moving from lithium ions to anodes made of lithium metal, which would pack even more power into a given volume. Again, finding a suitable solid electrolyte is the key. Chemists Mason Harrup, Thomas Luther, and Frederick Stewart of the Department of Energy's Idaho National Engineering and Environmental Laboratory in Idaho Falls have created solid electrolytes using phosphorus-and-nitrogen–based polymers known as polyphosphazenes, which can easily pass lithium ions between their chemical groups. By combining the polymer with a ceramic, compressing it, and then spinning the mixture into a thin film, the researchers made sheets of solid polymer flexible enough to wrap around a metallic lithium anode. When combined with a commercially available cathode, the result is a battery with "outstanding power-to-weight performance over a very large number of discharge and recharge cycles in a flexible package," Harrup says. Such a flexible battery would allow device manufacturers to cram the power source into odd-shaped nooks and crannies.

Ultimately, the needs of electronic devices will outstrip the ability of batteries to adapt, but battery designers are darned if they're going to give up yet. Says Caesar: "There's only so many chemistries that you can use to make a battery, and we're trying to milk them for all they're worth."

–JOE ALPER

Joe Alper is a writer in Louisville, Colorado.

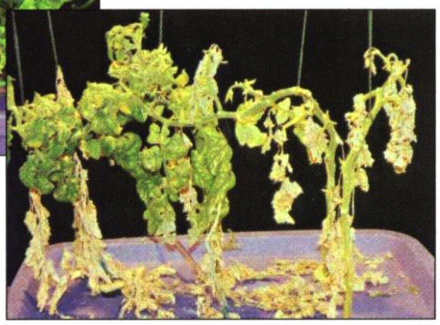
PLANT GENETICS

Finding New Ways to Protect Drought-Stricken Plants

With drought an ever-present threat, researchers are identifying genes that can help plants tolerate arid conditions in hopes of using them to produce hardier crops

Dry fields and stunted plants from Maine to Georgia show that the eastern United States has been hit with the worst drought in more than a decade. In the grain-farming and livestock-grazing states of Montana, Nebraska, and Wyoming, ranchers are also confronting parched soils. Even the Midwest, home to 20% of the world's fresh water, is in trouble: Areas only 65 kilometers from the Great Lakes have dangerously low water tables.

The global picture is just as bleak. Historically arid regions in Africa and the Middle East are expanding, and shortages of fresh water are appearing in places, such as the Asia-Pacific rim and Northeast Brazil, that once never doubted their water supplies. "Worldwide, drought is the biggest problem for food production," says Jeffrey Bennetzen, a molecular geneticist at Purdue University in West Lafayette, Indiana. And that makes the quest for drought-resistant crops even more urgent, he says.



Salt lovers. Tomato plants carrying a foreign gene that protects their cells from salt-induced dehydration (*above*) thrive in a 200-millimolar salt solution, whereas unaltered plants (*right*) wither.

CREDITS: E. BLUMWALD/UNIVERSITY OF CALIFORNIA, DAVIS

In the last decade or so, researchers in the developing world have successfully coupled molecular marker technology, which allows a more precise identification of strains carrying desired traits, with classical plant breeding to yield more drought-tolerant varieties. For example, 1 year ago, South Africa's Ministry of Agriculture announced the release of maize ZM521, which produces yields up to 50% higher than those of traditional varieties under drought conditions. Many organizations, including the Consultative Group on International Agricultural Research, the International Maize and Wheat Improvement Center, and the European Union, contributed to the development of ZM521.

More recently, plant researchers in the United States and Europe have taken a newer tack, focusing on identifying specific genes that help plants cope with arid conditions and, it turns out, with other stresses, such as cold temperatures and the high salt concentrations often found in irrigated soil. Indeed, from a plant's perspective, frost injury, which involves water leaving cells and forming ice crystals in intercellular spaces; salinity damage, which occurs when roots can't extract enough fresh water from salt-laden soils; and drought injury are all forms of dehydration. "If you increase a plant's tolerance to dehydration, it doesn't matter whether the stress comes from cold or drought, it will often help the plant survive," says plant molecular biologist Michael Thomashow of Michigan State University in East Lansing.

Researchers are now attempting to beef up the ability of crop plants to withstand dehydration by transferring in some of the genes they've identified. They've achieved some successes, albeit modest ones, with cotton and tomatoes, and they hope to extend the work to the most important cultivated crops: cereal grains.

