (e.g. establishment stage, intermediate stage, and reproductive phase/flowering time).
- Develop spatial maps of plant-microbial associations under different agronomic practices (e.g. plowed *versus* no-till soils, manure *versus* chemical fertilizers).
- Sequence genomes and transcriptomes from disease lesions on key crops, especially those in tropical and developing countries, to capture pathogens and plant responses to them (field pathogenomics).
- Collect associated proteomes (all the proteins) and metabolomes including "secretomes", subsets of plant and microbial peptides and metabolites secreted during their interactions on and in roots and leaves. This information would accelerate identification of key molecules affecting fundamental developmental and agronomic pathways and provide markers that could be used as targets for crop and soil sensors.

Sequencing partners would include those already identified for plant sequencing. An additional partner that could facilitate connections with the private sector is the Phytobiomes Alliance, a public-private partnership that facilitates and coordinates international efforts towards expanding research into phytobiomes. Functional discovery research on whole plants and microbiomes is underway at the LBL using fabricated ecosystems (EcoFabs). These 3D-microcosms allow cross-laboratory and repeatable and systematic reconstruction of plant-microbiome systems around the world.[2]

Field Phenotyping

Goal: To establish an international coordinated initiative to phenotype diverse crop plant species, plant genetic variants (mutants and diverse accessions) and associated microbiomes above- and below-ground under field conditions

The plant phenotype represents the set of its observable characteristics resulting from the interaction of its plant genotype with the environment (GxE). For crops, the "environment" includes biotic (beneficial and pathogenic microbes), abiotic components (water and temperature) as well as managed inputs (nitrogen, phosphorus, and potassium). Plant phenomics is lagging sequencing but is a key part of understanding phytobiomes. Many current studies are performed under controlled conditions in the laboratory or in specialized

[2] Sasse, J. et al (2019) New Phytologist 0. doi: doi:10.1111/nph.15662

phenotyping facilities, which allow detailed above- and below-ground analyses. While this approach allows collections of large volumes of high quality, standardized data, the scale is limited and/or may not always fully represent the agricultural environments in which crops are grown.

There are already examples of field phenotyping, such as the U.S. Genomes To Fields Initiative, which is conducting trials at thirty locations every year. All the genomes under study have been sequenced and large-scale field phenotypes are collected using rovers and drones. However, this project is not currently fully funded and its outcomes are not being combined with additional characterizations needed to gain the complete picture envisioned in this report.

Additional material to be phenotyped should include the scope of genetic diversity being sequenced. This includes crops in agricultural environments and wild crop relatives in their natural environment, as well as keystone trees and grasses at key lifecycle stages, both above and below ground. Field phenotyping should be performed under a range of conditions to capture all potential variation. For example, similar to dynamic water availability, dynamic light availability can greatly influence photosynthesis and growth. Specific datasets to be collected would include:

- Interactions of specific natural or engineered plant genotypes with microbes and microbiomes, including pathogens.
- Impacts of specific microbial molecules on plant growth and development.
- Environmental parameters: light, temperature, carbon dioxide levels in the surrounding environment, nitrogen and water status in the soil surrounding the root system.
- Physiological properties of different organs, such as photosynthesis, respiration, transpiration, water uptake and nutrient uptake.
- Physiological parameters related to soil microbes, including respiration and nitrogen assimilation.
- Molecular measurements of gene expression, including transcriptomes and epigenetic sequence modifications.
- Chemical and biochemical compositions of leaf, stem, root, seed, and fruit samples that include protein, cellulose, and starch measurements, as well as nitrogen and phosphorus content to link to nutrition and use efficiencies.
- Measurements of plant architecture, including canopy and root architectures.

Non-invasive tools[3] have been developed for root and rhizosphere phenotyping than can be deployed under field conditions, including state of the art approaches for root structure measurements and indirect measurements such as water and nitrogen uptake. Non-invasive imaging of root, water and carbon can be done in Germany at the Jülich Plant Phenotyping Center using magnetic resonance imaging (MRI) and positron emission tomography (PET) on roots growing in a range of field soils[4], but it is still used in pots rather than field settings.

