Land Report

Number 111, Spring 2015 · The Land Institute

About 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.

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Cover

A hybrid of crop wheat, an annual, and intermediate wheatgrass, a perennial. The first parent plant feeds much of humanity. The second preserves soil. The Land Institute is working toward a crop that does both. Stories about the effort begin on page 4. Scott Bontz photo.

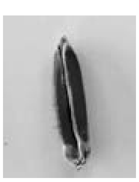
The Land Institute's breeding of annual crop wheat with perennial wheatgrass species makes for variety, and for the beginnings of a revolution in how to grow humanity's most important food. Scott Bontz photo.

When with bread the soil also rises

To save cropland, make a perennial of the world's most widely planted crop

SCOTT BONTZ

Three species amassed the genetic instructions collected in this one seed. The combination came not in a laboratory, but by chance mergers in ancient fields. This was somewhere just east of the Mediterranean Sea. There the hybrid plant might have stayed but for three things. One, the mergers gave it a protein that was elastic and springy. Two, the big, complex genome helped it adapt to different lands and climes. Three, humans loved it. They loved it for what they could make with that unique protein. They also loved how the plant grew and yielded grain, and how that grain nourished them. They made it sacred, even devoted to it a cult. They wanted it to follow when they spread over the world. With that versatile genome, it could. It adapted and stuck with them, yielding bread from sea level to 10,000 feet, from Scandinavia to the equator: the flexible bearer of the protein that bubbles, wheat.



This seed also carries a complex genome, and with it an ability that wheat lacks. The ability is important, because for all that wheat has gained us it is also a loser. So are all the other major grain crops, which together give humanity two-thirds of its calories, and of which wheat is supreme, commanding one-sixth of arable land. These crops lose water, lose soil nutrients, and lose soil itself, usually in a fraction of time it took to build. They are annuals. Most of Earth's natural vegetative cover is made of perennials. The seed pictured here is from a perennial called intermediate wheatgrass. An annual cannot match wheatgrass for the ingredients of soil health even when alive. Each year the annual must start from scratch. Come fall or sooner, it dies. From harvest to replanting, it is gone. Perennials, in addition to living for years, underground at least are alive all year. Earlier than annual crops, their leaves shield the soil. Their roots bind it. So they keep earth from loss to flood or wind. They also leave undisturbed and let work the worms, legged crawlers, and microscopic life that keep soil porous and friable for gentle permeation by air and water. All these things keep plants better fed.

This seed is from something new in the making, perennial wheat. One of its parents is annual crop wheat, the other is intermediate wheatgrass. This begins another genetic merger. Its combined strengths will give the staff of life a radical length. Its roots will be longer and thicker than today's wheat, with more take from the soil for green and grain, and at the same time more give to the soil of rich, black carbon. The plant also will live far longer. Each extra year of that life will save the farmer from toil, and save the soil from tillage. Then the field economy that feeds us will work more like land's mostly perennial natural economy. Humans might finally eat their cake and keep what makes it.

The pictures are to scale. The seed from perennial wheat is as yet 10 percent smaller than that of crop wheat. Its seed yield – the amount of grain per land area – is at 70 percent. Wheat also started small. Over centuries farmers made it bigger by saving and planting standout seeds. Through one year a perennial can collect sunlight longer than an annual, and outgrow it. Even while investing underground for winter, it might be bred to beat the annual at making grain. If it yields less, the perennial's much lower demands for field work still might be a net gain for the farmer. Success of perennial wheat depends on more than yielding like a crop. It also must behave like one. A field of plants must flower and set seed in synchrony. Before harvest they must not go wild and drop their seed. After harvest, the seed must grind well and make good dough. Through all of the genetic sifting to get these traits, the plant must keep the genetic code that says: Buckle neither to Kansas winter nor to Kansas summer, but live instead like the prairie grass. Live so a

Cut the tops from each green floret of the wheat head, and with them goes the male stamen. Now pollen can be applied from a different, perennial plant, and combine traits from two species. Scott Seirer photo.

toddler able to enjoy bread from you now can still enjoy bread from you when she is a young woman. And live so she can cherish what that ability means for the land.

The challenge of keeping perenniality in a wheat-wheatgrass hybrid is immense, but so are the prospects, and now at hand are the means. Humans have imagined perennial wheat for a century. The Soviets tried for decades without finding plants that both continue to produce well and to live for years. But they achieved tantalizing stock. These promising roughs inform the work of The Land Institute's wheat breeder, Shuwen Wang. The Russians and others in the previous century worked hit-and-miss. Like them, Wang continues after a needle in a thousand sheaves. With great advances in genetics and computing since the Russians went broke, however, his focus is much sharper and more refined than theirs and of the farmers before them, his method for progress far quicker and nearer the mark.

The Russians were not first to attempt a perennial grain from the grass tribe *Triticeae*, which includes wheat, rye, and barley. In the 1880's Gustav Bestehorn tried to cross annual barley with a perennial called bulbous barley. Peggy Wagoner tells of this in "Perennial Grain Development: Past Efforts and Potential for the Future," published by the journal Plant Sciences. Another source is Jonathan Harwood in the journal Life Sciences. Bestehorn also tried to cross wheat with a weedy perennial called couch grass. Although among German estate owners who improved the yields of annual grains by as much as 40 percent, Bestehorn did not succeed with perennial grain.

