


Unleashing a Decade of Innovation in Plant Science

A VISION FOR 2015-2025

To create crops that are flexible and adaptable to the challenges of environment and population, we must increase the predictive and synthetic abilities of plant scientists. **The sustainability of our agricultural enterprise is at stake.**

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Executive Summary

Genesis of the Plant Summit.

The goal of a sustainable future, with a more nimble and innovative workforce and a highly competitive research enterprise, is in the national interest. The challenge, however, is to execute this strategy in an era of economic limits, when anticipated outcomes must justify the investment of limited resources. This document is the product of a two-phase Plant Science Research Summit (see page 34 for more information) held at the Howard Hughes Medical Institute (HHMI) in 2011 and 2013, coordinated by the American Society of Plant Biologists, and supported by the National Science Foundation (NSF), the U. S. Departments of Energy (DOE) and Agriculture (USDA), and HHMI. Through an iterative, strategic visioning process, representatives of the plant science community developed this *Plant Science Decadal Vision* that responds to the urgent needs and tremendous opportunities that confront our nation and the world. We cannot meet the food, feed, shelter, and energy demands of the burgeoning global population—especially with climate instability as a backdrop—while the American investment in plant-related research stagnates. Ending that stagnation, instead, can leverage the new technologies that have transformed biology, accelerating the pace of discovery and promising solutions that can be both creative and sustainable.

The vision articulated here, which will dramatically increase the ability of plant scientists to understand, predict, and alter plant behavior, is synergistic with other national calls to action, including *A New Biology for the 21st Century,*[1] the *National Bioeconomy Blueprint,*[2] and the *Report to the President on Agricultural Preparedness and the Agriculture Research Enterprise.*[3] achieving the *Decadal Vision* will require cooperation among many stakeholders,

a sense of
urgency

“Ensure that the United States **leads the coming biology revolution.”**

"It is shocking—not to mention short-sighted and potentially dangerous—how little money is spent on agricultural research." – Bill Gates

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI)

***Sub1* Experiment**. Rice varieties with the *sub1* gene being tested at IRRI. The *sub1* gene is responsible for flood tolerance in rice.

including academia, federal agencies, the private sector, foundations, and international partners. To coordinate these efforts, we recommend the formation of a National Plant Science Council, which would serve as a forum for updating, communicating, and monitoring the impact of this initiative.

Failing to realize the promise for advances in plant science research will have sobering consequences. Chronic underinvestment leads to loss of competitiveness, missed opportunities, and environmental and community degradation through use of outmoded technologies. The 2012 *Report to the President on*

To feed a projected population of 9.15 billion in 2050, agricultural **productivity must increase by 60%**.

PRODUCTIVITY MUST INCREASE

by **60**%

Transformation and Opportunity: The Future of the U.S. Research Enterprise [4] detailed this situation and argued for an investment in research and development (R&D) of 3% relative to gross domestic product. In the case of agriculture, in which current R&D investment languishes well below this number[5] and other indicators are equally grim,[6] an inability to deliver nutritious food and therapeutics could be catastrophic, ultimately posing a national security threat reminiscent of riots associated with recent commodity price spikes in the developing world.

The unique value of the *Decadal Vision* arises from its embodiment of a consensus agenda developed by international and domestic plant scientists, its linkage to other calls to action, its anticipated economic impact, and the clear and urgent need to reimagine how the research enterprise can and must support the agricultural sector.

Specific Goals of the Plant Science Decadal Vision.

Five interwoven components are recommended to accomplish the objectives:

1 Increase the ability to predict plant traits from plant genomes in diverse environments.
Plant genetic blueprints underlie productivity, resistance to pests and diseases, and the ability to flourish in a wide array of environments and climatic conditions. However, the ability to interpret those blueprints, which reflect a complex evolutionary history, is only in its infancy. To bridge this knowledge gap, we recommend programs that will (1) link genome to performance during environmental change and biotic interactions by establishing the interconnections among a plant's genes, their myriad cellular products and functions, and the ways these determine agronomically important plant traits;
(2) expand plant phenotyping capabilities, in particular drawing on advances in computation and robotics;
(3) define how plant species have naturally adapted to stressful or extreme environments, specifying biological mechanisms that can be harnessed for agriculture;
(4) understand the dynamics of plant communication, from the intracellular to the interorganismal scale; and
(5) establish a comprehensive plant attribute database that integrates genetic, molecular, and chemical data with developmental, architectural, field performance, and environmental parameters.

The agricultural sector is currently responsible for **one in every 12 U.S. jobs.**

ONE IN EVERY

12 jobs

One of Earth's greatest assets is its immense diversity of life forms, yet we have only scratched the surface in cataloging plant-derived chemicals and their biological purposes, even as species are lost through extinction.

❷ **Assemble plant traits in different ways to solve problems.** Newly discovered traits will need to be introduced into crop species through 21st-century breeding strategies or the virtually unlimited possibilities of synthetic biology. To establish and implement these capabilities, we recommend (1) funding relevant research using challenge grants, collaboration strategies, and training programs that combine biology, breeding, engineering, and computational talent and (2) investing in large-scale genetic, genomic, and biochemical characterization of wild or heritage germplasm related to crop species.

❸ **Discover, catalog, and utilize plant-derived chemicals.** One of Earth's greatest assets is its immense diversity of life forms, yet we have only scratched the surface in cataloging plant-derived chemicals and their biological purposes, even as species are lost through extinction. These uncharacterized chemicals constitute a virtually inexhaustible but mostly untapped resource for agricultural, bioproduct, and biomedical applications. To realize this potential, we recommend (1) determining the chemical composition and biosynthetic pathways in 20,000 ecologically and medicinally important species to understand the synthesis and biological purposes of plant-derived chemicals and (2) utilizing plant chemistry for applications in human health, agriculture, and manufacturing.

❹ **Enhance the ability to find answers in a torrent of data.** For plant biology to become a reliably predictive science, data analysis must undergo a paradigm shift. Defining the complex relationships that underlie plant behavior will require (1) integrating data through the perfection of statistical models, application of machine learning, and validation of functional predictions from models and (2) facilitating data storage, retrieval, and analysis through incentivizing, enabling, and training scientists to share data freely and habituating scientists to develop or test hypotheses through intensive data analysis before conducting wet lab or field experiments.

