THE GREEN FRONTIER: A UNIFIED VISION FOR PLANT RESEARCH

PREFACE

The Plant Science Research Summit was held at the Howard Hughes Medical Institute in Chevy Chase, Maryland, on September 22-23, 2011. Some 150 representatives predominantly from academia and industry, encompassing a broad spectrum of basic to translational plant science research, gathered and began developing a consensus plan to invigorate and guide plant science research over the next decade. Summit participants were charged with articulating research priorities in plant science that will contribute to solving challenges in food, health, energy, and environmental sciences.

This report, which is based on discussions during the summit and incorporates extensive subsequent input from the plant science community, is addressed to the many stakeholders of plant science, including government, industry, universities, foundations, and the general public. It represents the beginning of an effort to marshal plant science to meet future challenges. The goals are to unify the plant science community; coordinate efforts among the many stakeholders in plant science research; recruit top scientists as ambassadors who can explain and advocate for plant science; garner support from policymakers and the public, and create momentum for change.

The Summit was held under the auspices of a broad range of scientific societies and other organizations and was supported by funding from the National Science Foundation (NSF), U.S. Department of Agriculture, National Institute of Food and Agriculture (USDA, NIFA), U.S. Department of Energy (DOE), the Howard Hughes Medical Institute, and the American Society of Plant Biologists.

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Executive Summary

We humans depend on plants for our survival. The oxygen we breathe comes from plants, as does the food we eat and the feed for animals we eat. Plants provide us with medicines, building materials, beverages, paper, fabrics, industrial chemicals, and many other products. Despite their importance, we know far less about plants than we do about many other kingdoms of life. With a global population expected to reach 9 billion by 2050, a limited food supply to satiate a growing population, and an ever changing climate, plant science is ideally poised to address the needs of our nation and world in the 21st Century. The plant science research community will be a catalyst for innovation as our nation looks to improve our economy, maintain our food supply, improve our health, provide energy security, and protect our environment. Now, more than ever, it is vital to increase public and private support for plant science research and recognize the critical need to invest in its future and embrace its potential.

Societal Grand Challenges: The summit participants unanimously agreed that an interdisciplinary and integrated approach of research and development will be required to address national needs in food, health, bioenergy, and environmental security. Summit participants identified the following four societal grand challenges requiring innovative solutions based in plant science:

1) **Assure nourishment for all, now and in the future**. Advances in plant science research are essential to produce higher yielding, more nutritious varieties able to withstand a variable climate and a host of pests and pathogens, thus supporting prosperity for other nations as well as our own.
2) **Protect, enhance, and illuminate the benefits of nature.** Innovations leading to improvements in water use, nutrient use, and disease and pest resistance are critical and will allow for increases in ecosystem services, such as cleaner air, cleaner water, fertile soil, and biodiversity benefits, such as pest suppression and improved pollination.
3) **Fuel the future.** Improvements in current biofuels technologies, including breeding, crop production methods, and processing, are required to help meet future energy requirements.
4) **Be sustainable.** The benefits bestowed by advances in plant science in such areas as food and fiber production, ecosystem and landscape health, and energy production must be economically, socially, and environmentally sustainable.

A 21st Century Agenda for Plant Scientists requires advanced understanding of the following areas of plant science research:

- **Genetic diversity across and within species.** The genetic diversity that exists within the plant kingdom provides humankind with the variety of benefits, including nutritious foods, beneficial pharmaceuticals, forest products, and a habitable environment. Technical advances in DNA sequencing have accelerated the ability to connect genetic diversity with beneficial traits. Further innovations are needed to fully apply our understanding of genetic diversity to benefit agriculture and the environment.
- **Biological processes.** The biological bases for many plant beneficial traits remain unknown and diverse research avenues are required in order to fill in our knowledge. Fundamental and systems-level understanding of plant processes will allow plant scientists to exploit and build

on the accumulating knowledge from a wide spectrum of plant science research, facilitating rapid translation of results from well-studied plants to their less familiar relatives. Recent advances in epigenomics, systems biology and synthetic biology need to be fully exploited.

- **Complex communities and ecosystems.** Organisms interact with each other, and with their physical environments, in many dimensions including nutrient and energy flow. Understanding these complex interactions in both managed and unmanaged ecosystems is essential if we are to address the societal challenges laid out by the Plant Science Research Summit participants. There is special urgency to improving our knowledge, given the context of a changing climate.
- **Transforming data into understanding.** Modern research tools generate an enormous amount of information; hence, virtually every scientific discipline is becoming increasingly data intensive and plant science is no exception. To store, manage, and transform this vast amount of data into understanding, improvements in hardware, computational analysis, and workforce will be essential.

Plant Science at the Forefront of the New Biology

The National Research Council’s 2009 report *“A New Biology for the 21st Century”* called for a new national initiative in biology that would be distributed and coordinated across agencies, multidisciplinary, and long term. Plant science should be at the forefront of this effort because many of the societal challenges identified in the report are linked to environment, food and agriculture.

Achieving the promise of plant science requires effective government policies and plant scientists’ taking initiatives in four areas: research support for both basic and translational plant science, evidence-based regulation for plant research and plant-based products, training of a new generation of plant scientists, and outreach to bring science to the public.

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The Green Frontier

We humans depend on plants for our survival. The oxygen we breathe comes from plants, as does the food we eat. Plants provide us with medicines, building materials, beverages, paper, fabrics, industrial chemicals, and many other products. The assemblages of plants in fields, on hillsides, and in the oceans purify water, decompose wastes, moderate climate, and provide many other services to human communities. Plants are a constant and reassuring feature in the landscapes of our lives, from rural communities to the most urban settings on earth.

Despite their importance, we know far less about plants than we do about many other kingdoms of life. Plants can survive environmental extremes, yet the biological processes responsible for their resilience and adaptability are poorly understood. Plants have been our richest source of novel chemicals, including some of today's most important medicines, but only a small percentage of the diversity found in plant compounds has been inventoried. Meanwhile, because of human actions plant species are today becoming extinct before they can be studied.

Our relative ignorance of plant biology threatens our future well-being. In the next few decades the world will face severe challenges that can only be overcome through a greatly increased understanding of plants. As human populations grow and standards of living improve, agricultural productivity must increase to avoid catastrophic food shortages and price increases. Agricultural and natural ecosystems must provide more goods and services to growing human populations while, at the same time, reducing negative impacts on the environment. Plants will be expected to provide increasing amounts of energy for human activity, including biofuels for transportation. And all of this must occur with as little harm as possible to Earth's biodiversity, on which we depend for crucial services.

The Plant Science Research Summit

The critical importance of plant science to our collective future was the impetus behind a major national conference held in Chevy Chase, Maryland, on September 22-23, 2011. More than 150 representatives from a broad spectrum of plant science research, including government agencies and various stakeholder groups, gathered to develop a consensus plan to invigorate and guide plant science research over the next decade. Summit participants identified critical gaps in the understanding of plant biology that must be filled over the next decade to address the grand challenges facing our nation and our world. They then articulated research priorities in plant science to fill those gaps and meet the challenges.

This report, which is based on discussions during the summit and incorporates extensive subsequent input from the plant science community, is addressed to the many stakeholders of plant science, including government, industry, universities, foundations, and the general public. It represents the beginning of an effort to marshal plant science to meet future challenges. The goal is to unify the plant science community, coordinate efforts among the many stakeholders in plant science research, create ambassadors who can speak on behalf of plant science, garner support from policymakers and the public, and create momentum for change.

A 21st CENTURY AGENDA FOR PLANT RESEARCH
Research Priorities

- Understand and exploit plant diversity within and across species
  - ✓ Deliver higher-yielding, sustainable cropping systems. This will require at least a doubling of current crop yields in the next 30-40 years
  - ✓ Developing crop varieties that can withstand more intense abiotic and biotic stress, especially in response to a changing climate.
  - ✓ Develop crops with enhanced water and nutrient use efficiency.
  - ✓ Master the ability to grow crops in a wider array of environments
  - ✓ Understand the nature, origin, and roles of plant genetic and metabolic diversity
  - ✓ Develop biofuel crops to meet the target to provide over 20% of the nation's fuel
  - ✓ Leverage investments in reference and model species to crop species
  - ✓ Establish new national multidisciplinary initiatives to deliver technology to support high-throughput phenotyping (including field phenotyping) and to remove bottlenecks to plant improvement (for example, through the development of high-throughput plant transformation)
- Understand plant biological processes
  - ✓ Develop plant systems biology so that predictable models can be developed for the most important agricultural and environmental traits (for example, yield and nutrient efficiency)
  - ✓ Catalogue and investigate plant diversity as a way to facilitate its preservation and to provide resources for its utilization
  - ✓ Understand the role of epigenetics in plant diversity, development, plasticity and trait stability
  - ✓ Enable the application of synthetic biology principles to plant biology by identifying discrete modules that can be manipulated
- Understand complex biological communities
  - ✓ Better understand and enhance the natural services provided by Earth's biodiversity and ecosystems
  - ✓ Integrate and utilize knowledge of plant systems across temporal and spatial scales
  - ✓ Further investigate the interactions between organisms and their environment (for example, through metagenomic studies of plant-microbe communities)
  - ✓ Develop long-term, vertically integrated field research sites to study managed (i.e., cropping systems) and unmanaged ecosystems.
- Transform data into knowledge and, ultimately, to application
  - ✓ Develop new cyberinfrastructure to store, analyze, visualize, and effectively integrate large biological datasets with the ultimate goal of generating new knowledge and understanding
  - ✓ Enhance the ability of plant biology and agriculture to help build the new bioeconomy

A Unified Plant Biology

As noted in the 2009 National Research Council report, *A New Biology for the 21st Century*, an increased understanding of complex biological systems and the development of tools and approaches to address their complexity have led to the realization that there is only one biology. Specifically, fundamental and applied biology are part of a single continuum of research that seeks to gain practical benefit from an understanding of biological systems. It is counterproductive to discuss these terms as if they are separate and to argue that they are competing priorities. The societal challenges involving plant science overlap, which is why the objective must be to build and fund a *unified plant science* rather than a collection of plant sciences.

