LAND REPORT

THE LAND INSTITUTE · SPRING 2011

THE LAND INSTITUTE

MISSION STATEMENT

When people, land and community are as one, all three members prosper; when they relate not as members but as competing interests, all three are exploited. By consulting nature as the source and measure of that membership, The Land Institute seeks to develop an agriculture that will save soil from being lost or poisoned, while promoting a community life at once prosperous and enduring.

OUR WORK

Thousands of new perennial grain plants live year-round at The Land Institute, prototypes we developed in pursuit of a new agriculture that mimics natural ecosystems. Grown in polycultures, perennial crops require less fertilizer, herbicide and pesticide. Their root systems are massive. They manage water better, exchange nutrients more efficiently and hold soil against the erosion of water and wind. This strengthens the plants' resilience to weather extremes, and restores the soil's capacity to hold carbon. Our aim is to make conservation a consequence, not a casualty, of agricultural production.

LAND REPORT

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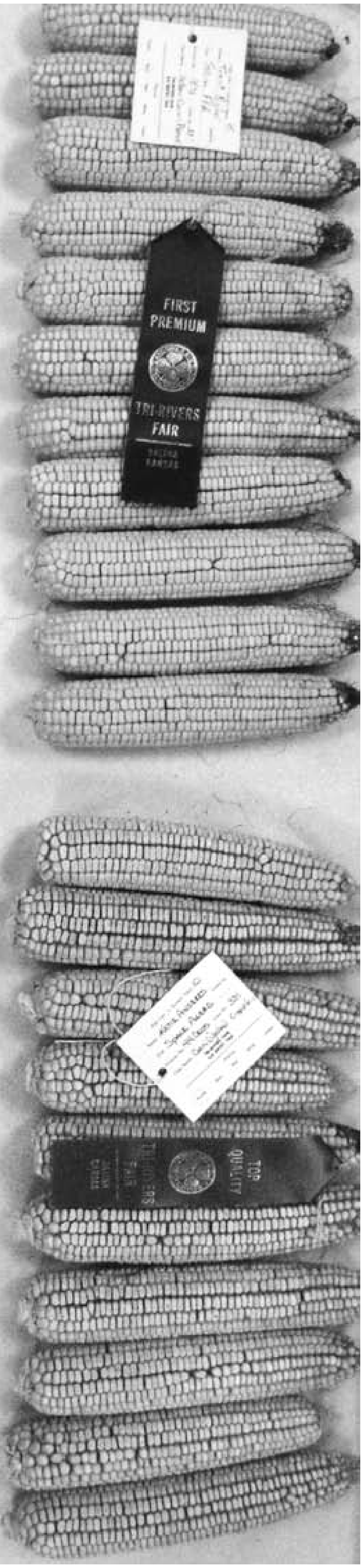

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Cover: "Rosemont, New Jersey," by Ansell Bray. Contents: corn at the county fair in Salina, Kansas. Scott Bontz photo. For a story about breeding perennial corn, see page 12.

At the Land

CROSSING THE LINE

A wild legume can spread seed by pods splitting or by pods falling off – pop or drop. It can also do both. Among thousands of observed plants, Illinois bundleflower researcher David Van Tassel found 40 that strongly held to doing neither: they kept seed off the ground, like a domestic crop plant.

About the same number were strong for both popping and dropping, and the other plants scattered across the range among all four corners of combined possibilities. So the traits appear not to come from single, independent genes.

This year Van Tassel will grow plants from those 40 best. In a report to The Land Institute board he called this a milestone: "For the first time, next year we should have some experimental populations that are uniformly non-shattering. We will have crossed the line from a wild plant to a primitive domesticate." He'll also plant from intermediates on the pop-drop scale, expecting to find among their diverse offspring more seed-keepers, along with valuable notes that might not appear in the top 40.

On another front, Van Tassel found plants with unusually large pods and large seeds. He plans to cross these with non-shattering types next year.

Bundleflower, maybe the most important North American prairie legume, already has relatively high yield for a perennial. Its seeds pack almost as much protein as soybeans.

They also stink, and until now have been difficult to make palatable. The odor might be eliminated through breeding, as similar chemical problems have been removed from other legumes, such as alkaloids from lupine. But that work could be complex and lengthy. And until the moment of consumption, the repellent trait is valuable. "The bugs don't go for the seed," Van Tassel said. "The rodents don't go for the seed. The birds don't go for the seed. They're very protected."

Land Institute technician Cindy Thompson might have made a breakthrough. Soaking the seed for 24 hours in a refrigerator nearly eliminated the bad odor and flavor. Alternately, cooking the bundleflower with a little baking soda in the water greatly softened the grain and completely eliminated the offending chemical. The best previous methods involved energy-intensive extended boiling or roasting. Thompson also found that sprouted bundleflower seed is quite palatable.

Van Tassel wants to repeat these trials. But he found literature showing that nearly all grain legumes have chemistry that inhibits nutrient digestion, and that soaking, sprouting, and boiling with baking soda help. "So IBF is in good company," Van Tassel told the board. "And we are not crazy to be trying things like baking soda."

Van Tassel also is domesticating perennial sunflowers. A few years ago he found among his Maximilian sunflower one plant that made one relatively large head on one stalk, like crop sunflower. Wild sunflowers, annual and perennial alike, grow dozens of branches and flowers. Now, working to develop a single-headed Maximilian sunflower has produced not only much bigger heads than ever seen before, but some that shatter much less than wild sunflowers. From his experience with those, Van Tassel had expected the vast majority of his new plants to keep less then 10 percent of their seed, and only a few to keep up to 50 percent. What he got ranged from 0 to 95 percent. The results seem more a varied genetic accumulation than the kind of recessive trait that Van Tassel had despaired of seeing occur naturally. Now the laborious process of artificially mutating genes might not be needed. Van Tassel called this a very exciting discovery.

Breeding bigger seeds from a perennial: the bottom row came from an intermediate wheatgrass forage variety, the middle from plants used to start breeding work seven years ago, the top row a 2010 result with good yield and seeds 2.5 times heavier. Lee DeHaan photo.

More encouragement came with his work to domesticate another sunflower, Silphium. He has been selecting to increase the number of seeds per head. Analysis showed no correlation between seed size and number of seeds per head. There is no reason to fear that increasing seeds will strongly reduce seed size.

