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Perennial Grains

Food Security for the Future

Developing perennial versions of our major grain crops would address many of the environmental limitations of annuals while helping to feed an increasingly hungry planet.

Colorful fruits and vegetables piled to overflowing at a farmer's market or in the produce aisle readily come to mind when we think about farming and food production. Such images run counter to those of environmental destruction and chronic hunger and seem disconnected from the challenges of climate change, energy use, and biodiversity loss. Agriculture, though, has been identified as the greatest threat to biodiversity and ecosystem function of any human activity. And because of factors including climate change, rising energy costs, and land degradation, the number of "urgently hungry" people, now estimated at roughly 1 billion, is at its highest level ever. More troubling, agriculture-related problems will probably worsen as the human population expands—that is, unless we reshape agriculture.

The disconnect between popular images of farming and its less rosy reality stems from the fact that fruits and vegetables represent only a sliver of farm production. Cereal, oilseed, and legume crops dominate farming, occupying 75% of U.S. and 69% of global croplands. These grains include crops such as wheat, rice, and maize and together provide more than 70% of human food calories. Currently, all are annuals, which means they must be replanted each year from seed, require large amounts of expensive fertilizers and pesticides, poorly protect soil and water, and provide little habitat for wildlife. Their production emits significant greenhouse gases, contributing to climate change that can in turn have adverse effects on agricultural productivity.

These are not the inevitable consequences of farming. Plant breeders can now, for perhaps the first time in history, develop perennial versions of major grain crops. Perennial crops have substantial ecological and economic benefits. Their longer growing seasons and more extensive root systems make them more competitive against weeds and more effective at capturing nutrients and water. Farmers don't have to replant the crop each year, don't have to add as much fertilizer and pesticide, and don't burn as much diesel

GFP Bunny

GFP Bunny, also known as *Alba* the fluorescent rabbit, is a transgenic artwork comprised of the creation of a green fluorescent rabbit, the public dialogue generated by the project, and the social integration of the rabbit.

EDUARDO KAC, *GFP Bunny*, 2000, transgenic artwork.

in their tractors. In addition, soils are built and conserved, water is filtered, and more area is available for wildlife. Although perennial crops such as alfalfa exist, there are no commercial perennial versions of the grains on which humans rely. An expanding group of plant breeders around the world is working to change that.

Although annual grain crops have been with us for thousands of years and have benefited from many generations of breeding, modern plant breeding techniques provide unprecedented opportunities to develop new crops much more quickly. During the past decade, plant breeders in the United States have been working to develop perennial versions of wheat, sorghum, sunflowers, and legumes. Preliminary work has also been done to develop a perennial maize, and Swedish researchers see potential in domesticating a wild mustard species as a perennial oilseed crop. Relatively new breeding programs in China and Australia include work to develop perennial rice and wheat. These programs could make it possible to develop radically new and sustainable farming systems within the next 10 to 20 years.

Currently, these efforts receive little public funding, in marked contrast to the extensive public support for cellulosic ethanol technologies capable of converting perennial biomass crops into liquid fuels. Yet perennial grain crops promise much larger payoffs for the environment and food security and have similar timelines for widespread application. Public research funds distributed through the U.S. Department of Agriculture (USDA) and the National Science Foundation (NSF) could greatly expand and accelerate perennial grain breeding programs. Additionally, the farm bill could include support for the development of perennial breeding programs.

The rise of annuals

Since the initial domestication of crops more than 10,000 years ago, annual grains have dominated food production. The agricultural revolution was launched when our Neolithic ancestors began harvesting and sowing wild seed-bearing plants. The earliest cultivators had long collected seed from both annual and perennial plants; however, they found the annuals to be better adapted to the soil disturbance and annual sowing they had adopted in order to maintain a convenient and steady supply of grains harvested from the annual plants.

Although some of the wild annuals first to be domesticated, such as wheat and barley, were favored because they had large seeds, others had seeds comparable in size to those of their wild perennial counterparts. With each year's sowing of the annuals, desirable traits were selected for and carried on to the next generation. Thus, selection pressure was applied, albeit unintentionally, to annual plants but not to perennials. Evidence indicates that selection pressures on wild annuals quickly resulted in domesticated plants with more desirable traits than their wild relatives. The unchanged wild perennials probably would have been ignored in favor of the increasingly large, easily harvested seeds of the modified annual plants.