This was before the event Harwood examines, rediscovery in 1900 of Gregor Mendel's pioneering of genetics. By mid-20th century scientists had tried to perennialize sorghum and corn. Wagoner said that by far the most work and money went to wheat. North American efforts involved the University of California, Davis. But the interest was not so much in grains as in large-seeded perennial pasture and hay crops, because plants from large seeds can grow faster and block weeds. For thinking big about perennial grains, the Russians led.

First success came in 1930 when Nikolai Tsitsin bred wheat to various perennial species called wheatgrass, and found hybrids that set a little seed. This inspired teams of breeders, botanists, and agronomists at institutions throughout the Soviet Union until the 1970's. "None of the subsequent breeding programs could compare to it in scale," Wang said. "Its influence is comprehensive to both breeding practices and studies. Part of its work has not been well recognized due to limited access to Russian publications. A few of its breeding lines are still among the best with respect to overall performance."

Tsitsin, whose name adorns the Russian Academy of Sciences botanical garden, admitted need for much more work to achieve perennial wheat. But Wagoner said, "He felt that development of a truly perennial wheat was just around the corner."

Tsitsin edited "Wide Hybridization in Plants," a collection of reports from Soviet scientists including those involved in the campaign to make perennial grains. In the introductory essay he said, "All present day domestic animals and cultivated plants owe their existence to man. Admittedly he did not create them *de novo*, but the fact that they bear little resemblance to their remote wild ancestors cannot be disputed. This fact testifies to the enormous significance of human endeavor. By pursuing definite practical aims, man has changed animals and plants,

continued on page 11

Wheat's descent, whence its rise

Making crop wheat perennial by union with other, wild species demands years of work. But pasta and bread wheat sprang naturally from such chromosomal mergers. These genetic combinations are more complex, but also more flexible.

Four million years ago, a plant of the scientific name *Triticum boeoticum*, was, as we are, writ by the code of just one paired set of chromosomes. Then this grass and a species in the genus *Aegilops* mated to make *Triticum dicoccoides*. The new plant did not mix the parental chromosome sets and keep the same number, it stacked them, doubled. There was genetic duplication, but now the genome from one ancestor could provide what the other lacked to make a better trait, or could override a genetic flaw.

Between 8,000 and 11,000 years ago, humans saving seed from favorite plants turned *T. dicoccoides* into something different enough to classify as a new species, *T. turgidum*. The domesticate branched into subspecies including the durum wheat now used for pasta. About the same time, early farmers tamed a close relative of *T. boeoticum* to make einkorn, German for "one grain." Land Institute scientist Stan Cox spells out this wheat genealogy in the February-March 2014 issue of Mother Earth News.

Where, when, and by what and whom the evolution of wheat has played out was not clear until 20th century archaeology and recent genetic analysis. Now scientists see that from 6,000 and 8,000 years ago, the wild plant *Aegilops tauschii*, goatgrass, pollinated another subspecies of *T. turgidum*, emmer. This tripled the original chromosome count to make a wheat called spelt. From spelt, farmers developed common wheat, or bread wheat, *T. aestivum*. The new genetic combination made for dough gluten not only elastic and stretchy, like durum's, but also resilient and springy. Thus came the unequaled rise of leavened bread. In "Six Thousand Years of Bread," E. H. Jacob calls this one of humankind's first great chemical triumphs. He also says, "The Albanian proverb, 'Bread is older than man,' springs from a poetic but misguided sense of history." But the hybridization that made for the bounce in bread came naturally. Even today, wild and domestic wheat spontaneously hybridize.

So wheat can be seen not as one plant, but several. In the first chapter of a compendium called "The World Wheat Book: A History of Wheat Breeding," Moshe Feldman presents a table showing *Triticum* with six species. Two have the original chromosome count of 14, two species have 28 chromosomes, and two have 42 chromosomes. Within the genus Feldman lists 18 subspecies. Further complication comes from distinction within the common-wheat subspecies used for most Western breadstuffs. It is classified as spring or winter wheat, soft or hard, and red or white. Kansas farmers grow overwintering hard wheat, most of it red. Other kinds of wheat fit better in climates wetter or colder.

That common wheat may have descended from a few happenstance hybrids made for what biologists call the founder effect. Though with very different parents, the new plant population was a highly select few, lacking genetic diversity. This made it vulnerable. Breeders have made up for this by working in traits such as disease resistance from other species, even from outside the *Triticum* genus. Developers of perennial wheat – still by traditional breeding, not engineered gene insertions – must repeatedly tap other species.

But like durum and bread wheat, perennial wheat will have more than one genome, and in such numbers may lie strength. From another chapter of "World Wheat," researchers Alain P. Bonjean and Pierre Lacaze say that though 85 percent of common wheat's genome is repetitive, it is six times as large as the maize genome, 40 times that of rice, and about 100 times bigger than *Arabidopsis*, the lab rat of plant science. Feldman says this "superstructure" combination of genetic materials enables new gene combinations of evolutionary advantage. It shows in the variety and adaptability of wheat, a plant grown from near the arctic to the equator. "The great diversity we see today in wheat is the result of millions of years of evolution capped by 100 centuries of breeding by humans," Cox says in Mother Earth News. Getting the right wheat for your purpose takes "wading into a deep gene pool."