KERNZA AT A FARM

In the fall of 2008, Charlie Melander, a local farmer and longtime collaborator with The Land Institute, let us plant 30 acres of his land to intermediate wheatgrass, a perennial grain crop in the making. Our trademark name is Kernza. In 2009, we tilled and cut weeds between the three-foot rows. Last August, Melander cut the Kernza with his combine. The field was virtually weed-free.

"Wheatgrass must be very competitive," he said. "There just weren't any broadleaves, even though it had been planted in wide rows." On harvest day he expected difficulty winnowing stems and leaves from the as-yet small, light seed. "But it was a beautiful grain sample," he said. The combine bin filled with a product as clean as wheat. "It was easy cutting, easy harvesting."

In January, Melander put cattle on the field. Their fare of winters past was sorghum stubble. But they quickly took to eating the dry Kernza stems while going for something annual sorghum fields could not offer in winter: bits of green growth. Like grazed winter wheat, come spring the wheatgrass should do fine.

Kernza researcher Lee DeHaan said the hoof action might work biomass into the soil. It also might beneficially thin the stand.

As stands of grasses age, they become dense, with more, smaller stems. This tends to limit seed yield. Grazing also will help clear the way for light to reach the plant crowns in the spring. DeHaan has fenced off plots for comparison.

In the greenhouse this winter, DeHaan crossed some of the best plants in his main breeding program with plants less developed but outstanding for one of three traits: large seed, early maturity, or seed that threshes free and doesn't require dehulling. DeHaan is most interested in early maturity genes. All of the plants in the main program mature at about the same time. Some of the wild plants mature about six weeks earlier. This is near the time wheat matures, an intentional result of breeding. And as with wheat, genes for earliness could enable Kernza to avoid Kansas heat and drought.

DeHaan plans this spring to seed 20,000 plants, quadrupling his field stock. Breeding programs depend upon finding the rare outstanding individuals. The more plants that can be grown, measured, and harvested, the faster progress will be toward achieving perennial crops with higher yields. The expansion depends on buying new equipment for transplanting, weed control, and data collection.

DeHaan will speak at a July 17-22 conference in Logan, Utah, and will meet with grass geneticists there. He said they are intrigued with the possibility of collaborating on wheatgrass research, and plan to begin mapping the genome soon. DeHaan called this great news. Basic knowledge of the species' genetic structure, especially how it relates to wheat, will speed breeding. For more about this kind of work, see page 17.

TWO-CYCLE ENGINE

Developing a perennial grain might take a quarter-century. Some stages can be halved, though not the whole process, with two breeding cycles a year. A greenhouse allows this on a small scale. But the chance of finding plants with desirable but elusive traits is better with a bigger population. Temperate-zone Kansas fields allow one planting a year. So sorghum breeder Stan Cox went to Hawaii, and for the first time squeezed in an extra generation on crop ground. It was mostly a test run, but encouraging.

He found a commercial service on Oahu, the Hawaiian Agricultural Research Center, which also is hired by researchers to grow coffee, wheat, cane, and corn. He mailed sorghum seed in October. The center planted 30 rows of 50 plants each. In January, Cox flew out to evaluate the work, discern his desired hybrids from among self-pollinated plants, and harvest the seed. "They did a beautiful job," he said of the center. This included covering the entire plot with netting to keep off birds, which can wipe out a sorghum crop in one day.

The plants were healthy and grew well. But Cox wants to select for many traits, and for evaluating some of these Hawaii's alien environment isn't good. In certain stages of the work, however, "You can save an entire year."

This also could benefit The Land Institute's work with sunflower, another big plant. The greenhouse can pack in many more wheat and wheatgrass plants. They are cool-season plants and wouldn't be helped in a tropical environment anyway.

The research center's good work took good pay, and Cox now wants to look for a more frugal arrangement in Hawaii.

PRESENTATIONS

Land Institute presentations: April 11, Brunswick, Maine. April 13, Williamstown, Massachusetts. April 14, Schenectady, New York. April 28, Brussels, Belgium.

FIELD NOTES

WIND POWER, WATER POWER and wood fuel are parts of the year-to-year revenue of sunshine. … But when coal became king, the sunlight of a hundred million years added itself to that of today and by it was built a civilization such as the world had never seen. – Frederick Soddy, "Cartesian Economics," as quoted in Vaclav Smil's "General Energetics"

THE NESTERS HAD REMOVED a perennial plant, a perfect fit for flat, wind-scraped land, and replaced it with a weak annual. – Timothy Egan, "The Worst Hard Time"

THE MIND LIKES a strange idea as little as the body likes a strange protein and resists it with similar energy. It would not perhaps be too fanciful to say that a new idea is the most quickly acting antigen known to science. If we watch ourselves honestly we shall often find that we have begun to argue against a new idea even before it has been completely stated. – Wilfred Trotter

'TIS NOT CONTRARY TO REASON to prefer the destruction of the whole world to the scratching of my finger. – David Hume

VISION IS THE ART of seeing things invisible. – Jonathan Swift

THANKS TO THE INTERSTATE highway system, it is now possible to travel across the country from coast to coast without seeing anything. – Charles Kuralt

IF A PLACE IS IN YOUR BLOOD, you leave it at your peril. You will never be happy anywhere else. – Caroline Llewellyn

IN MEXICO, I first encountered the attitude that was missing from the optimistic innocence of living in the United States: a tragic sense of life. Such a sense doesn't force us into a closed somber cone of depression and futility; it urges the opposite. The tragic sense opens a human being to the exhuberant joys of the present. To laughter, carnality, the comical varieties of love, to music and art, to the small human glories of the day. – Pete Hamill

LIVING IS ABOUT INTERACTING with one's living surround. Without constant, unceasing interplay with lives around us, like the prisoner in solitary confinement we are merely enduring. We may have been persuaded that the only living surround we need is the human community, but the condition of humankind today, to say nothing of the condition of nature, suggests otherwise. – John A. Livingston, "Other Selves," in the essay collection "Rooted in the Land"

WISDOM DEMANDS a new orientation of science and technology towards the organic, the gentle, the nonviolent, the elegant and the beautiful. – E.F. Schumacher, "Small is Beautiful"

WE WOULD RATHER be ruined than changed. – W.H. Auden, "The Age of Anxiety"

Averi Gengler sets young sunflower plants in The Land Institute's greenhouse, where they now have better climate control, more space,

and less disease. Scott Bontz photo.

A CLEANER, BRIGHTER PLACE

SCOTT BONTZ

In 2006, The Land Institute sent its greenhouse manager, Tiffany Durr, to a greenhouse management class. The institute was happy with Durr, but thought she might bring back something helpful. She did. Durr said, "It was a real eye opener for everything we were doing wrong."