Plant science has reached an unprecedented juncture. Like other biological disciplines, it is now confronting the daunting complexity of biological processes. Conceptual and technical breakthroughs are needed to move from the detailed description of biological molecules to understanding the dynamic systems on which the planet's ecosystems depend. The fundamental organizing principles that make biological processes and living cells work need to be understood. Biological systems need to be analyzed, modulated, modeled, and engineered. To address challenges involving food, fuel, the environment, and health, biology needs to make the transition from a descriptive to a predictive science, thus enhancing innovation.

Doing so will require the integration of the many subfields of biology. Indeed, plant science is now at a moment of unique opportunity due to the increasing integration not only of subdisciplines within the field but of other scientific fields of study. Additionally, many technological advances now have the potential to reap practical benefit from past investments. For example, fundamental research in plant genetics and genomics, currently being applied via modern molecular breeding techniques, is significantly accelerating the development of new plant varieties and the ability to predict how these varieties will respond to an ever changing climate. Advancement of the new (that is, integrative, innovative, and ultimately predictive) plant biology also is being driven by the increased coordination of the physical sciences, engineering, mathematics, and computation. The result will be a discovery-driven research engine that will be able to tackle extremely complex biological problems while also taking on societal challenges that require multidisciplinary and interdisciplinary approaches.

Significant obstacles stand in the way of this vision. Many of the concepts, tools, and technologies needed to realize the new plant biology have yet to be developed. As with much of biological research, plant science research is currently siloed into disciplines that function as largely self-contained entities. This undermines their ability to convey a unified message and collaborate across different scientific disciplines. This is mirrored in the organization of federal funding for plant science research, which is fragmented across more than 20 departments and agencies. Although these agencies have traditionally worked well together, this fragmentation may contribute to the lack of a unified message for plant research, an important goal of this report and much needed to draw future resources to confront the grand challenges that this report emphasizes. This need is exemplified by the fact that the National Institutes of Health (NIH) spends more for research on individual diseases, from schizophrenia to urologic diseases, than the U.S. Department of Agriculture (USDA) allots for the entire Agriculture and Food Research Initiative (AFRI) competitive grants program. Additionally, the future research workforce must be developed while also educating the public about the importance of plant science research.

Enhanced funding for plant science would bring many and substantial benefits. The "Frontiers in Plant Science" boxes scattered throughout this report highlight examples of how plant science research has transformed or is poised to transform the lives of U.S. citizens and our neighbors abroad.

Ambitious goals can generate the scientific and public determination to meet those goals. The decision to sequence the human genome captured the imagination of not only the scientists working in those areas but also of the general public and Congress. Furthermore, making the decision to sequence the human genome spurred the technological development needed to achieve that goal.

Structure of the Report

Summit participants identified four societal Grand Challenges, described in Section 2, which require major advances in plant science if they are to be met:

1. Feed everyone well, now and in the future. Advances in plant science research are essential to produce higher yielding, more nutritious varieties able to withstand a variable climate and a host of pests and pathogens.

2. Provide a healthy environment. Innovations leading to improvements in water use, nutrient use, and disease and pest resistance are critical and will allow for increases in ecosystem services, such as cleaner air, cleaner water, fertile soil, and biodiversity benefits like pest suppression and improved pollination.

3. Fuel the planet. Improvements in current biofuels technologies, including breeding, crop production methods, and processing, are required to help meet future energy requirements.

4. Be sustainable. The benefits bestowed by advances in plant science in such areas as food and fiber production, ecosystem and landscape health, and energy production must be economically, socially, and environmentally sustainable.

Section 3 then lays out a new Plant Science Research Agenda to meet these challenges through research in the following areas:

- Understanding diversity within and across species
- Understanding biological processes
- Understanding complex communities
- Transforming data into knowledge

Finally, Section 4 looks at policy and educational choices needed to assure plant biology leadership in the new biology.

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The Societal Grand Challenges

The plant science research community has the potential to provide solutions to most of the major problems affecting human society in the first decades of the 21st century. Feeding a growing population, curbing the effect of climate change on food and fiber production, providing additional plant products and ecosystem services, meeting the growing demand for energy, and reducing the effects of human activity on the environment all require much greater understanding of plant biology and of how plants can be modified and used to meet changing human needs.

The Plant Science Research Summit expressed the problems facing human societies in terms of four societal grand challenges that need to be confronted and overcome.

Feed everyone well, now and in the future

In late 2011 the earth's human population reached 7 billion. Given current projections, this number will continue to grow for the next several decades. Already more than one billion people worldwide are hungry, have an uncertain food supply, or are malnourished. The continued expansion of the human population will cause more people to go hungry unless agricultural productivity keeps pace.

An increase in wealth is also putting increased pressure on food supplies. Wealthier populations want more and better sources of food, and demand for animal protein requires greatly increased production of grains or forage to feed livestock animals. Food prices spiked in 2008 shortly before the worldwide recession that began that year. At the time of the Plant Science Research Summit, food prices were even higher than in 2008. While increases in food prices do not significantly impact the daily lives of most Americans, who on average spend less than 10 percent of household income on food, they can lead to political unrest in other countries, particularly where 30-50 percent of household incomes are spent on food.

The average rate of growth in world grain yield per decade decreased from 2.9% (1960's) to 1.6% (1990's) and is projected to go down to 0.8% before mid-century[1]. Past and future increases rest on a foundation of basic research that has been incorporated into agricultural production. Especially important have been new innovations in genetics and agronomy, improved statistical tools, and better engineering of food production systems. In particular, plant breeding programs have been extremely successful. For example, a single private seed company can produce on the order of 100 new high-yielding, corn hybrids every year. This growth in crop yield must be maintained as the world's population continues to increase even as less arable land is available and climate changes.

Plant breeding does not yet incorporate detailed biological insights into crop improvement. Some hybrids are more productive, but a detailed mechanistic understanding of this increased productivity is still lacking. Reaching this level of understanding may allow for increases in plant yield unimagined with conventional plant breeding alone. Also, continued increases in crop yields have required increasing investments in agricultural inputs, personnel, and research resources, which eventually will become unsustainable. New approaches are needed for yields to continue to rise.

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[1] UN Food & Agriculture Organization, 2009

The transfer of desirable traits into crops through plant biotechnology has been very successful. Major crop plants have gained important new traits such as tolerance to some abiotic stresses, improved yield, and resistance to some herbicides. But, like plant breeding, biotechnology is not yet a predictive science. Plant researchers do not fully understand the molecular pathways that lead to traits like drought tolerance, even as the tools for manipulating DNA and other biological molecules have become ever more sophisticated. There is a clear need to develop plant systems biology so that predictable models can be generated for the most important agricultural and environmental traits (e.g., yield, nutrient use efficiency). A complication is that conventional plant breeding and the utilization of plant biotechnology for crop improvement are multiyear processes.

Knowledge gained in simpler systems or in model plants cannot, at present, be translated quickly and easily into improvements in crop plants. Recent advances in phylogenetic analysis are likely to help in this regard, since knowing the precise relationship of any given model with a crop species can help determine how much extrapolation is needed from one system to the other.

Meeting these future food needs will require that plant scientists focus on nutritional quality in addition to yield and productivity. Plants provide most of the vitamins and minerals required by humans. We obtain these either directly, when we consume plant food products, or indirectly, when we consume food products from animals. Plants also supply a wealth of health-beneficial compounds, known as phytochemicals, which can enhance the quality of life or reduce the risk of disease. As plant breeders develop new high-yielding varieties that can cope with various biotic and abiotic stresses, or that have enhanced nutrient use efficiency, the nutritional value of these new genotypes must be monitored to ensure that the foods they produce are as nutritious, if not more nutritious, than current crop varieties. Attention also should be given to the whole food system, which includes plant foods consumed by humans as well as grains and forages fed to livestock. More knowledge is needed about the biochemical pathways that enable the synthesis of vitamins and health-beneficial phytochemicals in plants, and on the membrane transporters and storage systems that move and store minerals and phytochemicals within plants. Understanding how these nutrition- and health-related processes perform in the context of a changing climate also will be needed.

