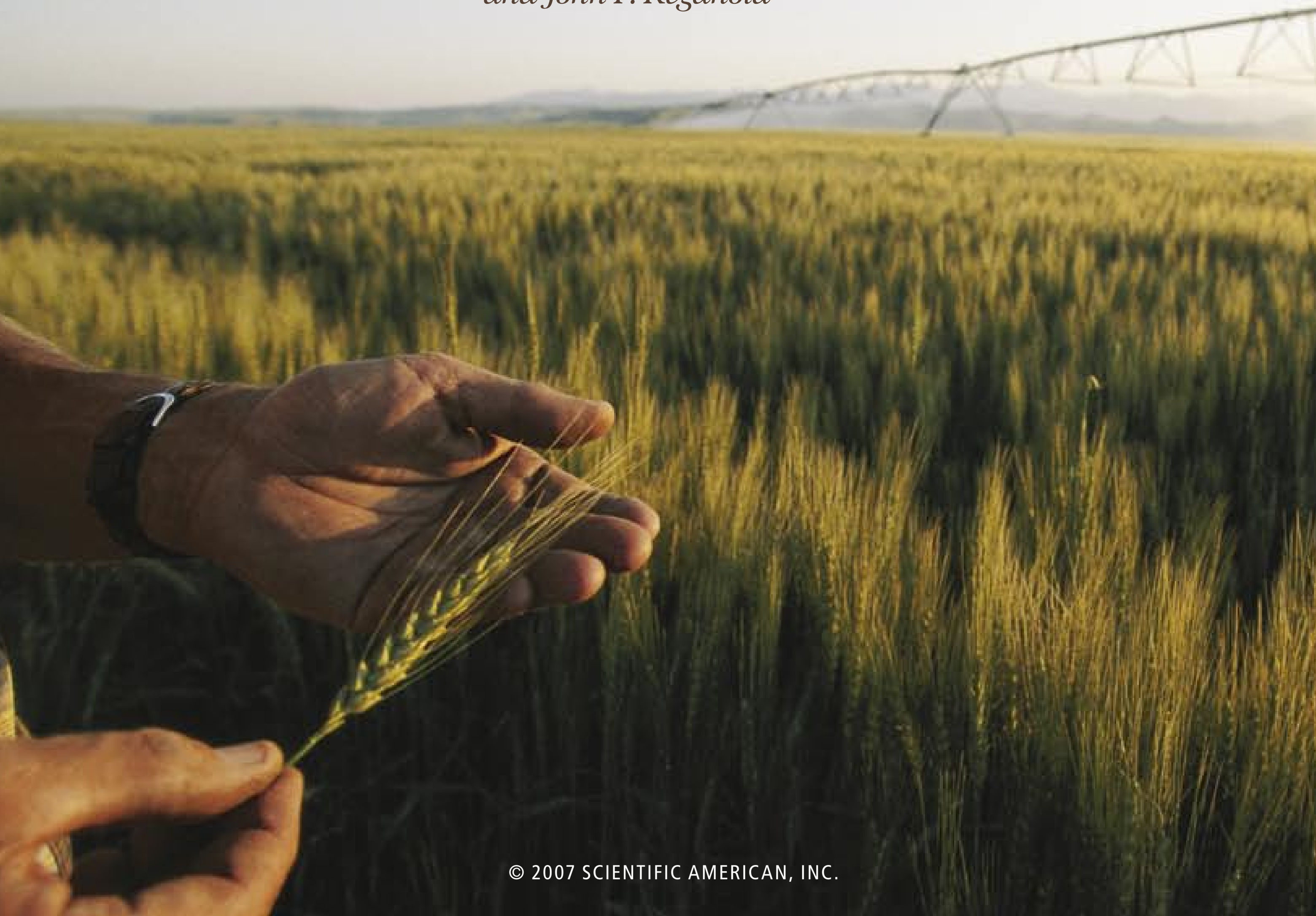
**MODERN FOOD CROPS** depend heavily on irrigation and other human inputs while depleting the land and polluting surrounding environments. Development of perennial versions, such as the experimental hybrid of intermediate wheatgrass and triticale shown on the opposite page, could reduce those burdens.

