Developing Global Priorities for Plant Research

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ABOUT THIS REPORT

This report results from a series of interviews and an in-person meeting on August 13, 2018, with ten leading plant scientists from Europe, China, and the United States. The Supporters of Agricultural Research (SoAR) Foundation sponsored these activities. The purpose of the dialogues was to produce a report articulating a concise set of plant-focused research priorities to inform the decision-making of agricultural research funders.

Agriculture represents the largest ecosystem on the planet [1] but the current trajectory for crop production will be insufficient to feed a growing world population. We must produce at least 60% more food to meet global nutritional needs from existing land with reduced environmental impacts by the year 2050 to deliver economic and ecologically sustainable food production [2].

Plants are crucial to any strategy to achieve this goal. We are at the dawn of a second Green Revolution, where new research-based technologies, management practices, and breeding tools will allow us to improve existing crops, develop new crops, and grow them more efficiently in ways that are tailored to a changing climate and rapidly evolving consumer needs. However, many specific challenges differ between the developed and the developing world, and the strategies deployed have to address local issues and needs. Also, the impacts of climate change differ across the globe and are not static. Therefore, effective mitigation and adaptation depend on a range of approaches, from tailored genetics to modern agronomy. Achieving robust and sustainable long-term improvements requires more than just specific solutions to each challenge since the individual components of plant productivity are interconnected. A “system of systems” view of plants will foster the research approaches that cut across disciplinary boundaries [3] to maximize and maintain crop yield faster than has been achieved in the past. Maintaining agricultural productivity will also require increasing the rate of yield gain while reducing land use, as well as water and energy inputs.

This report focuses on a vision for plant research to advance agriculture from a “system of systems” perspective. This perspective integrates the multiple systems that constitute the complex biological and physical interactions of plant structures and processes with the agricultural environment. It recognizes that basic research, training, advocacy, and communications are all critical to success. There has never been a more important time for international public and private research efforts to work together towards success.

The plant sciences offer exciting and rewarding career opportunities in existing and emerging fields. This includes jobs in the public and private sectors that incorporate plant research, engineering, data analytics, and modeling, as well as policy development and advocacy. Successfully attracting financial and human resources will depend on effective communication about the urgent need for plant research solutions. These solutions must be driven by stakeholder needs, from large-scale farmers in the developed world to small-holder farmers in the developing world, as well as the consumers of the food they produce.

The value of a “system of systems” approach

The complexity of plant structure and function and their environmental plasticity has driven research focused on specific developmental stages (e.g., flowering and root formation) or processes (e.g., nitrogen use efficiency, photosynthetic efficiency, water use efficiency). Continued research in these areas remains an important foundation on which new discoveries will be built. However, the components and processes underlying each are interrelated so that a change in one impacts the others and, in turn, the whole plant and its interactions with the environment. Advances in modeling will make it possible to visualize these complex interrelationships and, in allowing the determination of effective research targets, will fundamentally change research strategies. Thinking of plants in the environment as a “system of systems” will accelerate development of a secure and sustainable plant-based food supply.

While evolution has only sampled a small portion of the possible genetic space, the number of potential points of intervention is overwhelming. Predictive models can be used to narrow down the possible array of interventions [4,5,6]. For example, models and experimental manipulation of field crops show that the architecture of modern crop canopies and their root systems are far from optimized for maximum efficiency of light, water, and nutrient use. Computational design, facilitated by the rapid growth in high-performance computing, will allow *in silico* prediction of ideotypes for different environments and management situations, followed by selection of breeding materials or genetic manipulations that could achieve these ideotypes for field testing. Plant research is increasingly data driven and quantitative knowledge of plant structure and function, from genetics to field performance, will be key to developing useful whole plant models. Quantifying problems is also important so that rates of change can be tracked, and the biggest levers identified.