[3] Wasson, AP et al. (2020) Trends in Plant Science 25: 119-120. doi: https://doi.org/10.1016/j.tplants.2019.10.011.

[4] Pflugfelder, D et al (2017) Plant Methods 13: 102. doi: 10.1186/s13007-017-0252-9.

Initially, plant and microbial flux maps would be modeled separately. Integration of field crop phenotypic data would enable construction of metabolic flux maps of plant organs with associated microbes to build into whole soil-crop flux maps, greatly extending the basis of today's crop functional models which are based on above-ground biomass data and leaf physiological phenomena.

Potential partners would include specialized international public facilities brought together with industry in the International Plant Phenotyping Network (IPPN), and facilities like the IPK Gatersleben, which bridge laboratory and field conditions to phenotype crop climate acclimation and dynamic traits. The U.S. Department of Energy Environmental Molecular Sciences Laboratory (EMSL) hosts a range of high-end phenotyping facilities to enable systematic characterization of plant biomass composition and molecular level information, which could be another partner in crop phenotyping. The CGIAR research centers span a range of environments and smallholder crops relevant to the work proposed here. In addition, the International Center for Bio-Saline Agriculture (ICBA), an international non-profit applied agricultural research center, could be a potential partner in phenotyping impacts of salinity, water scarcity and drought on crops. The Center of Excellence for Molecular Plant Sciences, Chinese Academy of Sciences, has large programs on crop genetics and genomics and can be a potential partner on mining genetic basis of diverse physiological, morphological, and biochemical parameters on crops and plants under different conditions.

Modeling

Goal: To establish a public-private initiative to build broadly useful whole plant and microbial models linking sequence data with phenotypic and biochemical data to predict the performance of trait combinations under a range of environmental conditions.

This initiative's ultimate goal is to build models that can be used to understand plant responses to a range of environmental conditions and eventually predict which trait combinations best meet specific agricultural needs. Real depth is needed for this type of modeling: comprehensive datasets and deep knowledge of mechanisms. Prior investments have been made in GxE models but their prediction power are constrained by insufficiency in both aspects. Corteva's physiology-based Crop Growth Model developed for AQUAmax® maize works well but was developed for a small range of environments in the U.S. Midwest and for a subset of the germplasm. More comprehensive models are needed for the diversity of crops and environments envisioned here.

For the broader set of diverse crops under consideration, a fundamental, mechanistic understanding is lacking in some areas. For example, it will be important to investigate and optimize established genetic and proteomic networks to elucidate the function of individual genes and encoded proteins in specific biological pathways, such as affecting plant pathogen interactions or environmental stress tolerance.[5] Many genes have already been identified that impact plant responses to water and drought. While Syngenta has exploited such genes in breeding their commercial Artesian corn hybrids and Pioneer has used them in developing AQUAmax hybrids, there are many more crops that could benefit.

[5] https://www.sciencedirect.com/science/article/pii/S0092867420302269

The basic rules governing life are known but we do not yet know how to develop full-scale crop models. Climate modelers understood this challenge fifty years ago and started with the available information, refining models over time as more data became available. The models today are still reliant on these earlier leaf-level physiological principles and limited data. We need to start putting models together now with the available parameters and get them out to be used and refined over time.

Achieving the kind of comprehensive modeling envisioned will require a stepwise approach. The initial focus should be on getting sufficient depth of data where possible to start comprehensive model building. This may involve building individual system models and coupling these to get to whole plant models and, also, development of generic models for plant growth and development. Developing the first coarse models that include both above-ground and below-ground processes will be a major milestone, which can form a basis for stepwise refinements concurrent with the progression of deeper mechanisms and data sets. Linking sequence information to biochemical and phenotypic data will enable models to effectively bridge genetics to physiology and breeding. Since the goal is to develop models applicable to a wide range of crops, robust generic model(s) will also need to be developed for multiple plant species linking metabolism, growth, and environmental responses. Substantial efforts to develop such mechanistic models are under way in the U.S., UK, China, and Australia. The generic models can be developed through a community approach and there are initiatives for this purpose, e.g. Crops *in silico*.[6,7]

Adapting Agriculture to a Changing Climate

Goal: To improve climate models for biotic and abiotic plant stresses.