The Rockefeller Foundation in New York City, among others, wants to guarantee that such advances also benefit developing countries. Two years ago the foundation approved a 10-year global effort for up to $50 million to improve drought tolerance in maize for Africa and in rice for Asia. Given the resistance that greeted plants genetically altered to resist pests or herbicides, it remains to be seen how well accepted drought-resistant plants produced by the same technology will be.

Complex adaptations

Over the years, researchers have found that plants have evolved several mechanisms to guard against drought damage. One is by producing "osmoprotectants," compounds that shield proteins and membranes from the damaging effects of dehydration by forming a protective shell on their surfaces or by removing destructive hydroxyl radicals that would otherwise chop up proteins. Not all crop plants make osmoprotectants, which include sugars such as trehalose and certain amino acids and amino acid derivatives.

Almost 10 years ago, Hans Bohnert of the University of Illinois, Urbana-Champaign, decided to see whether the genes for osmoprotectants could be inserted—and made to function—in plants that don't normally carry them. He took a gene that produces the osmoprotectant D-ononitol from ice plants, the durable groundcover that blankets California's highway medians, and introduced it into tobacco plants. The modified plants were better able to withstand stresses such as drought—but not enough to make a difference in the field.

Still, the results provided a proof of principle. Since then, researchers in a dozen labs have introduced osmoprotectant genes into major crops, including potato, rice, canola, and, in Japan, the persimmon tree. Again, though, production of the compounds was too low to improve the plants' drought tolerance. University of Florida, Gainesville, plant biologist Andrew Hanson, among others, wants to solve this problem. "We need to diagnose what limits osmoprotectant levels in engineered plants and to use repeated cycles of engineering to overcome these limits," he says.

Even when drought-tolerance genes are present in plants, they are often poorly expressed during stress. A current strategy is to identify and manipulate the signaling pathways that trigger the potentially protective genes into action. "If genes are the hardware that seems to be present in all plants, what makes them tolerant are software differences," says Bohnert.

Indeed, recent research has shown that fine-tuning of regulatory systems can make or break drought tolerance. About 10 years ago, for example, Thomashow's group identified four genes involved in cold tolerance in *Arabidopsis*; at about the same time a team led by Kazuo Shinozaki of the Institute of Physical and Chemical Research in Tsukuba, Japan, and his wife Kazuko Yamaguchi-Shinozaki of the Japan International Research Center for Agricultural Sciences, also in Tsukuba, identified a group of *Arabidopsis* genes involved in drought tolerance. Sequence analysis showed that two of Thomashow's *COR* (cold response) genes are the same as the Shinozakis' *RD* (responsive to dehydration) genes.

The functions of most of these genes are unknown, but in 1998, Thomashow, in collaboration with the late Peter Steponkus of Cornell University, demonstrated that one of the *COR* genes makes a cryoprotective protein that stabilizes membranes against injury caused by freeze-induced cellular dehydration. First, Thomashow and his team tried simply overexpressing this or other *COR* genes alone to improve the ability of *Arabidopsis* to withstand freezing, but they had little success. But turning up the activity of several cold-responsive genes at once worked better.

In 1997, Thomashow and his colleagues identified a transcription factor, CBF1, that controls expression of a battery of *COR* and other cold-responsive genes in *Arabidopsis*. A year later, the researchers showed that overexpressing the *CBF1* gene increases the freezing tolerance of *Arabidopsis* plants. And in similar experiments a few months later, the Shinozakis showed that they could increase tolerance to both frost and drought by overexpressing a second member of the CBF family of transcription factors, which they designated DREB1. The altered *Arabidopsis* plants grew poorly, however.

Thomashow hopes to extend that work to crop plants. As he reported at a recent meeting,* parts of the CBF/DREB1 system are widespread in the plant kingdom. He and his colleagues found *CBF*-like genes in canola, a commercial oilseed related to *Arabidopsis*. And there are indications that wheat, rye, and even tomato have parts of what Thomashow calls the CBF cold-response pathway. The goal now is to crank up the activity of these genes—without stunting the plants' growth.

Fields of ... brown. Improving the drought tolerance of corn could make dried-out crops like this one a thing of the past.