❺ **Create a T-training environment for plant science doctoral students.** Innovation in agriculture will flourish only if training environments keep pace. The current doctoral training system, with its slow pace

"In 2012, USDA designated 2,245 counties in 39 states as disaster areas due to drought, or **71 percent of the United States.**"

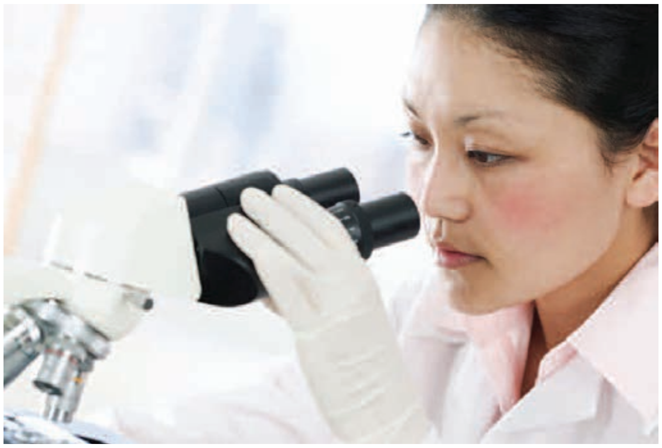
39 of 50 states

DROUGHT DISASTER AREAS

Fundamental laboratory discoveries currently drive agricultural improvements in most major crops because the agricultural sector excels at implementing promising technologies.

and focus on a traditional academic pathway with limited job prospects, is associated with dissatisfaction and attrition, stagnant trainee numbers, and stubbornly poor gender diversity at the faculty and executive levels. We propose implementation of a T-training format that retains the vertical, discovery-based scientific apprenticeship in a mentor's laboratory but adds horizontal skills that cross-train students and prepare them for a wide variety of careers while shortening the time to degree. To engage institutions, federally supported training grants would require suitable commitments from institutional and industrial partners.

GETTY IMAGES



Institutions must take a close look at how to expand and support modernized career preparation.

Outcomes.

Basic research has a tremendous track record of producing jobs, economic activity, and far-reaching societal benefits. Fundamental laboratory discoveries currently drive agricultural improvements in most major crops because the agricultural sector excels at implementing promising technologies. A recent example is submergence-tolerant rice; a gene identified through USDA-funded research has now been bred into multiple varieties grown worldwide.[7]

Likewise, the research proposed in the *Decadal Vision* can lead us to novel solutions for improving the sustainability of agriculture and the bioeconomy, even in the face of challenges such as climate change, population growth, and limited natural resources such as water and arable land.

Cross-train students and prepare them **for a wide variety of careers.**

T-training

A National Call to Action

Catalyzing the vision for 2015-2025

LITTLE_KAREN (FLICKR)

Icicles hanging from oranges on tree in Florida, USA.

The plant research community is not alone in recognizing the importance of 21st-century investments in plant and agricultural sciences and imperatively recommending substantial action to ensure the necessary infrastructure and human capital in research, education, and application.

The specific recommendations for plant science defined here are synergistic with, and emergent from, several recent reports that highlight this watershed moment in plant science research.

A New Biology for the 21st Century[1] is a 2009 National Academies study whose recommendations are meant to ensure that "the United States leads the coming biology revolution." One major recommendation of *New Biology* is that initiatives address societal challenges in food, energy, environment, and health. The *Plant Science Decadal Vision* tackles each of these through the lens of interdisciplinary, plant-driven science. *New Biology* further assigns priority to information technologies, cross-disciplinary collaborations and curricula, and interagency collaborations, all of which are components of the *Decadal Vision*.

The National Bioeconomy Blueprint[2] was published by the White House Office of Science and Technology Policy in April 2012. The blueprint extensively covers plant-based bioproducts and points to synthetic

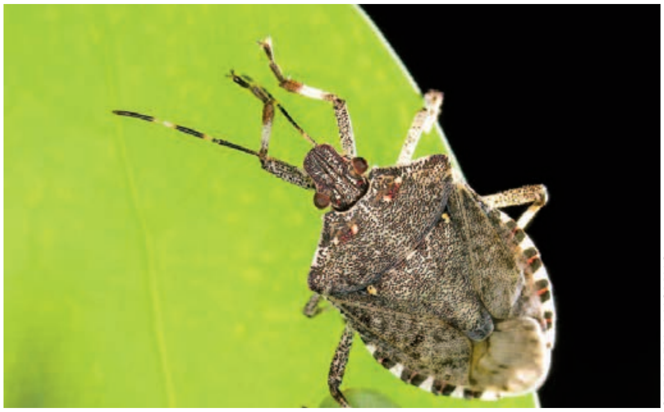
PCAST concluded that the nation is not prepared for future agricultural challenges and recommends major R&D investments achieved through expanding the role of competition at USDA and increasing support through NSF.

biology and bioinformatics as key modalities to achieve these goals. In the *Decadal Vision*, the emergence of new plant-inspired industries is envisioned in part through advances in these areas.

Finally, the President's Council of Advisors on Science and Technology (PCAST) *Report to the President on Agricultural Preparedness and the Agricultural Research Enterprise*,[3] published in December 2012, concludes that the nation is not prepared for future agricultural challenges and recommends major R&D investments achieved through expanding the role of competition at USDA and increasing support through NSF.

SCOTT BAUER

In soybeans, extreme drought can raise the proportion of the healthful antioxidant alpha-tocopherol.



STEPHEN AUSMUS

The brown marmorated stink bug (Halyomorpha halys), a winged invader from Asia that is eating crops and infesting U.S. homes, is spreading and is expected to continue to do so.

Each of these three reports, like the *Plant Science Decadal Vision*, imparts a sense of urgency and arose from a collaborative process among research scientists, policymakers, and the private sector. Together they point unambiguously to both the threats and the opportunities that face the nation and illuminate a path forward.

a national call to action

The nation is not prepared for **future agricultural challenges.**

Innovation

Unleashing a decade of innovation in plant science

BIOSERIE

Create new plant-inspired products for industry as shown by these phone cases from bioserie.

To sustain crop productivity in an increasingly unstable climate, to deploy agricultural systems that protect natural resources, to use nature's biological and chemical innovations to solve problems that crops increasingly face (water, thermal, salinity, and nutritional stresses), and to capture the economic opportunities in improved crop varieties and novel plant bioproducts all require a visionary and interdisciplinary research capacity that is accompanied by coordination and openness in data sharing. These requirements entail not only an unwavering commitment to excellence and innovation by the research community, but also a serious commitment to reforming the existing model of graduate education. Each of these research and educational goals is addressed through one or more components of the *Plant Science Decadal Vision*.

