PLANT RESEARCH

Can Genetically Modified Crops Go 'Greener'?

The next generation of genetically engineered crops may be created by tinkering with the plants' own genes, rather than by introducing completely foreign ones

Cotton and corn containing bacterial genes that make compounds toxic to insects; soybean and canola plants engineered to resist weed killers with other genes from bacteria; papaya carrying genes from viruses that make them resistant to deadly diseases. Opponents of genetically modified foods have had a field day labeling such transgenic crops "frankenfoods." But the next generation of engineered crops may be more difficult to demonize with that glib moniker: plants whose own genes have been modified to make them hardier and more productive.

Until recently, plant genetic engineers have had little choice but to transplant genes from foreign species. The reason: They generally knew little about the plant genes encoding the traits they wanted to improve. But a flood of new information from projects such as the sequencing of the mustard plant *Arabidopsis* has pinpointed genes involved in key processes such as speeding up flowering, changing a plant's basic architecture, or improving pest resistance (*Science*, 6 October, p. 32). As a result, researchers may be able to enhance the traits they want by introducing one or a few genes from another plant, or by modifying the regulation of genes in their original settings. "We can understand in molecular terms the genes that breeders have worked with for a long time," says plant molecular biologist Richard Flavell of Ceres Inc. in Malibu, California.

Armed with this new understanding, researchers are working on plant modifications that couldn't be achieved by simply transplanting bacterial or viral genes. For example, they are hoping to engineer plants to flower earlier, which could extend the growing season for grains and fruits. Manipulating plant genes may also produce larger leaves that permit more photosynthesis or more aggressive root systems for combating drought.

Rob Martienssen, a plant molecular biologist at Cold Spring Harbor Laboratory on New York's Long Island, says what plant biotechnologists are now trying to do isn't much different in principle from what the Aztecs did centuries ago when they used conventional plant breeding to transform the bushlike teosinte into the more productive single-stalked corn. But the new methods, Martienssen points out, are much faster and come without the uncertainties that accompany the mixing of whole genomes. "Current techniques," he says, "are 1000 times more precise than classical plant breeding."

Advancing spring

One of the most sought-after goals is to alter the timing of flowering. A delay would be desirable in leafy crops such as spinach and lettuce, which tend to "bolt"—send up long, energy-consuming stems—when they flower.

Fast-forward. Ordinary aspen trees flower only after 1 or 2 decades, but this 1-year-old plant, modified to overexpress the *LEAFY* gene, is already flowering. The inset shows a close-up of the flower.

CREDIT: D. WEIGEL AND O. NILSSON

In contrast, speeding up flowering in some plants could enhance fruit and seed development and perhaps enable farmers to grow more than one crop each year. Researchers have taken the first critical steps down this path, identifying genes that help choreograph flowering.

Over the past decade or so, about a dozen teams at places such as the California Institute of Technology (Caltech) in Pasadena, the University of Wageningen in the Netherlands, and the John Innes Centre in Norwich, U.K., have turned up more than 80 genes. The latest example comes from Caroline Dean of the John Innes Centre and her colleagues. On page 344 of this issue, they report the cloning of an *Arabidopsis* gene called *FRIGIDA* and show that natural mutations leading to loss of *FRIGIDA* function are associated with early flowering, a helpful adaptation in some cold climates.

Although it's too soon to say whether researchers can alter flowering times in other plant species by manipulating *FRIGIDA*, another gene, known as *LEAFY*, first cloned in the early 1990s by Detlef Weigel in the Caltech lab of Elliot Meyerowitz, is already showing promise. Weigel and Ove Nilsson of the Salk Institute in La Jolla, California, have introduced a highly active version of *LEAFY* into aspen trees, which flowered in 6 to 8 months, instead of the usual 12 to 15 years (*Nature*, 12 October 1995, p. 495). And Jose Miguel Martinez Zapater of the National Center for Biotechnology in Madrid, Spain, and his colleagues at the Valencia Agricultural Research Institute have manipulated the *LEAFY* gene to bring about first-year flowering in a hybrid citrus known as citrange, which normally needs 5 to 7 years to flower.