The International Panel on Climate Change (IPCC), an intergovernmental body of the United Nations, was established more than thirty years ago to provide objective scientific information relevant to the understanding the risk of human-induced climate change and its downstream impacts. Most recently, the IPCC released a Special Report on Climate Change and Land in January 2020, including desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems. The report includes heat and drought impacts on crops and their potential contributions to food security. This group of climate scientists should be consulted with regard to the agricultural component of the most recent models, with a focus on crops that will continue to be grown. It would make sense to cooperate to improve climate models in plant-related areas, such as:

- Drought, heat, and flooding
- Pests and pathogens

The current models are good for drought, heat, and flooding but are lacking for pests and pathogens. Better models are needed to predict climate effects on the movement of pests and pathogens. For example, Fall Army Worm attacks a wide variety of crops and is a difficult pest

[6] Zhu XG et al (2015) *Plants in silico*: Why, Why now and How? An integrative platform for plant systems biology research. *Plant Cell and Environment* 39: 1049-1057.

[7] Marshall-Colon, A et al (2017) *Crops in Silico*: Generating Virtual Crops Using an Integrative and Multi-scale Modeling Platform. *Frontiers in Plant Sciences*, 8: 786

to control on field corn in late-planted fields or in late-maturing hybrids, only being controlled effectively while the larvae are small. The ability to predict where future infestations are likely to occur would enable more effective control strategies. It would be useful to develop potential interventions on a time scale of utility to farmers.

Soil

Goal: Establish a coordinated public-private initiative to understand the role of soil in carbon sequestration as a strategy to increase efficiency and longevity of sequestered carbon in a wide range of environments.

An important goal for this activity is to understand the roles of soils in carbon sequestration and mitigation of climate change impacts. Most agricultural soils are carbon sources rather than sinks so any carbon that is sequestered by plants is not retained in soils in the long term. We need to find approaches to ensure that sequestered carbon stays in the ground. Part of the challenge is understanding what happens at different soil depths, for example one meter *versus* three meters, and which forms of carbon are the most stable. For crop plants, most of the root system would be within the one-meter zone. A challenge is how to develop annual crop plants capable of transporting fixed carbon to deeper soil layers. This is different for perennial crops, for example, *Miscanthus*, or rhizome crops that maintain fixed carbon in the ground.

A large component of organic carbon sequestered in soils comes from plants (for example, lignin and cellulose) and, also, fungi and arthropods (as chitin). These structural polymers vary in their stability with lignin being the most recalcitrant to degradation, but depth is also important to consider. If carbon is in the surface layers of the soil, it will be more likely to be broken down by microbes while deeper soil levels have a slower turnover of carbon. The key is to make chemically diverse and deep organic carbon additives to soil.[8] This would come at an energetic cost and would need to be coupled with increased photosynthetic efficiency above ground to maintain yield.

Soil sensing is an opportunity for public-private partnerships as well as coordination with ongoing projects to deepen plant root architecture. For example, the US Department of Energy ARPA-E Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS) project is developing improved crops that impart more carbon into the soil through their roots or grow deeper root systems. Another point of coordination would be the French Quatre Pour Mille (four per thousand) Initiative, which focuses on demonstrating that agriculture and agricultural soils can play a crucial role in food security and climate change.

Nutrient and Water Use Efficiencies

Goal: To use a systems approach to understand plant above- and below-ground nutrient and water use efficiencies to increase yield and promote yield stability.

There are multiple challenges to investigating water and nutrient use efficiencies. First, water use efficiency cannot be studied meaningfully in isolation since it is impacted by a range of plant traits and environmental factors, including microbial diversity in soils and the availability

[8] Lehmann et al (2020) *Nature Geosciences* **13**, 529–534. DOI: https://doi.org/10.1038/s41561-020-0612-3

of nutrients. There would therefore be benefits to conducting simultaneous analyses of the efficiencies of multiple inputs. Water and nutrient use efficiency involve complex genetic traits, complicating deployment. Combining new phenotyping technologies with genomics approaches should facilitate such deployment. However, below ground models are limited to a few plant species currently being studied and almost all the crop model frameworks currently in use do not include below ground data. While Arabidopsis and rice are useful models for investigating broadly conserved structures and processes, an expanded set of plants will be needed to capture structural variation such as cluster roots, which are important for surviving low phosphorus levels in some environments and perennial species such as trees, alfalfa, and grasses[9] that recycle nitrogen and phosphorus differently from annual species.