The conversion of native perennial landscapes to the monocultures of annual crops characteristic of today's agriculture has allowed us to meet our increasing food needs. But it has also resulted in dramatic changes. Fields of maize and wheat require frequent, expensive care to remain productive. Compared to perennials, annuals typically grow for shorter lengths of time each year and have shallower rooting depths and lower root densities, with most of their roots restricted to the surface foot of soil or less. Even with crop management advances such as no-tillage practices, these traits limit their access to nutrients and water, increase their need for nutrients, leave croplands more vulnerable to degradation, and reduce soil carbon inputs and provisions for wildlife. These traits also make annual plants less resilient to the increased environmental stress expected from climate change.

Even in regions best suited for annual crops, such as the Corn Belt, soil carbon and nitrogen levels decreased by 40 to 50% or more after conversion from native plants to annuals. Global data for maize, rice, and wheat indicate that they take up only 20 to 50% of the nitrogen applied in fertilizer; the rest is lost to surrounding environments. Runoff of nitrogen and other chemicals from farm fields into rivers and then coastal waters has triggered the development of more than 400 "dead zones" that are depleted of fish and other sea dwellers.

Annual crops do, however, have some advantages over perennial crops in terms of management flexibility. Because they are short-lived, they offer farmers opportunities to quickly change crops in response to changing market demands as well as environmental factors such as disease outbreaks. Thus, annual grain production will undoubtedly be important far into the future. Still, the expanded use of perennial grain crops on farms would provide greater biological and economic diversity and yield additional environmental benefits.

Perennial advantages

Developing new crop species capable of significantly replacing annuals will require a major effort. During the past four decades, breeders have had tremendous success in doubling, tripling, and even quadrupling the yields of important annual grains, success that would seem to challenge the notion that a fundamental change in agriculture is needed. Today, however, these high yields are being weighed against the negative environmental effects of agriculture that are increasingly seen around the world. And with global grain demand expected to double by 2050, these effects will increase.

The development of perennial crops through breeding would help deal with the multiple issues involving environmental conservation and food security in a world of shrinking resources. We know that perennials such as alfalfa and switchgrass are much more effective than annuals in maintaining topsoil. Soil carbon may also increase 50 to 100% when annual fields are converted to perennials. With their longer growing seasons and deeper roots, perennials can dramatically reduce water and nitrate losses. They require less field attention by the farmer and less pesticide and fertilizer inputs, resulting in lower costs. Wildlife benefit from reduced chemical inputs and from the greater shelter provided by perennial cover.

There are other benefits as well. Greater soil carbon storage and reduced input requirements mean that perennials have the potential to mitigate global warming, whereas annual crops tend to exacerbate the problem. With more of their reserves protected belowground and their greater access to more soil moisture, perennials are also more resilient to temperature increases of the magnitude predicted by some climate change models. Although perennials may not offer farmers the flexibility of changing crops each year, they can be planted on more-marginal lands and can be used to increase the economic and biological diversity of a farm, thereby increasing the flexibility of the farming system. Perhaps most important in a crowded world with limited resources, perennials are more resilient to social, political, health, and environmental disruptions because they don't rely on annual seedbed preparation and planting. A farmer suffering from illness might be unable to harvest her crop one season, but a new crop would be ready the next season when she recovers. Meanwhile, the soil is protected and water has been captured.

The increased use of perennials could also slow, reverse, or prevent the increased planting of annuals on marginal lands, which now support more than half the world's population. Because marginal lands are by their nature fragile and subject to rapid degradation, large areas of these lands now being planted with annuals are already experiencing declining productivity. This will mean that additional marginal lands will be cultivated. This troubling reality makes the development of crops that can be more sustainably produced a matter of necessity. Developing perennial versions of our major grain crops would address many of the environmental limitations of annuals while helping to feed an increasingly hungry planet.

Perennial possibilities

Recent advances in plant breeding, such as the use of marker-assisted selection, genomic in situ hybridization, transgenic technologies, and embryo rescue, coupled with traditional breeding techniques, make the development of perennial grain crops possible in the next 10 to 20 years. Two traditional approaches to developing these crops are direct domestication and wide hybridization, which have led to the wide variety of crops on which humans now rely. To directly domesticate a wild perennial, breeders select desirable plants from large populations of wild plants with a range of characteristics. Seeds are collected for replanting in order to increase the frequency of genes for desirable traits, such as large seed size, palatability, strong stems, and high seed yield. In wide hybridization, breeders cross an annual grain such as wheat with one of its wild perennial relatives, such as intermediate wheatgrass. They manage gene flow by making a large number of crosses between the annual and perennial plants, selecting offspring with desirable traits and repeating this cycle of crossing and selection multiple times. Ten of the 13 most widely grown grain and oilseed crops are capable of hybridization with perennial relatives.

The idea that plants can build and maintain perennial root systems and produce sufficient yields of edible grains seems counterintuitive. After all, plant resources, such as carbon captured through photosynthesis, must be allocated to different plant parts, and more resource allocation to roots would seem to mean that less can be allocated to seeds. Fortunately for the breeder, plants are relatively flexible organisms that are responsive to selection pressures, able to change the size of their resource "pies" depending on environmental conditions, and able to change the size of the slices of the resource pie. For example, when plant breeders take the wild plant out of its resource-strapped natural environment and place it into a managed environment with greater resources, the plant's resource pie can suddenly grow bigger, typically resulting in a larger plant.

Many perennial plants, with their larger overall size, offer greater potential for breeders to reallocate vegetative growth to seed production. Additionally, for a perennial grain crop to be successful in meeting our needs, it may need to live for only 5 to 10 years, far less than the lifespan of many wild perennials. In other words, the wild perennial is unnecessarily overbuilt for a managed agricultural setting. Some of the resources allocated to the plant's survival mechanisms, such as those allowing it to survive infrequent droughts or pest attacks, could be reallocated to seed production, and the crop would still persist in normal years.

Breeders see several other opportunities for perennials to achieve high seed yield. Perennials have greater access to resources over a longer growing season. They also have greater ability to maintain, over longer periods of time, the health and fertility of the soils in which they grow. Finally, the unprecedented success of plant breeders in recent decades in selecting for the simultaneous improvement of two or more characteristics that are typically negatively correlated with one another (meaning that as one characteristic increases, the other decreases, as is typical of seed yield and protein content) can be applied to perennial crop development.

Although current breeding efforts focused on developing perennial grain crops have been under way for less than a decade, the idea isn't new. Soviet researchers abandoned their attempts to develop perennial wheat through wide hybridization in the 1960s, in part because of the inherent

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difficulties of developing new crops at the time. California plant scientists in the 1960s also developed perennial wheat lines with yields similar to the then–lower-yielding annual wheat cultivars. At the time, large yield increases achieved in annuals overshadowed the modest success of these perennial programs, and the widespread environmental problems of annual crop production were not generally acknowledged.

In the late 1970s, Wes Jackson at the Land Institute revisited the possibility of developing perennial grain crops in his book *New Roots for Agriculture*. In the 1990s, plant breeders at the Land Institute initiated breeding programs for perennial wheat, sunflowers, sorghum, and some legumes. Some preliminary genetics work and hybridization research have also focused on perennial maize. Washington State University scientists have initiated a perennial wheat breeding program to address the high rates of erosion resulting from annual wheat production in eastern Washington. In 2001, some of those perennial wheat lines yielded 64% of the of the yield produced by the annual wheat cultivars grown in the region. Scientists at Kansas State University, the Kellogg Biological Station at Michigan State, the University of Manitoba, Texas A&M, and the University of Minnesota are carrying out additional plant breeding, genetics, or agronomic research on perennial grain crops.