# Future Farming: A Return to Roots?

**Large-scale agriculture would become more sustainable if major crop plants lived for years and built deep root systems**

*By Jerry D. Glover, Cindy M. Cox and John P. Reganold*



For many of us in affluent regions, our bathroom scales indicate that we get more than enough to eat, which may lead some to believe that it is easy, perhaps too easy, for farmers to grow our food. On the contrary, modern agriculture requires vast areas of land, along with regular infusions of water, energy and chemicals. Noting these resource demands, the 2005 United Nations–sponsored Millennium Ecosystem Assessment suggested that agriculture may be the "largest threat to biodiversity and ecosystem function of any single human activity."

Today most of humanity's food comes directly or indirectly (as animal feed) from cereal grains, legumes and oilseed crops. These staples are appealing to producers and consumers because they are easy to transport and store, relatively imperishable, and fairly high in protein and calories. As a result, such crops occupy about 80 percent of global agricultural land. But they are all annual plants, meaning that they must be grown anew from seeds every year, typically using resource-intensive cultivation methods. More troubling, the environmental degradation caused by agriculture will likely worsen as the hungry human population grows to eight billion or 10 billion in the coming decades.

That is why a number of plant breeders, agronomists and ecologists are working to develop grain-cropping systems that will function much more like the natural ecosystems displaced by agriculture. The key to our collective success is transforming the major grain crops into perennials, which can live for many years. The idea, actually decades old, may take decades more to realize, but significant advances in plant-breeding science are bringing this goal within sight at last.

## Roots of the Problem

Most of the farmers, inventors and scientists who have walked farm fields imagining how to overcome difficulties in cultivation probably saw agriculture through the lens of its contemporary successes and failures. But in the 1970s Kansas plant geneticist Wes Jackson took a 10,000-year step into the past to compare agriculture with the natural systems that preceded it. Before humans boosted the abundance of annuals through domestication and farming, mixtures of perennial plants dominated nearly all the planet's landscapes—as they still do in uncultivated areas today. More than 85 percent of North America's native plant species, for example, are perennials.

Jackson observed that the perennial grasses and flowers of Kansas's tall-grass prairies were highly productive year after year, even as they built and maintained rich soils. They needed no fertilizers, pesticides or herbicides to thrive while fending off pests and disease. Water running off or through the prairie soils was clear, and wildlife was abundant.

In contrast, Jackson saw that nearby fields of annual crops, such as maize, sorghum, wheat, sunflowers and soybeans, required frequent and expensive care to remain productive. Because annuals have relatively shallow roots—most of which occur in the top 0.3 meter of soil—and live only until harvest, many farmed areas had problems with soil erosion, depletion of soil fertility or water contamination. Moreover, the eerily quiet farm fields were mostly barren of wildlife. In short, sustaining annual monocultures in so many places *was* the problem, and the solution lay beneath Jackson's boots: hardy and diverse perennial root systems.

If annual crops are problematic and natural

MICHAEL S. LEWIS *National Geographic/Getty Images (opposite page)*; JIM RICHARDSON *(this page)*

### KEY FACTS

- Modern agriculture's intensive land use quashes natural biodiversity and ecosystems. Meanwhile the population will balloon to between eight billion and 10 billion in the coming decades, requiring that more acres be cultivated.
- Replacing single-season crops with perennials would create large root systems capable of preserving the soil and would allow cultivation in areas currently considered marginal.
- The challenge is monumental, but if plant scientists succeed, the achievement would rival humanity's original domestication of food crops over the past 10 millennia—and be just as revolutionary.

