Can Modern Agriculture Be Sustainable?

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Perennial polyculture holds promise

In October, a flurry of news articles hailed the arrival of a new beer produced by Patagonia Provisions, an offshoot of the outdoor clothing company. Long Root Ale is the first beer to be made from Kernza, a perennial grain bred from intermediate wheatgrass (*Thinopyrum intermedium*) by the Kansas-based Land Institute. Dubbed “an ecologist’s dream” by a *Washington Post* food writer, Kernza is on the leading edge of a global effort to develop perennial crops as a way to make agriculture sustainable and to support ecological intensification. Plant geneticists, evolutionary biologists, agronomists, food scientists, and agroecologists are collaborating...
to develop perennial crops, among them rice, wheat, sorghum, pigeon pea, barley, and sunflowers. A 2013 United Nations Food and Agriculture Organization expert workshop on “Perennial Crops for Food Security” concluded, “As feeding 9 billion people in 2050 with increasingly scarce and degraded natural resources is the main challenge faced by humankind, reinvigorating agriculture in a sustainable and productive way on a large scale will take nothing short of a significant shift in agriculture as we know it.”

That effort has been the Land Institute’s mission since it was founded in 1976. Its goal is to transform farming from annual monoculture to perennial polyculture. “We’re trying to develop an agriculture that functions more like the ecosystem that agriculture replaced,” says Tim Crews, director of research and lead scientist of the Land Institute’s ecology program. “In order to develop that ecosystem, you need perennial crops. They are not the goal, per se, but a central component of a more functional ecosystem. That will include transformation of the soil microbiome, and it will involve numerous crop species on the landscape.”

For millennia, humans have bred plants to grow faster and have higher nutrient value. Agricultural production accelerated dramatically during the “Green Revolution” of the 1970s, with farmers urged to use chemical fertilizers and pesticides and to intensify the mechanization of planting and harvesting. Productivity rose at astonishing rates. Today, in the Midwest, rows of soybeans and corn dominate much of the landscape that was once prairie.

“Modernizing was all about yields,” says Sieglinde Snapp, professor of soils and cropping systems ecology at Michigan State University, who leads a project to bring perennial grains to Africa (see the box at right). “If you just compare crops on yield, then you can’t beat fertilized corn. But if you also want green cover for the Earth and nitrogen fixation and clean water, you have to measure them and give the plant credit for that.” Agriculture, she argues, should be directed toward both ecological services and food production.

Kernza and other long-lived crops have much longer root systems than annuals do, allowing the plants to survive for several years without disturbing the soil. By planting perennial grains along with cover crops, such as alfalfa, farmers can reduce the need for tillage and for fertilizers and pesticides while fixing nutrients into the plants.

As Lee DeHaan, lead scientist of the Land Institute’s Intermediate Wheatgrass Program, and colleagues noted in the August 2006 *BioScience*, “The superior capacity of perennial plants to store carbon, manage resources, and stop soil erosion is widely recognized among ecologists...”
and soil scientists, yet in 2006, only a handful of plant breeders are working to develop perennial grain crops.

The pace is now picking up, thanks to advances in genome sequencing and in understanding the role of the soil microbiome. Support has come from the Gates Foundation, the US Agency for International Development (USAID), dozens of research institutes, and others.

Also spurring the research in the Midwest is growing concern over change in climate and over water quality degradation, says Craig Sheaffer, professor of agronomy and plant genetics at the University of Minnesota who collaborates with the Land Institute. “In the last 10 years, the issue of carbon sequestration has become more important,” he says. “Likewise, in Minnesota, there has been much greater emphasis on water-quality issues.” State agencies have documented sediment loading of rivers from field runoff, and there are a growing number of wells and streams whose waters exceed federal drinking-water standards for nitrate.

How climate change might affect perennial polyculture, on one hand, and how perennial polyculture might help mitigate the adverse effects of a warmer, drier climate, on the other hand, are big questions. “We’re interested in how much carbon can be sequestered in a perennial grain system,” says Crews. “There are all sorts of approaches people talk about to mitigate atmospheric carbon dioxide with land-use changes.... Most tilled lands have lost between 30 and 60 percent of their soil organic matter. How do you get that back?” By replacing annual crops with perennials, he says, carbon, over time, can be resequestered. “Over decades, it should be possible to approach where the ecosystem was to begin with, as long as the soil had not been too degraded from annual cropping,” says Crews.