Digital agricultural technologies already allow farmers to respond spatially and temporally to changing environmental conditions by planting optimized genotypes and managing inputs during the growing season. By understanding whole plant traits and dynamics, we can help farmers apply this knowledge to the broader range of crops grown globally.[10] Conceptual frameworks will need to include below ground modeling for yield gains, which would increase their utility to farmers in the developed and developing world when used in conjunction with low cost sensors and digital networks to inform crop and management actions. This is the focus of a new German Cluster of Excellence funded by the DFG, called PhenoRob.

We need more data to support below ground modeling to overcome the current above-ground bias for whole-plant analyses. Root structure function models such as OpenSimRoot are available openly and can augment root phenotyping data.[11] Integrated whole plant models are also needed for economic evaluation, especially to evaluate crop production under limited water and nutrient availability. To build better integrated models, it will be necessary to investigate structural and functional components of nutrient and water use efficiency above and below ground, including:

- Root architecture – diversity and turnover.
- Nutrient and water uptake mechanisms and regulation.
- Contributions of the plant-associated microbiota.
- Stomatal patterning and dynamics.
- Photosynthetic efficiency as a function of input (effective exchange of carbon for water and nutrients and *vice versa*).
- The relationship between plant growth and stress responses. In general, plant growth and stress resistance are antagonistic, and there needs to be a balance between the two to stabilize yield. Which pathways need to be enhanced or suppressed is unclear. We need models but do not yet have enough information to build them. Systematically collecting information on plant growth responses to stresses and identifying the genetic basis of growth regulation under stress will be required to develop systems models to predict the optimal balance point between the two.

---

[9] https://www.forevergreen.umn.edu/crops-systems
[10] Arsova B, et al (2020) Phytologist 225: 1111-1119. doi: 10.1111/nph.15955.
[11] Postma JA, et al (2017) New Phytol 215: 1274-1286. doi: 10.1111/nph.14641.

- Flooding tolerance.

Additional studies are needed to better understand microbial roles in plant metabolic functions. To get there, we need to:

- Characterize root microbial associations to determine how those associations regulate greenhouse gas (carbon dioxide, methane, and nitrous oxide) emissions.
- Undertake mechanistic analyses of how specific microbial peptides and metabolites interact with microbial and/or plant receptors (or other components) to affect plant growth, disease resistance or environmental stress tolerance.

There are opportunities to expand utilization of symbiotic endophytes, for example, arbuscular mycorrhizal fungi, to improve phosphorus uptake. However, we still lack fundamental knowledge about these associations. There is variation in the functional outcome for the plant that is influenced by plant and fungal genotypes and by the environment, but we do not understand the basis of this variation. We need deeper knowledge before we will be able to make better use of these associations in agriculture. There is a need to broaden the number of crop species that can fix nitrogen using engineering approaches. Integrated management of plant nutrients in the context of crops and farm animals could eventually allow development of a "circular economy" for phosphorus and nitrogen, leading to reduced environmental impacts and increased profits through reduced inputs.

We need to better understand the impacts on plant growth of associated micro-organisms, which could potentially be applied exogenously to deliver a substantial proportion of the plant's nutrient needs. These applications could take the form of natural or synthetic communities. However, the landscape is complex. The value of mycorrhizae and plant growth-promoting rhizobacteria can be highly dependent on the plant species and environmental conditions,[12] understanding these interactions is important to fully recognize their benefits.

There are already a number of start-up companies in this sector, and the knowledge gained here could lead to new public-private partnerships to foster development of new products as well as efficacy standards.

Pests and Pathogens

Goals: To develop tracking tools with predictive capabilities for major global above- and below-ground pests and pathogens; to gain knowledge of the mechanisms by which plants differentiate microbes that are beneficial *versus* pathogenic and the evolutionary biology of these interactions.

