Now, plants are leading the way in a number of exciting new areas of science, such as understanding inherited changes in gene expression, or teasing apart the fiendishly complex connection between genetic information and the appearance and characteristics—the phenotype—of an organism. “Plants show a lot to us,” says Howard Hughes Medical Institute (HHMI) investigator Joanne Chory, Howard H. and Maryam R. Newman Chair and director of the Plant Molecular and Cellular Biology Laboratory at The Salk Institute. “They've led to a lot of discoveries in basic biology.”

And they have much more to reveal. Whether it's the system that brings tons of water to the top of a towering redwood or the construction that enables a mighty oak limb to withstand gravity and hurricane winds, “plants are examples of a complexity beyond what engineers can conceive,” says Elliot M. Meyerowitz, George W. Beadle Professor of Biology at the California Institute of Technology. “If we could understand them, it would be eye-opening for engineering.”

This knowledge isn't just of academic interest. Understanding the intricate dance of hormones that controls crops' growth or the biochemical pathways that enable plants to fight pests or survive droughts has become a crucial necessity if humanity is to meet the challenges now facing the world. The numbers are sobering. According to the United Nations, today's global population of 6.8 billion people is expected to jump by 3 billion by 2050—and one billion people are already suffering from lack of proper nutrition. The demand for energy is rising, even as the long-term consequences of using fossil fuels become more apparent. That's putting pressure on agriculture to grow fuel as well as food. And the world must figure out how to produce increasing amounts of food and biomass as the climate changes, bringing the risk of more devastating events like the spread of the Ug99 strain of fungus, which is threatening some of the most important wheat-growing regions on the planet.

“Here we are, faced with another three billion people by 2050 or so, with no increase in land, no net increase in fresh water and facing significant changes in climate, all of which will impact agriculture,” says Roger N. Beachy, Founding Director of the National Institute of Food and Agriculture of the U.S. Department of Agriculture. “We need to change agriculture so that crops can be grown when it's really hot, and can maintain high productivity with less irrigation and chemical fertilizers. We need plants that don't succumb to attacks by insects or diseases in a warming climate.”

“NEW BIOLOGY” REPORT URGES MORE INVESTMENT IN PLANT SCIENCES

In September 2008, a National Research Council (NRC) committee began looking at some of society's most pressing problems—food, environment, energy, and health. It asked where biological research could make the biggest contribution. The answer: “It was apparent that across almost all those areas, plants are a major source of solutions to the problems,” says Nobel laureate Phillip A. Sharp, co-chair of the NRC “A New Biology for the 21st Century” committee and Institute Professor at the Koch Institute for Integrative Cancer Research at the Massachusetts Institute of Technology. The key question is whether the solutions will come in time. “There is so much more to be learned, and some of us worry about whether the learning will be fast enough,” says Beachy.
With so much at stake, one might think that plant research would be well funded around the globe. Recently, that has become the case in China, and increasingly in India where food production is insufficient. It is less so in the United States and in much of Europe where food is abundant. In the U.S., plant research is the poor cousin in the biological sciences. It receives less than two percent of the total $40-billion-plus annual federal life-sciences funding budget. The big winner is biomedical research. Why? “We are interested in ourselves,” explains Chory. “People in Congress tend to look at diseases and human health.” What’s more, says Beachy, American farmers have been so successful that in the recent past, the federal government paid billions to restrict crop production on some lands. As a result, farmers grew less. “Why pay for research that makes farmers even more successful?” he says. “We’ve been hampered by our own success.”

The signs of that funding disparity are readily apparent at the nation’s research universities. Cancer researchers have laboratories teeming with postdoctoral and graduate students, while plant scientists are lucky to get by with grants big enough to support one postdoctoral fellow and a technician. Running a productive lab “is a huge struggle,” says Vicki L. Chandler, chief program officer of the Science Program at the Gordon and Betty Moore Foundation and a leading plant scientist. Many promising graduate students in plant genetics and other fields must leave the botanical world behind to find research support, says Beachy. “It’s a shame. The potential for greater understanding isn’t being realized because of the limited funding.”

Yet the news isn’t all bad. Despite the relatively low level of support, plant biologists and geneticists have made tremendous strides over the last 10-15 years. When Chory made the jump from studying bacteria to plant biology in 1985, “there was one known plant receptor,” she recalls. Now, thanks to new tools and an explosion of genetic knowledge from the sequencing of the thale cress, Arabidopsis thaliana, the plant biologists’ lab rat, and scores of other plants, scientists have predicted the existence of hundreds of receptors encoded in plant genomes and have identified the receptors for all the known plant hormones.