U.S. academic institutions are the primary source of a knowledgeable workforce required by modern agricultural companies. Industry also depends critically on fundamental plant biology research, conducted primarily in U.S. academic, independent, and federal research institutes. This research provides the resources used by industry to develop new products, new techniques, and new tools, but fundamental research also needs to be translated into knowledge that is closer to potential applications. Industry does not have a powerful incentive to conduct fundamental research because individual companies have trouble capturing the economic returns from such work. Academic plant scientists have incentives to do basic research but lack a comparable set of incentives to conduct the translational research needed to eventually convert basic discoveries into new products. Thus, there is a disconnect between discovery and delivery. Section 4 discusses policies needed to bridge this gap.

Plant science advances could have an immediate and substantial effect on the U.S. economy and workforce. Part of the new Plant Science Research Agenda described in Section 3 focuses on enabling crops to grow in more stressful and unpredictable growing conditions, such as drier climates or degraded soils. Achieving this goal could enable an expansion of agriculture in the United States and around the world, which could increase U.S. agricultural exports and ease the pressure on food supplies elsewhere.

Frontiers in Plant Science – Advances in molecular plant breeding lead to flood-tolerant rice

Meeting increasing demands for food while navigating enhanced climate variability will require increased productivity on optimal, as well as suboptimal, cropland. An example of advances in molecular plant breeding needed to feed the world involves varieties of rice that have a higher tolerance for submergence[2].

Although typical rice cultivation involves periodic flooding, there is a limit to the depth and duration of the floodwaters that rice plants can withstand. In many rice fields, unexpected rainfalls can produce conditions that completely or largely submerge the plants. As a survival technique, rice naturally expends a large amount of energy to outgrow the flood waters to reach the air. This results in weak, spindly plants that are easily flattened when the waters recede. In cases of extreme submergence, plants may be unable to outgrow the floodwaters and they exhaust their energy reserves in their efforts to survive, which kills the plants within days.

For generations, local farmers in parts of the world have been selecting for rice cultivars adapted to growing under such extreme submergence conditions. Scientific research has demonstrated that the local varieties are able to manage their resources more efficiently under flood conditions, allowing for prolonged survival. Unfortunately, these local varieties are limited in yield compared with the high-yielding, semi-dwarf varieties derived during the green revolution.

Attempts to transfer submergence tolerance to high-yielding rice varieties began in the 1980's, but not until the mid-1990's, aided by molecular breeding techniques, was the trait successfully introduced. By sequencing the main genomic region in rice contributing to this trait in both local and high-performing varieties, breeders identified differences that allowed them to follow its presence without laborious screening for submergence tolerance at every step of the breeding process. This type of marker-assisted selection or precision breeding greatly accelerates the breeding process compared with traditional breeding. Additionally, it allows for a smaller region of the genome to be transferred into the high-yielding rice varieties, reducing the transmission of undesirable traits from the local variety that could lead to inferior performance in the field. In fact, the new submergence tolerant varieties, also known as "scuba rice," perform equally as well as the high-yielding parent varieties in the absence of flooding, and since 2009 scuba rice varieties have been introduced into many rice growing regions of the world.

Scientific research is continuing to reveal the molecular mechanism by which submergence tolerance functions in rice and other plants. In fact, the same mechanism of conserving limited resources during submergence can increase survival following drought stress[3]. Recent findings in the model plant Arabidopsis on submergence tolerance[4] may one day be applied to additional crop plants. This extension of knowledge from model plants is extremely important for improving traits.

Portions of this work were supported by grants from USDA, NSF, and the Bill and Melinda Gates Foundation.

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[2] Xu et al. 2006. Nature 442: 705-708.; Bailey-Serres et al. 2010. Rice 3:138-147.

[3] Fukao et al. 2011. Plant Cell 23: 412-427.

[4] Gibbs et al. 2011. Nature 479: 415-418.

Provide a Healthy Environment

As noted in Section 1, plants provide many products and services for humans besides safe, affordable and nutritious foods. Healthy landscapes provide clean air, clean water, biodiversity benefits such as pest suppression and pollination, and fertile soil, in addition to other services. Thus, maintaining human health requires maintaining the health of plants and the landscapes in which they grow.

Plants support human life on this planet, but human activities can impose a substantial toll on the environment. Phosphorous loss from cropping systems is eutrophying freshwater systems causing algal blooms that can deplete those systems of oxygen and lead to the death of fish and other organisms. Nitrogen fertilizer carried by the Mississippi River is creating coastal hypoxia (oxygen-free dead zones) in the Gulf of Mexico, and the same is happening in other marine areas around the world. Erosion degrades soil fertility and clogs waterways with sediment. Much of the world's agricultural land can be cropped only with irrigation, even though water is severely limited or becoming so in large parts of the world. Extensive deforestation, as seen in certain parts of the world, also contributes to these environmental problems. Agriculture is responsible for about 7 percent of the greenhouse gases emitted in the United States, and 14 percent globally. As agriculture expands to provide more food and fiber for a growing and more prosperous population, it must do so using less, better contained fertilizer, lowering the consumption of water and fossil fuels, protecting biodiversity, and reducing the release of nutrients, soil, and pesticides into the environment.

The greatest environmental threat facing human societies is climate change. Changing rainfall and temperature patterns are already affecting farmers' decisions and patterns of crop and forest productivity in the United States and around the world, as evidenced by the widespread drought of summer 2012. World temperatures are expected to rise between 2.5 and 10 degrees Fahrenheit over the next century, changes that will be beneficial in some regions and detrimental in others. However, in most regions climate change is expected to cause increased extremes of heat, cold, drought, and flooding, which will adversely affect crop growth and soil fertility. Changing climate also will likely result in the introduction of new pests into many regions, while warmer and potentially wetter weather may permit diseases to flourish where once they were held in check. In other areas where pests and diseases once flourished, stress levels may be reduced.

Environmental adaptation and mitigation of these changes require a combination of ecological, phylogenetic and biological knowledge. Identifying and developing plant varieties with the capacities to withstand more intense stress should be part of the solution. Designing landscapes to better capture nutrients and soil released by episodic rainfalls is another. Ensuring a sufficient level and type of plant diversity to protect crops from new pests and to provide ample pollinator habitat is yet another. Agricultural ecosystems, including forests, can be managed not just to reduce their emissions of greenhouse gases but also to store carbon dioxide removed from the atmosphere and thus mitigate climate change.

Plants could be improved to meet specific environmental goals. Screening a broad range of species for their ability to take up particular toxins could lead to phytoremediation of contaminated soils. Field crops could be developed that could use nutrients more efficiently, leading to less fertilizer use and reduced escape of harmful compounds into the environment. Plants exhibiting greater water use efficiency could reduce the need for irrigation water in addition to providing drought resistance. Improved pest resistance could result in crops with greater tolerance to new insects and diseases, reducing the need for pesticides. Improved cover crops (those grown in the off season, most often to capture nitrogen) could better contribute to soil fertility.

All of these potentials could be more fully realized through a better understanding of the metabolic pathways that generate the diversity of chemicals produced by plants, along with a more thorough understanding of how plants respond to their environment and interact with other members of complex plant communities and ecosystems.

Frontiers in Plant Science: Advanced biofuels

Most crops have been developed for use in food and fiber production. A biofuel crop, in contrast, may have very different characteristics, depending on the strategy used to convert plant material into fuels. For example, cellulosic biomass produces a mixed stream of sugars, glucose, arabinose, xylose, and other substances. These compounds create challenges in fermentation compared with the simpler sugars from corn seed. Also, the lignin in cellulosic biomass blocks access to sugars, making them hard to release with enzymes.

Current research is focusing of modifying plant biochemical pathways to create improved biofuel crops. Efforts are underway to increase/improve cellulose quantity and quality and develop inducible post-harvest degradation of cell wall materials. Lignin is an energy rich molecule, so for some bioenergy harvesting approaches (e.g., pyrolysis), higher lignin content, which could be achieved by exploiting plant diversity, is desirable. On the other hand, if fermentation approaches are targeted, biochemical pathways can be altered in plants to create lignin that is cleaved at much lower temperatures, resulting in plants that will release their sugars much more readily. Another approach would be to improve the production of oils by plants. Plant scientists have been investigating biochemical processes that increase oil production in biofuel crops, as well as create oils that can be used directly as fuel (drop-in fuels). These improvements require detailed knowledge of oil metabolism, knowledge of unusual plants with special features, transformation technology for the plants of interest, and knowledge of regulatory networks controlling oil biosynthesis.

The ultimate goal is to create biofuel crops that are perennial, productive, tolerant of polycultures and can be produced with low inputs. These are complex traits that will require significant knowledge of plant biology to understand and manipulate. An as example, genome-enabled research ongoing within DOE’s Bioenergy Research Centers (BRCs) are identifying, modifying and/or altering the expression of key genes or signaling compounds in potential biofuel crops, such as switchgrass and poplar, to produce favorable traits. By altering the expression of key genes involved in cell wall construction, the cellulose content of plant biomass can be increased or, alternatively, the lignin content decreased. Increasing the proportion of cellulose in plant biomass increases the yield of biofuels in downstream conversion processes in a biofuel production process. Similar studies are advancing methods to modify genes controlling nutrient requirements and/or drought tolerance. These studies are important to improve the sustainability of biofuel production by minimizing fertilizer requirements and/or developing crops able to grow on marginal lands where food crops cannot grow. These detailed studies of plant metabolism from a genome-centric, systems biology perspective are providing a foundation for the development of sustainable biofuel crops optimized for biofuel production from cellulosic biomass. Such a system is potentially carbon neutral. Plants fix carbon dioxide into structural and energy-storage chemicals using sunlight, the plants are converted to biofuels, and the use of those fuels closes the loop. Systems that also store carbon in soil are even more beneficial.