Plant pathogens are part of the environment and are continuously evolving. We also find many cases of co-evolution between pests, pathogens, and plants. We are facing ever increasing disease challenges as well as changing disease ranges with increasing climate variation and will need to improve surveillance and protection to get ahead of them. As the COVID-19 pandemic reminds us, pathogens do not respect borders and what happens in one region can have global impacts. Thus, international collaborations and real-time open exchange of data (e.g. pathogen

[12] Morcillo et al EMBO J. 2020 Jan 15;39(2):e102602. doi: 10.15252/embj.2019102602.

genomes) are paramount to responding to emerging infectious diseases. This can be implemented through open source platforms such as nextstrain.

As with plant pathogens, plant pests pose increasing challenges as their ranges move with a changing climate. There remains a funding gap for pests and pathogens beyond commodity crops. A handful of crops are well funded, but we need to look beyond these to a broader range of vegetable crops, trees, and tropical crops, some of which are currently underfunded. There is little research in these areas and tropical crops are a big gap.

We have difficulty predicting pest and disease outbreaks, partly because there is little available data on which to base models and there are only a few good examples of current successes in this area (for example, wheat stem rust lineage Ug99, and Agrobacterium).[13] Academic researchers would like this type of information to guide their programs for the next five to twenty years. As discussed earlier, climate models are lagging for plant pathogens and pests compared to abiotic stresses. The plant disease resistance genes are well studied but it is a huge challenge to validate interactions of genes or proteins with different types of microbes and pathways.

We still do not understand how plants differentiate between beneficial and pathogenic microbes. There are conserved components of pathogenic and symbiotic plant and microbial interactions yet potentially diverse impacts on the plant. We need a system-of-systems view of how plants use these interactions to control microorganisms in order to predict where pathogens would be likely to emerge and evolve in certain contexts. These are interesting questions that go beyond academia to impact growers and breeders, and it is an open research field that needs significant investment. Specific needs are to:

- Track pathogens and pests (e.g. fall armyworm, locusts) on regional to global scales to anticipate infestations and mitigate impacts. CGIAR has proposed a Global Surveillance System[14] (GSS) to accomplish this.
- Understand potential negative impacts of below-ground pathogens on nutrient use efficiency.
- Understand the roles of microbes in suppressing pathogen growth on plants.
- Understand the co-evolution of plants and microbes on leaves and their roles in plant growth (plant epidemiology, molecular genetics, and evolutionary biology).
- Understand the impact of climate change on microbes x pathogen x host plant interactions.

Additional Needs

Basic research and discovery are still important for providing the necessary depth of knowledge about plant structure and function for example, towards mechanistic and predictive modeling for crop development and field management. The greatest hurdle is

[13] Weisberg, AJ et al. (2020) Science 368, eaba5256. DOI: 10.1126/science.aba5256.

[14] Carvajal, M et al (2019) S*cience* **364** (6447) 1237-1239. DOI: 10.1126/science.aaw1572

perhaps the disconnect between basic research and its application in the private sector and in the field.

We know a lot about a few plants and a little about many plants. Generally, the public sector supports the broad discovery work, while the private sector supports deep knowledge about a few commercial crops. However, an increasing depth of knowledge for rice and cassava is now being supported through public and philanthropic funding. There are potentially useful crops that are difficult to deploy because of a lack of basic information, tools, and technologies for their improvement. These resources need to be expanded to a much wider range of crops and wild relatives.

More work is needed on crops themselves. Academic research is still strongly driven by model systems and while these are useful for understanding basic principles, the outcomes often do not translate directly to crops in the field. Ideally, a multidisciplinary team would start research in the field and the laboratory at the same time and connect scientific interests. For example, there is still a lack of genetic tools for studying cover crops.

One area that would benefit from the concurrent use of models and crops is the study of Nitrogen Use Efficiency (NUE), where there is currently a lot of work in A*rabidopsis* but not much in crop systems or in the context of other nutrients, or water. Much more integration is needed of model species hypothesis testing using transgenic plants in a Genomes to Fields-style system. For example, each project funded to study a model system could nominate several genes/constructs for evaluation in the national G×E trials in maize or soybean.