*—The Editors*


**PERENNIAL PLANTS, such as intermediate wheatgrass (*at right in panels above*), access nutrients and water in larger volumes of soil with their well-developed roots than do annuals, such as winter wheat (*at left in panels above*). In turn, perennial roots support microorganisms and other biological activity that enrich soil. The resulting dark, granular soil (*far right*), taken from underneath a perennial meadow, retains ample water and nutrients. Soil from an adjacent annual field (*near right*) is lighter with a weak, clumped structure.**

ecosystems offer advantages, why do none of our important grain crops have perennial roots? The answer lies in the origins of farming. When our Neolithic ancestors started harvesting seed-bearing plants near their settlements, several factors probably determined why they favored annuals.

The earliest annuals to be domesticated, emmer wheat and wild barley, did have appealingly large seeds. And to ensure a reliable harvest every year, the first farmers would have replanted some of the seeds they collected. The characteristics of wild plants can vary greatly, however, so the seeds of plants with the most desirable traits, such as high yield, easy threshing and resistance to shattering, would have been favored. Thus, active cultivation and the unwitting application of evolutionary selection pressure quickly resulted in domesticated annual plants with more appealing qualities than their wild annual relatives. Although some perennial plants might also have had good-size seeds, they did not need to be replanted and so would not have been subjected to—or benefited from—the same selection process.

## Roots as Solution

Today the traits of perennials are also becoming better appreciated. With their roots commonly exceeding depths of two meters, perennial plant communities are critical regulators of ecosystem functions, such as water management and carbon and nitrogen cycling. Although they do have to invest energy in maintaining enough underground tissue to survive the winter, perennial roots spring into action deep within the soil whenever temperatures are warm enough and nutrients and water are available. Their constant state of preparedness allows them to be highly productive yet resilient in the face of environmental stresses.

In a century-long study of factors affecting soil erosion, timothy grass, a perennial hay crop, proved roughly 54 times more effective in maintaining topsoil than annual crops did. Scientists have also documented a fivefold reduction in water loss and a 35-fold reduction in nitrate loss from soil planted with alfalfa and mixed perennial grasses as compared with soil under corn and soybeans. Greater root depths and longer growing seasons also let perennials boost their sequestration of carbon, the main ingredient of soil organic matter, by 50 percent or more as compared with annually cropped fields. Because they do not need to be replanted every year, perennials require fewer passes of farm machinery and fewer inputs of pesticides and fertilizers as well, which reduces fossil-fuel use. The plants thus lower the amount of carbon dioxide in the air while improving the soil's fertility.

Herbicide costs for annual crop production may be four to 8.5 times the herbicide costs for perennial crop production, so fewer inputs in perennial systems mean lower cash expenditures for the farmer. Wildlife also benefits: bird populations, for instance, have been shown to be seven times more dense in perennial crop fields than in annual crop fields. Perhaps most important for a hungry world, perennials are far more capable of sustainable cultivation on marginal lands, which already have poor soil quality or which would be quickly depleted by a few years of intensive annual cropping.

For all these reasons, plant breeders in the U.S. and elsewhere have initiated research and breeding programs over the past five years to develop wheat, sorghum, sunflower, intermediate wheatgrass and other species as perennial grain crops. When compared with research devoted to annual crops, perennial grain development is still in the toddler stage. Taking advantage of

JERRY D. GLOVER (*roots*); STEVE CULMAN *Cornell University* (*soils*); GETTY IMAGES (*wheat stalks*) the significant advances in plant breeding over the past two or three decades, however, will make the large-scale development of high-yield perennial grain crops feasible within the next 25 to 50 years.

Perennial crop developers are employing essentially the same two methods as those used by many other agricultural scientists: direct domestication of wild plants and hybridization of existing annual crop plants with their wild relatives. These techniques are potentially complementary, but each presents a distinct set of challenges and advantages as well.