The overarching objective of the *Decadal Vision* is to build across disciplines including plant science, chemistry, engineering, and computational sciences to advance research through the continuum of observational to predictive to synthetic. Among the possibilities within reach are improving the agronomic properties of crop varieties through, for example, rapid deployment of resistance to emerging pathogens[8]; designing plants for new functions; using native plants as "libraries" to harness their adaptive mechanisms and novel products for medicine and industry; and understanding the roles and regulation of plant genes in thousands of species. To preserve and increase agricultural productivity in a wide range of environments will require a much deeper understanding of everything from photosynthesis, in

These requirements entail not only an unwavering commitment to excellence and innovation by the research community, but also a serious commitment to reforming the existing model of graduate education.

which sunlight is initially captured, to the means by which plants perceive and communicate with many thousands of organisms that directly interact with them above and below ground. The exceptional ability of U.S. industry to implement technologies that have advanced through proof of concept is a further impetus to action.

Timely execution on the *Decadal Vision* is critical for many reasons. The goals being proposed are designed to protect and improve crop productivity, quality, and nutrition. They leverage conservation management activities that maintain and improve natural resources

LUKE CHANCHAN (FLICKR)

Protect and improve crop and forest productivity.

and precious, dwindling biodiversity, and they support the creation of new plant-inspired industries and "innovation ecosystems" directly in line with PCAST's recommendations.[3]

The objectives of the *Decadal Vision* are also aligned with international plant science priorities, which should facilitate the cooperation that will be required to understand the extreme complexity and diversity of plant life and to use the resultant insights. An international workshop held in 2009, for example, identified as

JESSICA WILSON (FLICKR)

Conserve our natural resources.

high-level objectives resource conservation, data collection and sharing, and integration of information to understand plant function.[9] International consensus on these research thrusts is perhaps not surprising given that the challenges facing agriculture are global.

The following pages describe the major objectives that will enable the desired outcomes. These ideas should not be pursued to the exclusion of other efforts, but they should be of high priority because they will synthesize different threads in a way that will excite a new generation of scientists, leverage the innovative capacities of public and private funding bodies, and contribute to a more secure and sustainable future for our nation and the world.

The exceptional ability of U.S. industry to implement technologies that have advanced through proof of concept **is a further impetus to action.**

Chapter 1: Predicting Traits

Increase the ability to predict plant traits from plant genomes in diverse environments

The ability to build a predictive model of plant environmental responses is within reach but will require coordinated, community-wide, large-scale data capture and integration. Just as the era of plant genomics was ushered in through the Arabidopsis Genome and National Plant Genome Initiatives,[10,11,12] the era of the "virtual plant" can be achieved through the goals of the *Plant Science Decadal Vision*. Functional knowledge of every gene and biosynthetic pathway contained within a limited number of reference species, selected for their key biological attributes, would provide important momentum and create numerous ancillary benefits in a much wider range of species. To accomplish this, we recommend the following research objectives.

Link genome to performance during environmental change and biotic interactions.

Although the rising number of publicly available plant genome sequences represents an unprecedented compendium of genetic variation, we are far from a full understanding of the relationships between genome features and plant traits. To bridge this gap will require extensive and methodical detailing of how gene regulatory processes work and how their outputs of RNAs, proteins, and chemical products mediate responses to environmental and biotic influences. A great depth of knowledge should be achieved initially in select reference species that include not only the well-studied Arabidopsis, but also key grasses, legumes, woody perennials, and algae. Programs should link the "omes" (e.g., genome, transcriptome, proteome, epigenome, ionome, and metabolome) to expressed plant features in controlled, agricultural, and natural environments. These data sets will facilitate modeling and improvement in a broad range of commercially, agriculturally, and ecologically important plants. By implementing and using a comprehensive plant attribute database (as detailed on page 15), the trove of historical genotype-by-phenotype data collected by USDA and other scientists in crop breeding experiments can gradually be integrated with the newer data sets.

Expand plant phenotyping capabilities.

The completeness of data will also depend heavily on augmented collection abilities. The advent of remote sensors linked to centralized databases makes large-scale auto-

Biologists, computational scientists, and engineers have collaboratively developed exciting prototypes such as robots designed for **3D sensing of plant growth.**

3D
SENSING OF PLANT GROWTH

Linking genomes to plant traits will expand dramatically the ability to predict how plants will grow and produce in a wide range of environments. Such knowledge is required to sustain crop yields in the face of climate change and with fewer inputs.

mated approaches possible. To achieve a much denser coverage of plant data, robotic devices will increasingly be used. Biologists, computational scientists, and engineers have collaboratively developed exciting prototypes such as robots designed for 3D sensing of plant growth[13] or row crop applications.[14] Continued development of high-resolution imaging methods and their installation in robotic, automatic phenotyping equipment in both field and laboratory are required. Although some applications will be cost-effective for individual laboratories, regional centers should also be used to rapidly drive development and

FORSCHUNGSZENTRUM JÜLICH. HANNO SCHARR

Robots are used increasingly to make real-time measurements in the laboratory and field. The GARNICS robot is designed for 3-D sensing of plant growth.

adoption of highly sophisticated data collection technologies, promote data standardization, enhance collaboration and efficiency, and reduce research costs for individual laboratories. This type of benefit is already occurring from established research centers, such as the DOE-supported Center for Advanced Algal and Plant Phenotyping (CAAPP)[15] at Michigan State University, which is focused on photosynthesis, and the DOE Joint

TONY GRIFT, UNIVERSITY OF ILLINOIS

The AgBo robot developed at the University of Illinois for row crop applications can track up and down rows

Genome Institute (JGI), focused on sequencing technology and its applications. Distributed phenotyping centers such as the National Ecological Observatory Network[16] will also contribute data. NSF, USDA, and DOE are currently considering the potential of further investments in phenotyping capabilities,[17,18] which must be carefully chosen for maximum impact and include analytical capacities at the organismal, cellular, and molecular levels.

Define how plant species have naturally adapted to stressful or extreme environments.

A plant's ability to adapt quickly while tethered in place is a survival strategy that relies on a combination of genetic potential and an innate capacity for remodeling and regeneration. The adaptation process is complex, integrating epigenetic, microbiotic, and extrinsic and intrinsic chemical and physical signals. Programs are needed that define the range of required components in species naturally adapted to heat, cold, drought, flooding, poor soil, and the presence of toxins with the goal of creating libraries of adaptive biological mechanisms, or "adaptomes," defined by sets of genes, proteins, and

Antarctic hair grass at Petermann Island, Antarctica.

small molecule signals. These naturally adapted species will include both understudied non-crop species and crop accessions. Diverse crop germplasm is likely to be a much richer resource than production varieties, in which domestication has led to a loss of plasticity in favor of uniformity and yield.

Understand the dynamics of plant communication.