Priorities differ between the developed and developing worlds

The Green Revolution tackled hunger using a combination of genetic and agronomic improvements to key crops in the developing world [7]. More than 60 years have passed since then and most of the cultivated crop varieties were selected when the carbon dioxide levels were lower, and temperature ranges narrower than today. There also continue to be negative impactors of production (e.g., poor soil fertility, limiting water, diseases, and pests). Research will need to focus on these targets and facilitate and integrate genetic improvements with modern agronomic practices using sensors and data-driven management. Although it may be difficult and expensive to improve soil fertility, this would ameliorate the impacts of other constraints. Decreasing losses from diseases and pests would also increase yield without requiring an increase in land use.

While food production in Africa has doubled over the past 50 years, population size has kept pace with these gains. A 3% increase in food production and population maintains the *status quo*, while a 6% increase in food production coupled with a 3% increase in population enables economic growth and public health benefits to accrue [8]. Research outcomes and their translation to farmers will be key to achieving these gains.

Soil health, including soil microbiomes as well as inputs, is critical to developing sustainable agriculture while maintaining yield. While the Green Revolution led to enhanced crop yields, it also created new problems from agricultural pollution that have negatively impacted sustainability and need to be addressed. In Europe, China, and India, the large amounts of fertilizers applied to fields carry the initial costs of production and application as well as the environmental costs for management of the excess. Further, while carbon and nitrogen are renewable resources, fossil phosphorus and potassium are not. Increasing yield in a sustainable way will require research-based knowledge and tools for biological solutions [9].

What are the key challenges?

To feed a growing global population, the greatest priority remains increasing and sustaining crop yields. The gains achieved by the Green Revolution were driven first and foremost by genetic increases in the yield potential of germplasm for the major staple grain crops, through dramatic increases in harvest index and to a lesser extent increased light interception and distribution within crop canopies. Altered agronomy to realize this improved yield potential was equally important. Both traits are now considered to have been bred close to their biological limits and may be a contributor to the stagnation in yield improvements noted over this century. Advances from plant research will be needed to increase productivity in these crops, as well those crops that did not benefit from the Green Revolution.

About two thirds of the world's calories currently come directly or indirectly from four major crops: maize, rice, soybean, and wheat [10]. These crops represent significant investment targets in the public and private sectors. Even with the use of gene editing and accelerated breeding technologies, it will take other crops a long time to catch up. The greatest impacts are likely to come from those approaches that are "crop-agnostic" and can be deployed widely when and where needed. Photosynthesis, water, and fertilizer use efficiencies, as well as biological nitrogen fixation, have genetic components that are conserved across many plants. Once a system is optimized for one plant, that knowledge can be applied broadly. These "cross-cutting" traits have greater potential impacts than specialized traits that can be used in only a small number of plants. For example, the detailed knowledge of the photosynthetic system and its underlying gene regulatory networks, which are well conserved across crops and so broadly applicable, is allowing identification of points of intervention that have reached successful tests of concept in tobacco and soybean in replicated field trials. Theory suggests that in total these could lead, as stacked traits, to a 50% - 100% increase in crop carbon uptake for little or no increase in water or nitrogen demand [11].

There are two major levers to increasing crop production. The first is increasing and achieving yield potential. The second is minimizing losses from biotic and biotic stresses through a combination of genetics and management. While genetic improvement is powerful, there are also major gains to be made through research-based improvements to crop management, especially in the developing world.

Addressing four overarching research challenges to agriculture worldwide using approaches directed by models could move crop production towards the gains needed by 2050. A fifth challenge is attracting and retaining the human capital necessary to achieve these gains.

Challenge:	**Fresh water is the most limiting resource for agricultural productivity.**
Magnitude:	**Agriculture already consumes over 70% of the fresh water humans extract from ecosystems [12]. In most of the developed world, agricultural productivity is already**

close to the maximum possible for a given amount of rainfall or irrigation. With limited capacity to increase irrigation and greater variability in rainfall, a breakthrough in water use efficiency is needed to drive the next generation of improvements in agriculture.