## Assisted Evolution

Direct domestication of wild perennials is the more straightforward approach to creating perennial crops. Relying on time-tested methods of observation and selection of superior individual plants, breeders seek to increase the frequency of genes for desirable traits, such as easy separation of seed from husk, a nonshattering seed, large seed size, synchronous maturity, palatability, strong stems, and high seed yield. Many existing crops, such as corn and sunflowers, lent themselves readily to domestication in this manner. Native Americans, for example, turned wild sunflowers with small heads and seeds into the familiar large-headed and large-seeded sunflower [*see box on page 88*].

Active perennial grain domestication programs are currently focused on intermediate wheatgrass (*Thinopyrum intermedium*), Maximilian sunflower (*Helianthus maximiliani*), Illinois bundleflower (*Desmanthus illinoensis*) and flax (a perennial species of the *Linum* genus). Of these, the domestication of intermediate wheatgrass, a perennial relative of wheat, is perhaps in the most advanced stages.

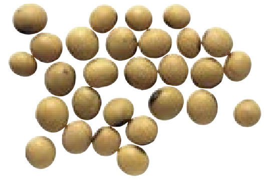
To use an existing annual crop plant in creating a perennial, wide hybridization—a forced mating of two different plant species—can bring together the best qualities of the domesticated annual and its wild perennial relative. Domesticated crops already possess desirable attributes, such as high yield, whereas their wild relatives can contribute genetic variations for traits such as the perennial habit itself as well as resistance to pests and disease.

Of the 13 most widely grown grain and oilseed crops, 10 are capable of hybridization with perennial relatives, according to plant breeder T. Stan Cox of the Land Institute, a Kansas nonprofit that Jackson co-founded to pursue sustainable agriculture. A handful of breeding programs across the U.S. are currently pursuing such interspecific (between species) and intergeneric (between genera) hybrids to develop perennial wheat, sorghum, corn, flax and oilseed sunflower. For more than a decade, University of Manitoba researchers have studied resource use in perennial systems, and now a number of Canadian institutions have started on the long road to developing perennial grain programs as well. The University of Western Australia has already established a perennial wheat program as part of that country's Cooperative Research Center for Future Farm Industries. In addition, scientists at the Food Crops Research Institute in Kunming, China, are continuing work initiated by the International Rice Research Institute in the 1990s to develop perennial upland rice hybrids.

At the Land Institute, breeders are working both on domesticating perennial wheatgrass and on crossing assorted perennial wheatgrass species (in particular, *Th. intermedium, Th. ponticum* and *Th. elongatum*) with annual wheats. At present, 1,500 such hybrids and thousands of their progeny are being screened for perennial traits. The process of creating these hybrids is itself labor-intensive and time-consuming. Once breeders identify candidates for hybridization, they must manage gene exchanges between disparate species by manipulating pollen to make a large number of crosses between plants, selecting the progeny with desirable traits, and repeating this cycle of crossing and selection again and again.

Hybridization nonetheless is a potentially faster means to create a perennial crop plant than domestication, although more technology is often required to overcome genetic incompatibilities between the parent plants. A seed produced by crossing two distantly related species, for example, will often abort before it is fully developed. Such a specimen can be "rescued" as an embryo by growing it on artificial medium until it produces a few roots and leaves, then transferring the seedling to soil, where it can grow like any other plant. When it reaches the reproductive stage, however, the hybrid's genetic anomalies frequently manifest as an inability to produce seed.