Evidence that this may in fact be possible comes from plant scientist Tuan-Hua David Ho of Washington University in St. Louis, working in collaboration with Cornell University biochemist Ray Wu and Min-Tsair Chan of the Institute of Agricultural Sciences in Taipei, Taiwan. These researchers attached the *CBF1* gene to a regulatory sequence that causes it to be turned on when the temperature drops and then introduced it into tomato plants. As a result, Ho says, "this new generation of transgenic tomatoes has normal yields yet has still displayed a higher level of stress tolerance."

Salinity, often caused by irrigation of croplands, produces plant dehydration just as dangerous as that caused by drought itself. But progress is being made here, too. At the University of California, Davis, Eduardo Blumwald and his colleagues have been studying an *Arabidopsis* protein called AtNHX1 that can protect against this threat.

Plant cells contain vacuoles that can sequester harmful materials. AtNHX1 is located in the membrane of one type of vacuole, where it pumps sodium ions from the cell cytoplasm into the vacuole. About 3 years ago, the Blumwald team showed that they could protect *Arabidopsis* from high salt concentrations by altering the regulatory sequence of the *AtNHX1* gene so that it makes higher than normal amounts of protein.

Last year, Blumwald extended these findings, showing that overexpression of the *AtNHX1* gene also protects greenhouse-grown tomatoes from high salt concentrations. Indeed, the fruit grows in a 200-millimolar solution of salt, about one-third the concentration of seawater, far higher than that of the fresh water used for irrigation. (The results appeared in the August 2001 issue of *Nature Biotechnology*.) Field trials are planned for next year.

Another way to protect plants from the drying effects of salt is to prevent it from getting into their cells in the first place. In results reported in the 20 November 2001 issue of the *Proceedings of the National Academy of Sciences*, Mike Hasegawa, Ray Bressan, and their colleagues at Purdue showed that they could increase the salt tolerance of *Arabidopsis* by inactivating the gene for a protein called AtHKT1 that transports sodium through the membranes of root cells.

These genetic manipulations were aimed at directly preventing dehydration of plant cells, but other drought-tolerance schemes are being investigated. Plant biologists have known since the mid-1980s that stresses such as high light, drought, or salinity increase production of toxic oxygen species, such as peroxide, the damaging effects of which include disruption of photosynthesis.

In work that began in the mid-1990s, plant molecular biologist Randy Allen and his colleagues at Texas Tech University in Lubbock introduced genes encoding two enzymes that mop up peroxides, ascorbate peroxidase (APX) and glutathione peroxidase, both together and separately, into tobacco plants. The researchers targeted the enzymes so that they would be active in the chloroplasts, where photosynthesis takes place. In lab studies described in the December 2001 issue of *Experimental Botany*, the Allen team found that the altered tobacco plants maintained near-normal rates of photosynthesis under stressful conditions while photosynthesis in wild-type plants was reduced by one-half.

Even before the tobacco studies were published, the researchers had begun work

* "Crop Productivity in Water-Limited Environments," 31 October to 2 November 2001, Donald Danforth Plant Science Center, St. Louis, Missouri.

CREDIT: RICHARD HAMILTON SMITH/CORBISS

on cotton, an important crop plant in Texas. In 2000, a preliminary field trial of cotton transformed with APX showed that, under dryland agriculture, the altered plants produced 280 kilograms of cotton per hectare, whereas the wild-type yielded only 168 kg.

Back to the future

Other researchers have gone back to the basics: studying the physiological underpinnings of tolerance, work that could also provide new ways of boosting drought tolerance. For example, in studies of maize seedlings grown with limited water, plant biologist Robert Sharp of the University of Missouri, Columbia, found that roots adapt to the scarcity in several ways. The structure of their cells changes, permitting more longitudinal growth deep into soils. Also, the roots adjust osmotically, taking in more solutes and water. This response mechanism might be beefed up via changes in regulatory mechanisms, possibly further enhancing roots' vertical exploration of the soils, Sharp says.

Dorothea Bartels of the University of Bonn, Germany, and others are seeking clues from plants with an extraordinary ability to deal with drought, such as the resurrection plant (*Craterostigma plantagineum*), which can become completely dehydrated but revives with moisture. One of its secrets for success is a revamped chemistry that allows cellular metabolism to go into an inert, glasslike state. Curiously, although the plant tolerates desiccation, it doesn't thrive in saline soils, which suggests "a unique metabolism for the plant," says Bartels.

