Molecular Plant • Volume 1 • Number 4 • Pages 561–563 • July 2008

Perspective

2020 Vision for Biology: The Role of Plants in Addressing Grand Challenges in Biology

In November 1998, a group of scientists met in Palo Alto, California, at an NSF-sponsored workshop to discuss the grand challenges facing biology at that time. Their primary aim was to identify areas in which plant science could provide important and lasting contributions to addressing these challenges. A key recommendation from their report was to focus sufficient resources on the reference plant *Arabidopsis* to be able to exploit fully its soon to be completed genome sequence. Nine years later, as we near completion of the 2010 program, it is appropriate to step back, assess progress and once again ask how plants can contribute to addressing the grand challenges in biology. What is crystal clear is that there are a host of real-world problems that involve plants: escalating pressures for food, the need for renewable biofuels, and habitat preservation are being driven by the demands of an ever growing and ever more prosperous human population. The ability to face these challenges is dependent on a fundamental understanding of the basic biology and ecology of plants. NSF-funded plant biology research in the past decade has provided the foundations for solving some of these pressing problems. By identifying the next set of grand challenges in biology, and how they can best be met by plant research, we will be preparing for the unforeseen problems of tomorrow. For this purpose, a workshop was held on 3–5 January 2008 in Arlington, VA, that focused on the future directions for plant research, with special emphasis on the role of the reference species *Arabidopsis* in uncovering fundamental biological principles that will enable us to face future challenges to our well-being and that of the global environment (see full report at www.arabidopsis.org/portals/masc/workshop2020.pdf).

During the last 20 years, *Arabidopsis* has emerged as the primary experimental system for essentially all aspects of plant biology. By focusing on a single tractable system, the international *Arabidopsis* community has made dramatic advances in nearly every area of plant research. Further, because of the close evolutionary relationships between all flowering plants, discoveries in *Arabidopsis* have been readily translated to other plant species such as economically important crops. In addition, discoveries made in *Arabidopsis* have impacted on research in animal systems including disease processes in humans.

The remarkable success of *Arabidopsis* research is partly the result of wise investment by the NSF, first through the Arabidopsis Genome sequencing program and attendant technology development and subsequently via the Arabidopsis 2010 Program. This project, now nearing its completion, has funded the generation of a broad range of powerful genetic and genomic resources and technologies. The *Arabidopsis* toolbox, together with the unique qualities of *Arabidopsis* and allied species, will now facilitate effective studies at all levels of biological organization, including, molecular, cellular, organismal, and ecological. In addition, the Arabidopsis 2010 Program has fostered the development of a vigorous and dynamic international community of researchers—a process that has included the training of many graduate students and postdoctoral researchers, and recruited many scientists not trained initially in plant biology. Because of this investment, the *Arabidopsis* research community is ideally, and uniquely, positioned to address the next set of Grand Challenges in Biology.

The workshop participants identified the following Grand Challenges:

1. How do cells work and how do they interface with the environment? The complex functions performed by multicellular organisms ultimately depend on processes that occur within cells. *Arabidopsis* will continue to be used extensively for the analysis of cellular processes because of its rich genetic and genomic resources and rapid generation time. In addition, advances in imaging technologies coupled with genome-wide knowledge of cellular components will provide the starting points for understanding the dynamics of regulatory networks controlling cellular states.

2. How do single cells develop into multi-cellular organisms? The development of all multi-cellular organisms requires the creation of a diverse set of specialized cell types that must be organized to form functional tissues and organs. Further, the organism must maintain pools of stem cells throughout their lifetimes. This requires developmental networks that are robust enough to ensure the correct assembly of parts, but flexible enough to modify development in the face of injury or environmental change. The ability to grow large populations of *Arabidopsis* in the lab or in the field makes *Arabidopsis* a powerful experimental system to dissect the contributions of genetic and environmental factors to development. The availability of genomic sequences for multiple ecotypes also allows *Arabidopsis* researchers to uncover the genetic changes underlying specific responses to the environment in natural populations.

doi: 10.1093/mp/ssn040
Received 19 June 2008; accepted 20 June 2008

3. How do genomes generate organismal robustness and diversity? A critical question underlying our understanding of the diversity of life on earth is how highly related or even identical genomes can yield distinctly different individuals. Plant science has led the way in elucidating connections between the genetic blueprint and its biological output. *Arabidopsis* has provided the proof-of-concept system showing that we can now map the dynamics of the genome at every level from DNA sequence to DNA methylation patterning to genomic association of histones and transcription factors.