A partially or fully sterile hybrid generally results from incompatible parental chromosomes within its cells. To produce eggs or pollen, the hybrid's chromosomes must line up during meiosis (the process by which sex cells halve their chromosomes in preparation for joining with



### TOP 10 CROPS

**Annual cereal grains, food legumes and oilseed plants claimed 80 percent of global harvested cropland in 2004. The top three grains covered more than half that area.**

| CROP | LAND % |
|---|---|
| 1. Wheat | 17.8 |
| 2. Rice | 12.5 |
| 3. Maize | 12.2 |
| 4. Soybeans | 7.6 |
| 5. Barley | 4.7 |
| 6. Sorghum | 3.5 |
| 7. Cottonseed | 2.9 |
| 8. Dry beans | 2.9 |
| 9. Millet | 2.8 |
| 10. Rapeseed/mustard | 2.2 |

GETTY IMAGES (*soybeans*); SOURCE: FAOSTAT

**[THE AUTHORS]**

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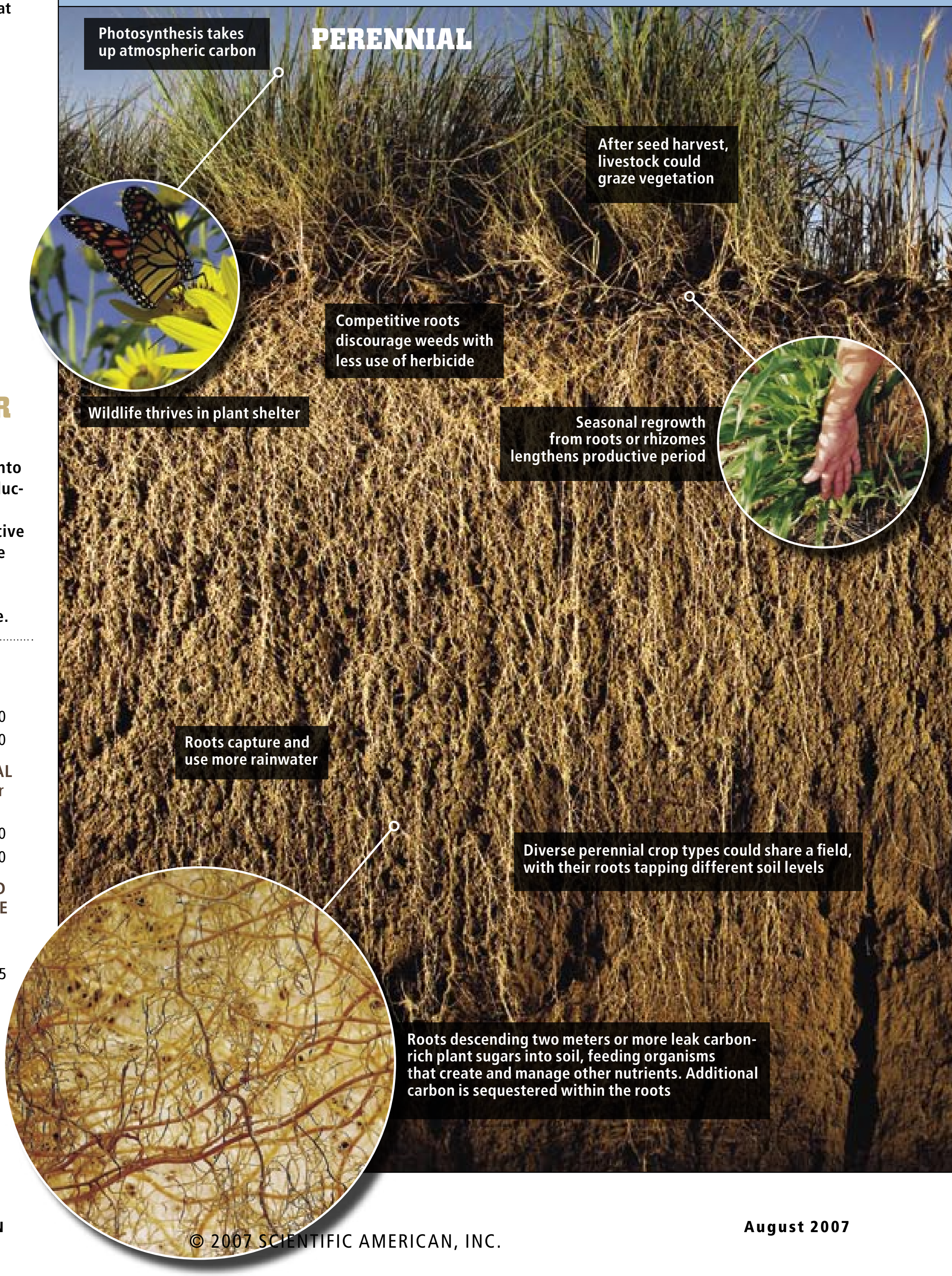
Experimental perennial wheat