Approaches: **Introduce a new metric of "crop per drop" to track improvements in water use efficiency, in addition to the traditional metric of yield per hectare. Invest in both incremental and breakthrough innovations that improve overall water use efficiency in agricultural systems. Target both genetic and agronomic traits to increase water capture by roots and minimize soil evaporation, as well as within-plant water use efficiency.**

Fresh water is a finite resource. Modeling can be used to predict crop genotypes with the highest water use efficiency to help focus genetics, gene editing, and advanced breeding strategies. Over 99.9% of water taken up by plant roots is quickly lost to the atmosphere by evapotranspiration in the unavoidable process of collecting carbon dioxide from the air [13]. To produce a bushel of corn, more than 2,500 gallons of water are transpired to collect the carbon dioxide that goes into that bushel. Under ideal conditions, the exchange rate of water for carbon ranges from 250:1 to 500:1. Boosting photosynthetic carbon capture relative to transpiration is one potential research target since photosynthesis leads to water loss through transpiration.

Another potential research target is the genetics of traits impacting allocation efficiency of carbon to roots, which is largely unexplored. The current efficiency equations do not include up to 50% of carbon allocated below ground, which impacts utility of models for these traits. New imaging techniques, such as ground penetrating radar and X-ray computed tomography in the laboratory, could be used to select germplasm with decreased investment in roots, where this would be beneficial given management and environment. Knowledge of root structure, development, and architecture could result in smarter ways of reducing investment without loss of water and nutrient uptake exploitation, such as increased aerenchyma tissue, more even distribution of roots between layers, and/or deeper roots. Enhanced management strategies, including improved irrigation technologies and soil sensors to maximize rainfall "crop per drop", will be also required to maximize yield in most cases.

Where water is not already the most limiting resource, water use efficiency could be improved by other interventions, including fertilizers (e.g., nitrogen, phosphorus, potassium, and trace elements) or pest and pathogen protection. Field sensors could enable the most effective use of these inputs.

Challenge: **Poor soil health and fertility negatively impact crop production.**

Magnitude: **Fertilizer is often the most expensive input for developed country farmers and can be several times more expensive in less developed countries with poor infrastructure and markets. Too much fertilizer may lead to run-off and pollution of surface and ground water.**

Approaches: **Invest in both incremental and breakthrough innovations that improve overall soil health, soil fertility, and nutrient use efficiency in agricultural systems.**

Soil structure and composition and the plant phenotype below ground are understudied because they are difficult to analyze in a non-invasive way. The maintenance of good soil structure and fertility is driven by root and root-microbiota processes that are poorly understood but could be greatly enhanced using genetics and biological soil amendments. In addition to fostering the development of new phenotyping technologies and soil analytics, a systems approach is needed to understand the interactions between plant genotypes and soil microbes. Soil microbiome research advances will be a key component of managing soil fertility. Using strategies that build on knowledge of conserved components of plant-Rhizobium interactions, it should be possible by 2030 to show proof-of-concept for achieving 100% reduction in dependence on applied nitrogen in some cereal crops, as well as 50% reduction in phosphate and potassium through combinatorial genetic strategies that exploit architecture, allocation, and soil microbes. By 2050, these gains could move agriculture in some developed world crop systems towards "fertilizer-free" management, while achieving fertilizer-efficient management in systems with degraded or poor soils. Increased productivity could then lead to soil structures with good aeration and porosity to increase root water capture in a feedforward effect on water use efficiency.

Improving photosynthetic carbon capture relative to transpiration is not only beneficial for water use efficiency, but also raises the potential yield ceiling. Combined enhancements to carbon, nitrogen, and phosphorus capture also have huge possibilities for raising yield potential. These approaches will depend on an increased knowledge of plant growth and development from basic research, as well as cutting-edge gene editing, genetics, and breeding.