An immature seed from a wheat cross. The seed, resulting from wheatgrass pollen applied to annual crop wheat, likely would not survive on its own. If an embryo is found, it will be nurtured in a test tube. Scott Seirer photo.

A hybrid perennial wheat seedling is removed from a test tube, where it had been grown from an embryo. Later generations of the hybrid will be more fertile, and breed without help. Scott Seirer photo.

continued from page 7
striving after the properties he wanted, and fixing them from generation to generation."

This might sound like the "industrial heroism" that Land Institute President Wes Jackson considers dangerously narrow-minded. In it is nothing about understanding and following nature as a model for a whole farming ecosystem, The Land Institute's goal. Institute scientists might change plants even more than the Soviets were able. But they differ in perspective. Their work is not just about bending things to human will. Scientists today can better see into what makes a plant work. They can find traits that competition in the wild has suppressed, and coax them into play for human benefit. They also can better see how this fits in and depends on a complex natural economy.

Tsitsin championed new "form creation" by wide crosses, combining genomes of species as distant as claiming different genera. Horses and donkeys are not this far apart, but animals lack the breeding leeway of plants, and the mating of these two species from *Equus* makes what is clearly a new form, the mule. In this case and others, such as what happened long ago with wheat, the new form can be better in some ways than either parent. The mule beats the donkey for speed and agility, and beats the horse for surefootedness, patience, hardiness, and lifespan. It is considered more intelligent than both parents. Bread wheat has that unique gluten and a more versatile genome than the plants it came from.

Parent plants too diverse cannot make offspring. But the nearer they are, the less chance they will show hybrid vigor. Wang has no choice there: in the wheat genus *Triticum* are no perennials. But he joined The Land Institute partly because even before learning of perennial grains, he was intrigued by the possibilities from wide crosses. (For more about Wang's life, see page 22.)

Tsitsin reported that the first such unions in the USSR were of fruit crops, including combinations of almond and peach, and of pear and apple. The Soviets also attempted by crossing to make woody plants herbaceous, like grasses. With wheat, Tsitsin said, a cross of the annual and wheatgrass yielded five times as much seed as the wild parent, and even slightly more than wheat. But in such wide crosses the new collection of DNA might be unstable. Future generations lose chromosomes. Also, because the parents' chromosomes are not really "made for one another," as they are within a species, usually the offspring are sterile, like mules.

Such is the fate of most natural crosses. The new form appears for one generation, then disappears. It may breed back to one of the parent species, and keep a different form. But backcrosses also likely are sterile. Survival of the new form is rare. To propel plant evolution, however, this suffices. Nature enjoys population numbers beyond that of all institutions combined, and time that scientists cannot imagine waiting. But the researchers exercise far greater, goal-driven control, and they can do things such as rescue fragile embryos from the plant, grow them in a sugary medium, and reach fruition with what nature would leave to loss. (See photo at left.)

The Russians were at this technical level by the middle of the 20th century. Tsitsin claimed crosses of wheat and wheatgrass that were "exceptionally tolerant and vigorous," capable of living for 20 years. They did not produce seed. Backcrossing to annual wheat solved that problem, and brought
continued on page 14

The plant makes the culture

In books such as "Wheat Belly," and in marketing response, with foods that never contained gluten now labeled as "gluten-free," the staff of life gets the shaft. Wheat, rye, and barley are blamed for problems well beyond celiac disease, in which gluten protein triggers abnormal immune response in about 1 percent of people. Land Institute scientist and writer Stan Cox says solid studies do not support such broad attack. We should not live by bread alone, but much can be said for wheat, and has, both in food science and literature.

Very unlike maize, much of which goes to livestock, about 90 percent of wheat feeds humans directly. Of the world's total dry edible matter from plants, wheat supplies one-fifth. Its share of the world's arable land is one-sixth. More wheat is grown than maize or rice. The importance is magnified if the measure is not by grain alone, but by tissue-building protein, Emilio H. Satorre and Gustavo A. Slafer say in an international scientific compendium called "Wheat: Ecology and Physiology of Yield Determination." Maize and rice are higher in carbohydrate.

Also in "Wheat," Peter J. Stone and Roxana Savin call it the "supreme" crop. The honor is earned with proteins that behave uniquely. When bread wheat flour is mixed with water, the proteins bind to make a coherent mass of gluten. There are different kinds of gluten. This one is plastic, strong, and elastic. It can accommodate carbon dioxide from yeast, to stretch but not burst. Without this we would not have leavened bread. The gluten in durum wheat springs back less, but still rolls out well to make noodles and flatbreads. In some countries it, too, is leavened.

Gluten's cohesion also makes it fairly simple to divide from other parts of the grain, and make secondary products for industry and food additives. Wheat is used not just in bread, pasta, crackers, cookies, pretzels, cakes, breakfast cereals, and puddings, but also in beer, vitamins, paper and textile binder and filler, cardboard, couscous, bran, biodegradable films, confectionery, and wheat germ. Rice and maize do not match this versatility.

Wheat grows from arid plains of Africa to humid valleys of Vietnam. But its popularity is not just because of its adaptability. Stone and Savin say, "Indeed, it is probably more logical to argue that wheat has become adapted to such a wide range of environments because humans have found it so useful that they attempt to cultivate it under even the most unlikely conditions."

Ancient Egyptians based their administrative system on wheat bread, H. E. Jacob says in "Six Thousand Years of Bread." He calls their ovens virtual mints. "For hundreds of years wages were paid in breads, the average peasant receiving three breads and two jugs of beer a day." Jews made bread the starting point of their religious and social laws. "The Greeks created profound and solemn legends for their Bread Church of Eleusis," Jacob says. He goes on to claim that the Romans made bread political: ruled by it, conquered by it, lost by it. He quotes ecologist Paul Sears, who visited the early Land Institute: "It is a much more serious task to write history in terms of bread than of battles." And Henri Fabre: "History celebrates the battlefields whereon we meet our death, but scorns to speak of the plowed fields whereby we thrive; it knows the names of kings' bastards but cannot tell us the origin of wheat. That is the way of human folly."

In "The World Wheat Book," Moshe Feldman says that Jewish scholars of the second and third centuries AD assumed wheat to be the tree of knowledge, and interpreted the Genesis story as expression of man's wish to fulfill his creation in the image of God by mastering his food production. Exodus 29:2 says that for unleavened breads, "of wheaten flour though shalt make them." Canadian Stephen Leacock provides a revisionist history: "The Lord said, 'Let there be wheat,' and Saskatchewan was born." And for a more general view of wheat's importance, and one suggesting the importance of making it a perennial, former Soviet leader Mikhail Gorbachev: "I grew up in a family of peasants, and it was there that I saw the way that, for example, our wheat fields suffered as a result of dust storms, water erosion, and wind erosion; I saw the effect of that on life – on human life."

Wheat, the most widely grown crop, receives testimony to its importance from the painting in an Egyptian tomb.

continued from page 11
genetic stability. Some first-year yields were comparable with annual wheat. Then yield dramatically fell. Reseeding was needed every two to three years. The Russians came closer to their goal with rye, but even under favorable conditions the hybrids produced only two crops of grain before death.

With high hopes unmet after decades, Russian interest in perennial grains finally waned. Then hybrids served only as bridges for moving disease resistance from hearty perennials into domesticated annuals. This tapping of perennials for traits determined by the smallest bits of genetic code continues around the world. It is key to keeping the most important food crop from devastation by diseases with names like leaf rust, karnal bunt, loose smut, and strawbreaker.

Perenniality, though, might depend not on one gene, but dozens. Finding these is hard enough. Then the researcher must try to move them to the crop plant and secure them there, while shedding the many more genes that would make the plant wild. The Russians and everyone else at the time lacked the technique to see their way through all this.

"The only certainty is that the procedures to achieve the hoped for result will be long and tedious," US Department of Agriculture scientist Douglas R. Dewey could still write of the prospect in 1984, and still be cited by Wagoner in 1990. But by then Wagoner could also say that the genetic problems were better understood.

Cindy Thompson harvests perennial wheat in The Land Institute greenhouse. The number on the tape identifies the plant in a pedigree of thousands, over many generations. Scott Bontz photo.

No wheat species is perennial. Nor is any near relative. But an ancestor of the *Triticeae* tribe might have been perennial, and the annual habit something that developed later. Wang said genes favorable to perenniality probably run higher in wild wheats than in modern varieties. Washington State University researchers found that just one chromosome from a perennial parent crossed with annual wheat gave the hybrid weakly perennial regrowth.

They also noted that some genera have both annuals and perennials – they are close relatives. One example is corn, *Zea mays*, and its wild kin, *Zea diploperennis*. Evolution from one growth habit to another might follow changing conditions. Some species, such as *Oryza rufipogon*, a wild rice, can be annual in one place, perennial in another. The Washington State scientists said a shift to perenniality might be made without dramatic genetic innovation. But their encouragement by one chromosome still leaves sorting through its genes.

Perennial species crossed with wheat by researchers worldwide now number in the dozens. The perennials are not only from the wheatgrass genus, *Thinopyrum*, but also from genera with the prophetic-sounding names *Elymus* and *Leymus*. Breeders of the annual crop play the perennial field for traits to be easily had, in the simplest genetic packages, such as resistance to rusts and tolerance of salty groundwater.

From the newest of these perennial candidates Wang has seen no progress toward perennial wheat. His breeding stable of perennials is all *Thinopyrum*. With the wheatgrasses it is relatively easy to make at least partially fertile hybrids.

The species called tall wheatgrass was where the Washington State researchers found that one chromosome for weak perenniality. Other researchers have found in the chromosome a key gene for the trait. Perenniality depends on more than a single gene. But this one has the strongest effect. Wang is working to find its molecular sequence, and how exactly it works. Then he can better understand and control results.

But Wang's favorite perennial is not tall wheatgrass. Russian scientists had already established as prime breeding stock a relative called intermediate wheatgrass. This has the same number of subgenomes as bread wheat, three, and the same number of chromosomes, 42. Wang likes it for the subgenomes, for how well it crosses with wheat, and for diversity and traits that lend themselves to agronomy. The Rodale Research Center in Pennsylvania, Wagoner's employer when she wrote about perennial grain history and prospects two and half decades ago, found *Thinopyrum intermedium* the best candidate for direct domestication – meaning no hybridizing with other species – and got The Land Institute started with early improved plants. Institute scientist Lee DeHaan's decade of gains with seed yield and other traits in that endeavor also benefit Wang's work.

When DeHaan began his work at The Land Institute, he was in charge of both wheatgrass and wheat. In 2010 he handed off wheat to Wang. DeHaan had improved hybrids through selection of the best performers in field and greenhouse. Wang added laboratory tools called chromosome painting and molecular markers. With these he could see past how a plant looked one year, which is partly a result of variables such as weather, and more clearly understand the part played by the plant's genes. He also sped improvements, no longer needing to grow each plant to maturity before determining whether it had the right stuff.

Wang picked a dozen genetically stable lines from two kinds of crosses. One was

John Mai labels bags for hundreds of hybrids being cut in the field. Getting the right plants for perennial wheat is partly a numbers game, just as from much horse breeding comes only one derby winner. Scott Bontz photo.

bread wheat by intermediate wheatgrass. The other was durum wheat by *Th. junceiforme*, popularly known by names including Russian wheatgrass. Like the wheat involved, both perennials had more than one subgenome. But in the crosses they passed along only one, while all of the annual material stuck. So the ratio of wheat to wheatgrass in the hybrids favored wheat, at about 3:1 or 2:1. The new plants had good traits: bigger seed, relatively short stature – not wasting energy to compete for sunlight – and early maturity – to avoid damaging heat. But they did not yet match the plants from other institutions for perenniality. Wang found that the hybrids with stronger perenniality had fewer chromosomes from wheat, and more from wheatgrass. Attaining perennial wheat appeared to lie not only in finding the right perennial parent. It might actually depend more on that parent's relative share of the hybrid's chromosomes, or, more exactly, on its share of genes for growth habit.

Wang began making crosses with wheat that had evolved earlier than 42-chromosome bread wheat, including durum, with 28 chromosomes, and einkorn, with 14. He also introduced bread wheat cultivars made to withstand heat or drought. The biggest challenge to perennial hybrid survival in Kansas is summer's high temperatures. For the other side of the combinations Wang employed DeHaan's intermediate wheatgrass plants that flowered relatively early. Beating the stress of heat allows them to make bigger seed.

The results included surprises. For one, crosses made with the smallest wheat genomes, like einkorn, and so with greatest share from the perennial parent, were not more perennial than those using durum. Also, wheat parents bred to take heat or drought made little difference. Hybrids using wheatgrass that flowered earlier actually did worse. Wang now concluded that making his plants perennial was about more than the perennial and its share of the hybrid genome.

Each year Wang has made hundreds of crosses, using nine annual species and seven from *Thinopyrum*. He screens them for perenniality and the traits needed to make a crop plant. He also has experimented with field technique for his unconventional plants, which might benefit from unconventional farming method. He tried irrigation, mulching, and different plant spacings and cutting heights. Wang found that the best hybrids came from the wheat on the middle path of genome size, durum. These new lines were more promising than others in grain yield, in total growth, and in perenniality. Early plants had little problem living for more than a year. But, as with bread-wheat hybrids, though to varying degree, the second life cycle brought trouble.

As the seed of annual wheat ripens, the plant dries and fades to straw, never to build anew. Wang found that after harvest most of his perennial wheat quickly made more greenery. But unlike wheatgrass, which keeps its regrowth to leaves, stems, and roots, investing for winter survival and flowering again only next spring, the hybrids tillered – sent up new stalks – too soon to reproduce. In hybrids made with wheat bred for Kansas, juicy seed heads appeared among dry ones even before harvest. This is not only ill preparation for winter, and would make for a waste of food and a mess in the combine, it is also fatal exercise during Kansas summer. Hybrids made from wheat bred for farther north took longer for the new tillers to flower and reproduce. But by fall they did, only to freeze.

continued on page 20

The state and flux of wheat

Kansas is called the wheat state. In most years production tops the 42 states growing the crop, the National Association of Wheat Growers says. But Kansas is not a good place to grow wheat. Yields in wetter, cooler places such as eastern Washington state and Europe are much better. Mercury at 100 degrees as early as April, after winter lows that can fall below zero, does not make Kansas the best place for *any* crop. It is just better for wheat than for others. How it came to lead helps illustrate the market and the making of our foods.

After English settlers landed at Jamestown in 1607, they had prepared ground for wheat within two weeks, according to "Wheat – Field to Market: The Story of the Golden Crop," published by Kansas Wheat Commission. New Jersey, Pennsylvania, and Maryland gained early reputation as "bread colonies." The crop's production center moved west with the frontier, enjoying cheaper land, good keeping quality of its seed, and lower labor demands than with other grains. The upper Ohio River Valley led in the early 19th century, Illinois by 1850. Then came Minnesota, a leap to California, back to North Dakota, and, in the early 20th century, Kansas. Other places found other crops more profitable.

Early Kansas growers tried spring wheat, which is planted in spring and cut in mid-summer. By the early 1870's winter wheat, which is planted in fall and cut in June, had proved best for the tough climate. History credits wheat's success in Kansas to Mennonite settlers who brought to Marion County, just south of The Land Institute, a strain of seed called Turkey Red, but also known as Russian, Bulgarian, Crimean, and Hungarian. Turkey is actually a broad term, including several strains. It is not all that the Mennonites imported. Other strains were favored until winter-hardy Turkey emerged as yield leader in tough conditions of 1894-98. It also withstood drought.

With concern about falling seed quality, farmers began importing new seed, including 15,000 bushels of Crimean wheat in 1901. New varieties were developed. So many new varieties, that the first decade and a half of the century became known as the wheat "propaganda era." Many claims were unreliable. The Turkey strains still held 80 percent of Kansas wheat acres in 1919, but yield was only fair, and losses to disease and pests mounted. In 1910-30, new varieties were found from natural crosses found in field. By 1932, success came from crosses that had become intentional and controlled.

Earl G. Clark, a farmer in Sedgwick, about 60 miles south of The Land Institute, was still more artist than scientist, the wheat commission history said, but he possessed acute abilities to spot desirable qualities for wheat selection. From 1917 to 1955 he developed and released 11 varieties, with names like Clarkan, Kanhull, Chiefkan, and Redchief. His technique included late sowing, little weeding, and harvest well after ripening, so he could find the most dependable plants. The Kansas Agricultural Experiment Station adopted his practices. Clark seed made attractive crops, with dark green leaves and large, plump kernels. They also yielded better than Turkey. They were not so attractive to processors and some consumers. The gluten was just as nutritional, but not as strong under battering by dough machines. The color was grayer. Clark types had about one-third of Kansas wheat acres until 1944, when many new varieties appeared. By 1956 their share was 1 percent.

State experiment station selection and breeding was more scientific. First came two-way crosses like Tenmarq, which combined the overwintering quality of Turkey with the early maturing of a strain called Marquis. Later varieties combined the strengths of multiple ancestors. Many took Indian names, and each was developed for local climes, such as Comanche for southwest Kansas, and Pawnee for near the Nebraska line. Grain was weightier and had better gluten, which made for higher milling yield and better dough.

So the breeding work continues, for higher yields, better breadstuffs, the endless challenge of resistance to evolving diseases, and now also for a tough climate getting tougher. A plant with deeper, thicker winter roots and quicker growth come spring may keep wheat the best crop to grow in Kansas, and better to grow anywhere.

Christian Hansen cuts a hybrid wheat plant by hand. Harvest by combine would mix this plant's seed with that of neighbors, and sacrifice measurement to find a prime candidate. Scott Bontz photo.

continued from page 17

In a hybrid made by German emigrant Jurgen Schaeffer lay something different. MT-2, named after his adopted home, Montana, has been available as genetic stock to breeders since 1986. This is not a commercially viable grain. It makes small seed, and with age it makes less. But it flowers just once each year, and so lives on to flower again the next. Like Wang's most promising plants, MT-2 came from crossing durum and intermediate wheatgrass. It has both of durum's subgenomes, and an equal number from wheatgrass. This balance does not fully account for its success. Schaeffer found MT-2 after most its siblings were killed by several extremely cold winters in Montana. "Some unknown events must have occurred in the wheat genome," Wang said. So to make the best perennial wheat, something might need changing in the annual.

There is the best, and there is the quickest. For perennial wheat the quick route is needed to check soil erosion as soon as possible, especially for places like China's Loess Plateau, which in addition to high erosion has high population. Even wheat that lives and produces for only two years should be better than wheat that lives only one. For the quickest route Wang looks to durum. "In order to improve persistency of perennial wheat, the percentage of wheatgrass chromosomes needs to be increased," he said.

But now Wang is not just trying to bring fewer wheat chromosomes to the cross. He is trying to reduce the number further during the cross. Those hybrids with subgenome ratios of 3:1 and 2:1 and 2:2 keep everything from the wheat parent, but lose material from wheatgrass. There are biological limits to genome size, and in these pileups of different species, something must go. Here the decision appears to be made by the mother plant. The crosses use wheat as mother because the work of cutting the male sex organs from a grass flower, so pollen can be brought to it from another, is meticulous. A crop plant has bigger seed, so it has a bigger flower, and that helps those with the job of emasculating them by the hundreds with tiny scissors. (See photo on page 6.)

How might "preferential elimination" of DNA and chromosomes fall to the mother plant? Look to the earliest cell divisions of a zygote made by the cross. With division comes disintegration of the envelope separating chromosomes from the cell's surrounding cytoplasm. In the cytoplasm is more DNA genetic code, but unlike DNA in the chromosomes, which come from both mother and father organisms, these strings of code are all from the mother. Wang said, "I speculate wheat cytoplasm favors the retention of wheat chromosomes" – over those of wheatgrass.

So to put the perennial's cytoplasm to work, Wang must make it the mother plant. That demands a more delicate and more difficult operation. One hundred of these crosses made just two hybrids. He bred one back to annual wheat, and from this came just three seeds. Plants from these all died early. Next year he used a chemical to double chromosomes for a more stable genome. He obtained three more seeds, but this time they lacked embryos. "From the failures we can see that cytoplasm really matters," Wang said. He presses on with more crosses and treatments to find viable progeny.

Wang and colleagues in China, Canada, and other countries, want wheat that is strongly perennial, genetically stable, and dependably competitive at making grain for many years. For this kind of hybrid they might need from the perennial parent no more than its perenniality. The other desirable crop traits, such as flowering synchrony, grain size, and not dropping seed, are already well bred into the annual parent. It might take longer to find some way to make the annual parent itself behave more like a perennial, but it might take longer yet to reclaim for a plant refined over millennia all that was lost or compromised by overwhelming it with genes from a relative that is distant and wild.

Besides, there is the problem of Wang's good perennials behaving badly, looking for too much sex. The solution to this might depend on a genetic change to the annual wheat parent. Somehow MT-2 ended up with different genetic directions than Land Institute crosses of the same species. Those Montana genes say, pace yourself. Their existence promises a way, through breeding, to tame and extend the lives of Wang's productive but short-lived plants.

That way now is sifting more than a million durum/wheatgrass hybrids. Wang wants to catch those rare combinations where plants hang on to chromosomes, grow like MT-2, and make larger seed. He is also trying a new technology called genome editing. This is not transgenics, the insertion of genes from distant species, such bacteria DNA in corn to kill pests. It is regulation of an existing gene. This comes back to how something in the annual might tip the scale in favor of perenniality.

Kansas wheat is planted in fall. Over winter, temperature low enough for long enough trips a gene for flowering. Two other genes in play here take their cue from day length changing by season. Together the three make a feedback loop so that come spring sunlight, the plant flowers and sets seed. Then the annual dies. Now it is summer. Wang's perennial hybrids live on. Change in day length might shift the growth gearing from reproductive to vegetative, so the plants behave like wheatgrass or MT-2. Instead, their genes seem to have taken from that first winter trigger an irreversible set. They cannot stop flowering.

Wang wants to dial down one flowering time gene and rebalance how the trio of genes plays. Another native Chinese working with wheat, Liuling Yan at Oklahoma State University, studies flowering time genes in cereal crops. Wang is enlisting him and other specialists, in China and Germany. From the collaboration he seeks three things: To explain at the molecular level what underlies the regrowth differences. To prove that lowering the influence of the wheat flowering time genes will bring stronger perenniality. Finally, with a special enzyme, to edit the right flowering time gene, and in the right way, without affecting the genes the make for traits desired in a crop, such as high yield and easy threshing.

When this happens, Wang and the other researchers might have made in the smallest molecular step the biggest leap to a productive and perennial wheat plant for humankind.

Where a researcher is coming from

When Shuwen Wang was born, his family worked on a collective farm, mostly with buffaloes and their own muscle. This was 1967 in Jiangsu, a province on the Chinese coast at the same latitude as Southern California. Harvest was by the sickle. Families dehulled and ate rice they grew. They cooked with the straw. A fraction of their wheat went to millers in trade for flour and noodles. In all they sold about a third of the farm product, and used the rest. Wang's father earned additional income as the farm's accountant.

Wang was the third of four children. He hoed weeds, picked cotton, and fed animals, mostly pigs, chickens, and ducks, though occasionally geese, goats, and rabbits. The feed was chaff, meal leftovers, and roadside weeds. The boy collected chicken manure to use as fertilizer. He cared for grains laid to dry. Each year the farm fit in the harvest of two grain crops, usually wheat and rice. Others were cotton, soybean, and canola.

While Wang grew up, farms introduced new, high-yielding cultivars, and the product proportion reversed: one-third stayed on the farm, two-thirds was sold. With surplus money the farmers bought machinery. Beginning in the late 1970's, Wang saw small tractors and diesel engines start to move in.

"Since I was part of the labor-intensive farming activities, I thought it would be great if I could learn something in college that could directly help farmers out of the heavy labors," he said. Wang was the only child in the family to qualify for higher education. Near the end of high school he chose as his career path the science of agriculture.

At The Land Institute, Wang quickly shuttles from his hundreds of plants in the greenhouse, to the laboratory where he and technicians explore the hybrids' genetic code, to his office, which, compared with the book-packed and homey environs of his colleagues, is Spartan: one bookcase, a desk, a computer, and walls posted with data.

Other plant breeders frequently stand in another's doorway and trade thoughts. Not Wang. If not at his computer or in the field – both places where all of the scientists spend much of their time – he will be found in the greenhouse, in the lab, or in one of his rooms devoted to microscopy. He does talk with colleagues, and offer advice about genetics technique, at which he is adept. But he seldom strikes up conversation. After lunch he likes stepping with the other scientists to the basement for a short game of doubles table tennis. He might invite the game simply with eye contact and a raised paddle.

When Wang finished his agronomy degree in China, he pursued plant breeding. This would be less about helping farmers directly, with method, but there was a breeding position open, and he took it without regret. So began his wheat work, in China. Then he traveled to Oklahoma State University for a doctorate. Post-doctorate work at South Dakota State included a genetic map for breeders to find their way through wheat, and development of genetic markers to speed and refine the crop's breeding. He also addressed soybean. But with wheat he stays, because, as Wang said, he likes to stick to a path until nothing more can be found.

Long before he heard that The Land Institute sought a wheat breeder, Wang had taken for granted what critics said about the idea of perennial grains. "But when I prepared for the interview, I did some in-depth literature reading and came to agree on many arguments underlying the necessity of perennial wheat or other crops in connection with many environmental degradation events I have seen in China."

"In my boyhood, people swam in rivers and drank river water directly without boiling," Wang said. "Few people do these nowadays." The Land Institute aims for perennial crops to cut all three problems.

This was not the only appeal for Wang to develop perennial wheat. He was already interested in wide hybridization to improve annual crops, bringing from one species to another such traits as disease resistance. "Many mystery genetic events could take place in wide hybridization," he said.