Even a modest advance in flowering time could benefit rice farmers, especially in the developing world, where rice is a staple. "Rice needs a bit longer than 6 months to grow and mature in some areas, so a small speedup in flowering could enable double-cropping a year," says Dean. Indeed, as Weigel and Chris Lamb, also from John Innes, report in the June issue of *Transgenic Research*, introducing *LEAFY* into rice provides just such a modest acceleration, with only a minor yield penalty.

Dwarfs preferred

Other researchers are homing in on genes that control an even more basic plant feature: height. They are looking for ways to produce short, sturdy "dwarf" varieties. This is a desirable trait in many crops, such as wheat and rice, because it allows the plant to put more energy into the grain instead of stalks, and it reduces the chance that plants will topple and be damaged by wind and rain. Indeed, the "Green Revolution," which greatly increased cereal grain production during the 1960s and '70s, was based on the development of dwarf strains of wheat and rice through conventional plant breeding. A gene discovery reported last year by Nick Harberd and his colleagues at John Innes may help plant biologists develop new dwarf varieties more directly (*Nature*, 15 July 1999, p. 256).

Last year, Harberd's group identified an

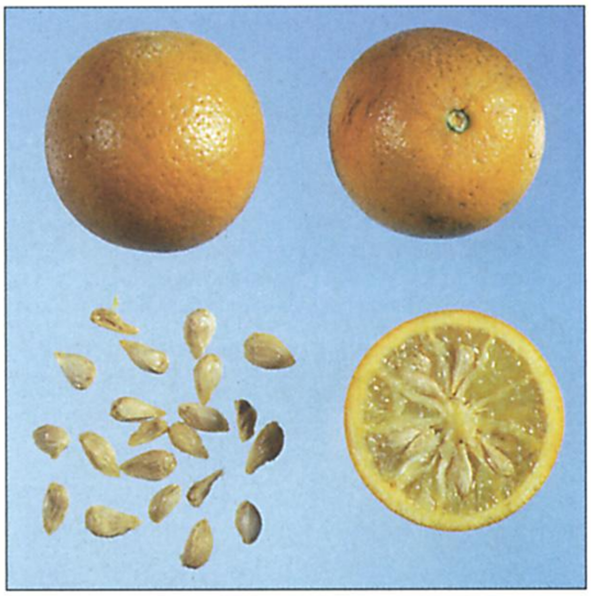
Arabidopsis gene called *gai* as that plant's equivalent of one of the mutant genes that causes dwarfing in both rice and wheat. The genes apparently code for a protein in the signaling system through which the hormone giberellin stimulates plant growth. But whereas it took the Green Revolution pioneers years to breed the mutant gene into the cereals, Harberd's team is introducing a mutated form of the *Arabidopsis gai* gene into wheat and rice much more quickly—with a gene gun. For example, the researchers are working with collaborators in India to produce a dwarf strain of basmati rice—a variety favored for its flavor and white color, but a balky crop to grow because the plant's long, weak stems often cause it to keel over.

Previous efforts to breed dwarf basmati rice failed, Harberd notes, because the crosses exchanged thousands of rice genes along with the dwarfing character, and breeders ended up with short plants whose rice had lost its fine taste. But by shooting the mutant *Arabidopsis* gene into cultured basmati rice cells and then regenerating them into whole plants, Harberd's team has produced short plants that retain their tasty grains. These promising results suggest that a mutant giberellin signal pathway "could be used to increase yields in a wide range of crop species," Harberd predicts.

Other groups are taking a more indirect route to influencing plant growth: modifying a plant's responses to light. Plants shaded by their neighbors often bolt upward to reach sunlight. "This makes sense in a natural setting, but it is a problem with agricultural crops, because all that upward growth is often at the expense of the harvestable parts of the plant," says plant scientist Peter Quail of the U.S. Department of Agriculture's Plant Gene Expression Center in Albany, California, and the University of California, Berkeley.