She and institute plant breeders were at their best in the greenhouse. But the building was almost 20 years old. Gravel-packed floors and wooden plant benches had accumulated enough leaf litter and other organic matter to sustain a zoo of pests and diseases. Antiquated temperature, humidity, and water controls further rattled the plants. Heating and cooling thermostats worked independently. Roof vents opened to dump in air so cold that it fogged. After shocking the wheat, sorghum, wheatgrass, and sunflowers, it triggered the heating system, which triggered the vents, in an endless and wasteful feedback cycle. The temperature over a week could swing 40-50 degrees, far from the ideal sought in greenhouses. It hurt work to get two breeding seasons in each year for the decades-long endeavor of breeding perennial grains.

Durr asked for an improved environmental control system. She said the scientists told her, "Dream bigger. What would you really like?" Now, she and they have it. Thanks to contributors to the institute's ongoing Perennials on the Horizon Capital Campaign:

· the greenhouse has two-thirds again more space for plants within the same exterior walls.
· the plants enjoy more light.
· a concrete floor makes work easier and reduces diseases.
· pumps filter and recycle water for the plants.
· humidity is controlled.
· a unified, programmed regulator keeps the temperature between 60 and 70 degrees.

"Before we didn't have any hope of keeping it that tight," Durr said.

For the first time, sunflowers in the greenhouse are producing good amounts of pollen, and breeder David Van Tassel should, like the scientists handling wheat and wheatgrass, be able to speed progress by cramming in a winter generation. "I'm extremely happy with it," said Stan Cox, the institute's senior scientist, and whose sorghum had suffered sterility under the old cold blasts. "The growth of plants is much better."

Before, walls split the greenhouse into four rooms and a hall along them. The walls are gone to make one big room, with about a quarter more light, and interior wall shadows gone. "It's like what a greenhouse is supposed to be," said technician Adam Gorrell: "open." Durr said, "Space is a huge advantage. Air flow is a lot better." With less shade and better, computer-designed artificial lighting, plants aren't going leggy to compete. They're shorter, like in the field. A possible further reason: the narrower temperature range lessening time to maturation and flowering. A four-foot plant is easier to handle for breeding work than a 6- or 7-footer. Durr once stepped up on the benches with the plants and still had to crane her neck to evaluate and handle their heads. Now she can stay on the ground and see the flowers at eye level.

Another gain is in bench space for plants. The benches are fewer but longer, with less space needed between them. They can hold 4,480 one-gallon pots. The old benches could take 2,664. A quarter of the space, about 1,000 square feet, remains without benches, for taller plants.

The greenhouse had floors and plant benches filled with gravel that harbored plant pests. Scott Bontz photo.

No longer can different conditions be made in each room for different plants – a cooler room for wheat, which grows in spring, and warmth for sorghum, which grows more in the summer. And a few of the sorghum plants in the breeding gene pool won't flower unless day length is tropically short. They'll require development of a blackout system. Durr and the breeders foresaw all of this, and accepted the tradeoff.

In winter's past, greenhouse workers might at times need coveralls. Now they could wear shorts. They also say the new place is easier to keep clean.

"I really enjoy it," Durr said, "and I'm really grateful to the donors who made it possible."

The $3 million capital campaign that included the greenhouse remodeling has about $300,000 to go.

When the greenhouse opened in 1988, all watering was by hand. Then came drip emitters stuck in the pots from the top and fed by a tangle of lines. Now the pots sit in plastic trays 6 by 24 feet atop the benches. Water twice daily automatically fills the trays for about 12 minutes while the pots soak it up. Soil is more evenly wetted. Unused water drains back for recycling.

At sunset an automated system draws shades across the roof's underside to cut loss of heat through the transparent ceiling. The old greenhouse couldn't do that. And it regulated the heating system by monitoring air temperature. It's better to go by soil temperature. Now a sensor stuck in a pot in the middle of the greenhouse signals for pumping hot water through pipes in the floor and plant benches.

Come summer, a high daytime temperature will automatically close the shades. A little more warmth will turn on a small fan at the west end to pull air through from a vent in the east. Warmer yet, and two large fans at the west will pull more air through a 22-by-6-foot cell of fiber filling much of the east wall. In the next step, water will soak the fiber for evaporative cooling. Last, emitters above the benches will add mist. Now researchers can use the greenhouse all spring and fall instead of only during cooler times.

This new way also will end clambering over the fragile roof to drape it with a circus tent-size shade cloth in spring, and being stuck with the shade until fall regardless of daily weather changes.

A light sensor controls when artificial lights come on. Before they were controlled manually – which might be neglected – and were placed according to the plant breeders' best reckoning. In the remodeled greenhouse fixtures are set by the manufacturer's calculations to distribute the light evenly.

One greenhouse enemy is powdery mildew. The Land Institute didn't want to fight it with synthetic chemicals. The new environment has better air movement, humidity control, and less harbor for mildew. It's still present, but a far smaller problem. Bags placed over plant heads to control pollination once became moldy, mildewy. Now they can be re-used, three or four times. And with no leaf decay in floor for laying eggs, so far there are no white flies. Aphids remain, and Durr must adjust how to use natural predators.

Pests and disease are facts of life in the world of a greenhouse. But The Land Institute's progenitors of perennial grains now have a place cleaner, brighter, and more healthful. "The plants are doing so much better than they used to," Durr said. Plant breeders didn't expect all of the larger capacity to be used this year. But by late January it had attracted them to fill it. Next year, Durr said, "I think there's going to be a battle for space."

Growth from an underground stem of corn relative Zea diploperennis that survived outside in a pot through what for Texas was a hard winter. Plant scientists are trying to breed that ability into corn, and push all the way to winters in Iowa. Seth Murray photo.

TO MAKE A PERENNIAL CORN

SCOTT BONTZ

Corn is the most productive food crop, and uses more land in the United States than any other – though now much of it feeds cars. Its fields lost 465 million tons of soil in 2007, the National Resources Inventory estimated. Much of that soil is the best: rich glacial deposits and former prairie of the upper Mississippi River drainage. To make corn a ground-holding perennial could be one of the single biggest steps for preservation of the nation's natural capital, and the world's.

The Land Institute chose to pursue other perennial grains. It has only a handful of breeders, and senior scientist Stan Cox said corn already enjoys high attention at leading agricultural schools better equipped to address making it a perennial.