Fuel the Future

About 85 percent of the total amount of energy used in the United States comes from fossil fuels, with 8 percent from nuclear power and 7 percent from renewable resources. Of the renewable sources of energy, biofuels account for about half of the total -- or about 4 percent of U.S. energy use.

About two-thirds of the energy used in the United States is produced domestically, and about one-third is imported. Much of the fossil fuel the United States imports comes from politically unstable parts of the world, and this instability may be exacerbated by food shortages. Furthermore, the costs of imported fuel are damaging the U.S. economy, and fossil fuels add substantial quantities of greenhouse gases to the atmosphere. These costs argue for a strong program to develop renewable energy resources.

A significant percentage of the U.S. corn crop is used to produce enough ethanol to meet about 10 percent of US transportation fuel needs, which has spawned a sometimes acrimonious debate over the use of corn for food or fuel. However, the US still produces an excess of corn in most years and simple arguments do not fully account for the complexity of the biofuel market. For example, the use of dried distiller grains for animal feed reduces the effects of corn ethanol production on food prices. However, advanced biofuels could require much less fossil fuel energy to produce. Therefore, plant scientists have been looking at other sources of biofuels. These include ethanol and other hydrocarbons made from cellulosic biomass such as crop residues, bioenergy grasses, and fast-growing trees, as well as diesel and other oils from soybean, algae and other sources (see box). The U.S. Energy Independence and Security Act of 2007 calls for a steady increase in the production of advanced biofuels from 2012 to 2022 to enable all biofuels to provide 22 percent of expected transportation fuel needs. Substantial investments in plant science will be required for these and future goals to be met. However, the potential is immense, as described in a recent report for the Department of Energy (*US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*; https://bioenergykdf.net/content/billiontonupdate). This report indicates that sufficient biomass can be harvested in the United States to offset up to 30 percent of the nation’s current petroleum consumption.

Be Sustainable

For all the benefits that plant science advances confer – in food and fiber production, in ecosystem and landscape health, and in energy production – if they are to have lasting and permanent benefits, these benefits must be sustainable. Broadly considered, sustainability has three dimensions: economic, social, and environmental. The economic dimension includes profitability, economic well-being, and wealth. If a practice or industry is not economically viable, it will neither develop nor persist. The social dimension involves issues important to society including food security, energy security, and individual and community health, among many others. The environmental dimension includes issues such as climate stability, biogeochemical containment, and the conservation of biodiversity.

The emergence of ecosystem services as measurable entities has helped focus sustainability discussions. Ecosystem services refer to the services or benefits provided by ecosystems to people. For example, ecosystems provide the basic materials for life and livelihood, including food, fiber, fuel, and other products. They can provide access to clean air and water, opportunities for well-being, and protection from disasters. They provide aesthetic, spiritual, educational, recreational, and other cultural services.

Agriculture, forestry, and other plant industries depend on and provide ecosystem services. Managed and unmanaged ecosystems affect nutrient cycling, soil formation, and other processes that provide the basis for plant production as well as influence climate, floods, disease, water delivery, and other important environmental properties.

Plant biodiversity is itself a major ecosystem service. Biodiversity benefits include protection of plants from pests and disease, pollination, and the raw materials for plant gene technologies. Currently, it is unclear whether individual species are interchangeable or whether each has a unique and important role in an ecosystem; the answer to this question has obvious ramifications for ecosystem stability. Managed ecosystems and landscapes are typically highly simplified compared to their pre-conversion state, and thus biodiversity services are typically diminished. Understanding, protecting, and rebuilding biodiversity is an important sustainability imperative that extends from landscapes managed for intensive crop production to landscapes scarcely influenced by human activity.

The concept of ecosystem services provides a way of moving past simple lists of the liabilities of agriculture and forestry to a full accounting of agricultural benefits and costs to society. It provides a way of optimizing the mix of services, so that any given agricultural system, whether grazing, cropland, forest, or aquaculture, can provide the most favorable mix of benefits.

Human behavior interacts with ecosystems and the services they provide through such factors as farmers’ decisions, consumer preferences, regulations, markets, and technology. Ecosystem services are thus the result of human actions, whether intentional or unintentional, which affect the ability of ecosystems, whether managed or unmanaged, to deliver them. Thinking about ecosystem services in this way allows for a much more complete assessment of the sustainability of specific practices and systems.

A Long-Term Study of Ecosystem Services

The Kellogg Biological Station (KBS) in southwestern Michigan is one of 26 NSF Long-Term Ecological Research (LTER) sites and the only LTER site focused on agriculture. For the past 20 years KBS has been investigating ecosystems that range from annual grain crops through perennial biomass crops to unmanaged communities at different stages of ecological succession. Annual cropping systems of corn, soybean, and wheat include a conventionally managed system, a no-till system, and low-input and organic systems with legume cover crops. Perennial biomass crops include alfalfa and hybrid poplars. The unmanaged communities range from early successional old fields to late successional forests.

A major goal of the site is to sufficiently understand the basic ecology of these systems to inform the design of future high-yield cropping systems that are both less reliant on external inputs and more environmentally benign. By making long-term observations across all systems simultaneously, researchers test hypotheses about the importance of different organisms and the ecological interactions that lead to the provision of different ecosystem services, including food and fuel production. For example, research revealed that winter cover crops play an unexpected role in soil carbon accumulation while providing to the primary crop a biological source of nitrogen that is less likely than fertilizer nitrogen to be lost to groundwater. A 13-year study of nitrate leakage showed that the conventional system lost much more nitrate than did the no-till, which lost more than the low-input and less-productive organic systems. The perennial biofuel crops lost virtually no nitrogen. This knowledge could be combined with genomic technology to design cover crops that are better at fixing atmospheric nitrogen into organic compounds that are more quickly mineralized to inorganic forms when most needed by the primary crop. It also could be used to design biofuel crops with high nitrogen use efficiencies.

Another project at KBS has been to explore ways to reduce the greenhouse gas impact of agriculture –and even to mitigate some of the global carbon dioxide increase. Twenty years of soil carbon and greenhouse gas measurements show that the single greatest source of global warming potential in cropped systems is the production of nitrous oxide by bacteria in soil. Nitrous oxide is 300 times more effective than carbon dioxide at absorbing heat in the atmosphere, and soil bacteria release more nitrous oxide when plants fail to take up all of the fertilizer and legume nitrogen applied. Designing plants that are better at capturing soil nitrogen could considerably reduce the global warming potential of these systems.

Research at KBS also has demonstrated the value of plant diversity. For example, soybean aphids, new to the United States in 2000 and now responsible for millions of dollars of annual insecticide use, can be effectively controlled where landscape diversity provides sufficient habitat for the ladybird beetles that prey on aphids. These and other pest control services can be well managed given sufficient understanding of the relationship between plants, pests, and their predators.

The National Science Foundation has recently established the National Ecological Observatory Network (NEON) to provide long-term environmental observations at 20 U.S. locations, including 6 LTER sites. The combination of long-term observations at NEON sites and long-term observations and experiments at LTER sites will provide valuable insights for continent-scale environmental change. It also will bring the number of U.S. sites established for long-term measurements to 40, though still only one of these will be focused on row-crop agriculture.

3

A New Plant Science Research Agenda

To meet the societal goals laid out in Section 2, plant science must develop a deeper and broader understanding of plant biology as quickly as possible. This section lays out a scientific agenda to achieve this goal by discussing scientific objectives in four broad areas:

- Understanding genetic diversity across and within species
- Understanding biological processes
- Understanding complex communities and ecosystems
- Transforming data to understanding

Understanding Genetic Diversity Across and Within Species

The tremendous diversity of plants offers the most immediate opportunity to benefit from plant science. Understanding the nature, origin, and roles of genetic diversity is fundamental to all aspects of plant science. In particular, it can help determine how ecosystems are maintained and which genes, species or biological functions are necessary to create a stable environment, whether it be grassland, forest, savannah, or managed ecosystem. It can identify what organisms will be able to evolve or adapt in the face of climate change, and which are likely to go extinct. It can identify organisms that produce particular compounds or that interact with particular beneficial or detrimental microbes or herbivores. It can help agriculture produce more outputs with fewer inputs while protecting the planet's biodiversity. A better understanding of the molecular basis of diversity also could produce a revolution in plant breeding to help feed the world of the future.

Models and Reference Species

Model and reference species contribute to plant science by demonstrating the utility of novel technologies or approaches, contributing baseline information about plant function, and providing a platform for the study of fundamental processes.