[BENEFITS]

# SUSTAINABLE FARMING: NEW VS. NOW

The potential advantages of future perennial crop plants are visible today by comparing perennial wheatgrass (*below left*) growing alongside domesticated annual wheat (*below right*). Although a perennial wheat could one day yield grains similar to those of the annual crop, it might live for many years and look much more like its wheatgrass relative belowground. Perennial crops would transform the process of farming and its environmental effects by using resources more effectively, thereby being less dependent on human inputs and more productive for a longer time. Perennials also anchor and support the ecosystem that nourishes them, whereas short-lived and short-rooted annuals allow water, soil and nutrients to be lost.




## CARBON FACTOR

**Global warming potential—greenhouse gases released into the atmosphere by crop production inputs, minus carbon sequestered in soil—is negative for perennial crops. The more resilient perennials are also expected to fare better than annuals in a warming climate.**

**SOIL CARBON SEQUESTERED**
(kilograms per hectare per year)

| | |
|---|---|
| Annual crops | 0 to 450 |
| Perennial crops | 320 to 1,100 |

**GLOBAL WARMING POTENTIAL**
(kilograms of $CO_2$ equivalent per hectare per year)

| | |
|---|---|
| Annual crops | 140 to 1,140 |
| Perennial crops | –1,050 to –200 |

**ESTIMATED IMPACT ON YIELD OF 3° C TO 8° C TEMPERATURE INCREASE**
(megagrams per hectare)

| | |
|---|---|
| Annual crops | –1.5 to –0.5 |
| Perennial crops | +5 |


JIM RICHARDSON (*soil cross section*); THE LAND INSTITUTE (*insets on opposite page*); JIM RICHARDSON (*farm machinery*); SEAWIFS PROJECT (*NASA/GSFC*) AND GEOEYE (*dead zone*); KEN CEDENO (*tilled land*); JACK DYKINGA *USDA/ARS* (*erosion*)

another gamete) and exchange genetic information with one another. If the chromosomes cannot find counterparts because each parent's version is too different, or if they differ in number, the meiosis line dance is disrupted. This problem can be overcome in a few ways. Because sterile hybrids are usually unable to produce male gametes but are partially fertile with female gametes, pollinating them with one of the original parents, known as backcrossing, can restore fertility. Doubling the number of chromosomes, either spontaneously or by adding chemicals such as colchicine, is another strategy. Although each method allows for chromosome pairing, subsequent chromosome eliminations in each successive generation often happen in perennial wheat hybrids, particularly to chromosomes inherited from the perennial parent.

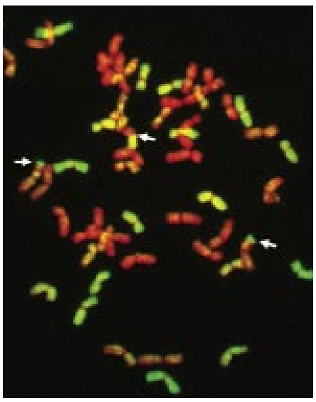
Because of the challenging gene pools created by wide hybridization, when fertile perennial hybrids are identified, biotechnology techniques that can reveal which parent contributed parts of the progeny's genome are useful. One of these, genomic in situ hybridization, for example, distinguishes the perennial parent's chromosomes from those of the annual parent by color fluorescence and also detects chromosome anomalies, such as structural rearrangements between unrelated chromosomes [*see bottom illustration on next page*]. Such analytical tools can help speed up a breeding program once breeders discover desirable and undesirable chromosome combinations, without compromising the potential for using perennial grains in organic agriculture, where genetically engineered crops are not allowed.