Photobiologists have learned, for instance, that specific light receptors in plants can sense shade being cast by nearby plants that are, in a very real sense, competitors. When this happens, the plant makes hormones to dial up its growth rate—at the expense of letting down its defenses against pests. The goal: to try to win the all-important race to be the tallest, even if that means becoming more vulnerable to pests. Chory, in collaboration with Detlef Weigel (now at the Max Planck Institute in Tuebingen, Germany) and their students, have also shown how photoreceptors from plants native to low-light countries, such as Sweden, are 10 times more sensitive than the same receptors in related plants from sunny Spain. “It’s amazing to think about the progress,” she says.

So just imagine how much more could be learned with boosted funding, says Beachy. “The time is ripe because we have invested so much in the genetic tools.” Indeed, increase in support for plant research “is likely to bring the biggest bang for the dollar, because the area is so underfunded and there are a great set of opportunities for which increased knowledge could have a big payoff,” adds Sharp.

Where are those opportunities? “The next challenges are yield, yield, yield,” says Chory. That means charting hundreds of plant pathways and other details—and then learning how to manipulate them. That, in turn, requires a deeper and more fundamental understanding of how those pathways are put together and controlled. “We have the parts list for plants, but not the assembly instructions,” states the NRC’s “A New Biology for the 21st Century” report.

Could the assembly instructions of corn be tweaked so that its roots develop a better rapport with nitrogen-fixing microbes in the soil, reducing its need for fertilizer? Other plants know how to do it, says Chandler: “Sugar cane has a lot of these relationships and requires much less nitrogen than corn—and they are closely related.”

Or could the biology of prairie grass be altered to help biorefineries turn the cellulose in the grass’s cell walls into ethanol or other fuels or chemicals? “There are fantastic images of plants that grow enormous amounts of biomass, and then you snap your fingers and they make cellulase enzymes to degrade all the cellulose,” says HHMI medical advisory board member Gerald R. Fink, Herman and Margaret Sokol Professor at the Whitehead Institute for Biomedical Research. “It’s science fiction now, but it could happen.”

Seemingly small changes to biochemical pathways can make huge differences. Take the most basic function of plants, converting the energy of sunlight into stems, leaves, seeds and fruit through photosynthesis. At the heart of the process is an enzyme named RuBisCo (short for ribulose-1,5-bisphosphate carboxylase/oxygenase), which grabs carbon dioxide and incorporates it into biomass. RuBisCo is probably the most abundant protein on earth, making up about 30 percent of the total protein in a plant leaf. It’s also a very inefficient enzyme, says Chory. Plants are able to capture only about 2.5 percent of the energy that hits them from the sun. Twist the RuBisCo enzyme to raise that level to, say, three percent “and we’ve got the world’s food problem solved,” says Beachy.
About three percent of plants (including corn and sugar cane) use a pathway known as C₄ because the first product of carbon fixation has four carbon atoms instead of three, as in the more common C₃ pathway. The C₄ pathway not only is more efficient at pulling carbon from the atmosphere, it also requires far less water. As a result, adding the C₄ process to C₃ plants could supercharge their growth and make them more tolerant of drought. Julian Hibberd of the University of Cambridge estimates that engineering C₄ into rice could boost yields by 50 percent.

**NOT JUST MORE MONEY, BUT MORE KNOWLEDGE**

Of course, altering biochemical pathways isn't just a simple matter of slipping in new genes. Back in the early 1980s, “we had just discovered how to gene engineer a plant, and there were a lot of expectations that it would rapidly revolutionize agriculture,” recalls Beachy. Beachy’s own lab at Washington University in St. Louis developed the first genetically engineered virus-resistant crops. Looking back on that time, Beachy recalls that the genetic revolution that followed was focused on producing crops that required less insecticide and were tolerant of herbicides. The new technology mainly put money in the pockets of farmers and companies such as Monsanto, DuPont/Pioneer Seeds, and others—thanks to corn, soybeans, and cotton that had been genetically modified to resist commercial herbicides and some pests. Plants that have intrinsically higher yields, or need less fertilizer, or resist drought or serious diseases, or those that pack better nutrition, have been slower to arrive.

Part of the reason is that, until recently, consumers haven’t been willing to pay more for more nutritious food, says Beachy—and there’s been little or no support for improving plants vital to the Third World, such as cassava or rice. Plus, it’s just hard to do. When funding organizations such as the Bill & Melinda Gates Foundation jumped in to tackle hunger and poverty around the world by developing more nutritious and more drought-resistant crops, “they found there wasn’t enough scientific knowledge to accomplish the goals,” says Beachy. “They made the decision to work with the National Science Foundation to engage fundamental scientists to help fill in the knowledge gaps.”