The foremost example of a model plant species is *Arabidopsis thaliana* and work on this important model has contributed to the overall health and vitality of plant science research, as well as contributing to crop improvement. But Arabidopsis is not a suitable model for all plant functions. Additional model species need to be developed that are appropriately matched with compelling biological questions. Examples might include a legume model for the study of biological nitrogen fixation and a grass model for the study of C4 photosynthesis. Better understanding of nitrogen fixation in a model plant could lead to a reduction of fertilizer application due to enhanced nitrogen utilization within crop plants. C4 photosynthesis is a more efficient form of photosynthesis common to certain grass crops like corn. If this process could be transferred to non-C4 crops, those crops also could reap the rewards of C4 photosynthesis, such as increased carbon fixation and water conservations in hot dry climates. Additionally, models need to include both woody and herbaceous perennials (plants that produce for multiple years before being replanted, which can lead to improved water use and a reduction of labor and energy costs, soil erosion, and herbicide use), since current models are not well suited to studying the perennial habit.

Translating information from model species to crops is still very difficult. Progress is possible by matching the appropriate reference species to each challenge, by developing the technology to make appropriate quantitative measurements, and by creating computational tools to develop predictive models (as discussed later in the section). Another challenge is to use crop plants as models for their own trait development and improvement. Knowledge from just a handful of crops could be leveraged for many other crops.

The number of model species studied in detail should be limited but sufficiently diverse to address the major, compelling questions of plant biology. One approach would be to subject first tier models to deep functional characterization and study second tier models to sample diversity. Fundamental understanding of basic processes in these models would serve as a baseline for studies of related plants in cropping and natural systems.

Identifying and Capturing Plant Genetic Diversity

Although biotechnology has and will continue to contribute greatly to crop production, continued success will depend on a deeper understanding of the natural variation existing in plants. Initially, a more in depth sampling of plant diversity will be important for defining evolutionary relationships and processes of environmental adaptation and plasticity; as a source of useful genes, proteins and metabolites; to fully understand biotic relationships in natural environments.

Identifying Plant Genetic Diversity

- Plant gene sequences vary among individuals within a population, often because of selective pressure
- DNA sequencing is a low-cost, high-throughput way to catalog this diversity
- The “epigenome,” which refers to heritable changes that cannot be directly attributed to DNA sequence alterations can now be assessed and is a new focus of attention

Capturing Plant Genetic Diversity

- Both traditional and modern methods of phenotyping can relate genomic and epigenomic variation to specific traits
- Modern methods of genotyping, including robotics, provide a high-throughput means to utilize natural variation for crop improvement through molecular breeding
- Biotechnology is another means to take advantage of genes associated with desired characters, especially in situations where sexual crosses are not possible

Related Fundamental Questions

- How do plants tolerate polyploidy and how does it contribute to genetic and phenotypic diversity?
- How important is the epigenome, and what traits does it control?
- What informatic tools can help relate DNA sequence variation to expressed traits? This relationship is sometimes called “From Genome to Phenome.”

Characterizing genomes to understand and utilize plant diversity

Costs associated with sequencing technologies have dropped four orders of magnitude in four years. It is now possible to sequence not just many species but many individuals within each plant species. Indeed, the Department of Energy Joint Genome Institute continues to be a leader in the sequencing of plant genomes, with an exciting recent interest in using sequencing technology to explore plant-microbe interactions (e.g., plant rhizosphere[5]). Given these capabilities, an ambitious but feasible goal would be to sequence the genomes of 1,000 plant species to produce high-quality and well-annotated genomic resources over the next five years. These species should be phylogenetically or ecologically important to shed light on key biological questions. Sequenced regions should include coding (regions where genes reside) as well as non-coding regions. Nonvascular land plants and marine plants, including single-celled and multi-celled algae, are important to include in this effort. This large genomic resource could provide information about the relationships among all agricultural plants, comprising forestry all the way through horticultural and emerging biofuel crops.

Plant systems are excellent experimental systems for fundamental evolutionary and quantitative genetics. Comparative genomics allows plant scientists to identify the core regulatory and metabolic networks shared between all species. Ancestral genomes can be reconstructed by sequencing a variety of closely related plants and comparing their structures. The evolution of genes then can be traced as plants adapted to different climatic zones. Even though the species sequenced may not be closely related to crops, the payoffs to agriculture and the preservation of plant diversity could be huge.

This sequence information could answer a variety of very practical questions, such as how disparate plants have addressed particular developmental or biochemical challenges? For example, most grasses investigated produce defense compounds known as benzoxazinones. Several unrelated dicots also produce these compounds, but use different proteins to produce them. Thus, if a dicot were going to be engineered to produce these compounds, it would be most productive to use the dicot genes rather than the grass ones. Genomic sequence data could also determine the extent and nature of genetic bottlenecks that occurred during the domestication of crop species, and help to illuminate how genetic diversity from agricultural varieties, wild progenitors, and related species can be utilized.

The Challenge of Phenotyping

New technologies have largely solved the genotyping problem, but the phenotyping problem is much more difficult. While sequencing the genome of a plant provides a parts list for an organism, the manifestation of those parts in an observed phenotype reflects the plant's interactions within and among its cells and with the environment. This produces an extremely complex organism that is continually interacting with and responding to a changing environment with a changing phenotype throughout its lifetime. The issue of phenotyping is made more complex by the many different aspects of the phenotype that might be assessed. Gene expression (RNA and proteins) is an aspect of the phenotype that can be assayed by existing technologies; the challenges in this case are analytical. In contrast, metabolite profiling, and certainly evaluation of plant architecture or whole organism phenotypes are far more difficult. Phenotyping also typically requires highly parallel and high-throughput data streams. Measuring and understanding the components of living organisms and their interactions in a variety of environments (both biotic and abiotic) is essential to understanding diversity and, as discussed later in this section, achieving systems-level knowledge in biology.

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[5] Lundberg et al. (2012) Defining the core *Arabidopsis thaliana* root microbiome. Nature 488: 86–90

Frontiers in Plant Science: High-throughput phenotyping

The advent of DNA-based molecular markers has greatly accelerated the development of new crop varieties (see “Frontiers in Plant Science: Advances in molecular plant breeding lead to flood-tolerant rice” box). However, many of the most important crop traits (such as yield and drought tolerance) are controlled by many genes and their complex interactions. The inability to associate observable parameters of the trait (phenotype) with specific genetic loci has limited progress. Indeed, given the current power of genotyping methods, the inability to accurately phenotype plants for multiple traits and on a large scale is the main limiting factor for future crop improvement.

Solving this problem would herald a new age of understanding of basic plant processes.

Taking a page from”big pharma,” where high-throughput phenotyping helped identify new drug targets, many of the major agricultural biotechnology companies have invested in high-throughput plant phenotyping centers. These centers incorporate automation in plant growth with multispectral imaging and other measurements to routinely analyze large numbers of plants in both greenhouse and field settings.

However, phenotyping activities by industry are understandably focused and, due to cost, utilize technology that is currently limited with regard to what can be measured and the accuracy of these measurements. Moreover, these industrial facilities are unavailable to academic and government researchers who make many of the basic discoveries of plant biology and develop the new germplasm used by industry for commercial plant breeding. Hence, there is a pressing need to establish regional high-throughput phenotyping locations that focus on detailed measurements of phenotype and the development of phenotyping technologies. Ideally, the technologies used in these phenotyping locations should be scalable from molecule to ecosystem. Government, academic, and industrial organizations would partner in these locations to develop and apply high-throughput technologies to plant biology. A key focus should be the acceleration of trait discovery by application of high-throughput phenotyping. Such efforts also should include the development of new phenotyping technology in collaboration with engineers, chemists, physicists, biologists, and computational scientists. A major current limitation is the lack of technologies that allow quantitative measurement and visualization of cellular components in real time using non-destructive methods.

An investment in these regional phenotyping centers would revolutionize the ability to relate genotype with phenotype and empower plant breeders to overcome the most pressing restraints to plant productivity, as well as empower plant biologists to fully utilize plant diversity for human benefit.

A focused, plant-phenotyping effort that is quantitative and based on standards developed by the plant science community is needed to establish a deep association between phenotypes and genotypes in multiple environments. This initiative would be undertaken at multiple phenotyping locations that would use innovative technologies to investigate a variety of plants and their responses (see “Frontiers in Plant Science: High-throughput phenotyping” box). Capabilities available at these locations would include methods of in vivo, continual recording along with the ability to perform destructive analysis such as metabolic profiling. Because of the importance of phenotyping to industry, the private sector should be involved in the establishment and support of these efforts.

Understanding the interactions between plant genotypes and the environment is critical, especially given the wide diversity of environments in the United States and around the world. Regional networks for field phenotyping should represent geographical ecoregions for unmanaged ecosystems and managed, cropping systems. Recognizing the diversity of plant systems worldwide and the role they play in global climate and productivity, the US should take a leadership role in promoting international networks to support field phenotyping. The goal is to understand all of the processes that control plant phenotypic variation. This information could then be applied to all aspects of plant biology, from breeding trees or row crops for specific environments to predicting the effect of climate change on particular species or ecosystems to assessing the response of an individual species to pathogens.

As an example of what is possible in the future, modern combines have an array of instrumentation that collects real-time data as the combine traverses a field. Future applications of this precision agriculture could provide feedback for companies, farmers, and plant scientists interested in genotype-by-environment interactions on a field-by-field or acre-by-acre basis. One could imagine similar technology being deployed from robotic aircraft to assess the health of forests or other natural ecosystems.

Needed Technologies

To understand and take advantage of plant diversity, an array of new technologies will be needed. Easier protocols for genetic transformation of diverse plants could provide for more rapid genetic improvements, and could help unravel the complexities of genetic networks shared by all, or large groups of, plants. An important overarching goal is to be able to transform any plant with new genetic material.

Tools for the analysis of genetic sequences are needed, including those from cross-pollinated species and polyploids, along with effective tools for data integration. Phenotyping tools need to be developed that enable, for example, real-time monitoring of root growth or growth of experimental multi-species plots. It is especially important that such efforts include unmanaged natural systems and relevant field conditions for diverse crop species.

The phenotyping locations discussed above could provide such services as crop transformation, crop phenotyping, and analysis on multiple scales. Crop-specific technologies need to be accessible so that new concepts can be directly evaluated in other crops, and so that new inventions can be easily deployed in other crops.

The phenotyping locations must also be long term in order to accommodate perennial crops that can take years to establish and to ensure that even annual crops are exposed to natural variations in climate and pest outbreaks. Policies would have to be enacted to address the issues of intellectual property and the movement of biological materials across state borders. Each of the phenotyping locations should also accommodate experimental manipulations that will span the range of environmental changes expected to affect crop growth over the coming decades, including changes in precipitation, temperature, carbon dioxide, and ozone. Partnering with existing networks [such as USDA Agricultural Research Service (ARS) and NSF Long-term Ecological Research (LTER)] field sites could leverage infrastructure and detailed knowledge of past environmental change for a wide variety of climate and soil settings.

Essential to understanding these data are software systems and the requisite computing infrastructure. These systems will be discussed below in the “Transforming Data to Knowledge” section.

Understanding Biological Processes

To overcome the societal challenges of the 21st century, plant science must obtain a deeper understanding of plant biological processes; such as, the mechanisms of response and adaptation to environmental change, biotic and abiotic interactions over temporal and spatial scales, and maintenance of biodiversity. This increase in understanding would have a multitude of practical benefits. For example, plant breeding has achieved steady, incremental improvement of crop performance without a detailed understanding of the plant functions that underlie these traits. This rate of steady improvement will be insufficient to respond to future, rapid changes in the environment, food demand, and market forces.

Toward a Predictive Understanding of Biological Systems

A major challenge to creating sustainable and adaptive agricultural systems is to develop and harness predictive models for plant growth and development. Moving beyond correlation to causation will require a deeper understanding of biological systems. This understanding must be embodied in models that extend across genotypes, across development, and across biotic and abiotic influences. Models are needed at the molecular, cellular, organismal, agricultural, and ecosystem levels, encompassing both model and non-model species. To build these models, the physiological state of the plant needs to be known at all times and all scales, with synthesis across various levels. The apparent randomness of molecular and cellular events needs to be reconciled with organization at higher levels.

Reductionist approaches need to be linked with holistic approaches, combining deep knowledge of individual biological components with understanding of whole systems. Plant scientists need to identify and understand the functions of not only every gene but every protein, metabolite, structural molecule, and so on. In addition, understanding the interactions of these components is needed to create predictive models. Initiatives will be needed to understand particular categories of molecules within cells, such as all proteins or all metabolites. A key frontier is to understand genome structure and how this structure contributes to gene regulation.

A major advance in the last decade has been increasing understanding of the role of epigenetic modifications of DNA and how these modifications control a variety of cellular processes. Epigenetics (with *epi* derived from the Greek for over, above) refers to heritable changes in gene expression or phenotype that arise from events other than direct changes of the DNA sequence. For example, plants that have encountered a pathogen during their lifetime may pass along a heightened sensitivity to that pathogen to their offspring through epigenetic “marks” in the genome, even if their genome sequences are not altered by the interaction[6]. Plant biology contributed many of the early observations that led to the current understanding of epigenetic phenomena across animals, fungi, and plants. However, understanding remains poor of how changes in the epigenome contribute to overall phenotypic diversity and, perhaps most importantly, how this information can be harnessed for crop improvement or how it contributes to ecosystem function. This represents a considerable, largely uncharted research opportunity that promises major improvements in plant performance.

Uncovering the genomes of plants through DNA sequencing has been only one step. Next, the plant science research community must connect the vast quantity of sequence data to protein and metabolite production, which ultimately controls the observable phenotype.

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[6] Alvarez et al. 2010. Mol. Plant Pathol. 11: 563-576.

Understanding metabolic and developmental pathways to the extent that changes in a pathway produce predictable outcomes could transform agriculture and other human endeavors that rely on plants. Complex traits, such as drought tolerance, are the primary limits on crop productivity. An understanding of these traits at a systems level will make it possible to increase productivity with fewer inputs.

Plants could be fundamentally redesigned to meet human needs. By exploring the limits of existing plants, it may be possible to define and create ideal plants for any setting. By applying an engineering paradigm to plants, it may be possible to achieve a wide variety of ambitious goals, such as:

- crops engineered to contain nutraceuticals or higher levels of micronutrients;
- simultaneous improvements in nutrition, taste, shelf life, and quality;
- plants that can grow in any environment for the purposes of food, fiber, and other products;
- new ways of manipulating and applying photosynthesis;
- nitrogen fixation in all major crop plants, including trees;
- plants with much smaller environmental impacts through reduced water and carbon footprints, efficient nitrogen and phosphorus use, and less dependence on pesticides;
- plants with new traits that work within current cropping systems;
- plants with more effective associations with endophytes, root symbionts, and rhizosphere microbes;
- plants with greater disease and pest tolerance;
- genetic mechanisms to prevent the spread of novel genomes to wild populations;
- novel cropping systems through, for example, the domestication of extremophiles or the use of synthetic genomes;
- the introduction of perennialism into major grain crops;
- the creation of new plant organs that, for example, accumulate lipids in leaves or produce valuable industrial feedstocks;
- plants that provide personalized nutrition; and
- plants that interact with the human microbiome to improve human health.

A systems level understanding is essential to answer some of the most important and fundamental questions in plant science. Can the selection of populations be sped up so they can adapt to global climate change? Can a genome be designed by picking the most favorable genes and alleles to yield a plant with specific desired properties? How do plants gain and lose genes? What happens to genes that are adaptive for crop plants when they end up in related, wild plants in unmanaged or less managed ecosystems? What is the mechanism of hybrid vigor? Why is polyploidy (the presence of multiple genomes) so common in plants?

Needed Technologies

The phenotyping challenges discussed earlier in this section are critical considerations in the development of systems biology in plant science. Technologies needed include comprehensive, high-throughput, and dynamic imaging at the molecular level, the organelle level, the cellular level, the tissue or organ level, and the whole plant level. Another need is to fully monitor a single plant in the field, including its microbial community and the substances it takes in and releases. Needed tools include gene replacement for any gene and any plant, control of any gene, real-time imaging, and quantitative sensors of plant form and development. High-throughput technologies are available for some categories of biological molecules, like genomes and the transcriptome, but are less available for others, such as proteins or the metabolome. In addition, appropriate cyberinfrastructure is needed to store, analyze, visualize, and share these data.

The phenotyping facilities discussed earlier could help to develop and provide these new capabilities. These phenotyping locations should include engineers, chemists, and physicists to develop a new generation of tools to measure quantitative plant components. Collection and use of phenotype data also will require new software and statistical analyses needed to store, analyze, and make sense of all the data. Plant phenotyping centers could work closely with plant cyberinfrastructure centers that specialize in the integration and management of large, complex sets of data and have access to high-performance computing for downstream analysis and modeling.

New technologies and concepts could allow population genetics and breeding to be merged with molecular analysis, creating a valuable interaction between natural variation and systems biology analyses.

Frontiers in Plant Science – Plant pathogen proteins to advance gene therapy

Research on a family of DNA binding proteins derived from plant pathogens has unveiled a customizable code used to engineer proteins for binding specific DNA sequences. In a process comparable to editing a written document, genome editing uses proteins that are designed to bind specific regions to correct typos (mutations) or delete words (genes). This ability to generate a protein that binds a specific sequence of DNA opens the door to countless possibilities for curing genetic diseases through gene therapy and to new approaches for basic biological research.

Much of gene therapy research in the last 15 years has been focused on zinc finger proteins, which through laborious, empirical approaches can be engineered to bind many DNA sequences. Currently, methods for genome editing involve linking zinc finger proteins to a nuclease, which cuts the DNA. Then a template is provided for the editing process, which occurs by an inherent mechanism within the cell. However, recent genome-wide studies[7] have shown that zinc finger binding is not always on target, opening up the possibility of introducing new mutations that in animals could lead to cancer or other diseases.

The new class of DNA binding proteins, known as transcription activator-like (TAL) effectors, were identified in *Xanthomonas* species, bacteria that cause disease in citrus, pepper, tomato, rice, and other agricultural crops[8]. Like zinc fingers, these proteins bind specific DNA sequences and can be linked to nucleases (in this form called TALENs for TAL effector nucleases) for genome editing. But unlike zinc fingers, TAL effectors have a simple code within the protein that corresponds to individual bases of the DNA[9]. This simple code offers an economical method for

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[7] Gabriel et al., 2011. Nature Biotechnol. 29: 816-823; Pattanayak et al. 2011

[8] Bonas et al. 1989. Mol. Gen. Genet. 218: 127-136.

