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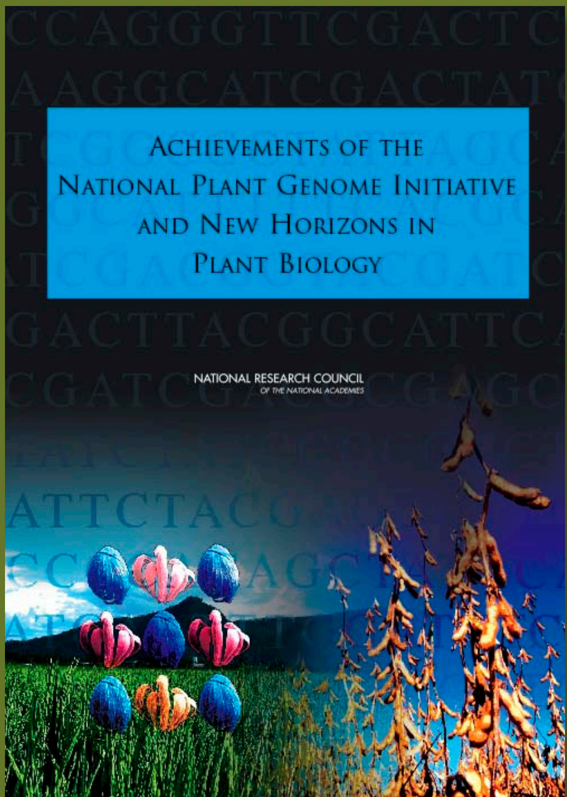
NEW HORIZONS IN PLANT SCIENCES

FOR HUMAN HEALTH AND THE ENVIRONMENT

NATIONAL ACADEMY OF SCIENCES · NATIONAL ACADEMY OF ENGINEERING · INSTITUTE OF MEDICINE · NATIONAL RESEARCH COUNCIL

The National Plant Genome Initiative (NPGI) is a unique, cross-agency funding enterprise for plant genomics in the United States. It was established in 1998 as a coordinated approach to advancing plant science and its applications to address issues of national interest. NPGI is coordinated by an Interagency Working Group with participation from many U.S. government agencies. For more information, visit www.nationalacademies.org/plant_genome.

The National Research Council report *Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology* recommends steps to expand NPGI and broaden its mission. Suggested future focuses include basic research on economically relevant traits in model and crop species, deeper investigations into plant diversity and adaptation, and expanded translation of basic science to practical applications for breeders and farmers.



NEW HORIZONS introduction IN PLANT SCIENCES

Human life would be impossible without plants

This fact was readily apparent to our agrarian ancestors, whose lives were intimately connected with the needs and rhythms of the plants that provided their food, fiber, shelter, and medicines. Today, with more people living in cities and suburbs, the link between humans and plants is less obvious—but just as critical.

Plants form the basis of the food web that sustains all other forms of life. Ultimately, almost all the food that humans eat—from the contents of a salad bar to the grain-fed beef in a hamburger—comes from plants. Plants provide the cotton in our clothes, the wood in our furniture and buildings, the rubber in our tires, and many other important materials.

PLANT SCIENCES HAVE BROUGHT US A LONG WAY

People have long sought to enhance the nutritional and aesthetic value of food, to increase crop productivity, to shorten the time from planting to harvest, and to cultivate crops that are resistant to pests, pathogens, and drought. Centuries of plant breeding and selection for preferred traits have helped us achieve these goals in many crops, resulting in tremendous and positive impacts on food security and an improved quality of life. More recently, scientific advances and genetic manipulation have expanded the ability to make rapid and targeted crop improvements.

But there is still much work to do—and many new goals to achieve. Constantly evolving plant pests and pathogens, global climate change, and changing social needs make plant sciences ever more critical.

21ST-CENTURY CHALLENGES

Plant genomics has a critical role to play in 21st-century agriculture, energy, and environmental stewardship. For example, Earth's climate is undergoing rapid changes—a fact that will have profound effects on where and how plants grow. By increasing our understanding of how plants cope with less water, rising temperatures, and other environmental stresses, plant genomics research can enable scientists to develop crops that can withstand changing climate conditions.

How can we feed and provide adequate nutrition to a growing world population? Can plants contribute to environmentally, economically, and socially sustainable sources of energy? How can agriculture-related pollution be reduced? Given these and other current challenges, the "genomic era" has come just in time. The increasingly powerful tools for genomic research—in which scientists study all of the genes in an organism collectively—make plant research more valuable now than ever before.

The reach of plant sciences stretches way beyond direct improvements to crops. Plants can provide scientists with a window to many types of biological phenomena and help answer fundamental biological questions. In fact cells, nuclei, genes, viruses, and other biological entities were all first discovered in plants. Plant genome science has significant cross-disciplinary applications and has already spurred advances in medicine, chemistry, and engineering, in addition to basic biology.

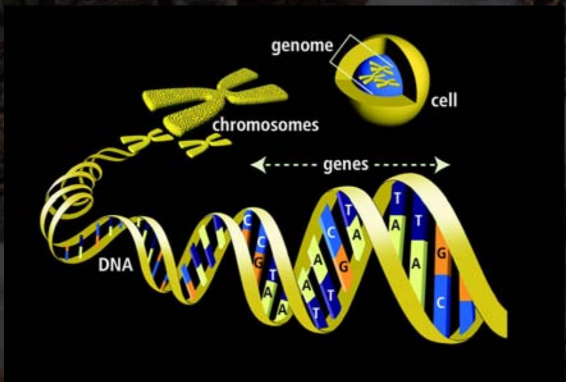
This booklet highlights examples that illustrate the achievements and promise of plant genome science. It is based on the National Research Council report *Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology.*

DNA, GENES, AND GENOMES

DNA, short for deoxyribonucleic acid, is the molecule of heredity and provides the genetic code for living organisms. DNA is made up of biochemical units called nucleotide bases; the order of these bases determines the nature and function of an organism's genes.