Researchers in New York, North Carolina, and Texas are taking early steps. Two face the challenges of time, cash, and crossing corn with close tropical relatives for a plant that thrives under temperate zone extremes. But they are hopeful. A molecular scientist wants to insert genes from a cold-hardy North American perennial. He says tremendous progress recently in the means and pricing of genetic detective work put the goal in reach.

Turning corn or any other annual crop into a perennial means finding a perennial relative and incorporating genes that tell the plant to not quit and die after producing seed, but to invest in underground growth for winter and rejuvenate come spring. The Land Institute's Shuwen Wang is breeding wheat with the perennial wheatgrass. David Van Tassel is crossing annual crop sunflower with wild perennial sunflowers.

Corn's scientific name is *Zea mays*. There are several *Zea* species and subspecies, from Mexico and Central America. Two are perennials. One of them, *Zea perennis*, in normal form has twice as many chromosomes and won't cross well with corn. *Zea diploperennis* was unknown until the late 1970's. A college student found an isolated stand in Mexican highlands. (See page 23.) A few more stands have been discovered. But the species remains rare. *Diploperennis* has the same chromosome count as corn, 10 pair, and the species can interbreed.

Jim Holland has made these crosses. The offspring are vigorous, tall, big plants. But the ears don't fill out, and the plants aren't perennial. He said, "We clearly need to recombine some genes in the process." Holland is a US Agriculture Department research geneticist at North Carolina State University. He wants to study what makes for perenniality in *diploperennis*, and how it could do the same in corn. For that he needs thorough field studies, and grants for genetic analysis. Then he could go to breeding for corn ears on a perennial plant. But Holland said, "I have too many other things going on." He needs the help of a graduate student or a technician. "We're not set up now to do perennial work."

Seth Murray was hired at Texas A&M University to breed corn for resistance to aflatoxin, a carcinogenic and occasionally lethal fungus toxin. Less than 10 percent of his time goes to perennial corn. But his administration supports the effort as a novel way to bring new opportunities to producers. Murray works with Holland's *diploperennis* crosses. He also uses crosses with *Zea perennis*, that relative with double the chromosomes. But in this case breeder Donald Shaver, developer of Corn Nuts snack food, took a cross of *perennis* with a corn whose chromosome count had been doubled experimentally, then found, through sieving, smaller pollen with the same chromosome count as regular corn.

Murray plants these hybrid populations twice a year, at A&M in College Station and, come fall, farther south. Perennial growths appear in the baking Texas summer. But in August the plants die off. Holland's plants can't take North Carolina summers either. The south Texas plantings of last fall did appear to show perennial growth habits this winter. Holland has used a nursery in Florida, but didn't have the time and money this year.

The upstarts can't yet take Corn Belt hard freezes. But their gene pool is tiny, from a handful of parents. And King Corn also began in the tropics.

There is another hurdle from low latitudes. The wild perennials sense the time from dawn to dusk, and won't flower during the long summer days of temperate North America. Holland's crosses still flower too late. This summer Murray will try to trick his perennials. The model is a shade house used by Germplasm Enhancement of Maize, a partnership in Iowa of the Agriculture Department and industry. GEM breeds into commercial corn helpful traits, such as disease resistance, from other corns and corn relatives found around the world. The shade house can make a 9 to 5 day.

Getting the perennials and corn to flower at the same time will remain difficult. "It's all a balancing act and hard to predict," Murray said. The perennials' pollen in summer heat dies in minutes. The breeder must catch the plant in the act of shedding and quickly gather and transfer the pollen to a corn plant's silks. Until that moment they are bagged to prevent fertilization by some unwanted male flower, including its own.

In work with annual corn from Latin America, the photoperiod problem generally is overcome in the first cross with corn bred for North America, Murray said. But if the photoperiod gene is closely related to pereniality, then he'll lose what he wants with what he doesn't.

A more certain challenge is that perenniality does not result simply from one gene. Edward S. Buckler, an Agriculture Department geneticist at Cornell University, said the trait likely involves 20-50 genes or more. But this likely means no one gene is that important, Buckler said: "You just need to get it mostly right for it to work." The complexity is true not just with corn and its relatives, but for all of The Land Institute's work of crossing annuals with perennials. But institute breeders are progressing. And corn enjoys the advantage of being one of the most thoroughly understood species in the world. It's also closely related to other wild perennial genera.

One of those is *Tripsacum dactyloides*, known by the common name of Eastern gamagrass. This North American prairie native can already take the winters that Holland and Murray's tropical *Zea* crosses have yet to survive. It's also adapted to Midwestern diseases. But *Tripsacum* has 18 pairs of chromosomes, to corn's 10. Some people continue trying to cross the plants.

Murray, The Land Institute's Cox, and others say perenniality genes won't stick this way – the *Tripsacum* will slough off the genome over generations. Knowing those genes, however, might help scientists find and use them in the *Zea* species.