Plants express their biological and chemical components within the context of architectural features such as leaves, stems, roots, cell walls, a circulatory system, cell layers, and specialized junctions,

Creating libraries of adaptive biological mechanisms, or **"adaptomes,"** defined by sets of genes, proteins, and small molecule signals.

adaptomes

ADAPTIVE BIOLOGICAL MECHANISMS

Programs are needed to explore how plants create and use their novel architecture to communicate in real time, which will provide indispensable information for predictive modeling.

permitting the communication required for small- and large-scale responses. Programs are needed to explore how plants create and use their novel architecture to communicate in real time, which will provide indispensable information for predictive modeling. Such signals are involved, for example, in the establishment and maintenance of symbiosis, pollination, resistance to herbivory or pathogens, competition with weedy or invasive plants, and allelopathy. Integration of organismal, environmental, chemical, and genetic information will be required, including that of host plants and associated microorganisms. Although some of these processes can be studied in isolation, native habitats—replete with all of the evolutionary forces that have sculpted plant genomes—are invaluable natural laboratories for the study of gene function and should be incorporated into plant trait assessments.

Establish a comprehensive plant attribute database.

With the goal of integrating a wide range of measurements to link genome to phenotype, the plant community must agree to and institute a cooperative and standardized process for data storage, formatting, and access. The requisite database, which is likely to be constituted as a virtual or distributed network, should house molecular and chemical information along with developmental, architectural, field performance, and environmental parameters. By standardizing data formats and metadata such as time, location, and method of collection, information will be readily available and interchangeable among all stakeholders, including environmental stewards, industry and academic laboratory scientists, funding agencies, and scientific journals. By promoting a machine-readable standard data format, a new generation of models and automated analysis will be enabled. The process of agreeing to standards and implementing them across the community should capitalize on federal investments already in place for large-scale plant data collection, including NSF-sponsored iPlant, DOE-sponsored Systems Biology Knowledgebase (Kbase), and USDA's Germplasm Resources Information Network (GRIN).

By promoting a machine-readable standard data format, **a new generation of models and automated analysis** will be enabled.

GRIN Kbase iPlant

LARGE-SCALE PLANT DATA COLLECTION

Chapter 2: Assembling Traits

Assemble plant traits in different ways to solve problems

Discovering through the lens of biodiversity the genetic, developmental, and metabolic basis of how plants maintain their vigor in the face of extreme temperatures, competition with weeds, pest and pathogen attack, nutrient deficiency, or poor soil conditions would represent a tremendous research accomplishment. Learning to introduce these capabilities into crop species will be required to continue the remarkable and steady progress in yield enhancement that accelerated in the 1960s. Current technology has allowed single genes to be introduced into many plant species to create herbicide, insect, or pathogen resistance or confer flood and water stress tolerance, and more recently small groups of genes have been introduced to change nutritional or energy content. But to introduce entire adaptive pathways will require the art of "plant design," which will entail collaboration among biologists, engineers, bioinformaticists, chemists, plant breeders, and agronomists. This "New Biology" will thus combine robust data mining and analysis with modeling to define genetic packages or adaptomes that will confer desired traits, technologies that move those adaptomes into target species through breeding or engineering, and a vigorous and transparent dialogue with seed companies, producers, and consumers. To accomplish this, we recommend the following objectives.

Empower multidisciplinary teams to identify and introduce desired traits

To foster the collaborations that are essential to successful plant design, innovative programs are needed that draw engineering and computational talent to these plant science–based endeavors while integrating economic, societal, and health perspectives.

Approaches that could accomplish this goal might include challenge grants and industry-sponsored innovation programs or models based on NSF Ideas Labs, in which invited participants engage in an intensive visioning process that leads to novel funded projects.

Another successful model, represented by the Defense Advanced Research Projects Agency (DARPA) and the Advanced Research Projects Agency-Energy (ARPA-E), is to solicit innovative and high-risk proposals in response to emerging needs. Collaborative arrangements could also be embodied within interdisciplinary graduate training programs or efforts that closely link industry to the basic research sector.

Promote creative use of plant breeding technologies

One way to shuffle adaptomes is through plant breeding. Even though genetic crosses are restricted to interfertile species, most of the tremendous genetic diversity available for this purpose, most notably wild relatives of crop species, remains to be exploited. Preservation of germplasm, like conservation of biodiversity, will be

Using technologies that were unthinkable a decade ago, scientists are learning to modify organisms to include custom complements of genes.

central to the ability of scientists to integrate desired traits from wild or heritage accessions. Furthermore, sequence and phenotype information must be obtained and archived for use. Laboratory-scale robotics and intensive "omics" analysis of diverse germplasm are two areas in which high-value investments can be made, leading to breeding strategies that can be implemented in the commercial or nonprofit sectors. For example, the International Rice Research Institute has used diverse accessions that are not normally grown for food to develop rice varieties tolerant to a range of climatic stresses that are becoming more frequent and intense.[19] Another example is HarvestPlus, an international consortium focused on developing biofortified crops.[20]

SOLAYZME

Knowledge of biochemical pathways and appropriate technologies has enabled companies such as Solazyme to robustly discover and develop algal strains that produce high-value products like those shown here.

Create novel phenotypes through synthetic biology

Using technologies that were unthinkable a decade ago, scientists are learning to modify organisms to include custom complements of genes. The transplantation of a plant pathway into yeast to produce a precursor of the antimalarial compound artemisinin[21] was a major achievement, but a new frontier was breached in 2010 when an entire bacterial chromosome was synthesized from scratch and brought to life in a cell.[22] In plants, dramatic progress has been made toward customizing chromosomes to provide complex genetic traits[23] and in achieving artificial photosynthesis.[24] Programs are needed to further understand chromosomal features required for stable inheritance and to support mechanisms for synthesis and introduction of customized chromosomes or for gene replacement. Although not strictly focused on plants, the DOE Joint Genome Institute's 10-year strategic plan includes efforts to link genome to phenotype and to use that information for synthetic approaches.[25] Thus, technology development for plant science can take advantage of these planned efforts.

Preservation of germplasm is central to the **ability of scientists to integrate desired traits from wild or heritage accessions**.

customizing
chromosomes

Chapter 3: Harnessing Plant Chemistry

Discover, catalog, and utilize plant-derived chemicals

Young wormwood *Artemisia absinthum*.

From algae to trees, from marine to terrestrial, plants have fed, clothed, and sheltered us; enriched our pharmaceutical and manufacturing industries; cushioned our agricultural systems against new pests, pathogens, and weeds; and supported a rapidly evolving bioenergy and bioproducts sector.

Yet these diverse societal roles use only a tiny fraction of what plants have to offer. For example, although Earth is home to some 400,000 species of flowering plants, a mere 30 of these presently provide over 95% of human food and energy needs, in contrast to the some 7,000 that have been cultivated for consumption during human history.[26] A much larger number of species, 20,000 or more, have been used for medicinal purposes, presumably because of their unique chemical compositions.[27] In the vast majority of cases, however, the basis for palliative properties is not known because of a dearth of information about those plants' components.

Efforts to catalog plant species diversity are making substantial progress[28] even as losses continue through extinction. Scientists have a window of opportunity to collaborate with biodiversity and conservation experts to conserve and explore this dwindling and priceless resource—one whose chemical repertoire

Earth is home to some 400,000 species of flowering plants, a mere 30 of these presently provide over 95% of human food and energy needs, in contrast to the some 7,000 that have been cultivated for consumption during human history.

did not evolve to serve humans, but instead underpins strategies that have allowed survival under extreme or unusual biological or environmental conditions experienced throughout Earth's geological history. To harness these assets for the agricultural, bioproduct, and biomedical industries and to attain a quantum leap in the appreciation of plant chemistry, the following interlaced efforts are required.

Understand the synthesis and biological purposes of plant-derived chemicals

No systematic effort has been made to discern the full diversity of plant chemistry—particularly the unique secondary metabolites found in specific biological niches—or to decipher the genetic programming that generates them. Yet, where efforts have been directed—for example, to volatile compounds that attract insects or the alkaloids that are heavily used in medicine—the "magic" of plant chemistry and its potential applications has been revealed. We recommend that the chemical compositions of at least 20,000 plant species, or roughly 5% of extant diversity, be determined. These species should be selected on the basis of knowledge about their phylogenetic and ecological character as well as evidence of their historical or present-day use as medicinal or biocontrol sources. Establishing the biosynthetic pathways for potentially bioactive compounds that are discovered and their regulation will necessitate gene sequence and expression information from thousands of plant species and will require collaboration among chemists, molecular biologists, and experts in plant gene evolution. Existing domestic efforts centered at the DOE's JGI, as well as international contributions, are expected to provide a foundation for this effort, which should be enriched by targeted complementary programs.

Utilize plant chemistry

Chemical discovery opens the door to the broad-scale use of compounds that are often found in small amounts and sometimes in threatened species. One path is xemplified by the antimalarial compound artemisinin, whose biosynthetic pathway was recently defined and transplanted into yeast, creating a low-cost source of this pharmaceutical for the developing world.[21] Similarly, the anticancer drug Taxol was discovered in a broad, federally funded screen of plants for useful chemicals[29] and today is economically produced from plant cell cultures.[30] Nearly 120 pure compounds extracted from plants are used globally in medicine,[31] hinting at the significant possibilities for future discoveries applicable to human health, agriculture, and manufacturing.

To achieve these goals, the modes of action for promising chemicals identified during screening must be determined, and pathways to commercialization must be smoothed and encouraged. The former will require appropriate high-throughput assays and significant abilities in complex synthetic chemistry, whereas the latter will require financial support and regulatory streamlining, as discussed in other recent reports.[2,4]

Chapter 4: From Data to Solutions

Enhance the ability to find answers in a torrent of data

For plant biology to become a reliably predictive science— a prerequisite for meeting the challenges defined in the *Plant Science Decadal Vision*—a new generation of data collection and analysis capabilities is required. Such a transition will be to the benefit of all life sciences not only by revealing commonalities across microbial, plant, animal, and human systems, but also by establishing a fertile environment for cross-training and collaborations among computational scientists, biologists, and engineers. To achieve this goal, the following objectives must be met.

Integrate data

Over the past five years, we have seen exponential increases in the efficiency and depth of genome sequencing. Similar advancements have hastened the ability to survey a wide range of cellular molecules. The rate of technological advancement and thus data collection will continue to increase, creating an urgent need for new tools and strategies to enhance the biological value of data modeling and analysis. As discussed on page 12, a strong infrastructure for data collection, formatting, and transparency will greatly accelerate analytical breakthroughs. A glimmer of how different kinds of information can be computationally integrated comes from the recent success in accurately predicting phenotype from genome through whole-cell modeling of a human bacterial pathogen.[32] What can be done for a single cell can and must be done for complex organisms such as plants. Investment in the improvement of statistical models, application of machine learning, machine-readable data repositories, processing and analysis resources, and validation of functional predictions from models are all needed.

Train scientists to maximize the utilization of data

Analysis of large data sets must be as integral to the training of the next generation of life scientists as biochemistry, physiology, genetics, molecular biology, and genomics have been to the current generation. Distilling these enormous data sets for biological meaning and the inherent opportunities for innovation that this process offers will usher in a new era of plant science research. Furthermore, a tremendous opportunity exists for scientists to make use of others' data, rather than generating their own, to develop or test hypotheses. Should this occur on a large scale—

What can be done for a single cell can and **must be done for complex organisms such as plants.**

single cell

COMPLEX ORGANISMS

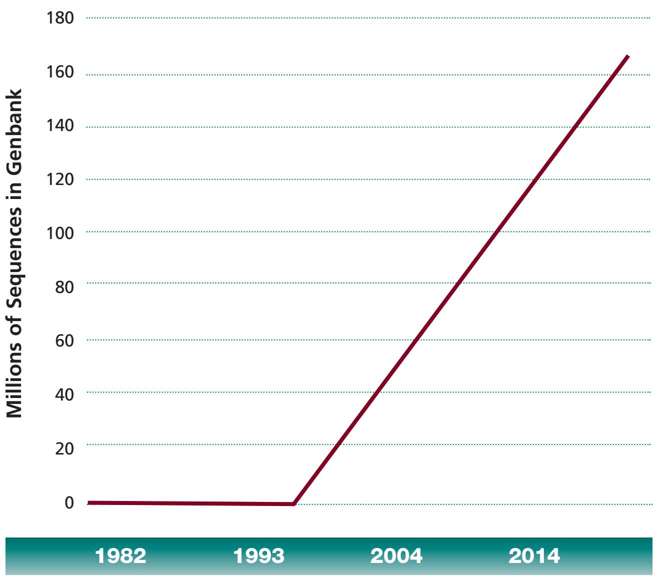
Because the proliferation of data and the need to access data globally is far from a plant science–specific problem, numerous efforts are already targeted to appropriate solutions.

something that can be triggered by improvements in data infrastructure—we will vastly increase the efficiency of the research enterprise, deepen the value of each data point, and ultimately increase the likelihood of practical outcomes.

Facilitate data storage, retrieval, and analysis

Because the proliferation of data and the need to access data globally is far from a plant science–specific problem, numerous efforts are already targeted to appropriate solutions. For example, both NSF and the National Institutes of Health (NIH) are investing in solutions to the "Big Data" problem[33] following an initiative developed by the White House Office of Science and Technology Policy.[34] The *Decadal Vision* prioritizes storage and access of, as well as derivation of knowledge from, data in both research and educational contexts. However, the plant community will need its own standards and analytical methods, including a community process, to implement those standards. Thus, Big Data solutions can be capitalized on for the benefit of plant science, but they must be customized for the specific activities of this research community.

Figure 1: Increase in Genome Sequencing



Inexpensive sequencing technologies have contributed to the exponential increase in the number of DNA sequences deposited in Genbank since 2000.

A tremendous opportunity exists for scientists to make use of others' data, rather than generating their own, to develop or test hypotheses.

deepen

THE VALUE OF EACH DATA POINT

Chapter 5: Reimagine Graduate Training

Create a T-training environment for plant science doctoral students

Although the entire science, technology, engineering, and mathematics (STEM) education chain from grade school through university has come under scrutiny, with several reports,[35,36,37] articulating possibilities for fundamental change, summit participants focused on the graduate training experience. In the United States, the lengthy training period and limited academic job prospects are associated with increasing disenchantment[38] on the part of PhD students, attrition, and a shrinking cohort of new trainees. Academic jobs will remain in short supply, but many other career paths are open to successful biology PhDs, including industry, law, venture capital, journalism, teaching, advocacy, and government service. In fact, only one of six biology PhDs in the United States lands a tenure-track faculty position within five years of graduation.[39] Therefore, doctoral candidates need to be prepared for multiple career tracks, but not at the expense of the scientific discovery opportunities that attracted them to graduate school and that will form a vital part of their qualifications for their future career. Moreover, it is crucial that we identify a training path that serves to close the gender gap at the level of fully established scientists.

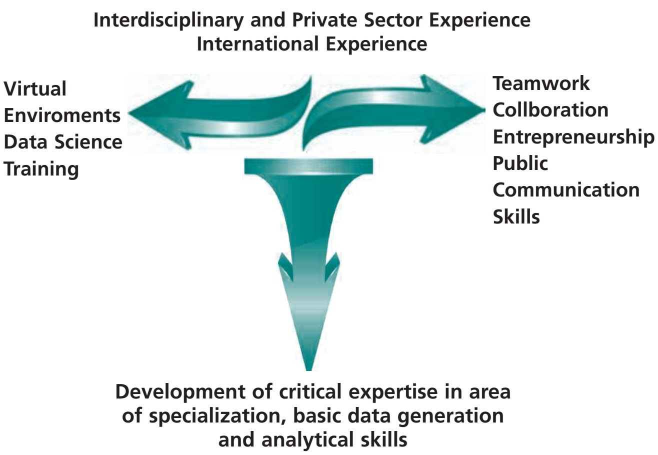
A richer training environment could be represented by the T-training figure shown on page 23. Programs would include traditional PhD training at the base of the T, corresponding to an apprenticeship in a mentor's laboratory. Adding horizontal skills, such as those shown across the top, would prepare students for a variety of career outcomes and reduce the frequency with which a tenure-track faculty position is seen as an all-or-nothing, overarching goal. Among the horizontal skills are those commensurate with data and Internet-driven science, in which programming, data mining, statistical analysis, visualization, and online collaboration are used to generate and execute research agendas. Other horizontal components include international and private-sector experiences. International training would enhance multicultural and networking skills, whereas industry experience would give firsthand insight into how selected discoveries are converted into products. Such training opportunities would also encourage greater industry commitment to the training process and help develop the impetus for a dramatic expansion of the currently very small agriculture-based start-up ecosystem. Finally, communication skills should be honed so that scientists can readily interface with policymakers and the public.

Only **one of six biology PhDs** in the United States lands a **tenure-track faculty position** within five years of graduation.

1 of 6
PhDs BECOME FACULTY

It is crucial that we identify a training path that serves to close the gender gap at the level of fully established scientists.

Figure 2: T-training for Multiple Career Paths



Refocus training and reduce time to degree

The nearly seven-year median for a life science doctoral degree in the United States[40] results in part from a lack of early specialization, compelling doctoral programs to require extensive coursework as a foundation for the increasingly sophisticated expectations of graduate trainees. To focus more resources on the skills required at the top of the T, undergraduate curricula should be tailored to allow committed students with the appropriate abilities to enter PhD programs without needing a significant amount of catch-up, textbook-style coursework. One option would be to offer a seamless seven-year curriculum combining bachelor's and doctoral education, which would make the career path more attractive, help close the STEM gender gap, and reduce costs to investigators, institutions, and funding bodies.

Incorporate institutional partnerships and address national imperatives in training grants

Federal agencies, including NIH, NSF, USDA, DOE, and the Department of Education, have funded or are funding the training of plant science PhDs. Most of this support is through individual fellowships, which appropriately reward select, high-achieving individuals. Such support, however, does not catalyze the type of multifaceted training that can occur in an organized program with a like-minded cohort. Training grants to fulfill the *Plant Science Decadal Vision* would require an institutional financial commitment; fold into existing training programs while incentivizing their modernization; provide a multiyear, T-training environment; and minimize the need for complex, program-specific bureaucracies.

seven-year
SEAMLESS CURRICULUM

"If you always do what you always did, you will always **get what you always got."** –Unknown

Impacts

What would the impacts be if these goals are achieved?

IRRI has developed drought-tolerant rice varieties with superior grain quality and yield potential. This requires understanding of the interface between the biophysical and socioeconomic circumstances of rice-farming communities and their constraints, needs, and varietal preferences for drought-stricken rice environments.

Understanding the fundamental principles of plant growth in different environments will enable the prediction and mitigation of adverse environmental conditions for agriculture and forestry production.

By documenting the communication between a plant's genetic potential and its external environment, both abiotic (e.g., water, soil, air, and temperature) and biotic (e.g., interacting microorganisms, nematodes, weeds, insects, and mammals), we can better appreciate the natural world and apply the principles of adaptation to agriculture, where productivity gains are increasingly expensive to obtain and improving plant resilience is critical.

Setting standards for data collection, management, and sharing will enable new forms of collaboration and experimentation.

Standardizing the rigor with which data are collected, labeled, and archived will support the necessary sharing among scientists that will help drive innovation.

Make sense of a vast amount of seemingly unorganized data.