4. What is the molecular basis of evolution? The long-term goal of evolutionary biology is to discover general principles and laws governing evolution. The detailed elucidation of the genetics of adaptation and speciation will require a focused approach using reference systems like *Arabidopsis*. In addition, genomics-based answers to important questions in evolutionary biology are within reach using plant reference systems as study organisms.

5. How are biological systems integrated from molecules to ecosystems? The genomic revolution has paved the way for understanding the integrated function of biological systems across molecular, organismal, and ecological scales. *Arabidopsis* is ideal for this endeavor because of the wealth of genomic and functional data and systems biology tools available, and because it is well suited to manipulative ecological experiments.

6. How can the environment be made sustainable for future generations? As primary producers, plants are the ultimate source of food, fiber, and fuel for all forms of terrestrial life, including humans. An integrative systems approach to plant biology will be necessary both to predict the response of biological systems to human perturbations, and to design adaptive strategies to enhance system resilience in the face of rapid environmental change. Systems biology approaches founded on model systems such as *Arabidopsis*, united with parallel efforts by ecosystem modelers, can provide the necessary tools to answer key questions in environmental biology

INTEGRATIVE BIOLOGY: FROM MOLECULES TO SYSTEMS

The overarching goal of biology is to fully understand life and the operation of biological processes. The achievement of this goal requires detailed knowledge of life's component parts at every level from molecules to ecosystems, as well as a holistic view of these components and their dynamic relationships over space and time. *Arabidopsis* is uniquely suited to research encompassing these diverse approaches. The development of powerful genetic and genomic technologies will continue to energize ongoing efforts to understand the molecular basis for cellular and physiological processes. These technologies will also facilitate major advances in our understanding of evolution. New analytical tools promise to provide near complete catalogs of all the constituents of every cell type as well as detailed knowledge of macromolecular function. Further, dramatic advances in cell imaging will produce unprecedented views of the cellular environment. Finally, the integration of this diverse knowledge to produce a unified view of life will require the development and application of novel 'systems' approaches.

A true systems-biology approach, encompassing all of life's components from molecules to populations, is now possible using *Arabidopsis*. To achieve this goal, we make the following general recommendations:

(1) NSF should continue to provide major and specific support to integrate molecular, cellular, organismal, and ecological research on *Arabidopsis* as a system to understand how a living organism develops, functions, and adapts to its environment.
(2) Funds should be provided for development of additional and new types of large-scale experimental genomics resources that will be required to effectively address the Grand Challenges.
(3) Efforts should be made to encourage the development of new quantitative approaches to the study of biological systems using *Arabidopsis* and allied species. This should involve the development of collaborations between biologists, mathematicians, computer scientists, engineers, and scientists in other quantitative disciplines.
(4) Data acquisition should remain a major focus of future programs to fuel iterative cycles of data analysis, integration, hypothesis generation, and testing. The emergence of new technologies will enable the collection of new and higher-quality data of all types, thus permitting more sophisticated systems analyses.

BROADER IMPACTS

Plant research plays a central role in broadening the appreciation and understanding of biological sciences. Beyond the fundamental appeal of plants, the focus on *Arabidopsis* has transformed biology over the past two decades. *Arabidopsis* provides a uniquely tractable multi-cellular experimental system. Its ease of culture and extensive toolkit make it an entry point to scientific discovery at every level, from the classroom to cross-disciplinary and international collaborations.

Perhaps the most significant way in which *Arabidopsis* has shaped science today is by drawing in researchers trained in other fields who would not otherwise have considered working with a plant system. Furthermore, *Arabidopsis* is leading the way in projects that bring together biologists with chemists, mathematicians, physicists, statisticians, engineers, and computer scientists. *Arabidopsis* is now widely accepted as one of the premier laboratory organisms for studying basic eukaryotic processes, and it has the added value of serving as a direct reference for other plants.

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