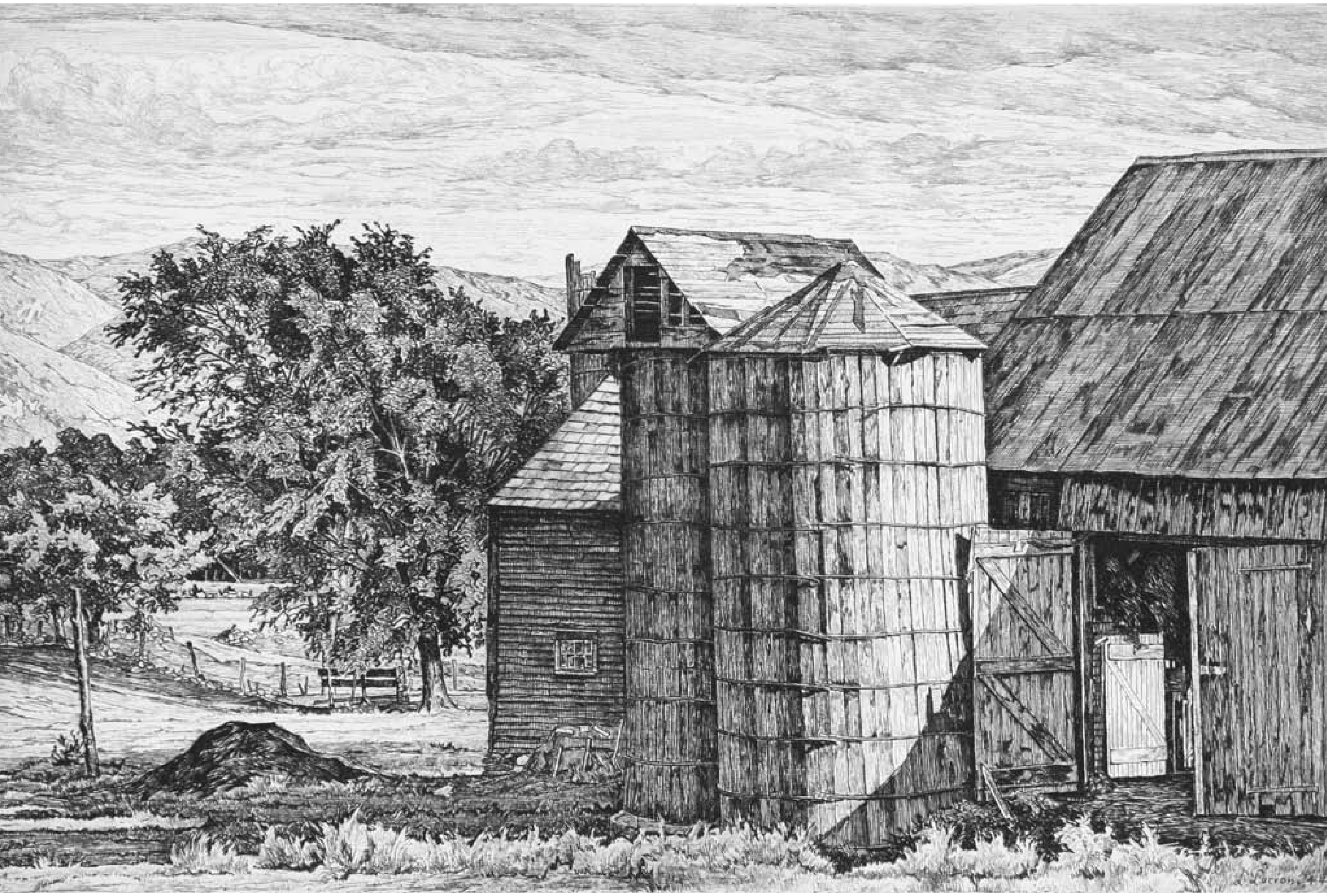
Buckler wants to find *Tripsacum's* keys for cold tolerance and engineer them into corn. Technically this would be transgenics. But it would be between species closely enough related that a cross might occur naturally, albeit not to the desired lasting effect. Buckler recently mapped the *Tripsacum* genome and has in the works a paper showing the relation is closer than imagined. He said, "There aren't that many steps away from cold-tolerance." As with perenniality, the trait involves multiple genes. But technology is reaching the ability to insert dozens of transgenes at once, Buckler said. "I would try to put all hypothesized genes in together and then apply breeding selection to see which ones actually work."

In just the past couple of years there has been great advance in mapping genetic code and in computer statistical modeling for researchers. Developing a new annual crop variety has taken six to eight years of growing out and examining plants, Buckler said. Once researchers have studied natural variation in the plants, however, they can look at the genes and, without even sowing the seed, predict how the plant will look and grow with high accuracy. They can throw out the 90 percent of seed that was expected to be bad. "Maybe 99 percent," Buckler said. And they can advance their varieties in four months rather than years. At The Land Institute, Wang is applying this technique to perennial wheat. (For more about the technique, see page 17.)

Buckler said that much of the advance owes to drug companies and the National Institutes of Health working to sequence human genomes. Competition of machinery manufacturers has been fierce, and prices have plummeted. Now a genome region of interest to a plant breeder can be read for less than $20. This formerly would cost 100 times more. Sequencing of the corn genome concluded last year, at a cost of $30 million. Resequencing now could be had for $1,000. It wouldn't be of the quality that geneticists prefer, Buckler said, but, "From a breeder's perspective, it's plenty good. That has been an amazing shift. That really opens up great vistas for breeding perennial crops."

Murray was inspired to become a plant breeder – and of perennials – after a high school teacher shared Wes Jackson's "Becoming Native to this Place." Transgenics is not his first choice. He said, "My philosophy is, if it's native, why bother?" And though he thinks Buckler will succeed, Murray doubts the job will be so easy. He wants to focus on *Zea perennis* and *diploperennis*. He hopes to expand their genetic pool and achieve perennial corn by traditional breeding. Buckler said *Zea* probably is the best source for getting perenniality into corn, but still needed is *Tripsacum's* better cold tolerance.

Holland doesn't work with *Tripsacum* because of the crossing difficulty, and is not set up to insert genes like Buckler imagines. But if someone else gets *Tripsacum's* cold tolerance into corn, he would work with it. Holland said, "We might need it all."



"Late Shadows," by Luigi Lucioni, 1944. *Etching*, 8¾ *by* 13¼ *inches*. *Courtesy of Bone Creek Museum of Agrarian Art*, *gift of Dr. Stuart and Lynn Embury*, 2008.18.1.

BIOTECH WITHOUT FOREIGN GENES

PAUL VOOSEN

For the past two decades, promises of crop improvement have been the domain of genetically modified plants: mostly, crops supplemented with bacterial genes to resist pests or weed-killers like Roundup. More than 85 percent of U.S. corn, soy or cotton grown contains such genes.

But there is more than one way to transform a plant.

Using advanced biotechnology, long hidden in the background and only now starting to pay dividends, scientists are changing crops without tapping foreign genes – and often without the regulatory oversight that is given to GM crops.

Many of these crops use latent effects of genes squirreled away in discarded seed varieties to create breeds that at first glance seem artificial. There is corn so infused with vitamin A precursors that it practically glows orange, rice that can survive more than two weeks of flooded conditions, and wheat that resists the advance of devastating aphids.

Such specialized crops are possible because researchers are mastering the science of breeding. Using techniques collectively known as molecular breeding, geneticists have started to return results in a variety of plants, said Ed Buckler, a plant geneticist at Cornell University who recently helped sequence the corn genome.

"We know that old-fashioned good breeding works," Buckler said. "And a lot of that is an intelligent numbers game" based on genetic theories elaborated by Gregor Mendel more than a century ago. Molecular breeding, he added, "is now a way to do that much faster."

Increasingly affordable with improved technology, molecular breeding is becoming the mode of business in the crop world, said Bonnie McClafferty, development head at HarvestPlus, a nonprofit funded by the Bill & Melinda Gates Foundation that supports molecular breeding research into improving plant nutrition in Africa and Asia.

"People don't understand that we're not working with Gregor Mendel anymore," McClafferty said. "The science is advancing, and there's a whole variety of tools to use."