Plant transformation and regeneration are still significant bottlenecks for many crops. While there have been successes in the private sector in transformation of major crops such as corn, large numbers of transformants are still required for commercial development. The fundamental knowledge underlying these approaches often came from public research, then the private sector optimized the transformation methods for high throughput pipelines.

Protocols are needed to engineer any plant. To get there, we need to know what determines why some plants can be transformed and others cannot, or why some genotypes of a given species can be transformed while others cannot. We need to develop genotype-independent, species-independent transformation methods and explore interdisciplinary collaborations to expand beyond current limits. There are opportunities for genome editing without the need for stable transformation which perhaps can be expanded to additional plant species.[15] There is also a need for improved chloroplast transformation in any crop since plastids in few plants other than tobacco can be transformed.

The identities of plant and microbial peptides and metabolites controlling plant and microbial interactions are largely unknown. For example, the core database of the KNApSAcK family of databases currently contains more than 52,000 metabolite entries and more than 124,000 metabolite species pair entries. Metabolomics and proteomics have benefited from technological advances in mass spectrometry, nuclear magnetic resonance, and data analytics.

[15] https://www.nature.com/articles/s41477-020-0670-y

However, metabolite and secretome identification remains a major bottleneck[16] and the full breadth of metabolomes and secretomes remains unknown in plants and microbes.

Development of low-cost sensors is needed for both smaller-scale and large-scale farming in all the categories listed below. This could be accomplished *via* public research and public-private partnerships. This is a cross-cutting need for multiple data types for:

- Plant germination and growth parameters in agricultural settings
- Soil nutrients
- Rhizosphere chemistry
- Morphological traits
- Plant nutritional status

There are some public funding programs in the U.S.,[17] but greater investment is needed to bring sensor costs down and ensure widespread availability. Start-up companies building on these investments include FloraPulse,[18] which is commercializing microsensors inside plants for monitoring water use by commercial crops. This type of sensor would also be useful for obtaining below ground data for modeling. Another start-up venture, Hi Fidelity Genetics,[19] which received ARPA-E funding, uses its RootTracker sensor to collect data on maize root traits for predictive modeling to accelerate breeding of hybrids for better performance in specific environments. While the current focus is on corn seed, this technology has the potential for wider deployment. In the public sector, the Dutch Plantenna consortium of four universities is bringing together plant scientists with engineers to build better soil sensing technologies. This group promotes training and open data access as part of its mission.

A wide range of low-cost sensors is also needed for field management for the broader range of crops grown globally. Outputs from sensors can allow farmers to respond quickly to environmental changes by adjusting water and nutrient inputs. High income countries make substantial investments in precision technology for a few major crops but in other parts of the world, there is little control of water or fertilizer use. Significant opportunities also exist in Africa to increase food productivity without huge infrastructure or input investments through the use of sensors. Expanding networks of sensors connected to cell phones could help farmers accelerate the use of more sustainable and productive agricultural systems.

There are challenges to open sharing of data and information. Publicly funded data and information should be available to all, but other types of farm and private-sector data may not be for a number of reasons. Data collected from farmers may have associated privacy issues that have to be managed. If we do not know how data can be used, the private sector is not going to invest. There are also challenges to using digital data across national boundaries that will need to be resolved for any international collaborations.

While public research efforts are identifying genes underlying complex traits, the private sector is still largely using single genes to tackle biotic and abiotic stress challenges. To date, a

---

[16] Monge, E.M. et al. (2019) *Annual Review of Analytical Chemistry* **12**, 177-199.

[17] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505720

[18] https://news.cornell.edu/stories/2017/02/water-sensor-moves-basic-research-promising-business

[19] https://www.ncbiotech.org/news/getting-down-roots-breeding-better-corn

few single gene traits such as insect and disease resistance have been low-hanging fruit for commercialization. However, drought resistance and nitrogen use efficiency are complex traits involving many genes that will require different strategies and transfer of basic knowledge from the public sector to the private sector for implementation. In quantitative genetics and algorithm development, the animal field is more highly funded and ahead of crops. Companies recognize this and collaborate with animal researchers to advance crop development. These efforts need to be better connected to public efforts to accelerate trait discovery and deployment globally.

There is still a critical lack of plant breeders who have been trained in quantitative genetics, genomics, and data science in both the public and private sectors and training programs are not keeping pace with demand.