The potential for perennial crops to tolerate or prevent adverse environmental conditions such as drought or soil salinity has attracted interest in other parts of the world. The conversion of native forests for annual wheat production in southwest Australia resulted in the rise of subsurface salts to the surface. This salinization threatens large areas of this non-irrigated, semi-arid agricultural region, and scientists there believe perennial crops would use more subsurface water, which would keep salts from rising to the surface and produce high-value crops. During the past decade, Australian scientists have been working to develop perennial wheat through wide hybridization and to domesticate a wild perennial grass for the region. More recently, plant breeders at the Food Crops Research Institute in Kunming, China, initiated programs to develop perennial rice to address the erosion problems associated with upland rice production. It is believed that perennial rice would also be more tolerant of the frequent drought conditions of some lowland areas. Scientists at the institute have also been evaluating perennial sorghum, sunflower, and intermediate wheatgrass for their potential as perennial grain crops.

Vision of a new agriculture

The successful development of perennial grain crops would have different effects on the environment, on life at the dinner table, and on the farm. Producing grains from perennials rather than from annuals will have large environmental implications, but the consumer will see little if any difference at the dinner table. On the farm, whether mechanically harvested from large fields or hand-harvested in the parts of the world where equipment is prohibitively expensive, perennial grains 20 to 50 years from now will also look much the same to the farmer. The addition, however, of new high-value perennial crops to the farm would increase farmers' flexibility.

Farmers could use currently available management practices, such as no-till or organic approaches, but with a new array of high-value perennial grain crops. These would give farmers more options to have long rotations of perennial crops or rotations in which annuals are grown for several years followed by several years of perennials. Crop rotation aids in managing pests, diseases, and weeds but is often limited by the number of profitable crops from which farmers can choose. There are also opportunities to simultaneously grow annual and perennial grain crops or to grow multiple species of perennials together because of differences in rooting characteristics and growth habits. And because perennial grains regrow after seed harvest, livestock can be integrated into the system, allowing for greater use of the crops and therefore greater profit.

Although the environmental and food-security benefits of growing perennial grain crops are attractive, much work remains to be completed. For the great potential of perennial grain crops to be realized, more resources are needed to accelerate plant breeding programs with more personnel, land, and technological capacity; expand ecological and agronomic research on improved perennial germplasm; coordinate global activities through germplasm and scientist exchanges and conferences; identify global priority croplands; and develop training programs for young scientists in ecology, perennial plant breeding, and crop management.

Where, then, should the resources come from to support these objectives? The timeline for widespread production of perennials, given the need for extensive plant breeding work first, discourages private-sector investment at this point. As has occurred with biofuel production R&D, large-scale funding by governments or philanthropic foundations could greatly accelerate perennial grain crop development. As timelines for the release and production of perennial grain crops shorten, public and philanthropic support could increasingly be supplanted by support from companies providing agricultural goods and services. Although perennial grain crops might not initially interest large agribusinesses focused on annual grain crop production, the prospect of developing a suite of new goods and services, including equipment, management consulting, and seeds, would be attractive to many entrepreneurial enterprises.

Although public support for additional federal programs is problematic given the current economic conditions, global conditions are changing rapidly. Much of the success of modern intensive agricultural production relies on cheap energy, a relatively stable climate, and the public's willingness to overlook widespread environmental problems. As energy prices increase and the costs of environmental degradation are increasingly appreciated, budgeting public money for long-term projects that will reduce resource consumption and depletion will probably become more politically popular. Rising food and fuel prices, climatic instability that threatens food production, and increased concern about the degradation of global ecological systems should place agriculture at the center of attention for multiple federal agencies and programs.

The USDA has the greatest capability to accelerate perennial grain crop development. Most important would be the use of research funds for the rapid expansion of plant breeding programs. Funds for breeding could be directed through the Agricultural Research Service and the competitive grant programs. Such investments directly support the objectives of the National Institute of Food and Agriculture (NIFA), created by the Food, Conservation and Energy Act of 2008, which will be responsible for awarding peer-reviewed grants for agricultural research. Modeled on the National Institutes of Health, NIFA objectives include enhancing agricultural and environmental sustainability and strengthening national security by improving food security in developing countries.

As varieties of perennial grain crops become available for more extensive testing, additional funds will be needed for agronomic and ecological research at multiple sites in the United States and elsewhere. This would include support for the training of students and scientists in managing perennial farming systems. Currently, less than $1.5 million directly supports perennial grain R&D projects around the world. USDA funds will provide less than $300,000 annually over the next few years through competitive grant awards, primarily for the study and development of perennial wheat and wheatgrass. Much of the rest is provided by the Land Institute.