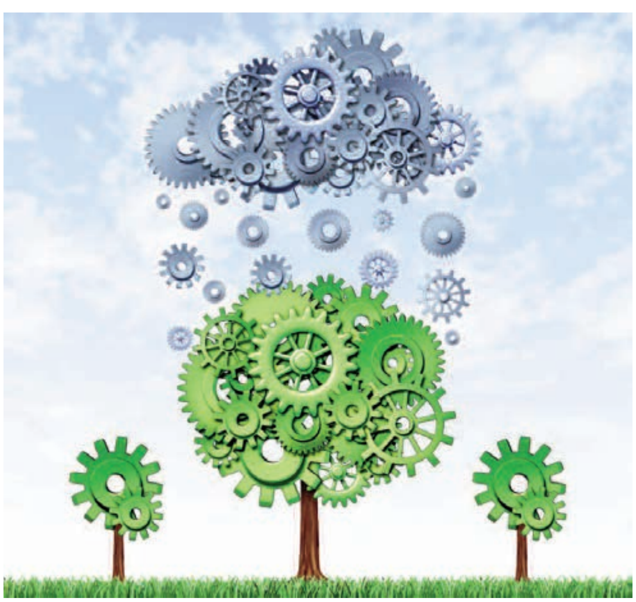
Agriculture is already one of America's most profitable export sectors, but the bioeconomy will rapidly grow beyond its traditional products of food, feed, fuel, and fiber.

The ability to cross-check and combine molecular, chemical, and environmental data sets from around the globe, collected by many means and with accelerating rapidity and depth, will create unparalleled opportunities for scientists to derive new hypotheses from data that might otherwise go unexplored.

Reaching across disciplinary boundaries will be a norm for plant scientists.

Collaborations between biologists and computational and information scientists are already redefining the frontiers in the understanding of plant function. Additionally, the participation of chemists, mathematicians, engineers, geologists, physicists, and meteorologists, among others, will be required to attain the goals of the *Decadal Vision*. This need will drive the implementation of new training paradigms that blur disciplinary lines and prepare young scientists for a variety of career paths by building skills in

SHUTTERSTOCK



Interdisciplinary research.

SHUTTERSTOCK

New bioproducts for improved pharmaceuticals.

bench science, communication, and collaboration; by encouraging appreciation of diverse disciplines; and by giving early exposure to the laboratory-to-market path.

New plant-based industries will become integrated into the economy.

Agriculture is already one of America's most profitable export sectors, but the bioeconomy will rapidly grow beyond its traditional products of food, feed, fuel, and fiber. Exploring plant biodiversity will serve many goals, including providing an impetus for its preservation, identifying genetic modules for transforming agriculture, and defining biosynthetic pathways for new bioproducts such as high-value hydrocarbons and pharmaceuticals. Newly available information will encourage entrepreneurship and an invigorated business startup environment for plant-related technologies.

Strategy

Implementation of strategy and milestones

The *Plant Science Decadal Vision* represents a commitment across the plant research community to achieve training, technology, and discovery milestones that will help meet societal and global challenges related to agriculture and its many outputs. An implementation strategy was agreed on that will accelerate the path to success.

1 **The stakeholder community** must remain engaged to support and update this strategic plan. We propose the establishment of a National Plant Science Council to facilitate communication among stakeholders, including

ARS-USDA

Wheat harvest on the Palouse.

the research community, funding agencies, industry, and policymakers, as well as communication of researchers directly with the public. The Council will

Citrus diversity.

initially derive its leadership from Plant Science Research Summit participants and will incorporate industry and academic leaders representing a range of expertise, including members of relevant commodity and advocacy groups and key science educators.

2 **Goals related to informatics**—data and metadata storage, management and standardization, reciprocal accessibility of public and available private data sets, and development of statistical and analytical computing capabilities—should fall under the aegis of existing programs such as Kbase, the National Center for Biotechnolo-gy Information, USDA-GRIN, and the NSF iPlant Collaborative or their successors. Cooperation among these efforts will be critical to develop agreed on

The experimental and informatics communities **must agree on mechanisms to implement standards rigorously.**

informatics

IMPLEMENT STANDARDS

Accelerate basic discovery and innovation in economically important plants and enable enhanced management of agriculture, natural resources, and the environment to meet societal needs.

standards and to avoid redundancy. Most importantly, the experimental and informatics communities must agree on mechanisms to implement standards rigorously, including open sharing of data. The availability of properly curated data must not be a consequential limitation to progress.

3 **Philanthropic organizations and industry** should contribute to the visioning and implementation of new training paradigms. In doing so, the human capital that fills American jobs, competes internationally, and helps our nation accomplish its global development goals will be ensured. A strong relationship between the public and private sectors will also increase possibilities for adding discovery value to privately created and held data that would otherwise be sequestered and eventually be lost or become obsolete.

ANDREW DAVIS

Purple tomatoes that have been engineered to produce high levels of anthocyanins will extend the life span of cancer-prone mice when provided as a dietary supplement'.

4 **Partnerships within and among funding agencies** will enhance the possibilities of success in these interdisciplinary endeavors. As an example, iPlant and Kbase were designed to advance cyberinfrastructure well beyond plant biology. The National Plant Genome Initiative, established in 1998 and coordinated by an interagency working group, was lauded in a National Research Council report[41] for making possible revolutionary discoveries in plant biology and continues to "accelerate basic discovery and innovation in economically important plants and enable enhanced management of agriculture, natural resources, and the environment to meet societal needs." An analogous group should coordinate decisions on specific milestones and programs that form the *Decadal Vision* described in this document through appropriate workshops or other forms of outreach to stakeholders. Involvement of the Office of Science and Technology Policy may facilitate this effort and also help coordinate implementation of related initiatives, particularly those outlined in the PCAST report on agricultural preparedness.[3]

Accelerate basic discovery and innovation in economically important plants and enable enhanced management of agriculture and natural resources.

coordinate
decisions

MILESTONE AND PROGRAMS

Milestones

Planned Milestones for the Community

Years 1–5

- Immediate constitution of the National Plant Science Council.
- Establishment of an undergraduate–graduate training grant program aimed at propagating new accelerated training models, introducing the T-training concept, and increasing recruitment of strong domestic talent with excellent communication skills to the STEM disciplines.
- Establishment of specific national goals in data acquisition, integration, and community cooperation.
- Identification of target species and varieties and initial collection of "omic" and biochemical mechanistic data relevant to plant productivity and survival in diverse environments and identification of target species and initial collection of chemical diversity data from 20,000 medically and ecologically important plants. Appropriate user facilities, including nuclear magnetic resonance and different types of mass spectrometry, will be required to identify these low-abundance molecules.
- Implementation of challenge grants, Ideas Labs, or other idea-generating programs to stimulate development of new and powerful computation resources for large-scale data integration, biological systems modeling, and mechanistic dissection in plants.
- Establishment of field-based and controlled-environment plant phenotyping centers throughout the United States equipped with technologically advanced, high-precision instrumentation, including robotics and 3-D imaging, for high-resolution study of plant–environment interactions in the field and laboratory. As needed, existing genotyping (e.g., JGI) or phenotyping (e.g., CAAPP) centers (see page 13) should be upgraded to incorporate emerging technologies. Selected USDA-affiliated facilities may also be targeted for modernization. Broad access to such facilities must be incorporated into their missions, which will increase the diversity of usage and promote training objectives.
- Design and implementation of uniform metadata standards for public plant database uploading, publication, and assembly of phenotype data sets from the research community. This effort must be coordinated internationally and should take full advantage of existing working groups such as those that assemble annually at the Plant and Animal Genome meeting.