Washington University plant biologist Ralph Quatrano and his colleague David Cove of the University of Leeds, U.K., have just started studies of *Physcomitrella*, a moss that tolerates severe desiccation. Mosses were among the first land plants and may provide a good source of genes needed for coping with limited water. "Just 6 or 7 years ago, given the then capacity to control transformation, I would have scoffed at the [value of] 'weird and wonderful' genes from resurrection grasses or mosses," says Rockefeller Foundation scientist John O'Toole, who has developed research programs on drought tolerance for more than 25 years.

Now, he says, identification of such genes is a promising next step, offering researchers a significant new opportunity for manipulating drought tolerance into crops. More knowledge of plants' diverse physiological adaptations to drought, coupled with an understanding of their genetic basis, should help world agriculture do its part to conserve an increasingly rare resource, fresh water.

–ANNE SIMON MOFFAT

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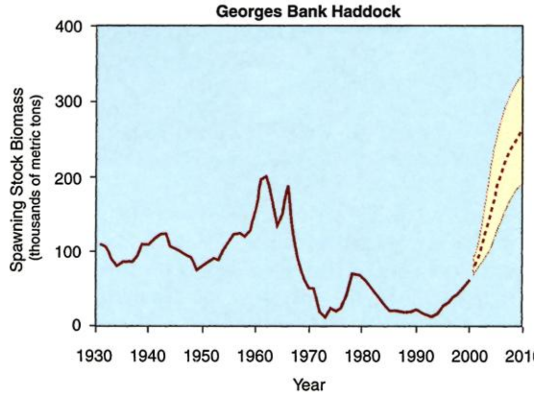
FISHERY SCIENCE

Bigger Populations Needed For Sustainable Harvests

The future of the New England fishing industry rests on the willingness of fishers, environmentalists, scientists, and the courts to find common ground

In 1998, scientists at the Northeast Fisheries Science Center (NEFSC) in Woods Hole, Massachusetts, took on a huge challenge. They helped calculate the mass of Atlantic scallops needed to support a stable and productive scallop industry, something that hadn't existed for decades. Their answer: It would take a fivefold increase over the recent depressed mass of scallops in the Georges Bank—a prime fishing area 100 kilometers off the Massachusetts coast—to bring back what had once been the continent's most productive scallop fishery. The calculation was more than an academic exercise. The New England Fishery Management Council (NEFMC) worked the target into its scallop management plan in 1998, which helped guide the opening and closing of the region's scallop grounds over the next 3 years. That injection of science into government regulation has paid off, yielding a robust harvest that seems to be sustainable, says Steven Murawski, director of the center's fisheries population dynamics branch.



Now scientists hope to replicate that success with similar calculations for the much larger groundfish industry, once the backbone of the New England economy. Groundfish harvests—which include 14 bottom-dwelling species such as flounder, cod, hake, and haddock—have been inching back since a crash in the mid-1990s prompted an economically wrenching series of fishing restrictions. Some populations are now nearing targets set in 1999, but new findings issued by NEFSC in March suggest that existing targets may be too low and that more reasonable goals would limit fishing to ensure the mass of some stocks climbs higher than levels seen at any time in the last 40 years.

Out of bounds? Scientists say the mass of fish needed to rebuild troubled New England haddock fisheries exceeds the estimated stock that has existed at any time since 1930.

Those findings could have a major impact on the livelihood of tens of thousands of people in the Northeast. The new biological targets have already been accepted—pending revisions and debate—as the goals for an NEFMC management plan that will guide regulators starting in August 2003. And they have influenced a court-ordered settlement between the National Marine Fisheries Service and conservation groups on new rules designed to help northeast groundfish recover. The settlement rules—approved last month by Judge Gladys Kessler, who tightened some provisions—slash the number of days commercial fishers can operate, mandate the use of coarser nets, increase the size of legally catchable fish, and add thousands of square kilometers to areas already closed year-round or during certain seasons. They went into effect 1 May.

The compromise rules seem to please nobody. Although everybody agrees that the fish are coming back, opinions diverge over how high the bar should be set, and how to tell if it's been cleared. Indeed, three of the four con-

CREDITS: (LEFT TO RIGHT) SOURCE: RUSSELL BROWN/NORTHEAST FISHERIES SCIENCE CENTER; VINCE STREANO/CORBIS