GENES are sections of DNA that encode the instructions for making proteins and other molecules that drive the activities in the cells of all life on Earth. GENETICS is the study of the inheritance of specific traits through genes.

A GENOME is the entire collection of DNA in an organism, including all its genes, plus noncoding DNA (sections that do not make protein, but often have important functions in regulating the activity of genes). GENOMICS is the study of genomes. In genomics, researchers study an organism's genes collectively and look at the interactions among genes and between genes and the environment.



SPOTLIGHT ON... food crops: MUTATIONS AND MANIPULATION

You eat mutants! Everybody does, every day. Genomes are constantly undergoing variations in DNA code—mutating—with each generation. Every item in the grocery store has been touched by genetic changes, ranging from the minor to the profound. Today's mammoth tomatoes, for example, can weigh as much as 1,000 times the weight of their wild ancestors. Everything about our food, from size to texture, color, taste, and nutritional content—plus much, much more—is influenced by plant genes.

For many centuries, humans have deliberately cultivated plants with desirable mutations through selective breeding—choosing plants with the best traits and breeding them together. Kiwi fruits, originally hard, unpalatable (but edible) berries from China, were dramatically altered through selective breeding in New Zealand to become the fruit we know today. Scientists can now delve into plants' genomes to find the genes behind particular traits—a much more targeted approach than selective breeding. Identifying key genes enables them to influence changes in plant characteristics more rapidly than ever before.

Genetic mutations—in plants, animals, or any living thing—can be good, bad, or irrelevant for the fitness of the organism itself, or for its human uses. Sometimes, mutations that are beneficial in one way can be debilitating in another. For example, celery naturally produces psoralens, which are irritant chemicals that deter insects from feeding on the plant. Celery plants with elevated levels of psoralens suffer less damage from disease and insects and appeal more to consumers, and therefore, were selectively bred in the 1980s. Unfortunately, workers harvesting or packaging high psoralen-producing celery developed severe skin rashes as a result, and the celery strain was subsequently removed from the market.

CORN: IMPROVING A CRITICAL STAPLE CROP

You'd be sorely disappointed to find an ear of corn's predomestication ancestor, known as teosinte, on your plate. The edible portions of that plant consisted of just 5 to 12 tiny kernels, each encased in a rock-hard shell. Thousands of years of selective breeding have produced a vastly more productive corn—offering 500 or more delectable kernels on each cob—that has become a staple food in many cultures.

Interbreeding modern corn with its ancestor teosinte has shed some light on the genetic changes behind corn's domestication, and even offered clues on when (6,000–10,000 years ago) and where (in southern Mexico) domestication occurred. Scientists have already identified several genes that are responsible for the main changes that differentiate corn from teosinte; these genes have a huge effect on plant growth, as well as on fruit and seed formation. This research has advanced understanding not just of corn, but of how new physical characteristics evolve in other plant species.

Armed with advanced molecular research tools, scientists and farmers are working to improve corn even more. For example, researchers recently identified the genes responsible for corn's vitamin A content. Inexpensive molecular markers, used to identify which plants are expressing a particular gene, are being used to help farmers selectively breed for strains that produce increased amounts of vitamin A. In developing countries, vitamin A deficiency causes eye disease in millions of children each year, as well as many other health effects. Producing corn with a higher concentration of this critical nutrient will be a major boon to public health, particularly in cultures with a corn-based diet.

THE CORN WE KNOW TODAY is the result of thousands of years of selective breeding. Genomic analysis has revealed some of the genetic changes that turned teosinte (left) into modern corn (right). Inset image courtesy Nicolle Rager Fuller, National Science Foundation.

CULTIVATED MUTANTS: ROMANESCO CAULIFLOWER

Romanesco cauliflower attracts attention for its branching, spiraling pattern of growth. Scientists have traced the origin of Romanesco and related cauliflowers to selective breeding by 15th-century Italian farmers. The vegetable's striking shape highlights the incredible amount of variation that can occur within a single plant species; studying such natural variation can provide clues as to how traits develop in plants.

A head of cauliflower or broccoli is actually a collection of immature flower buds. Studying Romanesco and its relatives has provided clues to how flowers are formed. Researchers identified a gene that allowed them to induce *Arabidopsis*, a weed not closely related to cauliflower, to produce cauliflower-like structures instead of flowers. They dubbed the gene responsible "CAULIFLOWER."

MANIPULATION OF PLANT GENES

Many people are aware of the debates about the safety and long-term effects of genetically modifying food crops. Most are not aware, however, of the broad range of approaches genetic modification can include. Altering a plant's genes does not necessarily mean transplanting genes from another species into the plant's genome.

Often, it can mean using the variability of the DNA sequences in a plant's own genes (generated by the mix of DNA from each of its parents) to trigger or suppress certain processes. For example, scientists are searching for ways to change the time when rice plants flower. If they are able to trigger flowering earlier, it could allow farmers to harvest more crops within a single year in some areas. Other scientists are investigating genes that can make rice plants produce as much as twice the number of rice grains per plant.