Once the suitability of a perennial grain crop is well established, support from federal programs for farmers might be needed to encourage the initial adoption of new crops and practices. Farm subsidies, distributed through the USDA and which now primarily support annual cropping systems, could be used to encourage fundamental changes in farming practices, such as those offered by perennial grain crop development. Public funds supporting the Conservation Reserve Program (CRP) could be redirected toward transitioning CRP lands, once the federal contracts have expired, to perennial grain production. The CRP, initially established in the 1985 farm bill, pays farmers to remove highly erodible croplands from production and to plant them for 10 years with grasses, trees, and other long-term cover to stabilize the soil. Some 36 million acres are enrolled in the program, and most are unsuitable or marginal for annual grain crop production but would be suitable for the production of perennials.

One obstacle to supporting programs necessary to achieve such long-term goals is the short timeframes of current policy agencies. The farm bill is revisited every five years and focuses primarily on farm exports, commodities, subsidies, food programs, and some soil conservation measures. Thus, it is poorly suited to deal with long-term agendas and larger objectives. The short-term objectives can change with changes in the political fortunes of those in charge of approving the bill. The Land Institute's Jackson has proposed a 50-year farm bill to serve as compass for the five-year bills. This longer-term agenda would focus on the larger environmental issues and on rebuilding and preserving farm communities. In the near term, Jackson proposes that, during an initial buildup phase, the federal government should fund 80 plant breeders and geneticists who would develop perennial grain, legume, and oilseed crops, and 30 agricultural and ecological scientists to develop the necessary agronomic systems. They would work on six to eight major crop species at diverse locations. Budgeting $400,000 per scientist-year for salaries and research costs would add less than $50 million annually to the farm bill, a blip in a bill that will cost taxpayers $288 billion between 2008 and 2012.

Some limited federal money has already been awarded for research related to perennial grain through the USDA's competitive grants programs. Most recently, researchers at Michigan State University received funding to study the ecosystem services and performance of perennial wheat lines obtained from Washington State University and the Land Institute. The Green Lands Blue Waters Initiative, a multistate network of universities, individual scientists, and nonprofit research organizations, is also advocating the development of perennial grain crops, along with other perennial forage, biofuel, and tree crops.

Although agriculture has traditionally been primarily the concern of the USDA, it now plays an increasingly important role in how we meet challenges—international food security, environmental protection, climate change, energy supply, economic sustainability, and human health—beyond the primary concerns of that agency. Public programs intended to address these challenges should consider the development of perennial grain crops a priority. For example, programs at the NSF, Department of Energy (DOE), Environmental Protection Agency, and the National Oceanic and Atmospheric Administration and U.S. international assistance and development programs could provide additional incentives through research programs or subsidies.

Currently, no government funding agencies, including the USDA, specifically target the development of perennial crops as they do for biofuels. In the 2009 federal economic stimulus package alone, the DOE was appropriated $786.5 million in funds to accelerate biofuels research and commercialization. The displacement of food crops by biofuel crops recently played a significant role in the rise of global food prices and resulted in increased hunger and social unrest in many parts of the world. Although some argue that biofuel crops should be grown only on marginal lands unsuited for annual food crops, perennial crops have the potential to be grown on those same lands and be used for food, feed, and fuel.

Substantial public funding of perennial grain crops need not be permanent. As economically viable crops become widely produced, farmers and businesses will have opportunities to market their own seeds and management inputs just as they do with currently available crops. Although private-sector companies may not profit as much from selling fertilizers and pesticides to farmers producing perennial grains, they will probably adapt to these new crops with new products and services. The ability of farmers to spread the initial planting costs over several seasons rather that meet these costs each year opens up opportunities for more expensive seed with improved characteristics.

Although the timelines for development and widespread production of perennial grain crops may seem long, the potential payoffs stretch far into the future, and the financial costs are low relative to other publicly funded agricultural expenditures. Adding perennial grains to our agricultural arsenal will give farmers more choices in what they can grow and where, while sustainably producing food for the growing population.

Recommended reading

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