Coordination

International coordination is a significant component of this report's proposed activities. A successful model for coordination will need to be:

- Science-driven
- Organized around a vision that serves the needs of individual stakeholders
- Aimed at goals that could not otherwise be tackled individually

To accomplish effective international coordination of a system-of-systems-oriented approach to tackling climate impacts on agriculture, we need to develop global platforms that build on and connect to ongoing national initiatives. This report outlines a plan that is not prescriptive and leaves flexibility to the researchers undertaking the work across the globe as to how to tackle each goal. However, the plan is specific enough to allow potential funders to integrate the goals into national strategies and frameworks while reaching out to international partners.

The research goals need to be understandable to policy makers and the broader public. For example, discussing sustainability as reduced pesticide usage would be understandable to many different audiences. In the EU, the SCAR definition of sustainability is used, which is both scientifically robust and useful for broader audiences. In addition, research goals may need to be framed in terms of downstream impacts rather than the other way around. For example, yield needs being enhanced by photosynthetic improvements rather than studying photosynthesis to understand yield.

There are already ongoing national discussions as to how to bring together cross-disciplinary teams. For example, the Chinese Academy of Science (CAS) and the Chinese Agricultural Academy of Science (CAAS) has held large gatherings of cross disciplinary actors to identify critical components of yield potential and yield stability and directly use them in modern crop breeding programs. In the EU, the planning activities for Horizon Europe have included similar types of forecasting exercises. In the US, a significant platform for initiation and coordination of multi-agency initiatives is the National Science and Technology Council, which develops research and development strategies through its six primary committees. One example is the National Plant Genome Initiative, which was established under the Committee on Science in 1998 and coordinated activities in plant genomics across multiple federal agencies through development of five-year plans. The activities proposed in this report would align well with such national strategies.

A challenge in any international research program is the management of national funding contributions. In many cases, funds can only be awarded to researchers in the contributing country. There are mechanisms to allow coordinated research that use a “virtual common pot,” where research proposals are jointly solicited and reviewed with separate funding provided to each group from the participating national program. The EU ERA-PG and ERA-CAPS programs used this mechanism and included non-European funders from the US and New Zealand.

Another approach is the use of bilateral agreements, where the funders agree to use a common call for proposals and review process, again awarding the funds to the respective national research groups. This strategy was used for the joint US National Science Foundation (NSF) - Biotechnology and Biological Sciences Research Council (BBSRC) Ideas Labs on photosynthesis and nitrogen fixation. Multilateral agreements involving multiple partners can be challenging to implement but could be more straightforward to manage through multiple bilateral agreements with a single agency serving as the hub for review.

Some funders will allow international distribution of funds, for example, the USDA National Institute of Food and Agriculture (NIFA) and these opportunities would allow participation of partners such as the CGIAR in U.S.-funded projects. Foundations such as the Bill & Melinda Gates Foundation and the Rockefeller Foundation can also play an important role in providing support for international collaboration that is country independent.

Implementation of the approaches proposed in this report will require advocacy at multiple levels including by leading scientists with experience in public engagement and foundations that advocate for or support international research initiatives. Engagement of international coordination bodies such as the Global Plant Science Council, which promotes plant science across borders and disciplines, will be needed to amplify these messages. Trade associations such as the American Seed Trade Association (ASTA) may also be helpful in advancing public-private partnerships. Early engagement of funders will be important to build the research platforms into budget plans and gain support for coordination activities.

Summary

Five interconnected approaches focused on genetic diversity, climate variability, soil, nutrients and water, and pests and pathogens, will be deployed through internationally coordinated platforms to develop plant models that can be used for predictive trait analysis across the diversity of available crop germplasm in international gene banks. The data and resources emerging from these activities will be openly accessible to the maximum extent possible. Public-private partnerships will be developed to accelerate progress in an ecosystem of industry and academic actors to enhance translation of basic discovery outcomes into crops and resources for farmers. These resources will provide farmers worldwide with resource-efficient crop systems resilient to climate variation, with increased yield under favorable conditions and yield stability under unfavorable conditions.