Wang's 81-year-old father died last fall. By then most of the heavy work on the farm was done by machines. His mother, her whole life a grower of food, keeps a strip of the farm as her garden. She and his younger brother's family farm their share of the disassembled collective, about an acre. Their most common crops remain rice and wheat. These are the two biggest human foods, and both are being developed as perennials.

Technician John Mai, left, a Kansas native, and researcher Shuwen Wang, from China, grew up on very different farms. They are working to make something very different of grain agriculture. Scott Seirer photo.

Land Institute shorts

Funding for perennial grains enjoys a boost large and long

The Land Institute entered a $22.5 million, 15-year joint project with the Denver-based Malone Family Land Preservation Foundation to expand perennial grain research. The arrangement is of unprecedented size and long-term dependability for development of perennial grains grown in ecological mixes. Tim Crews directs the new Perennial Agriculture Project. He is also The Land Institute's research director.

The Land Institute budget this year is $3.1 million. The Malone foundation will add to the perennial grains endeavor $1.5 million each year for a decade and a half. The arrangement gives confidence and stability for work whose success might take decades. The project leverages the expertise of The Land Institute research staff, and will bring to the job more equipment, more scientists, and the involvement of more institutions.

The Malone foundation also paid $1.7 million for 230 acres and a home recently donated to The Land Institute by Jim and Cindy Haines of nearby Lawrence, a growing city and home of the University of Kansas. The Gorrill farm includes cropland, native woods, a large barn, a granary that has been turned into a meeting place, and a 1872 limestone house listed on the Register of Historic Kansas Places. The property was purchased for use by the Perennial Agriculture Project. The foundation intends to protect the Gorrill farm from development. The Land Institute has the option to buy back the property. The institute is developing a consortium with researchers at the university and Kansas State University.

The foundation was created by John Malone to conserve and preserve rural land. Malone, chairman of Liberty Media, is the largest private landowner in the United States, with an estimated 2.1 million acres.

Land Institute sorghum passes first, droughty season in Africa

Seed production by The Land Institute's perennial sorghum suffered from drought and disease, but plants rooted and leafed out encouragingly in their first African trials. Institute scientist Pheonah Nabukalu said perennial sorghum showed high survival and growth potential for the tropics. She returned early this year to her native Uganda and observed plantings made in two locations last fall.

Ninety percent of the seed sown in Uganda germinated. In their first year a third of the plants grew healthy rhizomes, the underground stems of perennials. The vegetation above ground looked vigorous, Nabukalu said, despite drought and no irrigation. "Plants relied on the limited soil moisture reserves for the entire growing season," she said in a report. This could partly explain the low yields observed. However, sorghum is versatile, and the well-developed rhizomes enabled the crop to mature.

Diseases new to the Kansas-bred plants struck their seed heads. Other differences in the tropics include length of night and day, which affects the flowering of many plants. Land Institute and African researchers will look for the plants that do best in Uganda, and then breed them with sorghum varieties resistant to local pests and diseases.

This blending might begin after two seasons of evaluation. Uganda enjoys two growing seasons. More hybrid seed will be sown in April.

Sorghum originated in Africa, but the crop plant used to make the institute's hybrids has been bred for the temperate US Plains. The hybrids' other parent plant is perennial *Sorghum halepense*, which came from the Mediterranean region but now grows as a weed on every continent but Antarctica.

Scientist DeHaan will develop Kernza market in Minnesota

With University of Minnesota funding, Land Institute researcher Lee DeHaan will work to bring the Kernza grain from farms to markets in that state. Central to the work will be small-scale processing of the grain. This is the second time that DeHaan has won from the school an "endowed chair in agricultural systems." He is to serve for a year and a half, occasionally traveling to Minnesota, but still working full time on Kernza at The Land Institute. He will collaborate with Richard Warner of Green Lands Blue Waters, which aims to conserve farmland by keeping ground covered with crops. The university will reimburse the institute for DeHaan's time.

Articles elsewhere about The Land Institute, and by its staff

For Volume 101 of the American Journal of Botany, Land Institute plant researchers David Van Tassel and Lee DeHaan wrote a 14-page scientific exploration of useful insights that evolutionary biology has for development of perennial grains.

Farm Journal wrote about DeHaan's work to develop Kerza grain.

The Land Institute's scientists published a short essay called "New Roots for Ecological Intensification" in the November issue of Crops, Soils, Agronomy News, and the November/December issue of Resource Magazine, a publication of the American Society of Agricultural and Biological Engineers. The title is the same as that of the international conference hosted in October by The Land Institute. It argues for perennial grains grown in species mixture as the answer to call for farming to cut waste and damage.

The Public Broadcasting System program Nova published in its online edition a feature about work by The Land Institute and other researchers to develop perennial grains. The writer was Brooke Borel, the title "The Quest for Everlasting Agriculture." Borel worked from long interviews with Land Institute scientists Tim Crews and Lee DeHaan.

Face-to-face presentations by Land Institute researchers

Staff members gave presentations in Ohio and New York. Scheduled appearances are April 29 in Kansas City, Missiouri, and June 4-7 in Claremont, California. For more information, call 785-823-5376 or see the web site, landinstitute.org.

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Jamie Bugel, left, and Christian Hansen funnel hand-cut perennial wheat into a bag for later measurement. Wheat is the biggest source of plant protein for humans, and covers one-sixth of arable land. Making it a perennial could vastly reduce soil erosion. Stories about work toward this goal begin on page 4. Scott Bontz photo.