Challenge: **Biotic and abiotic stresses decrease crop yield.**

Magnitude: **A large portion of global crop production is lost to increasingly aggressive pathogens and pests every year, both during growth and post-harvest storage, causing significant economic losses to farmers. More erratic weather patterns in a changing climate make efficient crop production increasingly unpredictable.**

Approaches: **Invest in improved genetic, field management, and surveillance strategies that produce new crop varieties with robust performance and yield stability that require lower pesticide and water inputs.**

The next generation of gene editing tools will usher in new ways to modify genes to enhance traits or remove deleterious traits. It will also become possible to stack genes that confer broad spectrum resistance to diseases and abiotic stresses, building on basic discoveries regarding resistance and tolerance mechanisms. In the developing world, smallholder farmers are unable to benefit from the current yield gains offered by plant genetic improvement and have little access to chemical interventions so improved management remains important [14].

Plant disease outbreaks often spread rapidly, and effective interventions must be swift. Current examples of disease threats include Citrus Greening disease or Huanglongbin [15], *Xylella fastidiosa* [16], which has severely impacted olive production, and Wheat Blast, caused by the fungus *Magnaporthe oryzae* [17]. Global sentinel surveillance networks are needed for key plant diseases and pests as well as rapid-response systems to manage and contain outbreaks. These could comprise local and regional efforts, including crowd-sourcing, and would benefit from public-private partnerships with local sponsorship where appropriate. In terms of production, an attainable systems goal is to produce twice the harvested crop yield with half the water by 2050, which includes water capture. This is predicated on being able to increase photosynthetic efficiency by 20% by 2030 and 50% by 2050. Optimizing resource allocation between plant organs could lead to a 20% increase in yield through development of physiologically optimized plants. Data management, pest control, soil fertility improvements, and gains from water use efficiency would contribute to these advancements. Modern management practices that include field sensors would allow farmers to monitor crop status in real times using mobile phones and adjust inputs as needed.

Challenge: Malnutrition results from both under-consumption of key nutrients and over-consumption of calories and leads to health issues such as obesity and diabetes.

Magnitude: Today, 1.6 billion people globally suffer from iron deficiencies as the result of unvaried diets [18], and millions do not have regular or economic access to food that provides the needed vitamins for human health. At the other extreme, the increasing consumption of highly processed food and sedentary lifestyles negatively impact human health and impose economic burden on societies.

Approaches: Invest in improving the nutrient density of globally important staple crops. Work with specialists in nutrition, social sciences, and communication to increase consumer awareness and attractiveness of nutritious food crops, especially under-consumed crops, to promote health.

While there are many social and economic components to this challenge, there are also potential approaches to addressing it through plant research. Genetic interventions can be used to develop robust and cost-effective solutions to plant nutrient content. Together with agronomic biofortification, this could provide immediate and effective routes to enhancing micronutrient concentrations in edible crop products [19]. Basic research leading to advances in the understanding of plant growth and development have already led to the creation of a novel strategy to enhance rice and wheat yield and plant nutrient-use efficiency by balancing the expression of a transcription factor and a DELLA protein [20]. In addition, genetic improvements have been made for the content of iron, zinc, and beta-carotene in rice [21].

Quality traits, including the content of iron, vitamins, oils, flavor, and starch could be modified using gene editing and introduction of stacked traits. Minor crops such as quinoa and broomcorn millet are naturally stress-resistant and contain nutritional components that benefit human health. Modern breeding tools including gene editing can be used to improve their yields. These kinds of next-generation crops can be developed to address local needs in preferred crops and varieties.

Challenge: Too few young scientists are being trained for or choose careers in plant and agricultural research.

Magnitude: There has been no growth in the number of PhDs produced in the plant sciences in the U.S. over the past two decades and there is a deficiency of personnel to meet the needs for research and training in the public and private sectors [22].

Approach: Invest in development of training programs and career opportunities to attract young plant scientists, breeders, and modern agronomists.