[9] Mouscou et al. 2009. Science 326: 1501; Boch et al. 2009. Science 326: 1509-1512.

researchers to generate their own TALENs using standard laboratory techniques. Furthermore, TAL effectors are less susceptible to offsite targeting, reducing the risk of unintended deleterious effects due to accidental genomic editing during gene therapy.

Since its discovery in 2009, TAL effector technology has been licensed for commercialization to a variety of agricultural biotechnology companies. Funding for the initial research on TAL effectors in the United States was through the National Science Foundation and US Department of Agriculture, National Institute for Food and Agriculture, exemplifying the importance of fundamental research that can lead to applications that will support a national bioeconomy of the future.

Understanding Complex Communities

The ability of plants to respond to a changing environment and grow in marginal soils will require understanding many more different plants and crops at a detailed molecular level than we have achieved yet today. Evolutionary and ecological dynamics include such factors as pest/pathogen-plant interactions, domestication, use and liberation of nutrients, and plant-plant competition. Optimized management of ecosystems in the field, the greenhouse, the watershed, and the landscape could enhance ecosystem services. Despite the vast amount of diversity within the plant kingdom, only about 30 crops account for 95 percent of human nutritional needs. Just four of these crops—rice, wheat, maize, and potatoes—account for more than 60 percent. Approximately one third of the world’s population suffers from poor nutrition because of a scarcity of food or because their diet relies heavily on a single staple crop. Meanwhile, deforestation, urbanization, diseases, and pests are continually reducing diversity. Landraces and wild relatives of all major crops are disappearing rapidly, removing important yield traits and yield protecting traits from global gene pools. These trends make it imperative that continuing, strong support be provided for plant conservation and germplasm collections, not only for crop species but also wild species.

Fully understanding biodiversity requires characterizing genes outside crop plants. Non-crop plants may defend themselves in novel ways against pathogens, insects, or other types of pests, and they may grow sustainably in particular environments.

Non-agricultural Ecosystems

Diversity is also a prominent concern in nonagricultural ecosystems. The number of species and the extent of genetic variability in those species can affect the productivity and stability of ecosystems, as well as the propensity of individual species to fend off diseases and pests. This biodiversity is being lost by human-influenced landscape changes (such as deforestation), changes in climate and precipitation chemistry, and the introduction of exotic and invasive species.

Available biological resources need to be catalogued, annotated, and retained. Thousands of plant species are thought to await discovery. For the vast majority of named species, little information is available other than a few herbarium specimens and a name. DNA sequences are often not available to assess relationships and even the most basic aspects of development and biochemistry are unknown. Certainly novel biochemical pathways leading to new and potentially beneficial chemical compounds are awaiting analysis. The scientific community has collected considerable diversity, but the degree to which these resources are well defined and accessible is highly variable.

Communities of Organisms

Agriculture—as an enterprise that manages biotic and abiotic parts of cropped, forested, and grazed ecosystems—depends fundamentally on an ecological understanding of how processes and organisms interact. Plant science needs to investigate communities of multiple species and study non-plant influences on plant growth and development. For example, a deep understanding of leaf and soil microbial communities could better define plant ecosystems, optimize crop growth, and identify microbial biocatalysts for biofuel production. Through better understanding of such systems, it may be possible to predict which ecosystems are the most vulnerable to climate change and to other human impacts. Farther in the future, one could imagine building community interactions that drive ecosystems in particular ways.

Conserving and reinforcing plant communities that can effectively provide provisioning, biogeochemical, and biodiversity services requires knowledge of key plant-associated organisms: in particular, beneficial insects and soil, the rhizosphere, and endophytic microbial communities. Processes underlying co-evolution of plant-pest associations and the metagenomics of roots, leaf surfaces, and other communities affecting plant growth will be expanding areas of investigation. These studies will be especially important in considering the use and, in some cases, restoration of marginal lands by biofuel crops, as well as in understanding community-level dynamics that affect attributes like invasiveness. For example, what traits make particular plants good invaders, and what traits make certain communities resistant to invasion?

Technologies and Facilities

The capacity to organize and manipulate data and high-throughput imaging (a specific type of phenotyping) will be essential for ecosystem monitoring. In particular, gene-by-environment interactions need to be understood for the most important species for various ecosystems. Needed research includes field experimentation, modeling, measurement of environmental variables, and assessments of biotic and abiotic variables.

These measurements will need to be performed on large scales in different ecoregions. Partnerships with existing networks of experimental field sites such as the NSF LTER Network and with new environmental observatories such as NEON will provide opportunities for valuable synergies.

Transforming Data to Knowledge

The fourth major scientific goal applies to all three of the preceding goals. It is now possible to gather more data in a week using digital technologies than could once be gathered in an entire career. As with nearly all biological disciplines, plant science has become highly quantitative and massively parallelized. Examples include genomics and transcriptomics driven by advances in DNA sequencing technology, proteomics and metabolomics driven by advances in mass spectroscopy, and phenomics driven by advances in imaging and remote sensing and climate monitoring. Due to these new technologies, accumulating data is often not the rate-limiting step. Rather, the scientific challenges are managing the data, identifying the necessary resources for analyzing them (both people and computers), and interpreting the results to test hypotheses and design new experiments.

Dealing with massive quantities of data quickly goes beyond what a single lab can manage due to limits of both resources and expertise. Producing large quantities of data requires a set of downstream resources to effectively manage and analyze those data. The lifecycle of data following their production includes storage, management, transfer, analysis, and interpretation. Each of these tasks requires specialized hardware, software, and personalized resources, which are unlikely to exist in a single laboratory. Hence, progress requires the collective action of a team of researchers, providing complementary expertise in biology, statistics, and computer science.

All of these steps can be facilitated by agreement on standards for data sets and application programming interfaces (APIs). These standards should encompass data collection, management, and sharing, including common quantification tools for phenotyping. Core data sets would allow different researchers to work together on overlapping problems. In addition, best practices need to be defined and disseminated throughout the plant science community, and

The Goals of NSF iPlant and DOE KBase[*]

iPlants stated goals: “iPlant is a community of researchers, educators, and students working to enrich all plant sciences through the development of cyberinfrastructure - the physical computing resources, collaborative environment, virtual machine resources, and interoperable analysis software and data services.

The goals for the Collaborative defy easy description because there are no role models in the Life Sciences. iPlant aspires to create advanced computer tools to help tame the data overload that plagues biologists across subdisciplines, from the organismic and ecological to the molecular scale. Another goal is to promote interactions across the areas of plant biology and between biologists and computational scientists. Perhaps our most challenging goal is to help radically transform the way biological problems are approached, shifting from the single laboratory or small collaborating group to community-driven science.

What is iPlant cyberinfrastructure? Broadly defined, it is the set of tools and data needed to tackle grand challenges in plant biology. This will require a range of technologies and expertise enlisted from throughout the science and social science communities: from data processing, storage and analysis methods, through math, modeling, visualization and collaboration tools.

The cyberinfrastructure developed by the iPlant Collaborative will provide the community with two main capabilities to enhance research and education: 1) access to world-class physical infrastructure, such as persistent storage and computer power via local and national resources, and 2) a platform that promotes interaction, communication, and collaboration in the community and that advances the understanding and use of computational thinking in plant biology.”

KBase stated goals: “A high priority of the plants research community is to link genetic variation, phenotypes, molecular profiles, and molecular networks, enabling model-driven phenotype predictions. A second goal will be to map plant variability onto metabolic models to create model-driven predictions of phenotypic traits. Initial work will focus on creating a workflow for rapidly converting sequencing reads into genotypes. We will also build tools for data exploration, and the linking of gene targets from phenotype studies such as genome-wide association studies, with co-expression, protein-protein interaction, and regulatory network models. Such data exploration will allow users to narrow candidate gene lists by refining targets, or be able to visualize a subnetwork of regulatory and physical interactions among genes responsible for a phenotype in question. Users can also highlight networks or pathways impacted by genetic variation.”

[*] Copied from the respective websites:
http://www.iplantcollaborative.org/
http://www.systemsbiologyknowledgebase.org/

infrastructure development should be open and transparent.

The plant research community has been a model for other communities regarding access to data and resources, despite the diversity of projects it undertakes. The National Plant Genome Initiative, which was coordinated under the National Science and Technology Council through the interagency working group on plant genomes, has instilled an ethic of data access. Since 1998, it has operated under three five-year plans, each of which has had a clear statement about the importance of sharing data and resources. This access is particularly important in attracting students to a field of study, since they know data resources will be available immediately for their use.

One investment made by the National Science Foundation to create an ecosystem of cyberinfrastructure for the plant science community is the iPlant Collaborative (see inset box). iPlant has made significant headway in deploying the necessary hardware and software systems to create an infrastructure for plant research data, which includes developing essential computing resources for storing and managing data, accessing high-performance and cloud computing environments, and building APIs to access those resources. Combined, this infrastructure powers a diverse set of high-level bioinformatics and computational biology software systems, which can be easily scaled and focused on delivering scientific achievements. The Office of Biological and Environmental Research within the Department of Energy has also funded the Systems Biology Knowledgebase effort (see inset box), which includes a significant component focused on plant science. However, while these efforts are laudatory, a much more extensive infrastructure will be needed as data needs and capabilities in plant science grow, driven by high-throughput data acquisition, data integration challenges, and the need to build and test predictive models of biological and ecological systems. To have maximal impact, such infrastructure will need to include commercial-grade web interfaces that allow data access by the many plant scientists who are not computational biologists.