As the climate becomes hotter and drier, researchers are breeding plants that can survive in tough conditions. The Land Institute, for example, is domesticating silphium as a substitute for annual oilseed crops. A native prairie perennial, silphium survived the Dust Bowl and other extreme events by extending its taproot, several meters long, deep into the ground for water.

“Ultimately, we’re looking to be able to grow these [perennial] crops profitably on lands in order to result in improved ecosystem services—improve soil quality, reduce runoff and nitrogen leaching, and improved water quality and wildlife habitat,” says DeHaan. For now, “the breeding program is focused primarily on grain yield, because it is essential to the economic success of perennial grain systems.”

Breeding a better plant
The Land Institute use two strategies to breed plants: domesticating wild species, as it did with Kernza, and crossbreeding perennials with annuals.

Advances in genome sequencing have been “a game changer in what we can do in terms of genetics of any of our crop plants,” says DeHaan. The wheat genome, for example, is nearly complete. “We don’t know what all the genes are and what they do—but the complete sequence is there, and that serves as a reference. Now, we can pull in the information from other model species and organisms. We’ve studied many genes for decades, and now we can look for those same genes in our crops.”

DeHaan’s team is identifying genes that confer superior yield, shatter resistance, seed size, and grain quality. “We can plant thousands of seedlings in a greenhouse, take their DNA, sequence...
these small portions, and predict which will be the best without growing them to maturity, based on these genetic markers,” says DeHaan. “By the next spring, we can select again—we can do much more rapid cycling.”

The research that led to Kernza began in 1983, with plant breeders at the Rodale Institute experimenting with intermediate wheatgrass. Twenty years later, the Land Institute took up the baton. In the last decade, DeHaan’s team has doubled Kernza’s seed size and yield. DeHaan is optimistic that within two decades, Kernza will be nearly as economically viable and high yielding as traditional annual wheat.

To speed up the development of perennial polyculture, the Land Institute collaborates with partners around the globe.

At the Swedish University of Agricultural Sciences, biologist and plant geneticist Anna Westerbergh has been working since 2011 on developing perennial barley, an important cereal in Scandinavia. “We are using two different breeding strategies to develop cultivars for northern conditions,” she says. One is wide hybridization, crossing annual barley with its closest wild perennial relative, *Hordeum bulbosum*. The other is domesticating a perennial wild barley. “In addition, we have developed mapping populations as a first step to investigate the genetic basis of traits associated with perennial growth habit,” Westerbergh explains. “We have crossed annual and perennial species. We look at the diversity in traits and genotypes in offspring populations and try to associate the phenotypes with the variation in the genotype.”

Westerbergh is also involved with a multisite comparative study of Kernza and more than 20 wheat cultivars, along with the Land Institute and other researchers in the United States, Canada, China, Australia, Turkey, and Italy. “We are studying the interaction between the genotype and the environment to see how they behave in these different climates,” says Westerbergh. “We will be able to select which do the best, for example, here in Sweden for further breeding.”

In China, geneticist Fengyi Hu of Yunnan University and colleagues have successfully improved through breeding a cross between *Oryza sativa*, an annual rice, with a wild African perennial, *O. longistaminata*. The cross, known as PR 23, is now being grown in test paddies, where, after 3 years, it is proving to be nearly as productive as annual rice. Papers are forthcoming, according to Crews, who collaborates with Fengyi Hu.

Andrew Paterson, director of the Plant Genome Mapping Laboratory at the University of Georgia, is crossing wild and agricultural sorghums, seeking to transfer the perenniality trait while retaining high yield. In 2013, a team led by Paterson was awarded a nearly $5 million grant from USAID to develop a more drought- and heat-resistant sorghum for farmers in Africa and India. A secondary goal is to develop a semiperennial crop, with farmers getting a second crop out of a single planting.

“Our notion is to try to combine the high level of productivity that’s been accomplished through hundreds of years of breeding with the ability to survive a cold or dry season,” says Paterson, who led the genome sequencing of sorghum in 2009. “We have experimental materials that can do this in Kansas, where it’s cold, and in Mali, where it’s hot and dry. They don’t yet recover the high yield of elite sorghums, and they don’t necessarily have the quality factors that would be desired in Africa, where sorghum seed is substantially consumed by people. We have quite a lot of work to do, but we have proof of concept that this can be done.”
Maintaining a healthy soil microbiome

Other researchers are focusing on the soil microbiome and its relationship to annual and perennial plantings. “We’re just beginning to appreciate the importance of microbes in plant fitness and in the structure of plant communities in land-managed systems,” says Jim Bever, distinguished professor of ecology and evolutionary biology at the University of Kansas. “There has been an appreciation for plant pathogens but less of plant mutualists. As we move to perennial agriculture, there are opportunities for exploiting mutualists and minimizing the effects of pathogens.”

Bever’s lab has found that longer-lived plants are more dependent on arbuscular mycorrhizal (AM) fungi that help the plants take up phosphorus and nitrogen. Perennial plants also are more particular than annuals as to which fungi species are in the soil.

In conventional annual monocultures, tillage and fertilization damage these beneficial fungi. “What we’ve found in prairie restoration in fields that were tilled for many years is that when we reintroduce the native fungi, these perennial plants do much better,” says Bever. In a study published in the *Journal of Applied Ecology* in 2016, Liz Koziol, now a postdoc at the University of Kansas, and Bever found that test plots “inoculated with certain AM fungal treatments were dominated by desirable prairie plants, whereas plots inoculated with other AM fungal species and the noninoculated control were dominated by nondesirable plants, including weeds and exotic species.”

Future research by Bever’s lab will investigate whether Kernza and other perennial plants will respond favorably to these fungi. “We’re excited about the possibility of developing management applications to what we’ve been finding in unmanaged [prairie] systems,” he says.

One unexplored area, says Bever, is the soil microbiome’s role in improving the nutritional quality of perennial grains. “The arbuscular mycorrhizal fungi improve plant uptake of a lot of soil resources, such as phosphorus and nitrogen, and of course that gets packed into the grain,” says Bever, “so it will affect the nutritional quality. We haven’t looked at that in particular, and it’s an interesting direction to go.”

Bever’s colleague at the University of Kansas, Ben Sikes, a soil microbial ecologist, studies the soil microbiome and its relationship to perennial polyculture. Among the big questions his lab is investigating, says Sikes, are the following: “What happens to the soil microbial community when you have no tillage? What happens when you have a plant that’s there for more than one year, when the root system has more things accumulating over time than an annual plant? How does the polyculture dilute diseases or mitigate benefits that you might get? When you have a higher diversity of plants, often you have higher diversity of beneficial fungi—that drives greater gains in growth and production. We don’t have any idea of the relative importance of those things.”

To learn more, his team examined the microbiome in three types of fields the Land Institute had planted: one in annual wheat that is tilled, another in perennial wheat (Kernza), and a third that is restored prairie. The Kernza-planted fields looked more like the prairie system in terms of number and diversity of soil microbes than did the annual, says Sikes. Nevertheless, “in prairie, we still have a lot more kinds of microbes that are a lot more varied than the perennial crop alone. The perennial was still a monoculture,” confirming the importance of a polyculture system.

Understanding which microbes are beneficial—or even whether diversity always has a benefit—is unknown. “We’re used to dealing with a prairie with 100 plant species,” says Sikes. In contrast, “A single teaspoon of soil can have a million different species. We
Allison Miller, a plant evolutionary biologist and associate professor at Saint Louis University (SLU), came to appreciate the potential of perennial polyculture while attending the 2013 meeting of the UN Food and Agriculture Organization on perennial crops. "I've been studying perennial crop evolution for most of my career, but until recently, all of our projects had to do with woody plants," says Miller. "When I heard about the Land Institute and the new domestication of wild species, I wondered, how do you decide which species you're going to domesticate, and what do we know about perennial herbaceous plants in general? Where do they grow? The questions started piling up.

Her curiosity and enthusiasm led her to help develop the Perennial Agriculture Global Inventory Project. A collaboration of SLU, the Missouri Botanical Garden, and the Land Institute, the project got up and running in 2015.

The inventory aims to list all the perennial herbaceous members of the grass, legume, and sunflower families. "We're not starting from zero," she explains. "The botanical research communities have been documenting diversity in families and in regions for decades. A lot of that information is slowly becoming digitized. And so our vision was really to try to take that information generated by plant taxonomists and extract from it what we needed. We have a lot of collaborators and a ton of help from around the world."

The inventory includes 6500 perennial herbaceous members of the legume family and 7281 grasses. "The sunflower family has other challenges we haven't yet overcome," she says.

The second part of the inventory will include ethnobotanical data on the plants, as well as agronomic traits, such as seed size and reproduction. Going through herbarium specimens and the global ethnobotanical record is laborious. "It's quite slow because the information is diffuse," she says. Eventually, the project may use automated extraction of information from digitized text.

"What's exciting to me is the union of botanical diversity science and agriculture science," says Miller. "This is a terrific opportunity for these two fields to come together for a common goal."

She hopes the project will continue far beyond its initial 3 years of funding. "The huge-picture goal is to develop a form of agriculture that is sustainable," she says. "For this specific project, my goal is to build a botanical foundation for this perennial polyculture agriculture, with the understanding that we don't know which species, which crops, and in which combination might work. My hope is to provide a database of morphological form, human use, and taxonomical data that breeders can use as they figure out how to focus their efforts."
don’t have a very good handle on what differences in diversity really mean at that scale.” (He jokes that soil researchers say that their medium is a poor man’s tropical rainforest—if you can’t afford to go to Brazil, go in your backyard.)

With 1 million species in a small amount of soil, “We don’t have the time or funding to painstakingly look at each species and organism that might change to see if there’s a silver bullet that’s great or that’s bad. But we can learn a whole lot without deconstructing into individual species.” His team takes a “black box” approach, trying to understand how hundreds of microbes working together confer a function such as enhancing plant nutrition or disease protection.

Moving forward
In what could give perennial polyculture a push forward, General Mills is considering using Kernza in its products. “It ties in really well with General Mills’ global sustainability goals,” says Laura Hansen, senior principal scientist for General Mills R&D. General Mills has pledged to sustainably source 100 percent of 10 priority ingredients, including wheat, by 2020. The corporation also has a water stewardship program and a commitment to reduce its greenhouse-gas emissions by 28 percent by 2025, compared with its 2010 emissions. Using Kernza, says Hansen, “would tie in nicely with our whole sourcing and sustainability program from a global perspective.”

Hansen, who says she’s been working in product development at General Mills for many years, notes that she was happy to find out that Kernza “actually tastes good. And it has so many benefits for soil and the Earth. It has great nutritional protein; it’s high in fiber—there are lots of reasons for us to be looking at it.”

The main drawback, she says, is having a reliable supply of the grain, and that is where a large corporation can play a role. “If farmers know there’s a market available, they will start planting it,” she says. “The other approach is we can contract with farmers to grow Kernza.” No decisions have been made, she adds.

In the meantime, increasing yield of Kernza will be the primary challenge in order to persuade farmers to shift from monoculture and to ensure enough food for the world’s growing population. “We do not have enough grain production to meet market demand, and because of that, we haven’t been able to establish a pricing structure,” says Sheaffer. “It’s complex; you have to consider the supply chain from field production all the way to the consumer. As agronomists and plant breeders, our immediate goal is to increase the grain yield and the sustainability of yield over time while we maintain the perennial nature of the crop.”

Although much is understood about the ecological importance of perennial crops, says Snapp, “In terms of having options that fit in the modern agriculture context, we’re at the very beginning. These have to be practical and profitable, but they are very feasible in my view. In my lab, we’ve shown there are no biological barriers to improving yields.” But to transform agriculture on a wide scale, she adds, “We’d have to have a Manhattan Project to throw brainpower and real money at this. We’re just at the beginning. It’s kind of exciting.”

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