ABOUT THE SUPPORTERS OF AGRICULTURAL RESEARCH FOUNDATION

SoAR leads a non-partisan coalition working to educate stakeholders about the importance of agricultural research and focus more of our best minds on feeding America and the world. For the U.S. to remain a global leader, public research funding that accelerates the productivity, profitability, and sustainability of American agriculture is needed.

Together with our partners, SoAR works to increase federal investments in agricultural research so our farmers can continue to produce safe, nutritious food for the world's growing population. SoAR advocates for additional agricultural research support, including full funding of the Agriculture and Food Research Initiative (AFRI), USDA's flagship competitive grants program. Sufficient federal investment and wise policies are essential if the United States is to continue to be a leader in agricultural innovation and production.

Participants

Dr. Edward S. Buckler
Research Geneticist, USDA-ARS
Adjunct Professor of Plant Breeding and Genetics, Cornell University, Ithaca, NY, USA

Dr. Wilhelm Gruissem
Dr. Wilhelm Gruissem
Professor of Plant Biotechnology, Department of Biology, ETH Zurich, Zurich, Switzerland
Professor and Yushan Scholar, Biotechnology Center, National Chung Hsing University, Taichung, Taiwan

Dr. Maria Harrison
William H. Crocker Professor, Boyce Thompson Institute
Adjunct Professor of Plant Pathology and Plant Microbe Biology, Cornell University, Ithaca, NY, USA

Dr. Scott A. Jackson
Genetic Pipeline Lead, Bayer Crop Science
Professor, University of Georgia, Athens, GA, USA
Adjunct Professor, Institute of Crop Science, Chinese Academy of Agricultural Sciences, China

Dr. Sophien Kamoun
Group Leader, The Sainsbury Laboratory and Professor of Biology, University of East Anglia, UK

Dr. Giles Oldroyd
Russell R. Geiger Professor of Crop Science, Crop Science Centre, Department of Plant Sciences, University of Cambridge, UK

Dr. Shaobing Peng
Professor, Crop Physiology and Production Center (CPPC). College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, China

Dr. Pamela Ronald
Distinguished Professor, Department of Plant Pathology and the Genome Center, College of Agricultural and Environmental Sciences Genome Center, University of California, Davis, CA, USA

Dr. Ren Wang
Director and Senior Vice President, BGI Group
Director, China National Genebank, Shenzhen, China

Dr. Michelle Watt
Professor and Adrienne Clarke Chair of Botany, School of Biosciences, University of Melbourne, Australia
Chief Investigator, Jülich-University of Melbourne Postgraduate Academy (JUMPA)
Fellow, PhenoRob DFG Cluster of Excellence, University of Bonn and Jülich Forschungszentrum

Dr. Jian-Kang Zhu
Senior Principal Investigator and Director, Shanghai Center for Plant Stress Biology, Chinese Academy of Sciences, Shanghai, China
Distinguished Professor, Department of Horticulture and Landscape Architecture, Department of Biochemistry, Purdue University, West Lafayette, IN, USA

Dr. Xinguang Zhu
Professor, Center of Excellence for Molecular Plant Sciences, Chinese Academy of Sciences, Shanghai, China

Facilitator

Dr. Jane Silverthorne
Senior Science Advisor, SoAR Foundation

Commentators

Dr. Jeremy Harbinson
Associate Professor, Department of Agrotechnology and Food Sciences, Wageningen University, The Netherlands

Dr. Ekaterina Krivonos
Deputy Director, Programs, CGIAR

Observers

Dr. Ben Allen
Head of Agriculture and Land Management Programme, Institute for European Environmental Policy

Mr. Ammad Bahalim
Program Officer, Policy Advocacy and Communications, Bill & Melinda Gates Foundation

Ms. Rose Barbuto
Board of Directors, SoAR Foundation

Dr. Roger Beachy
Board of Directors, SoAR Foundation

Mr. Tom Grumbly
President, SoAR Foundation

Dr. Renee Lafitte
Deputy Director Crops R&D, Bill & Melinda Gates Foundation

Ms. Andrea Putman
Senior Vice President, SoAR Foundation

Mr. Josh Stull
Vice President for Policy and Analysis, SoAR Foundation

Dr. Yumei Zhang
Associate Research Fellow, Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences