

Invited Review

Perspective: Plant biology—A quiet pioneer

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Abstract The study of plants contributed to establishment of the foundation for modern biology. For example, it was observations first made in plants that led to two fundamental theories of biology—cell theory and genetics. Throughout the 20th century, plant biology continued to make contributions to the conceptual and technological advances in basic biology and biotechnology, although plant biology's contributions were not always recognized by the field of biology at large. Plants have direct applications to today's major societal challenges including food security, climate change, energy, and sustainability. Solutions to these challenges require innovative technologies that are solidly based on science.

Key words: Biology education, history of plant biology, Nobel Prize and plants, plants and society.

Plant biology, defined here as the study of plants or the use of plants as an experimental system, has made significant contributions to the foundation and advancement of modern biology. Plants obviously have direct implications to many of today's major societal challenges including food security, climate change, energy, and sustainability. It is expected that revolutionary technologies are needed to address these challenges, and that a solid scientific basis is essential in their development. Is plant biology ready for the challenge? If the history of plant biology is any indication, the answer is “yes”.

This article is intended to review the contributions of plant biology to the field of biology at large in a historical context, and to discuss how best to realize the full potential of plant biology in advancing science and meeting society's needs.

Plant biology—Frontier science

Table 1 summarizes the major scientific discoveries or conceptual advances that plant biology contributed to the overall field of biology. Two fundamental concepts of biology—cell theory and genetics—were based upon observations and experiments on plant systems. Revolutionary concepts such as the proteinacious nature of enzymes and transposable genes were born out of research with plants. Because of the ease of manipulation and the availability of abundant materials, plants played a key role in establishing the field of

biochemistry. Plants also inspired development of novel chemical syntheses as scientists recognized the ability of plants to manufacture a broad array of useful compounds.

Until the middle of the 20th century, biologists despite the fact that they were often identified as botanists and zoologists appeared to have communicated with ease, based on the common interest in elucidating the laws of nature. Plants provided a convenient system to study a number of biological processes. In retrospect, plant biology was at the right place at the right time.

Around the 1950s, several events took place that changed the landscape of biology. One event was the determination of the structure of DNA by Watson and Crick in 1953, which opened up an entirely new perspective in the study of living organisms and triggered tremendous growth in the biological sciences. Another significant factor was that after WWII, the direct connection between basic scientific research and technological advances were recognized (<http://www.nsf.gov/od/lpa/nsf50/vbush1945.htm>). This resulted in establishment of science agencies that managed the public investment in scientific research. There were significant increases in public funding of biomedical research in the United States and elsewhere, which had a major impact on the rapid growth of the biological sciences. The availability of research funds had the effect of focusing the attention of biologists, and more importantly, universities and colleges, to research directly relevant to human disease. The study of animals

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Table 1. The role of plants in major advances in biology.

Year	Event	Reference
1665	Robert Hooke observes “Cells” (cell walls of cork)	a
1827	Robert Brown discovers Brownian motion by observing movement of <i>Clarcia</i> pollen grains	b
1831	Robert Brown recognizes the “Nucleus” in orchid leaf cells	a
1838	Matthias Jakob Schleiden suggested that every structure element of plants is composed of cells or their products. (The Following year, Theodor Schwann extended the observation to animals.)	a
1839	Matthias Jakob Schleiden and Zoologist Theodor Schwann found the “Cell Theory”	a
1866	Gregor Mendel establishes the laws of heredity using pea plants	c, d
1900	Three botanists—Hugo DeVries, Carl Correns, and Erich von Tschermak—independently rediscover Mendel’s work	c, e
1902	Gottlieb Haberlandt publishes a paper on his work to culture isolated somatic cells of higher plants in vitro. In the paper, he predicted the totipotency of plant cells.	f
1908	Wilhelm Johannsen coins the word “Gene” to describe the Mendelian units of heredity. He also made the distinction between “Phenotype” and “Genotype”, by studying the inheritance of seed size in self-fertilized lines of beans.	c, g
1915	Richard Willstätter receives Nobel Prize for Chemistry for his work on plant pigments, especially chlorophyll	h
1926	J.B. Sumner isolates jack bean urease, the first enzyme molecule to be prepared in pure crystalline form. He was also the first to suggest that enzymes are proteins. (Sumner received the 1946 Nobel Prize in chemistry for this work.)	h
1935	Wendell Stanley crystallizes tobacco mosaic virus (Stanley received the 1946 Nobel Prize in chemistry with John H. Northrop for this work.)	h
1937	Albert Szent-Gyorgyi receives Nobel Prize for Medicine and Physiology for his research on biological oxidation, with special reference to vitamin C. He isolated vitamin C from the pepper plants.	h, i
	Walter Norman Haworth receives Nobel Prize in Chemistry for his investigations on carbohydrates (including glucose, starch, and cellulose) and synthesis of vitamin C	h
1944	Maize geneticist Barbara McClintock discovers transposable elements (jumping genes) (McClintock received the 1983 Nobel Prize in Medicine or Physiology for her work)	j
1947	Robert Robinson receives Nobel Prize in Chemistry for his investigations on plant products of biological importance, especially the alkaloids	h
1961	Melvin Calvin receives Nobel Prize in Chemistry for his research on the carbon dioxide assimilation in plants. He was one of the first to demonstrate the utility of isotopic carbon to follow metabolic pathways	h
1970	Norman Borlaug receives Nobel Peace Prize for his work on Green Revolution	k
1983	First stable and reproducible Eukaryotic genetic transformation achieved in Tobacco plants	l
1986	GUS reporter system and Luciferin/Luciferase reporter system developed in plants	m
1992	Gene silencing (RNAi) discovered in plants	n

^a Nature Cell Biol 1 E13-E15 (1999). ^b <http://galileo.phys.virginia.edu/classes/152.mfl1.spring02/BrownianMotion.htm>. ^c <http://www.esp.org/timeline/>
^d <http://www.mendelweb.org/Mendel.html>. ^e Vries, Hugo de 1900. Concerning the law of segregation of hybrids. First published in English as: De Vries, H 1950. Concerning the law of segregation of hybrids. *Genetics*, 35(5, pt 2): 30–32. Originally published as: De Vries, H 1900. Sur la loi de disjonction des hybrides. *Comptes Rendus de l’Academie des Sciences (Paris)*, 130: 845–847. ^f <http://plato.stanford.edu/search/searcher.py?query=Johannsen>. ^g Haberlandt, G (1902). *Sitz-Ber Mat Nat Kl Kais Akad Wiss Wien* 111: 69–92 [translated into English in 1969: Krikorian, AD, and Berquam, DL *Bot Rev* 35: 56–67]. ^h <http://nobelprizes.com/nobel/chemistry/chemistry.html>. ⁱ *Biochemical J* Vol XXVIII: 1625–1628 (1934). ^j <http://almaz.com/nobel/medicine/>. ^k http://nobelprize.org/nobel_prizes/peace/laureates/1970/press.html. ^l Downy, K. et. al. (1983) “Advanced in Gene Technology: Molecular Genetics of Plants and Animals (New York, Academic Press). ^m Ow DW et al. 1986; Chalfie M et al. 1994. ⁿ Jorgensen R et al. 1992.

and organisms associated with humans became linked with medicine. Studying plants became linked with agriculture. As a consequence, plant biology became isolated from mainstream biology dominated by biomedical sciences.

Nevertheless, plant biology continued to make novel observations and discoveries. The significance of some of them became apparent only at a later date when the same phenomenon was observed in animals. “Reprogramming Cells” that was named by *Science* as the 2008 breakthrough of the year (Vogel G 2008) is one of those cases. The concept of cellular totipotency was first proposed in 1902 by an Austrian botanist, Gottlieb Haberlandt (See Table 1), who tried to establish somatic cell cultures from plant roots. By 1957, reprogramming cell lines were well established in plants by Folke Skoog and his group (Skoog F et al. 1957). Another example is nitric oxide. A discovery that “a gas can act as a signal

molecule in the organism” (Kende H 1998) was first made in plants with ethylene in the 1930s. Ethylene’s basic mode of action was known by the 1960s (Saltveit ME et al. 1998), 30 years before the Nobel Prize in Physiology or Medicine was awarded to R. F. Furchgott, L. J. Ignarro, and F. Murad for their discoveries on the role of nitric oxide as a signaling molecule in the cardiovascular system, thereby establishing a “new” principle that a gas can act as a hormone.

Perhaps the most famous recent example was the discovery of RNA interference (RNAi). The 2006 Nobel Prize in Physiology or Medicine was awarded to Andrew Fire and Craig Mello for their discovery of “RNA interference—gene silencing by double-stranded RNA” (http://nobelprize.org/nobel_prizes/medicine/laureates/2006/press.html). In reporting the Nobel Prize, *Science* (Couzin J 2006) acknowledged that the phenomenon of gene silencing was first observed in plants, citing the

work of two plant biologists who pioneered the field, Richard Jorgensen (Jorgensen R 1992) and David Baulcombe (Mueller E et al. 1995). Research on RNAi and small RNAs has led to a new field of research, *Epigenomics*, which addresses the mechanism of controlling heritable gene expression without changing the primary DNA sequence of a genome.

With knowledge accumulated from prior research, plants became powerful experimental model systems to understand the epigenome. Steve Jacobsen and his colleagues discovered hypermethylated epigenetic alleles in *Arabidopsis* (Jacobsen SE et al. 1997) and determined a link between RNAi and gene silencing at the chromatin level (Jackson JP et al. 2002). Rob Martienssen discovered that heterochromatic sequences of the *Arabidopsis* genome are transcribed and correspond to small interfering RNA (Lippman Z et al. 2004). Another pioneer in this area is Vicki Chandler, a recipient of the 2005 NIH Director's Pioneer Award for her work on "paramutation" in maize on which she had been working since the 1980s (<http://nihroadmap.nih.gov/pioneer/Recipients05.aspx>). To the benefit of everyone, discoveries made in plants are being used to make further advances toward a complete understanding of the epigenome.

In the area of bioinformatics, plant biologists are again exploring a new frontier. Genomics and subsequent "omics" research have created high throughput analytical tools, which have enabled biologists to study biological processes at the whole systems level. Systems level science produces huge quantities of diverse datasets in thousands of laboratories around the world. Data storage, maintenance, access and utilization have become a major challenge to the scientific community with no easy solution in sight. In this regard, a consortium of plant biologists are conducting an experiment with a new kind of cyberinfrastructure called "iPlant Collaborative" (<http://iplantcollaborative.org/>). If successful, iPlant will serve as a model for accessing and organizing large distributed datasets to discover how individual processes are integrated into the total biological system.

Plant biotechnology—A frontier technology*

With the advent of recombinant DNA technology, a new industry—biotechnology—was born in late 1970s. In the area of genetic transformation of a whole organism, plant biology was at the forefront, marking several "firsts in biotechnology." In 1983, the first stable and reproducible production of a genetically modified eukaryotic organism was demonstrated in tobacco. The

first field trial of transgenic crops was conducted in France and the United States in 1986, marking the enormous potential of genetic engineering for the agricultural industry. The Flavr Savr tomato was the first commercially grown genetically engineered food to be granted a license for human consumption by U.S. Food and Drug Administration (FDA) in 1994. Behind these firsts was solid scientific research carried out in plants early in the 20th century.

A successful genetic transformation of an organism requires three components; target cells to be transformed, a vector to carry a foreign gene into the target cell's nucleus, and the transformed cell's ability to stably transmit the new genetic information from generation to generation. In plants, tissue culture was established in the late 1930s using various plant root tips as the experimental system through the pioneering work of Gottlieb Haberlandt and Philip White. Building on the earlier work, Skoog and Miller demonstrated (Skoog F et al. 1957) controlled organ formation from undifferentiated somatic cells in culture in 1957, and Steward et al described somatic embryo production from carrot callus cells in 1958 (Steward FC 1958). Cell/tissue cultures formed the basis of the plant biotechnology industry prior to the development of genetic transformation technologies (<http://www.danforthcenter.org/iapb-stl/historytemplate.htm>).

Having a whole plant regeneration system in hand meant that the only element needed for complete genetic transformation of a plant is a vector to carry a foreign gene to a target cell. That was provided by a modification of a naturally occurring genetic engineering system found in *Agrobacterium tumefaciens*. The fact that *A. tumefaciens* caused crown gall diseases in plants by transmitting a chemical factor into the host plant cells was established by the mid 1940s. In the ensuing 40 years, the molecular mechanisms of *A. tumefaciens* infection were shown to use its T-plasmid as a vector to genetically transform the host cell: and research to modify the plasmid into a stable vector for genetic transformation of plants was conducted by a number of groups worldwide. In 1983, several groups published papers demonstrating successful transformation in plants using disarmed (non-disease causing) T-plasmids as a vector. In 1985, a Monsanto group published a paper (Horsch RB et al. 1985) outlining a simple and reproducible method to transform plants. For this work and its subsequent application of the technology to crop production, Robert Fraley, Robert Horsch, Stephen Rogers, and Ernest Jaworski of Monsanto Corp were awarded, in 1998, the National Medal of Technology,

* For original papers on the work described in this section, readers are referred to a review article by Ian Sussex, *The Plant Cell* 20: 1189–1198 (2008). The Sussex article describes in detail seminal discoveries that contributed to the establishment of modern plant biotechnology and contains complete references to the original publications.

which represents the highest honors for achievement in science & technology bestowed by the President of the United States.

Other notable biotechnology tools first developed in plant systems include the GUS reporter system (Jefferson RA et al. 1986) that has been widely used in many organisms as a marker for gene fusion as well as a reporter of expression of specific genes in the transformed cells and tissues. Another reporter system, the luciferin/luciferase system from the firefly, was developed by Stephen Howell and his colleagues at University of California at San Diego using transgenic tobacco plants as the experimental model (Ow DW et al. 1986). Both systems were published in 1986. After 22 years, researchers still use both of the reporter systems along with the newer GFP (Green Fluorescent Protein) system. The GFP was isolated from the jellyfish and its use as a marker and a reporter was established in 1994 in *C. elegans* (Chalfie M et al. 1994). (It received the 2008 Nobel Prize in Chemistry.) Each of the three systems offers advantages depending on the purpose of the experiments.

Plant biology and biology education

Contributing, in part, to the isolation of plant biology within the field of biology is the way colleges and universities have taught biology and trained young biologists for the past 50–60 years. Biology is the study of living organisms—what they are made of, how they function, how they reproduce, and how they interact with the environment. However, in most people's minds, biology is synonymous with biomedical science. At many universities, people who study animals and biomedical sciences, or cell and molecular biology, can and do go through their entire graduate career without learning anything about plants. On the other hand, people who study plants are exposed to a much broader curriculum and are afforded opportunities to learn about the biology of other organisms.

Whatever the reason, plant biology when isolated from the rest of biology is a detriment to all biological science. There are many research questions in biology that are common to all living things. The best results are obtained when scientists choose the best system to answer the question at hand, as amply demonstrated by scientists in the early days of modern biology. For a scientist to be able to choose the best system, he/she must have a functional knowledge of the different organisms found in nature. Science advances by building on the prior work by others, for the most part. In order to avoid reinventing wheels, every scientist should be trained to recognize significant work of his/her interest being conducted in different organisms.

From a purely intellectual standpoint, biology

education would become a richer and thought-provoking experience if all students were exposed to research topics that are, or appear to be, unique to plants such as photosynthesis, phytochrome, symbiosis, double fertilization, dormancy, and cell walls. This may even lead to a discovery of new principles in eukaryotes as discoveries are often made by studying unique, unusual, or odd phenomena.

Concluding remarks

Today at the start of 2009, there are signs that plant biology is slowly becoming visible again and more integrated into the biological sciences at large. After sequencing major genomes, comparative genome study is providing new insights about genome function. Plant genomes are very diverse in their structure and show an organization with many unique features. For example, plant genomes are especially suited to investigate quantitative genetics (Nordborg M et al. 2008). Genome researchers value the diversity represented in plant genomes. Emergence of new fields of research such as systems biology and epigenomics attract researchers who select their experimental system based on the quality and quantity of available information, and here *Arabidopsis* is as powerful a system as *C. elegans* or *Drosophila*. The advent of information technology and the Internet have leveled the playing field for all subdisciplines of biology. Scientists today use the internet as a primary source of information. Internet searches of cyberspace for the past and current research on a subject of interest will expose researchers to data and information that are inclusive.

The level of funding for plant genome research has increased world-wide over the past 10 years, which has resulted in the increased interest in plant biology from both scientists and universities. It is expected that the trend will continue, fueled by the recent major investments in research and development of plant-based alternative energy and other plant-based materials. With a \$500M grant from BP, the Energy Biosciences Institute was established in February 2007 as collaboration between the University of California at Berkeley, the Lawrence Berkeley National Laboratory and the University of Illinois (<http://www.energybiosciencesinstitute.org/>). The US Department of Energy (DOE) announced in June 2007 the establishment of three Bioenergy Research Centers with a total investment of \$375M (<http://genomicsgtl.energy.gov/centers/>).

There is an encouraging recent trend among research universities to remove disciplinary barriers and emphasizing an environment where students are exposed to different perspectives and approaches not only within biology, but outside of the biological sciences including physics, materials science, mathematics and computer

sciences.

Plant biology seems to be at the right place and at the right time again. It is hoped that the next generation of biologists will take full advantage of plant biology's pioneering capacity for the advancement of science, and to realize full potential of plants to address the many challenges facing society. After all, humans cannot survive without plants while plants can survive without humans.

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