In fact, molecular breeding is only the start of a bewildering diversity of biotech approaches to crop development that defy the conventional notion of splicing foreign genes into plants. This next generation could shake up what has become a stalled debate – call it the Roundup Ready stalemate – by introducing GM crops that, for example, use only their species' native genes or have the expression of their own genes silenced.

While the techniques draw from the same pool of knowledge, and travel together in scientific circles, many environmental groups do not oppose molecular breeding, while stridently critiquing current GM crops, according to Marco Contiero, the European biotech policy director for the environmental group Greenpeace. “Genetic engineering is just a part of modern biotechnology,” Contiero said. “We are against this specific application. We are not against marker-assisted selection.”

Most scientists believe that molecular breeding and advanced genetic modification will eventually form a powerful tandem, said David Baulcombe, a professor of botany at the University of Cambridge and the chairman of a recent report issued by the United Kingdom’s Royal Society on the future of agriculture.

“Within genetic modification, you’ve got to remember there’s a whole bunch of technologies,” Baulcombe said. “There’s GM where you move plants’ genes around. GM where you use artificial genes to silence gene expression. And then there’s the technology that is out in the field now in which bacterial genes have been moved into the crop.”

For thousands of years, crop breeding remained much the same: Farmers crossbred plants with desirable traits like high yield, as often as not reproducing those traits in offspring. Mendel clarified the situation, but conventional breeding practices today, though stirred by developments like the green revolution’s hybrids, would remain roughly familiar to farmers of a century ago.

Molecular breeding has, to some extent, overturned this framework, even prompting some scientists to call for new, post-Mendel theories of breeding. The techniques rely in principle on the increasing inventory of genes that have been identified as influencing, if to a limited degree, traits in plants. For some genetically simple crops, like rice, these clusters of genes have strong effects, while the genes of more complex grains like corn and wheat have been more difficult to pin down.

Most simply, once these genes, or bits of DNA tied to the genes (known as markers), have been identified, molecular breeders can quickly target offspring inheriting the genes for further development, cutting breeding time and improving the crop’s “genetic gain,” the generational improvements made to a crop, like increased height, by human selection.

To little public notice, the world’s largest seed companies, such as Monsanto Co., Pioneer Hi-Bred International Inc. and Dow AgroSciences LLC, have used molecular breeding to improve their seed varieties in parallel with genetic engineering. At Monsanto, the practice has become so common that, in a recent paper, the firm said “molecular marker assisted breeding is becoming our conventional breeding process,” noting that many of its commercial crops are derived with the process.

A company like Pioneer is well aware of the expense and European resistance to genetically modified, or transgenic, crops. They will exhaust molecular breeding options before turning to GM, said John Soper, Pioneer’s soybean research director.

“Both transgenics and the use of markers have risen in priority. ... It’s been a very exciting time for us,” Soper said. “I still think it’s kind of the tip of the iceberg on both of these issues.”

Markers are also being used to breed traits from otherwise discarded varieties back into cultivated crops. A well-known breeding technique called backcrossing has become far more potent recently, as markers have allowed scientists to locate rare offspring that retain only the desired – and now detectable – genes from orphan crops. Previously in backcrossing, many other genes would also migrate from the orphan plant, reducing yield or taste, to farmers’ dismay.

At least one trait added with molecular breeding has already been introduced in

Asia and Africa: New varieties of rice that resist flooding damage are now being adopted in India, Bangladesh and Southeast Asia. And corn rich in vitamin A precursors is being targeted for release in Zambia by HarvestPlus.

Crops made with molecular breeding are not classified as genetically modified, since the first step in their development is pollination – an important distinction. Yet they would be nearly impossible to create without genetic engineering used to evaluate gene function, said Nora Lapitan, a wheat geneticist at Colorado State University.

Recent innovations have made it easier than ever to "knock out" or silence the expression of selected genes. This gene loss can then, in some rare cases, cause large enough changes to demonstrate a genetic function that can be targeted. These are bedrock trial-and-error experiments, Lapitan said. "It's really classic," she said.

On its own, gene silencing is also being used to create GM crops. Pioneer used the method for soybeans that produce oil with no trans fats, the type of consumer-focused GM improvement seed companies have long promised but failed to release. Many other applications are arising – for example, Lapitan's lab discovered that inhibiting one gene can broaden wheat's resistance to the devastating Russian wheat aphid.

Sometime in the near future, it is reasonable to expect that crop genes could be more easily shifted between species – say, adapting the efficient photosynthesis of corn to rice. But even discounting this future, scientists can now move genes within crop varieties, essentially accelerating a natural process, Cambridge's Baulcombe said. It is an open question whether such modification should be considered equal to introducing bacterial genes.

Increased public-sector involvement in crop development – much of which has been ceded to companies over the past decades as seeds evolved into patentable commodities – will be needed to apply increasingly cheap biotech improvements to subsistence crops like cassava, for example, Baulcombe said.

"For many of those [crops], there may not be an incentive for companies to get involved," he said.

Such innovation is required. Food security will be one of the pressing issues of the next half-century as the world's population rises by several billion. That many hungry mouths will necessitate higher yielding and better crops, and advanced GM crops will need to be a part of this mix, the Royal Society said.

However, since many developing nations lack the apparatus to regulate GM crops, molecular breeding may be the quickest way to carve out immediate gains for at-risk populations, like frequently flooded rice farmers in Asia, scientists say.

Asian rice farmers get little warning before floods.

More than 3 billion people in the world depend on rice as their primary food, and nearly one-fourth of the world's crop is grown in rain-fed lowland plots prone to seasonal and sustained flash floods. Even the most common, hardy varieties of rice will die after four days spent underwater. Each year, lowland floods in South Asia destroy 4 million tons of rice, causing chronic food insecurity for subsistence farmers across the region. More than 15 million hectares – an area the size of Bangladesh – is commonly stricken, and the lost rice is enough to feed 30 million people, said Pamela Ronald, a plant geneticist at the University of California, Davis. Now imagine if this rice could maintain its traditional qualities, like its robust yield, but could survive flooded conditions for weeks. "[That] rice has the potential to fill this incredibly huge gap," Ronald said.

Using molecular breeding, Ronald and Dave Mackill, a crop scientist at the International Rice Research Institute in the Philippines, have done just that, developing multiple strains of rice that can survive for more than two weeks in flooded conditions. Varieties of the submergent-resistant rice – nicknamed "scuba rice" – have already been introduced in India and the Philippines, with expansion into Bangladesh expected within a month, Mackill said.