It will be critical to attract, train, and retain the next generation of plant scientists and breeders globally if we are to meet the goal of increasing and sustaining ecologically and environmentally sound food production. The importance of plants to everyday life is a message that needs to be conveyed well and often to the public, and especially to young students. Plant sciences need to be better integrated into biology curricula with animal sciences if the brightest and best students are to be attracted from all research areas. The message that training in the plant sciences provides opportunities for globally impactful careers should be highlighted, along with the diverse attractive career options and the future employment opportunities that will not be solely in traditional fields. For example, the increasing use of sensors to monitor fields will result in a need for data scientists and engineers who can develop and use these technologies, both in the public and private sectors.

What tools and technologies are needed to get there?

Cross-cutting tools that can be applied to any plant hold the promise of a much greater pay-off than those developed for specific plants. The next generation of gene-editing technologies have the potential not just to remove the deleterious genes carried along in earlier traditional breeding efforts, but also to introduce precise modifications of individual target genes alone or in pathways and networks.

Genome editing, using the next generation of tools based on Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) or Transcription-Activator-like Effector Nucleases (TALENs), as well as other new tools, will enable going beyond modification of single gene targets. Increasing the number of edits to more than a hundred targets simultaneously would be game-changing. A major bottleneck in achieving these gains is the low efficiency of transformation for many plant species. A better understanding is needed of the factors critical to transformation efficiency. Stimulation of research to get there may require support using a milestone-driven approach to funding as well as public-private partnerships, especially for minor crops that are not a private sector focus.

Tools for accelerated breeding such as genomic selection, speed breeding [23], and doubled haploids will be critical in getting the new genotypes into desired crops and elite lines and out into the field as quickly as possible. Low-cost, high-throughput phenotyping tools and technologies are needed for evaluation of new genotypes under field conditions in the developed and developing world. There are gaps in our knowledge of below-ground aspects of plant growth and development, as well as soil microbiomes and plant-microbe interactions in the field, that need to be addressed if the major challenges are to be solved.

Low-cost sensors that transmit field data to a farmer’s mobile phone can facilitate better management of inputs and the impact of diseases and pests. Mobile phone cameras have potential as powerful data collection tools when combined with appropriate software, algorithms, and deep learning analytics. Information and communications technologies offer huge opportunities for real-time data collection and feedback for crop management during the season. These data can also feed into identification of targets for future genetic improvement.

Data and modeling are central to a “system of systems” approach

We are on the threshold of being able to develop whole-plant predictive models that allow potential targeting of specific traits, genes, and pathways for editing. Data resources are becoming available to facilitate this new area. However, there are significant limitations to data access and in data quality. Missing data types include climate measurements, genetic diversity, below-ground data (e.g. soil nutrients and plant root performance), as well as dynamic data such as plant phenotypes in the field *versus* inputs. In Africa, the limited support for statistical services and collection of farm-level data has negatively impacted the data availability and quality. As a result, information on current production and rate-limiting nutrients in digital soil maps for precision agriculture are missing. There is also a critical need for access to global data collected through monitoring of disease appearances and outbreaks so that interventions can be timely and precise. Plant disease research urgently need the same levels of investment made for human disease outbreaks since the potential economic and health impacts of crop loss are just as significant.

Large, high-quality plant datasets, from genetic data through to performance, will foster predictive modeling as an approach to understanding targets for research and management interventions. Current challenges include the lack of key datasets, the existence of multiple models, and the need for whole plant models. Models can indicate where to focus and speed up breeding and translation. However, current models have been developed independently and are less useful for a "systems of systems" approach without integration. Also, knowledge of what, how, and where to edit is needed given the extraordinary diversity of potential targets. Platforms like *Crops In Silico* [24] allow linkage of models across different biological scales, from cell to ecosystem level. This could provide more accurate simulations of plant response to the environment than any single model could achieve alone.