In other cases, scientists suppress certain genes to improve a crop's performance. For example, leafy greens such as spinach and lettuce are more productive if flowering is suppressed. This increase is because flowering diverts energy from leaf production to flower and seed production, slowing the growth of the harvested parts of the plant.

Another type of manipulation includes turning a plant's genes on or off to change its height or shape, which can make crops sturdier and more resistant to wind and weather damage.

GENETIC RESOURCES

Wild plants that humans don't eat can still be used as a genetic resource. A dozen varieties of apples or four types of potato at the supermarket may seem like a large selection, but these represent a miniscule fraction of the thousands of varieties of apple and potato that exist currently or have existed historically somewhere on Earth. Studying the DNA sequence variation in the genomes of the relatives and ancestors of today's crops can yield insights into basic plant processes and improve crop strains and farming methods.

For example, humans have cultivated an enormous variety of tomatoes through selective breeding, and, more recently, genetic manipulation. These efforts have been targeted toward producing a more marketable and easily transported fruit. However, some of these beneficial changes to the tomato's size, shape, color, sensitivity to bruising, and rate of spoilage have been gained at the expense of flavor, fueling an increased interest in heirloom and other tomatoes known for their superior taste. Genome sciences provide valuable tools for scientists in search of the optimal good-tasting, but robust, tomato.

Another reason the wild ancestors of crops are of value is their potential for holding the cure to future plant diseases or pests. When a new plant foe emerges, the more places scientists have to look for genes that can boost crop defenses, the higher their chances of finding the right cure for the disease.

THE IPLANT: TOOLS FOR THE FUTURE OF PLANT GENOMICS

Genomics research generates enormous amounts of data. One goal is to integrate all of these data to create the "iPlant." The iPlant is conceived as a large family of mathematical models that generate computable "plants" that would provide insight on how plants grow and develop as a system and could be used to predict plant behavior under a range of environmental conditions. Such a tool would allow researchers to do "virtual" experiments to identify the most promising avenues of research before doing experiments in the field. The National Research Council report *Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology* recommends the development of computational tools that are sustainable, adaptable, interoperable, accessible, and evolvable to achieve the goal of the iPlant.

THE PLANT-PATHOGEN ARMS RACE

Between 1950 and 1954, a rust-colored fungus known as wheat stem rust wiped out as much as 20 percent of the wheat crop across a large swath of midwestern states.

Following the outbreak, scientists created a stem rust-resistant wheat strain that quickly became a favored breed worldwide. But in 1999, a new strain of the fungus was discovered on what had been rust-resistant strains in Uganda. The new stem rust, named Ug99, has many people worrying about the possibility of a global wheat catastrophe.

Wheat provides a substantial proportion of food calories around the globe. It also serves as a feedstock for cows and other livestock. Given the current climate of increasing food prices, combined with the fragile structure of food systems in developing countries, now would be a particularly bad time for a new strain of stem rust to strike. Since its discovery, Ug99 has spread from Africa to the Middle East and appears to be on a track headed toward Asia and North America.

Scientists are racing to develop Ug99-resistant wheat strains. But breeding or engineering a stem rust-resistant wheat strain is a tiny—and moving—target. Wheat and stem rust have co-evolved in an epic arms race in which a change in a single gene in the wheat or the fungus can make a plant resistant or susceptible to disease. Genomics research, on both wheat and the wheat rust fungus, are crucial to fighting Ug99 in this high-stakes race against time.

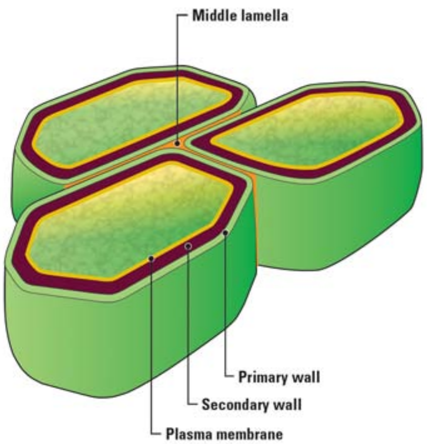
WHEAT AFFECTED BY UG99, a fierce new strain of the fungus known as wheat stem rust. Image courtesy Yue Jin, USDA.

SPOTLIGHT ON... biofuels:
PROMISES AND CHALLENGES

Rising oil prices, combined with an increased awareness of the effects of greenhouse gas emissions, have spurred a race to develop alternative sources of energy. Biofuels—fuels derived from biological materials—have the potential to decrease America's dependence on foreign oil, but significant challenges remain to making biofuels a viable petroleum alternative. Special attention must be paid to developing and expanding biofuel production in a socially, environmentally, and economically sustainable way.

Currently, the main biofuel in the United States is ethanol derived from corn kernels. However, the high amount of energy, water, fertilizer, and pesticides needed to produce corn makes it an unappealing long-term biofuel choice. Additionally, corn kernels are important for food and livestock feed; therefore, the use of kernels to produce ethanol has sparked social debates over "food versus fuel" priorities.

One of the most promising new sources for biofuel is "cellulosic ethanol," made from the cellulose in fibrous plant material such as cornstalks, grasses, and forest trimmings. Production of cellulosic biofuels could use plants that require less irrigation, fertilizer, and pesticides than corn-derived ethanol per unit of energy gained. However, the process required to produce cellulosic ethanol is currently more expensive than that required for corn kernels. Large-scale, cost-competitive methods for producing cellulosic ethanol are a critical medium-term research goal.



PRODUCING CELLULOSIC ETHANOL requires breaking down plants' tough cell walls. Genomics provides insight on what aspects of cell wall structure and composition make some plant materials easier to break down than others. Image courtesy of the Genome Management Information System, Oak Ridge National Laboratory.

GENOME RESEARCH TO ACHIEVE BIOENERGY GOALS

One reason cellulosic ethanol is harder to produce than ethanol from corn kernels is that it requires breaking down relatively tough cell walls into their component sugars. This is a necessary step before microorganisms can ferment the sugars into ethanol. One way of making this process easier is to grow plants with weaker cell walls. Unfortunately, the genes involved in making and maintaining cell walls are complex and not yet well understood.

Research on how plant genes control the composition and structure of their cell walls could help scientists develop new energy crops with cell walls that are easier to deconstruct. In one promising approach, scientists are engineering corn to produce the enzymes that break down cellulose, so that its leaves and stems would virtually "digest" themselves—but only after the corn is harvested.

Plant genome sciences could also lead to other improvements in energy crops, including maximizing their productivity, increasing their resistance to pests and drought, and reducing the need for fertilizers.

FOR FURTHER DISCUSSION OF CORN-DERIVED AND CELLULOSIC ETHANOL, SEE *WATER IMPLICATIONS OF BIOFUELS PRODUCTION IN THE UNITED STATES* (NATIONAL RESEARCH COUNCIL, 2007).

SPOTLIGHT ON...

environmental stewardship

AND PLANT GENOMICS

The enormous scale of agricultural production—and the resulting environmental impacts—has made developing more sustainable and environmentally friendly agriculture a significant 21st-century challenge.

STRETCHING LIMITED RESOURCES: PLANTS THAT CAN HOLD THEIR WATER

Water is one of the most precious resources on earth. Although it covers 71 percent of the planet, only a small fraction is available as freshwater for use by humans, animals, and plants. Competition for water resources is increasing as human populations expand and water demand grows. Increasing temperatures caused by climate change are likely to mean thirstier plants and people, putting even more pressure on limited water supplies. Although some crops have been bred for drought tolerance, the genome sciences have vastly enhanced the ability to manipulate this important quality in many different species.

The Resurrection Plant (right) has attracted the attention of scientists interested in deciphering how it survives extreme drought conditions. Seeds, also, may provide clues to plant mechanisms for surviving on limited water; many plant seeds go through periods of intense dryness before germinating. Identifying the genes and mechanisms that allow seeds and drought-resistant plants to stay alive could help scientists create more drought-resistant crops for the future.

One approach to developing drought-resistant plants is to identify the genes behind the physical mechanisms through which certain species manage to survive drought. Another approach is to decipher the signaling system through which normal crop plants activate such genes under conditions of extreme stress, and find ways to trigger those signaling activities more quickly. Other approaches focus on "predrought preparation" by encouraging certain growth patterns or behaviors that would help plants survive drought, should it occur.

THE RESURRECTION PLANT is known for its remarkable ability to revive after becoming completely dehydrated during dry periods. Investigations of the plant have offered valuable insights into the genetic underpinnings and physiological pathways that give the Resurrection Plant its resilience to extreme water stress.

REDUCING FERTILIZER USE

Historically, farmers in developed countries have blanketed their fields with enormous quantities of fertilizers several times per year to ensure maximal plant growth. But a rising awareness of the negative consequences of this practice—downstream algal blooms that block sunlight, deplete water of oxygen, and kill marine and aquatic organisms—has prompted researchers to take a closer look at how to effectively fertilize crops without jeopardizing the health of downstream ecosystems.

Genomic sciences are helping scientists to pinpoint exactly when and how plants actually use nutrients so they can advise farmers on the most effective times to apply fertilizers. Scientists are also gaining insights on genes that help plants to efficiently extract nutrients from soil; plants that can utilize existing nutrients more fully would also reduce the need for fertilizers.

FUTURE DIRECTIONS: WHAT IF PLANTS COULD CLEAN UP POLLUTION?

Contamination by harmful metals or chemicals can cause vast swaths of land to become unusable. In some cases, no plants will grow in contaminated soil; in others,

CURRENT AGRICULTURAL PRACTICES use a tremendous amount of water, fertilizer, and other inputs. Genomic sciences are helping scientists develop crops that can thrive with less water and fertilizer for a more sustainable approach. Image courtesy USDA/ARS.

plants will grow but can pass harmful contaminants up the food chain to consumers.

Historically, contaminated soils are either avoided or treated by scooping topsoil away to landfills—a measure that is costly, wasteful, and disturbing to natural systems. But new alternatives have recently surfaced: Scientists are discovering some amazing plants that can actually clean up soil contaminants themselves, through a process known as *phytoremediation*.

Arabidopsis halleri thrives even in soils with astoundingly high concentrations of typically harmful metals such as zinc and cadmium. Where most plants would be poisoned by an accumulation of 1,000 parts per million (ppm) zinc or 50 ppm cadmium in their shoots, this plant can withstand as much as 21,500 ppm zinc and 350 ppm cadmium with few or no symptoms of toxicity. *Arabidopsis halleri* and other plants, when grown on contaminated soil and then appropriately disposed of, can be an effective tool for cleaning up contamination.

Another plant, *Amaranthus retroflexus*, has been shown to effectively remove cesium (the radioactive form of which is present in the environment as a byproduct of above ground nuclear testing) from soil. Researchers estimate that two to three yearly crops of the plant could clean up an entire contaminated site in less than 15 years.

Phytoremediation research could also help to identify plants that can survive in acid soils—those with naturally occurring high levels of aluminum. Acid soils have historically been avoided because they limit crop productivity, but they are widespread, comprising over half of the world's 8 billion acres of land that would otherwise be considered arable. Scientists are working to identify the genes that help some plants deal with high aluminum concentrations, with the ultimate goal of developing more tolerant crops that farmers could cultivate on lands currently considered marginal.

FIGHTING PLANT PATHOGENS IN A CHANGING CLIMATE

THE GLASSY-WINGED SHARPSHOOTER carries the deadly bacterium *Xylella*, the cause of Pierce's disease, to California's grapevines. Image courtesy ARS/USDA; photo by Peggy Greb.

In 1989, a half-inch flying insect known as the glassy-winged sharpshooter hitchhiked from its home in the southeastern United States to southern California. There, it found a hospitable climate and a bountiful supply of what quickly became its favorite food—grape vines. Within two years, the insect had made a name for itself as one of the most serious threats ever to face the California wine industry.

The glassy-winged sharpshooter is a voracious eater, but that isn't how it shut down most of the vineyards in California's Temecula Valley and continues to threaten vineyards and other crops elsewhere. The true culprit is another hitchhiker—a bacterium called *Xylella fastidiosa*. Glassy-winged sharpshooters inadvertently carry *Xylella* in their mouths as they flit from plant to plant, injecting the bacterium into healthy plants after feeding on sick ones. The resulting infection is known as Pierce's disease, which causes the vines to slowly die over a period of one to three years.

As global climate change brings warmer temperatures, biologists predict that the ranges of *Xylella* and other crop pathogens could expand. Areas that are currently too cold for the sharpshooter may eventually become more hospitable, causing the threat of Pierce's disease and others to continue to grow.

Currently, there are few ways to fight Pierce's disease. Farmers prevent its spread by removing infected crops at the first sign of symptoms, and they also use insecticides to contain its insect vector, the glassy-winged sharpshooter. But there is new hope that grapes may be able to resist Pierce's disease on their own. Some plants appear to be more susceptible to the disease than others; scientists are hard at work in search of the genes that allow certain plants to resist infection. Uncovering genes for *Xylella* resistance could help breeders grow plants with natural immunity to Pierce's disease—reigning in this fierce pathogen even as climate change expands its potential reach.

NEW APPROACHES: THE SCIENCE OF METAGENOMICS

No plant is an island. In fact, plants are surrounded by millions of microorganisms that play a crucial role in their survival. Microorganisms manufacture nutrients, for example, by converting atmospheric nitrogen into ammonia and recycling nutrients from decaying plants and animals. Some microorganisms living in soil actually protect plants from diseases—when these microorganisms are removed, the plants are far more susceptible to infection.

The new science of metagenomics bypasses the need to isolate and culture individual species, enabling scientists to apply genomic analysis to entire microbial communities in the environment at once. Metagenomics offers scientists unprecedented access to crucial soil microorganisms and can reveal much about a microbial community's members and the functions they are performing.

A better understanding of microbial communities in and around plants could lead to ways to harness the power of these communities to produce healthier and more robust crops. One example of this is an approach called "no-till" farming. In no-till farming, the plant biomass that remains on a field after a crop is harvested is simply left on the soil surface rather than being plowed under before reseeding. This leaves soil microbial communities intact and allows them to continue to perform their vital functions.

FOR FURTHER DISCUSSION OF METAGENOMICS AND PLANT-ASSOCIATED MICROBES, SEE *THE NEW SCIENCE OF METAGENOMICS: REVEALING THE SECRETS OF OUR MICROBIAL PLANET* (NATIONAL RESEARCH COUNCIL, 2007).

IN NO-TILL FARMING, unharvested plant biomass is left on the soil surface rather than being plowed under, leaving critical soil microbial communities intact. Metagenomics offers new insights on the functions of microorganisms in soil. Image courtesy USDA/ARS.

SPOTLIGHT ON... arabidopsis: WINDOW TO THE PLANT GENOME

Mice, fruit flies, and a small weed called *Arabidopsis thaliana* are all used as model organisms—and have helped scientists make great strides in understanding how cells, organisms, and ecosystems function.

Arabidopsis, a ubiquitous weed related to the mustard plant, is an ideal research model. Laboratory strains of the species grow from seed to mature flowering plants in just six weeks. The plant can also self-fertilize and produces copious numbers of seeds, enabling scientists to quickly detect and study genomic changes from generation to generation.

Typically, the goal of investigations using animal models is the betterment of human health. In plant science, basic research on model organisms has many different goals, reflecting the many ways humans use plants. Plant model species serve as proofs of concept, illuminating phenomena in simpler systems that can be applied to more complex plants and ecological systems.

Researchers recently identified a gene in *Arabidopsis* that allows it to grow in salty soil conditions. That insight could help scientists develop crops that are able to produce high yields even in salt-affected soils, which pose a challenge for farmers in areas throughout the world.

Arabidopsis research, combined with studies on flax, tomato, barley, rice, and tobacco, has also helped scientists to build a detailed diagram of the plant immune network. This diagram can aid scientists in developing more disease-resistant crops, since features of the *Arabidopsis* immune network also operate in many other species.

HOW TO MAKE A PLANT

Arabidopsis has one of the smallest genomes (number of genes) among plants—a relatively miniscule collection of just 135 million base pairs or so in its genome of five chromosomes (for comparison, wheat and corn each have billions of base pairs in their genomes). Despite its small size, the *Arabidopsis* genome contains all the genes it needs to make roots, grow leaves, form flowers, produce seeds, and fight off disease.

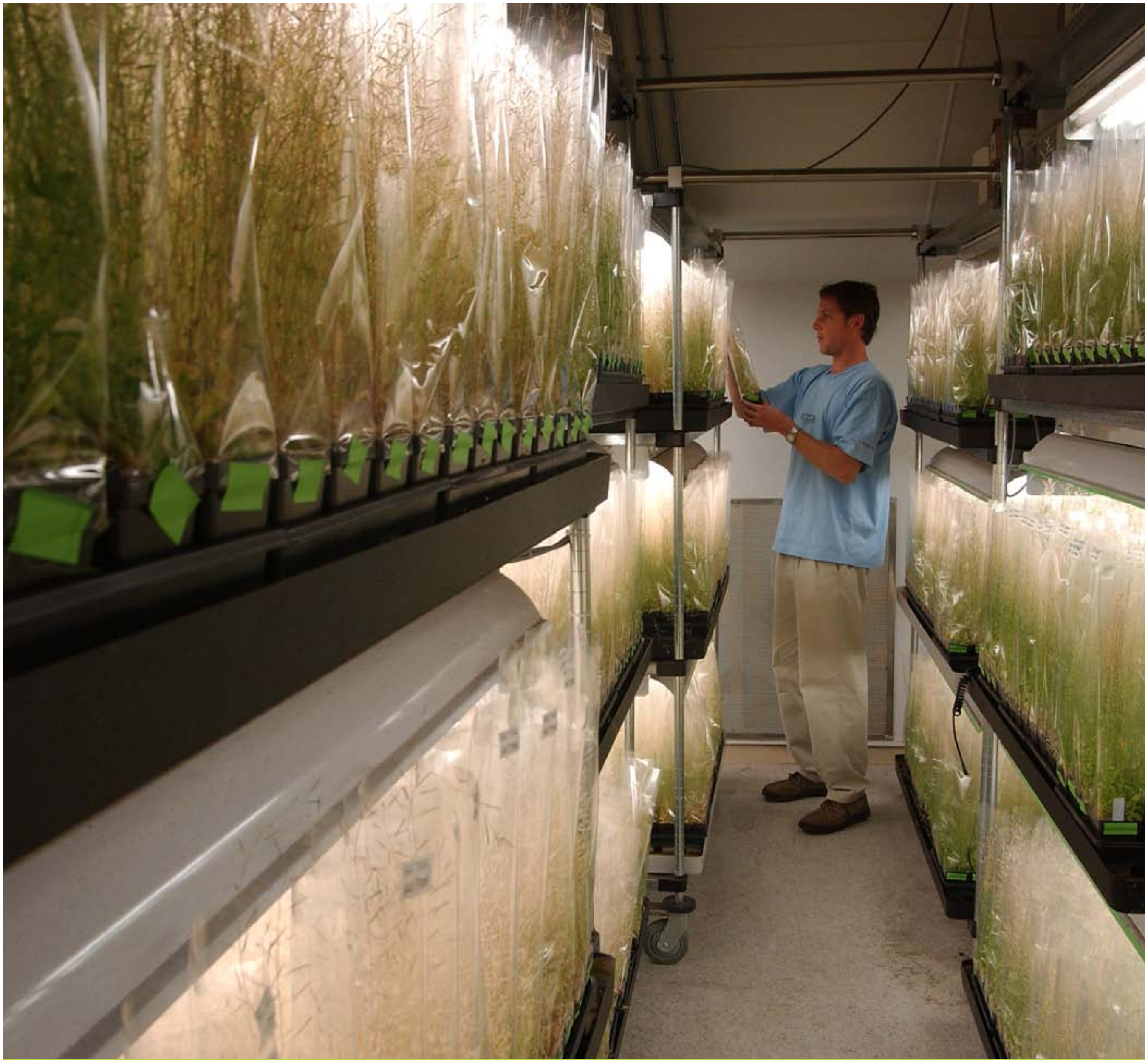
The small size of its genome made *Arabidopsis* an attractive candidate for investigating the basic set of genes that code for all plant functions; in the early 1990s, *Arabidopsis* was chosen as the focus for the first full sequencing of a plant genome. In late 2000, thanks to the efforts of thousands of researchers around the world, the *Arabidopsis* reference genome was completed. It is called a "reference" genome not only because it was the first plant genome sequenced, but also because it has served as a point of comparison for subsequent efforts to compare genes among different strains of *Arabidopsis*.

But the work is not over. Having the sequence of one *Arabidopsis* individual in hand, researchers' next task is to match each gene to its function in the plant—a monumental undertaking for which the National Science Foundation formed a project known as *Arabidopsis* 2010.

Of course, *Arabidopsis* is not the only model organism for studying plants, just as mice and fruit flies are not the only organisms that animal researchers use in their experiments. Since the *Arabidopsis* genome was sequenced in 2000, researchers have also turned their focus to the genomes of rice, corn, poplar, tomato, grape, and other plants.

TRANSLATING FROM BASIC TO APPLIED SCIENCE

Basic research on *Arabidopsis* and other plants has made a strong start toward understanding the fundamental challenge of how plants work. To most effectively translate knowledge from basic science into commercial innovation, however, there is a need for additional tools and methods for transferring science from model systems to crop species, says the National Research Council report *Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology*. Such tools would better enable translation of basic plant genomics toward sustainable deliverables in the field.