Some of that needed knowledge comes in the form of better understanding of how genes are regulated. It turns out that plants are masters at using small bits of RNA to control their genes. The phenomenon was first observed in 1986 by Richard A. Jorgensen, who was then working at DNA Plant Technology, Inc. He thought he’d wow investors by adding an extra purple gene to petunias to create an especially dazzling purple flower. But the transgenic plant he created had white flowers instead. The reason it took a decade to figure out: Using small bits of its own RNA, a plant cell is able to detect and destroy RNA both from threats such as viruses, and from its own genes that it wants to silence. The challenge for scientists trying to figure this out is that the key regulatory microRNAs seem to be swimming in a sea of RNA transcripts that have no known purpose. “There is a massive amount of transcription,” says Chandler. “A lot may be junk, but why is all this energy being spent making transcripts that don’t seem to be doing something? There’s a lot we don’t understand.”

Working out how the multiple classes of small RNAs control plant genes should have a big payoff, both scientifically and agriculturally. “It’s clear that temperature changes and growth conditions can influence the amount of gene silencing,” Chandler explains. Recent work in barley shows that plants that live at different altitudes have different patterns of transposon activity, which are regulated by small-RNA pathways. So learning how to tweak the dials on this gene regulatory mechanism could help crops cope better with stresses such as drought or heat waves. “RNA-mediated regulation is really a very ripe and very exciting area of research that’s exploding across the field,” says MIT’s Sharp.

But if RNA-mediated regulation isn’t complicated enough, there’s an additional level of genetic control—so-called epigenetics. At various places along their strands of DNA, cells attach methyl groups to the genes. This methylation then marks whether a gene is to be turned on or off. In many organisms—plants included—these patterns of methylation can be inherited. A plant’s stem and leaves experience environmental stress, which can cause changes in the methylation pattern, and thus, gene expression, explains Salk Institute plant geneticist Ryan Lister. When those vegetative tissues give rise to the seeds, with the same epigenetic pattern, the methylation changes are transferred to the next generation. “Plants are a really great system for looking at this,” Lister says.

The scientific payoff extends far beyond plants. The method Lister perfected to read the epigenome of Arabidopsis paved the way for the first complete map of the human epigenome, which revealed an unexpected methylation pattern. That’s just one of many advances. As an editorial in the September 2010 issue of Nature Structural & Molecular Biology observes, “Arabidopsis thaliana is a valuable model system that has already yielded insights into processes important to human health and disease.”

In plants, the epigenome offers another set of levers for tweaking growth, stress tolerance or yield. In fact, plants probably have used epigenetic changes to adapt to new environments, researchers suspect. “One of the reasons epigenetics is so powerful in plants is that it can be a mechanism to try out alternative regulatory pathways that may become fixed later through genetic changes,” explains Chandler.
EXCITING NEW FRONTIERS

These new insights are tantalizing glimpses of the enormous advances scientists will make as they delve more deeply into plant pathways, Chandler adds: “I think we’ve only seen the tip of the iceberg.” Even more will be discovered when plant scientists team up with researchers in other disciplines to take a broader systems approach, Beachy and others believe. For instance, why and how do certain plants live together in communities? “To understand how an ecosystem works would be huge,” says Chory.

Another productive line of research, which is becoming more urgent with climate change, is exploring how plant diseases may be worsened by stress from environmental changes, says Crispin Taylor, executive director of the American Society of Plant Biologists. “A systems biology approach could look in great detail at the molecular mechanisms of a pathogen in a plant, then fold in all these other stresses that will occur in real life situations.”

For Caltech’s Meyerowitz, “the exciting frontier is the intersection of math and engineering in trying to understand plant development.” The architecture of a tree branch, for instance, is the result of the complex interaction of genes and mechanical stresses. This interaction, and the actual physical structure of the cells that make up the limb, could be mathematically modeled, with implications both for the design of man-made structures and the study of bone, Meyerowitz says.

Similarly, most of the practical applications of today’s research are still to come. There are projects underway to increase the nutritional content of sorghum, to boost the uptake of nitrogen by the roots of plants, to add protein, vitamins and minerals to crops like cassava, and to better understand the links between the nutrients we obtain from plants and human health. By 2030, scientists at Monsanto have pledged, they will be able to double the yield of maize, soybeans, and cotton varieties. So far, “we are just scratching the surface of what’s possible,” says MIT’s Sharp.

The bottom line: The study of plants is not only as scientifically exciting as neuroscience or cancer biology, but it also offers a better chance of saving the world. All it needs is a boost in support, scientists argue. “We are still vastly underfunded in taking advantage of the opportunities,” says Sharp. Beachy worries about the vast gulf between discoveries in basic science and companies’ need to focus on products with a quick financial return. “This gulf is not yet filled with a pipeline fueled by enough resources,” he says. And Chory points out that, without more funding for basic work, universities won’t be able to train the researchers industry needs to create tomorrow’s higher yielding crops. Says Meyerowitz: “I hope it will not be a problem for our children and grandchildren that we haven’t been minding the store.”

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Veteran science writer John Carey considered doing a Ph.D. in forest science after graduating from the Yale School of Forestry and Environmental Studies thirty-one years ago, but he was lured away by journalism instead.