20,000

MEDICALLY AND ECOLOGICALLY IMPORTANT PLANTS

Years 6–10

Goals and milestones for Years 6–10 will be subject to modification as progress is made and opportunities arise during Years 1–5. In particular, the National Plant Science Council will have a key role in engaging the community to refine and prioritize strategic areas for investment.

- Implementation of new graduate training systems nationwide on the basis of outcomes from training grant programs initiated in Years 1–5. A well-designed strategy will incentivize universities to partner with the private sector as they innovate and broaden their scope of training.
- Enlargement of postdoctoral training programs to increase domestic talent and impart broad skill sets to complement the T-training concept proposed for doctoral students.
- Use of the chemical diversity screen through the development of private-sector and foundation partnerships to pursue scientific and commercial applications of the findings. One role of the National Plant Science Council will be to ensure rapid dissemination of this information and facilitation of these partnerships.
- Deployment of novel, robust sets of tools that enable integration of plant network data from around the globe for discovery of novel plant pathways and design of innovative agricultural production strategies.
- Broad distribution of real-time phenotyping capabilities in natural and agricultural settings, with seamless integration of resulting data sets. Coordinated phenotyping trials will be required to test hypotheses generated through data mining and computational predictions.
- Development of innovative plant breeding and genome modification technologies, with demonstrated implementation of these strategies to create improved or novel crop varieties.

incentivize **universities**
PARTNER WITH PRIVATE SECTOR

Integrate plant network data **from around the globe.**

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- Botanical Society of America
- Crop Science Society of America
- Entomological Society of America
- Iowa Soybean Association
- National Corn Growers Association
- Phytochemical Society of North America
- United Soybean Board
- Weed Science Society of America

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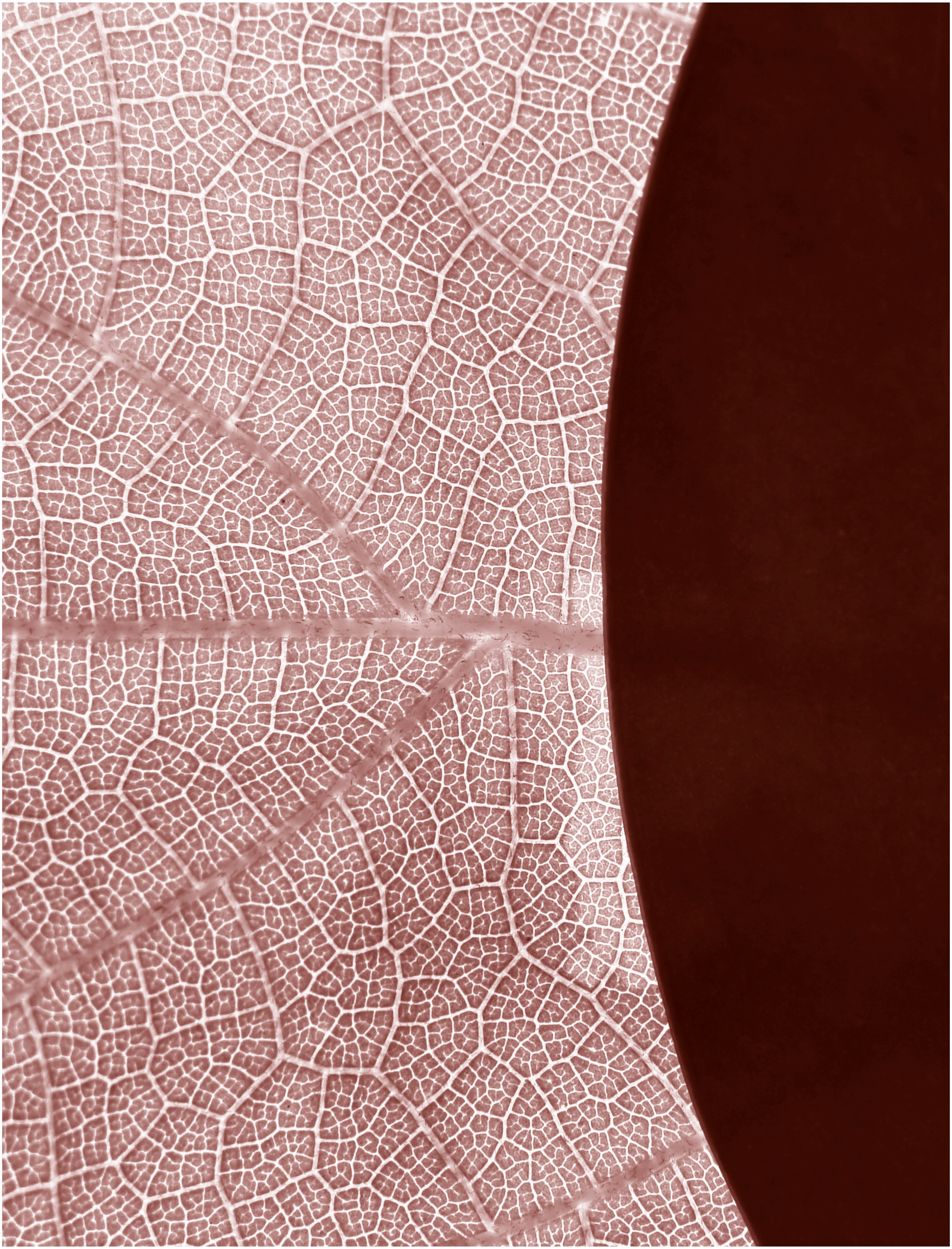
History

In September 2011, representatives from the full spectrum of plant science research—from basic to applied and industry to academia—gathered to develop a consensus plan to invigorate and guide plant science research over the next decade. The meeting marked the first time this diverse community assembled to unify their vision for the future. Summit participants were charged with articulating research priorities in plant science that would address grand challenges in areas such as health, energy, food, and environmental sustainability. A document, "The Green Frontier: A Unified Vision for Plant Research," reflecting the consensus of the discussions and opinions exchanged during the 2011 Summit was assembled and distributed. Additional information can be found at http://plantsummit.wordpress.com/.

A second meeting of 17 participants, whose charge was to build on the foundational work of the 2011 summit and develop a succinct compilation of recommended plant science research priorities, was convened in January 2013. The *Plant Science Decadal Vision*, as detailed in this report, arose from the strategic plan developed at the 2013 meeting and serves as the final product of the Plant Science Research Summit.



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