PLANTS INCLUDE ORGANISMS OF ALL SIZES AND SHAPES, from tiny *Wolffia*, which can fit through the eye of a needle, to giant redwood and teak trees, to the diverse plants in rainforests and grassland communities around the planet. Although *Arabidopsis thaliana* stands less than 18 inches tall and currently has no agricultural value, it has offered researchers a window to the genes responsible for all plant functions.

SPOTLIGHT ON... biomedical ADVANCES

Although it's been 1.6 billion years since humans shared a common ancestor with, say, *Arabidopsis*, we still have in common many basic genes, processes, and functions. Studies of basic plant biology have drawn from these commonalities and have led to significant advances in our approaches to disease and medicine. Some discoveries originally made in plants have turned out to be fundamental to understanding human biology. For example, some of the most basic aspects of biology, such as the existence of cells, nuclei, genes, and viruses were all first discovered in plants. Plants also produce a tremendous variety of chemical compounds, many with medicinal value.

DRUG DISCOVERY

In ancient Greece and Rome, the bark of the willow tree was widely used to treat fever, aches, and labor pains. Ancient writings—from as early as 3000 B.C.—make it clear that people have been aware of the tree's medicinal properties for a very long time. Scientists isolated the potent compound that gave the bark its healing power in the early 1800s, naming it salicylic acid (after *Salix*, the Latin name for willow). Salicylic acid continues to figure prominently in medicines: today it is used to treat acne, psoriasis, warts, and diarrhea, among other ailments. It is also well known for its key role in the production of aspirin, which is simply a slightly modified form of salicylic acid.

Although many medicinal plants have been in use for thousands of years, new ones are still being discovered. In the 1960s, the U.S. government embarked on a project to screen plants for cancer-fighting compounds. Scientists identified a promising compound in the bark of the Pacific yew, a smallish evergreen that grows in the Pacific Northwest. The compound, which was named taxol, has since been shown to disrupt cell division and growth and has been used to treat ovarian, breast, lung, head and neck, and gastrointestinal tract cancers. Scientists have also found a way to synthesize taxol in the laboratory, greatly reducing the need to harvest the Pacific Northwest's ancient trees.

The Food and Agriculture Organization of the United Nations estimates that the active ingredients of 25 percent of all prescription drugs come from plants. Continued research is likely to unearth even more. Genomic sciences will be critical to isolating and manufacturing medically useful plant-based products.

IMMUNITY AND MECHANISMS OF DISEASE

Like humans, plants also get diseases—and use their immune systems to respond. Sometimes, the immune system overreacts and exhibits responses with deleterious effects. This is the case with human autoimmune diseases, such as Crohn's disease, a chronic inflammatory bowel disease.

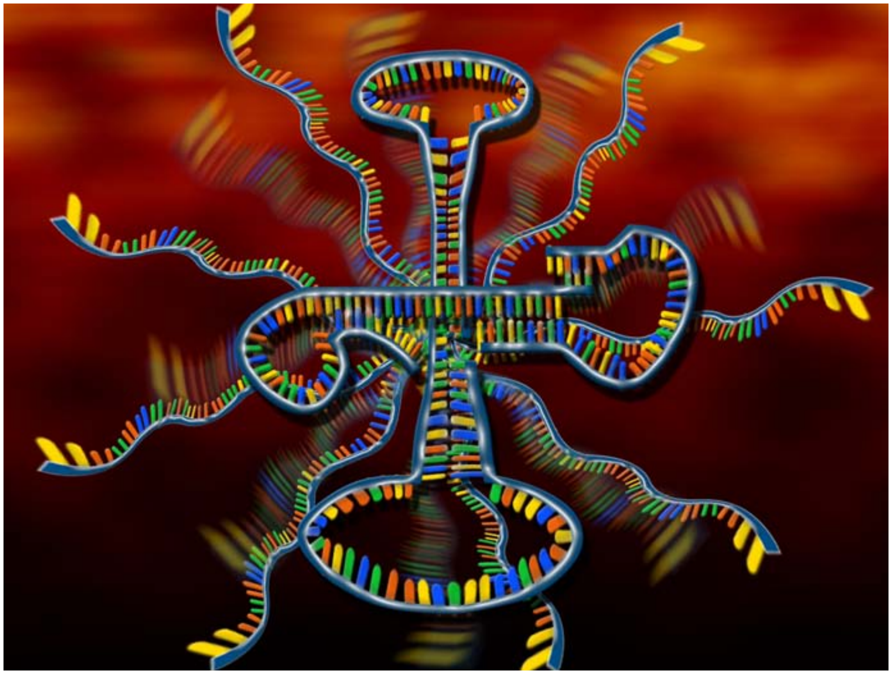
In the mid-1990s, scientists studying plants identified proteins called NB-LRR proteins, which are the key receptors of plant immune systems and are used for fighting disease. Scientists later identified related genes in humans. These human genes also code for proteins involved in immunity and inflammatory responses, and studying them has provided clues about the mechanisms behind inflammatory diseases. Similarities between the plant NB-LRR disease resistance proteins and these human genes also helped a team of researchers identify the gene responsible for Crohn's disease.