Another valuable method for speeding and improving traditional plant breeding is known as marker-assisted selection. DNA sequences associated with specific traits serve as markers that allow breeders to screen crosses as seedlings for desired attributes without having to wait until the plants grow to maturity [see "Back to the Future of Cereals," by Stephen A. Goff and John M. Salmeron; SCIENTIFIC AMERICAN, August 2004]. At present, no markers specific to perennial plant breeding have been established, although it is only a matter of time. Scientists at Washington State University, for example, have already determined that chromosome 4E in *Th. elongatum* wheatgrass is necessary for the important perennial trait of regrowth following a sexual reproduction cycle. Narrowing down

[THE NEXT STEP]

## CREATING A NEW CROP

To develop high-yield perennial crop plants, scientists and breeders can either domesticate a wild perennial plant to improve its traits or hybridize an annual crop plant with a wild perennial relative to blend their best qualities. Each method requires time- and labor-intensive plant crossbreeding and analysis. Native Americans spent thousands of years domesticating the small-seeded wild annual sunflower (*a*) into the modern annual crop plant (*b*) by selecting and cultivating plants with desirable traits, such as large seeds and yields. Efforts are currently under way to directly domesticate wild perennial sunflower species (*c*) and also to produce hybrids of the modern annual and wild perennials (*d*).

**CHROMOSOMES of an experimental hybrid perennial wheat plant are tagged with fluorescence to reveal whether they originated with the hybrid's wheatgrass (*green*) or wheat (*red*) parent. This technique helps to identify desirable chromosome combinations and highlights anomalies, such as fused chromosomes (*arrows*).**

the region on 4E to the gene or genes that produce the trait would reveal relevant DNA markers that will save breeders a year of growing time in assessing hybrids.

Perennialism is nonetheless an intricate life path that goes well beyond a single trait, let alone a single gene. Because of this complexity, transgenic modification (insertion of foreign DNA) is unlikely to be useful in developing perennial grains, at least initially. Down the road, transgenic technology may have a role in refining simple inherited traits. For example, if a domesticated perennial wheatgrass is successfully developed but still lacks the right combination of gluten-protein genes necessary for making good-quality bread, gluten genes from annual wheat could be inserted into the perennial plant.

### Trade-offs and Payoffs

Although perennial crops, such as alfalfa and sugarcane, already exist around the world, none has seed yields comparable to those of annual grain crops. At first glance, the idea that plants can simultaneously direct resources to building and maintaining perennial root systems and also produce ample yields of edible grains may seem counterintuitive. Carbon, which is captured through photosynthesis, is the plant's main building block and must be allocated among its various parts.

Critics of the idea that perennials could have high seed yield often focus on such physiological trade-offs, assuming that the amount of carbon available to a plant is fixed and therefore that carbon allocated to seeds always comes at the expense of perennating structures, such as roots and rhizomes. Doubters also often overlook the fact that the life spans of perennial plants exist along a spectrum. Some perennial prairie plants may persist for 50 to 100 years, whereas others live for only a few years. Fortunately for breeders, plants are relatively flexible organisms: responsive to selection pressures, they are able to change the size of their total carbon "pies" depending on environmental conditions and to change the allocation of pie slices.

A hypothetical wild perennial species might live 20 years in its highly competitive natural environment and produce only small amounts of seed in any year. Its carbon pie is small, with much of it going toward fending off pests and disease, competing for a few resources and persisting in variable conditions. When breeders take the wild specimen out of its resource-strapped natural setting and place it into a managed environment, its total carbon pie suddenly grows, resulting in a bigger plant.