Researchers, including Quail, are focusing on pigment-containing proteins called phytochromes that help a plant tell when it's in the shade. Sunlight filtered or reflected by leaves has more light at the far red end of the spectrum than clear sunlight does, and certain phytochromes can detect that difference and pass the information on to nuclear genes involved in growth control. Earlier this year, for example, Quail's team found that when phytochrome B is exposed to red light, it binds to a protein known as PIF3, a transcription factor that regulates the expression of a variety of genes, including some involved in photosynthesis and the plant's circadian clock (*Science*, 5 May, p. 859). Suppressing phytochrome B activity could therefore make plants less responsive to far red light, which should reduce the tendency to bolt. The strategy is now being tested with potatoes.

In addition to suppressing unwanted vertical growth, plant genetic engineers are trying to encourage growth in other directions. For example, Robert Fischer and Yukiko Mizukami of the University of California, Berkeley, have identified an *Arabidopsis* gene called *Aintegumenta* (*ANT*) that Fischer says "can make organs larger without altering the basic proportion of the organs." When this gene is continuously active in *Arabidopsis* and tobacco, the plants have bigger flowers, leaves, seeds, and seedlings. Fischer and his colleagues are now working with scientists at Ceres Inc. to see whether they can use *ANT* to create crop plants with thicker, and therefore sturdier, stems or with more roots, which could increase drought resistance.



New target. Citrange, with fruit and seeds shown here, is another tree that has been genetically modified to speed up flowering.

Depending on the crop, yields might also be increased by making seedpods either stronger or weaker. Strong, shatterproof seeds are desirable in the oilseed canola, for example, because pod shatter can cause major losses—up to 50% in bad weather—whereas a more fragile seedpod might make harvesting easier for crops such as cotton. A recent discovery by Martin Yanofsky and his colleagues at the San Diego and Davis branches of the University of California may provide a means to manipulate seed shattering. They've identified two related *Arabidopsis* genes, called *SHATTERPROOF 1* and *2*, that control this property by promoting production of tough lignin compounds in the seedpods (*Nature*, 13 April, p. 766).

Fighting disease

Although genetic engineers are focusing much of their efforts on altering plant architecture, they are also using new genetic information to beef up plants' resistance to viral, fungal, and bacterial pathogens. One such example comes from molecular plant pathologist Brian Staskawicz of the University of California, Berkeley.

Blackspot disease, which is caused by the bacterium *Xanthomonas campestris pv. vesicatoria*, causes major damage to pepper and tomato crops in Florida and in humid areas of the Midwest. About 10 years ago, plant scientists identified genes that make peppers resistant to the disease, but they couldn't find comparable genes in tomatoes. However, in the 23 November 1999 issue of the *Proceedings of the National Academy of Sciences*, Staskawicz and colleagues at San Francisco State University and the University of Florida in Gainesville report introducing one of the resistance genes from the pepper into tomatoes. "Now those tomato plants are resistant to the pathogen," says Staskawicz. Modified tomatoes are being readied for field trials.

Less advanced, but perhaps of more general value, is work with a gene called *DIR-1*, which is involved in systemic acquired resistance, a broad-spectrum response that plants activate to fight off many bacteria and fungi. These defenses enable the plant to prevent a pathogen from spreading by a variety of means, including walling it off or even killing the infected cells. A few years ago, research teams at the Salk Institute and at the Noble Foundation in Ardmore, Oklahoma, identified the *DIR-1* gene as encoding a key component of the signal pathway that activates systemic acquired resistance in *Arabidopsis* in response to an infecting pathogen. Because other plants have very similar pathways, the genes found in *Arabidopsis* "should be usable in other plants," says Animesh Ray, a molecular biologist at Akkadix Corp. in La Jolla. His team is now testing that assumption by introducing the *Arabidopsis DIR-1* gene into wheat, rice, corn, and alfalfa in hopes of boosting their defenses against fungal pathogens.

So far, plant researchers have barely scratched the surface of plant genomes, but what they've learned already has made them eager to know more—a desire that will no doubt be partially fulfilled when the *Arabidopsis* genome is completely sequenced later this year. Other plant genomes are much larger than that of *Arabidopsis* and so may provide even more genes useful for plant genetic engineering. As Purdue University plant biologist Jeffrey Bennetzen says, "It's time to get to know plant genomes better."

–ANNE SIMON MOFFAT

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