A computational core will be needed to fully support future modeling efforts. Development of strategies to achieve this could effectively build on the expertise and experience in other fields such as defense, high energy physics, and astronomy.

The potential impact of the next generation of predictive models in a "system of systems" approach will be profound. It will become possible to design and model traits, identifying new areas of genetic potential and sampling of new genetic space that has not been previously tapped.

Basic research is critical for sustained momentum

Basic research outcomes have been the foundation of many gains in agriculture. A steady decline in agricultural research funding means that basic research outcomes are drying up, and there is an urgent need to increase basic research required to address and accelerate agricultural outcomes. Improvements in our understanding of plant growth and development emerging from basic, discovery research has allowed the development of better strategies for crop improvement, from biological nitrogen fixation to photosynthetic efficiency. Similarly, the development of disease resistant crops has built on an improved understanding of plant disease resistance mechanisms and the underlying genes in the plant and the pathogen. However, there are many traits for which we still do not know the underlying genes or how they interact, and many traits are waiting to be tested in crops rather than in model plants. More rapid and advanced breeding technologies using genomics and phenomics are required to introgress potentially beneficial traits currently at the laboratory or academic literature stage.

Genetic diversity within crop species and across the plant kingdom is a vastly underexploited opportunity. The Green Revolution decreased the diversity of germplasm in use, but we cannot simply return to the older varieties without giving up the gains we have made in crop yield during the last 60 years. Instead, we need to move forward using improved knowledge and tools to exploit genetic diversity in new ways towards sustainable intensification of agriculture [25].

Basic discoveries that were not driven by the need to find solutions to specific problems have fueled the development of new tools and technologies. Two examples are CRISPR and Bt toxin; the latter is now widely used as a plant-incorporated protectant against Lepidopteran insects.

The underlying mechanism or mechanisms of heterosis (hybrid vigor) are still poorly understood. Tremendous yield gains have been made using hybrid technologies in maize, primarily through private sector investments. Research gains are being made in rice and more slowly in wheat with private and public investments. Application of hybrid technologies to a broad range of crops in a precise and directed way will be advanced by a mechanistic understanding coming from basic research outcomes.

Basic research discovery, from genetics to precision agronomy, remains the engine of innovation for agriculture and a central part of any strategy to address the major challenges, those known now and those yet to come. The considerable agricultural gains made on farms in the last century came from the genetics of plants and microbiota in combination with the agronomic management. Looking forward, plant research must create system synergies to realize the potential of new genetics and use global resources efficiently.

Summary

Plant research has yielded many advances in agriculture and served as the foundation of the first Green Revolution. The second Green Revolution will benefit from, and could be guided by, whole-plant modeling to pinpoint the most effective points of intervention, from genetics to field management. It will build on continued discoveries from basic research, from advances in understanding of plant growth and development of new tools and technologies. The next generation of researchers will require new skills to lead these efforts. Effective cooperation and coordination across the public and private sectors at national and international levels will be necessary to approach the challenges outlined here. Flexibility and agility will continue to be key as plant research tackles current and emerging challenges brought about by population increases, climate change, and limiting natural resources.

ABOUT THE SOAR FOUNDATION

SoAR is a non-profit, non-partisan coalition of partners representing more than 6 million farming families, 100,000 scientists, hundreds of colleges and universities, consumers, veterinarians, and others. Together, we are working toward our mutual goals of increasing federal investments in agricultural research to produce the best possible food and agriculture science and focusing more of our best minds on feeding America and the world. SoAR advocates for additional agricultural research support, including full funding of the Agriculture and Food Research Initiative, USDA's flagship competitive grants program. This will be a benefit by:

- Protecting public health by enhancing the nutrition, affordability, and safety of food
- Improving soil, air, and water quality
- Discovering new treatments and cures to diseases
- Strengthening the U.S. economy, creating jobs, and increasing profitability
- Contributing to the food security and stability of all nations.

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