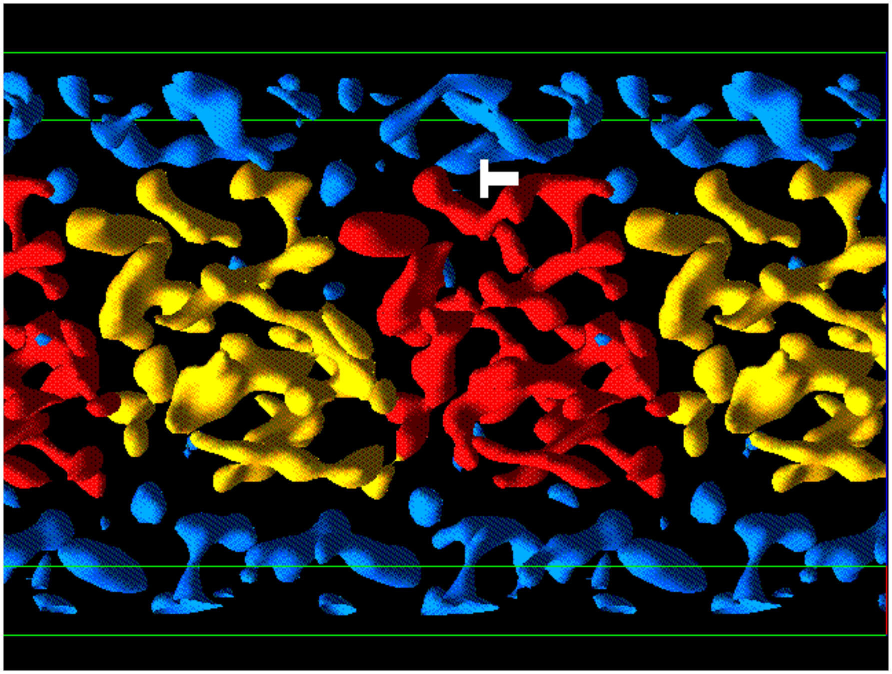
SMALL RNA AND PLANT DEFENSE

Small RNA is a short molecule that packs a big punch. Historically, it was believed that RNA served merely as a messenger, shuttling genetic instructions between DNA and proteins. But thanks to plant research, scientists now recognize the diverse array of functions performed by these small strands of RNA—measuring just 18–24 nucleotides long.

What is a plant to do when an herbivore, say, an insect, begins to eat it? The answer, for some plants, is to call in the troops—sending small RNAs to coordinate defense responses, including regeneration by the plant's stem cells. Recent research even suggests that some small RNAs can directly fight herbivorous insects by silencing specific genes in the insect when the plant is ingested.

Insights from plant research have also expanded our understanding of the functions of small RNAs in animals and humans. Some small RNAs silence, or suppress the expression of, certain genes. This is known as RNA interference. Understanding how RNA interference works could lead to major medical advances. Such diseases as Alzheimer's and arthritis are triggered by the expression of genes. Scientists are exploring ways to use RNA interference to silence those genes, and thus prevent those diseases.





(ABOVE) Artist's rendering of RNA. Image courtesy of Nicole Rager Fuller, NSF. (BELOW) The site (marked with a "T") where the anti-cancer drug taxol interacts with tubulin proteins to prevent cell division. Taxol was first discovered in the bark of the Pacific yew. Image courtesy Lawrence Berkeley National Laboratory.

MAXIMIZING THE potential OF THE PLANT GENOME SCIENCES

Plant genome sciences, and plant biology as a whole, are vital enterprises that contribute significantly to human health, energy security, and environmental stewardship. The time is now ripe for a major research effort toward sustainable and environmentally responsible models of production for food, fuel, and fiber.

Genomics offers unprecedented access to these critical resources. Much has been learned—and applied—already, and there is a huge opportunity to capture and expand upon the momentum of the past 10 years of plant research to tackle national and global challenges. The National Plant Genome Initiative should be expanded and its mission broadened in order to increase the contributions of plant sciences to vital areas of national interest.

This booklet is based on the National Research Council report *Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology (2007)* by the Committee on the National Plant Genome Initiative: Achievements and Future Directions. It was developed by Anne Jurkowski and designed by Green Rhino Design. Related reports include *The National Plant Genome Initiative: Objectives for 2003–2008 (2002)* and *Protecting Our Food Supply: The Value of Plant Genome Initiatives (NAS Colloquium, 1998)*. Reports are available from the National Academies Press, 500 Fifth Street, NW, Washington, DC 20001; 800-624-6242; www.nap.edu

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Jeffery L. Dangl, Chair, Univ. of North Carolina, Chapel Hill / **Lois Banta**, Williams College, Williamstown, MA / **Roger Boerma**, Univ. of Georgia, Athens / **James C. Carrington**, Oregon State Univ., Corvallis / **Joanne Chory**, Salk Institute for Biological Studies, San Diego, CA / **Steve A. Kay**, Univ. of California, San Diego / **Suzanna Lewis**, Lawrence Berkeley Nat. Laboratory, Berkeley, CA / **Thomas Mitchell-Olds**, Duke Univ., Durham, NC / **Neelima R. Sinha**, Univ. of California, Davis / **Michael Snyder**, Yale Univ., New Haven, CT / **Steven H. Strauss**, Oregon State Univ., Corvallis / **Eric R. Ward**, Two Blades Foundation, Durham, NC

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Human life would be impossible without plants. They provide food, clothing, shelter, medicines, and many other goods and services; plant sciences and crop improvements have already had a major impact on food security and human quality of life. The increasingly powerful tools for genomic research make plant research more valuable now than ever before. Plant genomics has a critical role to play in meeting 21st century challenges in agriculture, energy, environmental stewardship, human health, and more.

This booklet, based on the National Research Council report *Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology*, highlights achievements and new horizons in the plant genome sciences.

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