The mass deployment of scuba rice is the culmination of more than a decade of research for Mackill, who long ago identified a gene in rice's DNA, known as Sub1A, that seemed to strongly influence how a weedy but flood-resistant rice variety in India – rejected because it had a low yield and poor taste – could survive so much longer than normal varieties. With molecular backcrossing, Mackill, Ronald and their many colleagues were then able to breed this overexpressed gene into rice already popular in India, such as the legendary Swarna variety. Previous attempts to backcross this trait with conventional breeding had always failed, reducing Swarna's taste or yield. "Conventional breeders can only bring in one trait at a time that are very simple traits," Ronald said. The exciting aspect of submergence was that they could bring in what is known as a "quantitative trait locus" – a more genetically complex region that influences measurable changes to the crop. "This is one of the very first instances where we could tackle" such a locus, she said.

Rice has proved to be the best grain to be manipulated with marker-assisted breeding, Mackill said. It has a limited number of genes – it was the first crop to have its genome sequenced, earlier this decade – and the individual genes tend to exert strong influences. Such individually powerful genes can be rare in other plants. "That's one of the most difficult things to find in any crop," Mackill said.

Partly because other grains are not so easily influenced by a few genes, molecular breeding is not as popular in public breeding circles as was hoped a decade ago, when it first arose. Besides scuba rice, most other published applications have been used for disease or pest resistance, which are genetically simpler to breed.

There are other reasons for this lull. Many genetic markers have only been discovered this decade, prompting Mackill to predict a large increase in molecular breeding next decade. And, he adds, while seed firms like Monsanto and Pioneer have invested heavily in molecular breeding, none of their research has been published, due to competition.

Over the past two years, Pioneer has stressed its use of molecular breeding to improve its soy varieties, most of which are also genetically modified. The base for Pioneer's soybeans is relatively simple, and a lot of natural variation lies outside the varieties typically used, said Soper, Pioneer's soybean research director. "In the future," Soper said, "we'll be using some of these new molecular tools to fish some needles in the haystack that we can pull out."

For a century, individual breeders, scientists and firms have bred crops for their capacity to improve yield – the amount of crop grown. Yield is a far more complex trait than Mackill's flood tolerance. It is not a matter of one or two genes – it takes "dozens if not hundreds of genes to get what farmers perceive as yield," Soper said.

"We've done extensive modeling to find genes that have been selected over time," he said. "Since we know that plant breeders have bred for yield, we have a theory that a lot of the genes have increased in selection over time."

These genes have had tangible yield impacts, some increasing soy's production by up to a bushel. Over the last five years, Pioneer has learned much about these individual genes, and is now probing how they interact, Soper said. "It's not about simply adding genes and stacking them," he said. Combine two genes that separately increase yield, and suddenly the improvements disappear. Add two others together, and the effect doubles. "It's complex," Soper said.

Corn, also known as maize, is genetically complex – its genome, only recently sequenced, was much more difficult to piece together than the human genome. Its genes have been active over the past 5 million years, behaving selfishly and scrambling the genome, giving the crop an incredible diversity, Cornell's Buckler said.

"There is as much diversity between any two maize varieties as between chimp and man," Buckler said. "This is why breeding efforts have been so successful in maize."

Partially because of this complexity, however, the type of molecular breeding used for scuba rice has had limited success for corn. Buckler made this clear in a paper looking at what genes influenced the time corn took to flower, where the many genes surveyed had little impact on the trait.

"There really are no big effect [genes], at least for flowering time," Buckler said. "That has an implication of how we're going to make progress in the future. ... [It] means we can make very powerful predictions, but also means it will be harder to figure out individual genes."

Given the limited power of individual genes in corn, Buckler has established a research method called nested association mapping. His lab grows row upon row of corn in upstate New York, crossbreeding one reference strain – the widely grown B73 – with 25 different varieties. (It took seven years to breed the populations.) These diverse populations, combined with high-powered computation, should allow breeding predictions for a variety of incremental improvements in traits like drought tolerance, nitrogen use, and aluminum tolerance.

Buckler's lab and many others have begun to use what is considered the next step in molecular breeding, called genomic selection. First pioneered by cattle scientists earlier this decade – there is an actual field called "bovine functional genomics" – genomic selection capitalizes on computing power and the large number of markers now available to rapidly make breeding decisions based on every gene influencing a trait, not just a few.

"[It] allows very accurate predictions even with small effects," Buckler said.

Buckler's fields have already helped identify genes that provide a threefold increase in the vitamin A provided by corn, turning ears a brilliant orange. The crop will be used by HarvestPlus in Zambia, part of its effort to develop staples that contain nutritional, and not just yield, improvements.

Buckler, Ronald and others are bullish on the potential of molecular breeding and advanced GM crops. But they remain wary of making predictions of genetic mastery that characterized the field previously. Much needs to be learned about the influence of environment on gene expression, they stress.

Yet it is clear that the promise of genetic engineering and molecular breeding has at least started to catch the hype.

With so many crop genomes sequenced, there is "so much more information that is available now than 10 years ago ... an overwhelming amount," Ronald said. "There's enough to occupy us geneticists for the ends of our lives," she said.

New Jersey Farm - Fall, *by Ansell Bray.*

THE LIVING LIBRARY

HUGH ILTIS

In early 1976, I sent a large New Year's card, really a poster, to botanists around the world, following an annual tradition of our herbarium at the University of Wisconsin to keep friendships alive, and to cajole, inspire, and arouse my taxonomic colleagues to their environmental responsibilities. A confirmed plant-lover and hard-line preservationist, I am awed by the beauty, elegance, and usefulness of the plant kingdom, and the (undoubtedly inherited) human need for contact with nature.

Since the overall goal of my annual message is to help restrain the steady, worldwide march toward environmental degradation in the name of progress, I never expected this mailing to lead – in an exquisite example of scientific serendipity – to perhaps the most important discovery of my scientific career.

Each poster features a plant that, for one reason or another, I consider significant. The 1976 edition portrayed my drawing of *Zea perennis*, a perennial grass, one of several corn relatives that Mexicans call "teosinte," the "grain of the gods." As an expert on the evolutionary origins of corn, *Zea mays*, I'm fascinated by the structural changes that occurred when teosinte evolved into corn, and every one of the species of the genus *Zea* is important to me. Furthermore, wild crop relatives supply plant breeders with new genes that allow crops to adapt to new conditions, and since corn is the third-largest crop on the planet, teosintes may well turn out to be critical to the global food supply. (To be quite clear, though, I see the problem not as one of growing more food, but as one of growing fewer people!)