Over time, breeders can also change the size of the carbon slices within that larger pie. Modern Green Revolution grain breeding, when combined with increased use of fertilizers, more than doubled the yield of many annual grain

THE LAND INSTITUTE (*sunflowers*); CINDY M. COX (*chromosomes*)

crops, and those increases were achieved in plants that did not have perennating structures to sacrifice. Breeders attained a portion of those impressive yield expansions in annual crops by selecting for plants that produced less stem and leaf mass, thereby reallocating that carbon to seed production.

Yields can be similarly increased without eliminating the organs and structures required for overwintering in perennial grain crops. In fact, many perennials, which are larger overall than annuals, offer more potential for breeders to reallocate vegetative growth to seed production. Furthermore, for a perennial grain crop to be successful in meeting human needs, it might need to live for only five or 10 years.

In other words, the wild perennial is unnecessarily "overbuilt" for a managed agricultural setting. Much of the carbon allocated to the plant's survival mechanisms, such as those allowing it to survive infrequent droughts, could be reallocated to seed production.

## Greener Farms

Thus, we can begin to imagine a day 50 years from now when farmers around the world are walking through their fields of perennial grain crops. These plots would function much like the Kansas prairies walked by Wes Jackson, while also producing food. Belowground, different types of perennial roots—some resembling the long taproots of alfalfa and others more like the thick, fibrous tangle of wheatgrass roots—would coexist, making use of different soil layers. Crops with alternative seasonal growth habits could be cultivated together to extend the overall growing season. Fewer inputs and greater biodiversity would in turn benefit the environment and the farmer's bottom line.

Global conditions—agricultural, ecological, economic and political—are changing rapidly in ways that could promote efforts to create perennial crops. For instance, as pressure mounts on the U.S. and Europe to cut or eliminate farm subsidies, which primarily support annual cropping systems, more funds could be made available for perennials research. And as energy prices soar and the costs of environmental degradation are increasingly appreciated, budgeting public money for long-term projects that will reduce resource consumption and land depletion will become more politically popular.

Because the long timeline for release of perennial grain crops discourages private-sector investment at this point, large-scale government or philanthropic funding is needed to build up a critical mass of scientists and research programs. Although commercial companies may not profit as much by selling fertilizers and pesticides to farmers producing perennial grains, they, too, will most likely adapt to these new crops with new products and services.

Annual grain production will undoubtedly still be important 50 years from now—some crops, such as soybeans, will probably be difficult to perennialize, and perennials will not completely eliminate problems such as disease, weeds and soil fertility losses. Deep roots, however, mean resilience. Establishing the roots of agriculture based on perennial crops now will give future farmers more choices in what they can grow and where, while sustainably producing food for the burgeoning world population that is depending on them. ■

**BREEDING HYBRID plants can require rescuing an embryo from the ovary (*left*). A researcher bags annual sorghum heads to collect pollen, with tall perennial sorghum in the background (*right*).**

THE LAND INSTITUTE (*above left*); JIM RICHARDSON (*above right*); GETTY IMAGES (*below right*)

## ➡ MORE TO EXPLORE


**Perennial Grain Crops: An Agricultural Revolution.** Edited by Jerry D. Glover and William Wilhelm. Special issue of *Renewable Agriculture and Food Systems,* Vol. 20, No. 1; March 2005.

**Wes Jackson (35 Who Made a Difference).** Craig Canine in special anniversary issue of *Smithsonian,* Vol. 36, No. 8, pages 81–82; November 2005.

**Prospects for Developing Perennial Grain Crops.** Thomas S. Cox, Jerry D. Glover, David L. Van Tassel, Cindy M. Cox and Lee D. DeHaan in *BioScience,* Vol. 56, No. 8, pages 649–659; August 2006.

**Sustainable Development of the Agricultural Bio-Economy.** Nicholas Jordan et al. in *Science,* Vol. 316, pages 1570–1571; June 15, 2007.

The Land Institute: www.landinstitute.org