The development and increased use of social networking technologies and sites also offer great potential for plant science. Increasingly, large datasets may be utilized by a diversity of scientists working on distinct problems. Through collaborative and social networking technologies, scientists will more easily be able to identify experts to help with an analysis and bridge diverse scientific disciplines. A “meta-web” could marry the social web with the information web so that people can readily share knowledge by accessing the same data, tools, and models.

Finally, a new level of training is needed so that plant scientists know how best to use computational resources. This includes implementing good data management practices, knowing which resources are best suited for a particular computational task, accessing analytical tools and resources, and modifying algorithms for use on massively parallel supercomputers, cloud computing services, and high-throughput computing.

4

Plant Science Takes a Leadership Role in the New Biology

The 2009 report *A New Biology for the 21st Century* called for a new national initiative in biology that would be distributed and coordinated across agencies, multidisciplinary, and long term. Its mission would be to define and conduct research to understand complex biological systems and to tackle a broad range of scientific and societal problems. The initiative would "attract the best minds from across the scientific landscape to particular problems, ensure that innovations and advances are swiftly communicated, and provide the tools and technologies needed to succeed."

Plant science should be at the forefront of this effort because many of the societal challenges identified in the report are linked to environment, food and agriculture. The scientific problems in plant science are complex and inherently interdisciplinary and are tightly linked to pressing problems facing our society, including feeding a growing global population with adequate nutrition, providing new sources of energy, managing climate change, and improving health and nutrition.

The plant science summit was held during the initial stages of development of a "National Bioeconomy Blueprint" by the Obama Administration released in 2012. Directed at national challenges in health, food, energy, and the environment, the blueprint seeks to apply biological understanding to human needs. For instance, it calls for adapting any food plant to any growing condition through the genetically informed breeding of transgenic plants, study of plant development and tolerance of environmental conditions, and understanding of the influences of ecosystems on plants.

Achieving the promise of plant science requires effective government policies in four areas: research support, regulation, education, and outreach.

Basic and Translational Research

Basic research remains the engine that opens new areas of research and drives future advances. Often, these advances are in unexpected directions, as with the discovery of small RNAs as cellular regulators or the use of proteins derived from plant pathogens as tools to manipulate mammalian genomes (see box above). However, the outcomes of basic research often require significant research and development and considerable time before they have applicability to a commercial setting. Though federal funding for research is currently tight, continued support for basic research will create the scientific and economic wealth of the future.

The economic risks associated with transitioning early stage, encouraging results into commercial products, known as translational research, are often too great to entice industry to fund new innovations. Government has a key role in supporting some phases of this research; for example, through SBIR and STTR programs. The increased productivity of agricultural products as a result of translational research could provide potential additional support for both basic and transitional research.

Greater attention and funding of translational research will help attract researchers and entrepreneurs to this form of research. This research tends not to result in high-impact publications, which is the main focus of academic reward systems. Institutions need to adapt accordingly to reward activities that include a service component, such as translational research and other forms of technology transfer.

Industrial-academic- partnerships can be especially valuable in both basic and translational research in the plant sciences. Moreover, private individuals and foundations can be attracted to the problems at the center of plant science because of their close connection to human needs. Coordinated funding is needed to take advantage of current opportunities.

One model that should be considered is provided by the Defense Advanced Research Projects Agency (DARPA) and the recently formed Advanced Research Projects Agency-Energy (ARPA-E). Development of an initiative, such as the "Advanced Research Projects Agency-Agriculture" (ARPA-Ag) could increase support for high-risk research projects with potentially large societal payoffs.

Regulatory Considerations

The regulatory framework that oversees innovation in agriculture is a prominent consideration in the development of many new agricultural products. For example, commercializing a biotech trait takes on the order of a decade. The costs to develop a new trait can range from $3.5 million to as high as $135 million for developing a new trait via genetic engineering to release of a commercial product. These high costs are due, in part, to the time needed for regulatory studies and approval for international markets.

Exaggerated concerns about new traits in crops continue to hinder the development of new agricultural products. Today, the only genetically modified (GM) crops in widespread use are cotton, soybean, corn, and canola, with lesser amounts of GM papaya and squash. Furthermore, the pipeline for new genetically modified crops in the U.S. is constrained by the time and financial costs of product development. Regulations that determine if and when a new trait is released need to scientifically based, focused on real safety issues related to the trait of the new varieties rather than the processes used to achieve the traits. If this were the case, many more improved crop varieties would be in development for a more diverse set of crops. After more than 15 years since the large-scale emergence of genetically modified crops, it is clear that the concerns regarding health and environmental risks do not justify the current regulatory burden.

Regulations also affect plant exploration and discovery of new plants with potentially valuable new pathways. Plant collecting outside the U.S. is increasingly difficult because of treaties that give individual countries sovereign rights over their germplasm growing within their borders. In many countries, concerns about potential biopiracy have led to tight restrictions and extensive bureaucracy regarding collecting activities. This limits the ability of the USDA-GRIN to acquire new material, and hampers efforts of botanical institutions to investigate biodiversity in a global context. Because of the interconnections of the world, the US needs to find a way to establish a path through what is currently an international bureaucratic quagmire, to allow science to proceed while simultaneously protecting the interests of other countries.

Training a New Generation of Plant Scientists

The future of plant science depends not only on research that will drive the field forward but on a trained workforce that is well prepared to conduct and translate the research to serve mankind.

Plant scientists are diverse. They include scientists who investigate the biology of plants from basic or applied perspectives using a wide range of approaches: biochemical, molecular, cellular, evolutionary, organismal, ecological, and others. Researchers who examine the interaction of plants with pathogens, pests, symbionts, herbivores, soil, and society further broaden and diversify the field.

Science is becoming increasingly interdisciplinary. Groundbreaking research in plant science occurs at the interface of biochemistry, biophysics, chemistry, metabolism, bioinformatics, computational biology, genetics, evolution, and development. The undergraduate and graduate curriculum needs to be more integrated and less siloed, not only in plant science but throughout biology. Individuals in the expanding range of plant science disciplines relevant to a particular area need to be able to understand each other's science and communicate effectively. Short courses can bring together people from diverse fields and create communities of shared interests. Granting processes could promote bridges across academic disciplines. In addition, core data sets could allow different researchers to work together on the same or overlapping problems.

Education and training in the plant sciences need to emphasize computational and statistical courses. Skills in informatics will be particularly important as data-sets grow in size and complexity. In addition, education in plant science needs to be coordinated with education in chemistry, physics, engineering, mathematics, and computer science.

Good undergraduate and graduate education can help students who are interested in plant science follow their hearts and replace scientists who are on the verge of retiring today, but should also provide these students with realistic career paths. Model curricula for plant science could attract talented students into the field, as could research experiences for undergraduates focused on plant science problems. Simple efforts, such as providing plant examples for the teaching of fundamental biological principles at all grade levels, can go a long way toward breaking down cultural barriers and raising awareness of the value of plants.

Finally, plant science research and education need to be coordinated across countries to take advantage of the worldwide network of plant scientists, and give the newly trained scientists global opportunities to contribute their knowledge

Engaging the Public

In an ideal world, policy makers and the public would understand the importance of plant science to human health and economic well-being, distinguish real risk from myth, and support a balance of discovery and translational research. Much needs to be done to achieve such a world.

The plant science community needs to bring its science to the public. Many members of the public do not know where their food comes from. Connections need to be made between crop plants and the foods people eat every day. The same can be said of the role plants play in providing wood products, ecosystem services, textiles, pharmaceuticals, and other benefits to our everyday lives. A major program of advocacy and education could interest people in the world of plants and emphasize the importance of plants to a sustainable future. One possibility is to create an American Plant Council, which could work with the recently formed Global Plant Council (globalplantcouncil.org) to coordinate the message and work on common goals.

The plant science community has an exciting story to tell. Many groups are involved with plants, from grocers to home gardeners. Plant science has the potential to produce plants that are more attractive, nutritious, and taste better. Plant scientists can make important contributions to providing food choices. They can improve health and protect the environment in ways that are impossible to envision today. And plant science can create jobs here in the United States based on this country's history of innovation and entrepreneurship.

Plant science should be more prominently featured in the K-12 and undergraduate curricula. K-12 teachers need help to find good teaching materials and reduce cost and information barriers. As genetics curricula are rewritten because of the ongoing genetics revolution, examples from the plant sciences should be included. Plant science can change how people think about the world by demonstrating our many connections to the biological world. Better education at all levels also can help counter the many myths (such as misconceptions about "Frankenfoods" arising from genetic engineering) that surround food among some members of the public.

The plant science community needs to listen to the public to understand and appreciate what the public wants to know. Plant science is a component of economics, philosophy (through the link to sustainability), and literature, and these disciplines have much to contribute to plant science. Plant scientists can work with the entertainment community and investigate the potential of new social networks to disseminate information about the green world.

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