Zea perennis had last been seen in the wild in 1921 at its only location, in western Mexico, by two US Department of Agriculture botanists, who introduced it to university greenhouses, including ours at Wisconsin. Since I, and other botanists, had tried to relocate the wild population and failed, I wrote "extinct in the wild" next to the drawing, mailed off some 250 posters, and went back to my other duties.

My attention was forcibly returned to the teosintes two years later, when I received a handwritten note from a man who worked for a messenger service in New York City. "I know little about corn," wrote Anthony Pizzati. Nonetheless, he said, a Mexican friend had found "*perennis* … the long-lost original corn." Pizzati concluded with a question that, for the beauty of its understatement, made me laugh. "What do you think – interesting?" I reasoned that Pizzati could only be referring to *Zea perennis*, so I directed a graduate student, John Doebley, to answer his letter – what else are graduate students for? – and see if we could get some seeds and find out what Pizzati was *really* talking about.

Before we go further, I should explain a little about the "old-fashioned science" that has consumed my career, taxonomy, the classification and naming of living organisms. In this age of gleaming molecular laboratories, available only to those who have survived endless technological training, field taxonomy must seem rather quaint. Yet without such taxonomy, Charles Darwin would not have recognized the principles of evolution – and thus not initiated the greatest intellectual revolution of all times. Without taxonomy, evolutionary biologists can't know what they are talking about. "Nothing makes sense in biology except in the light of evolution," said Theodosius Dobzhansky, the great Russian biologist.

Now, as in Darwin's time, we field biologists take our clues wherever we can. We get help from the oddest sources – often from people we've never heard of. And we stay in touch, because we need each other.

As I later reconstructed the events, my poster had been placed on a bulletin board at the University of Guadalajara by the local taxonomist, my friend Luz Maria Villareal de Puga, who, slightly irked, had urged her students, "Go and find this teosinte, and prove that gringo Iltis wrong."

Maestra Puga's forthrightness fired up Rafael Guzman, one of her undergraduate students, to hunt for this *Zea perennis*. Guzman went to the original locality in the mountains of Jalisco, a state that runs from the Pacific coast to the Sierra Madre de Sur and over to the capital city, Guadalajara. By the second day, directed by a knowledgeable campesino, he'd dug up a sterile plant and, back at the Universidad de Guadalajara, it proved, in the next two months, to grow into the long-lost *Zea perennis*.

Rafael is a persistent, determined fellow. Most students might have stopped at that point, satisfied to have refuted the Norteamericano expert – but not Rafael. Within a month, he learned from a fellow student that *Zea perennis* was growing in another location. Guzman located that population and sent me seeds – by this time, we were in contact by mail. When grown in Wisconsin, this teosinte turned out to be not only a perennial, but, one with half the number the chromosomes of *perennis*. It was a totally new species, and we soon named it *Zea diploperennis*.

Unlike *Zea perennis*, this species freely interbreeds with corn, which raised the possibility that the crop could be grown for several years from one rootstock. If corn could be grown as a perennial, like apples or hay, it would lead to a tremendous savings in soil erosion and an improvement for the farmer's bottom line. The discovery was promising enough to earn coverage on the front page of The New York Times.

But *Zea diploperennis* has an attribute that I consider much more significant: USDA specialists in Wooster, Ohio, showed that it is immune to, or tolerant of, seven corn viruses, and is the *only* member of *Zea* that is immune to three of them. As if to demonstrate how wild relatives supply raw material to plant breeders for improving crops, *Zea diploperennis* has been studied by every seed corn company in the country, and its immunity has already been transferred into corn, at least in South Africa.

But since I'm a conservationist and preservationist, to me the most important echo of that challenging New Year's poster was the establishment in 1987, after eight years of frantic talking, writing, and outright pleading, of the 350,000-acre Sierra de Manantlan Biosphere Reserve, under the direction of the University of Guadalajara. What with *Zea diploperennis* scattered on some 900 acres of the reserve, and nowhere else in the world, this became the first reserve established principally for the preservation of a wild crop relative.

The Sierra de Manantlan reserve stretches up from tropical forests at the base, to oak and oak-pine on its slopes, and cloud forests on the top. Its biological diversity is enormous: although the reserve is only about 1 percent of the size of Wisconsin, it has one-third-again as many higher plant species – 2,650. But this botanical treasure house is threatened by increasing population pressures from neighbors who depend on it for wood, pasture, and water.

The final result of that not-quite-accurate New Year's poster was to start a long, fruitful collaboration between University of Guadalajara and the University of Wisconsin, in which more than a dozen students have come here, many, including Rafael Guzman, for advanced degrees.

What have I learned from all this? With botanical exploration, you can never tell what you'll find – or where you'll find it. Genetics, now almost the archetypal high-tech science, is still dependent on information that plants and animals have been storing up since the beginning of life. When we need a corn that resists a new leaf blight or virus, we may be forced to turn to the "living library" of corn relatives, the teosintes. And if we allow that library to be destroyed – or if we stop communicating with the people who know where the "books" live and what they contain – our children may be faced with disaster that they will not be able to survive.

As Carol Bartz, the CEO of Autodesk Inc., a software company, said, "Most of us are put on this Earth to do one simple thing – and that is to be a good ancestor." Both from a biological and moral standpoint, we cannot, must not, do less.

Originally in R&D Innovator, June 1994.

WHAT WE KNOW

WILLIAM SHELDON

We come to this place and begin by naming
the things we know: Big Bluestem, Little
Bluestem, Switchgrass. We indulge
a moment's satisfaction, move on:
"Red Tail," we say, and later,
squinting against the impossibly
bright sky, ask, "Cooper's Hawk?"
Now we are less certain
of our birthright, as the Cottonwoods
obscure our sight; now we are closer
to our home. We make our way,
unsure, and at our feet, everywhere,
the stone for which we have named
a place that has carried on
under other names, and none. This
is the place we want to come to, walking
in grass waxing our hands
when we roll it in our fingers,
walking under the smell of trees
whose heart-shaped leaves
sing up the wind,
and when the bird rises again
above a band of green,
soaring into the golden circle,
it does so as a god. Now,
we can sing this moment,
this place.

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I had no daily intimacy with country, the condition that I've come to believe is necessary if one is to receive life instead of merely taking it. – Ted Kerasote, "Bloodties"

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