AGRICULTURE

Increased Food and Ecosystem Security via Perennial Grains

Perennial grains hold promise, especially for marginal landscapes or with limited resources where annual versions struggle.

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Despite doubling of yields of major grain crops since the 1950s, more than one in seven people suffer from malnutrition (*1*). Global population is growing; demand for food, especially meat, is increasing; much land most suitable for annual crops is already in use; and production of nonfood goods (e.g., biofuels) increasingly competes with food production for land (*2*). The best lands have soils at low or moderate risk of degradation under annual grain production but make up only 12.6% of global land area (16.5 million km^2) (*3*). Supporting more than 50% of world population is another 43.7 million km^2 of marginal lands (33.5% of global land area), at high risk of degradation under annual grain production but otherwise capable of producing crops (*3*). Global food security depends on annual grains—cereals, oilseeds, and legumes—planted on almost 70% of croplands, which combined supply a similar portion of human calories (*4*, *5*). Annual grain production, though, often compromises essential ecosystem services, pushing some beyond sustainable boundaries (*5*). To ensure food and ecosystem security, farmers need more options to produce grains under different, generally less favorable circumstances than those under which increases in food security were achieved this past century. Development of perennial versions of important grain crops could expand options.

As highlighted in discussions of biofuel production, perennial crops generally have advantages over annuals in maintaining important ecosystem functions, particularly on marginal landscapes or where resources are limited (*6*) (fig. S1). Perennial grain crops would have similar advantages and also produce food. Compared with annual counterparts, perennial crops tend to have longer growing seasons and deeper rooting depths, and they intercept, retain, and utilize more precipitation (*6*–*10*). Longer photosynthetic seasons resulting from earlier canopy development and longer green leaf duration increase seasonal light interception efficiencies, an important factor in plant productivity (*7*). Greater root mass reduces erosion risks and maintains more soil carbon compared with annual crops (*9*). Annual grain crops can lose five times as much water and 35 times as much nitrate as perennial crops (*10*). Perennial crops require fewer passes of farm equipment and less fertilizer and herbicide (*9*), important attributes in regions most needing agricultural advancement.

Obstacles and Opportunities

Past efforts to develop perennial grain crops were limited by technologies and resources of the time. Efforts in the former Soviet Union and the United States to develop perennial wheat in the 1960s were abandoned in part because of plant sterility and undesirable agronomic characteristics (*11*). More recently, programs have been initiated in Argentina, Australia, China, India, Sweden, and the United States to identify and improve, for use as grain crops, perennial species and hybrid plant populations derived from annual and perennial parents: rice, wheat (see the figure on page 1639), maize, sorghum, pigeon peas, and oilseed crops from the sunflower, flax, and mustard families (*11*–*16*). Additional plant taxa have potential to be developed as perennial grains (*11*).

Plants may face physiological trade-offs between seed productivity and longevity; resources otherwise allocatable to seeds may instead be needed belowground to maintain perenniality. However, this would not necessarily prevent perennial grain crops from being high-yielding and economically viable, for at least two reasons.

First, crops are grown for unique characteristics, of which high potential yield is but one. For example, despite lower yield potential, wheat is grown on more cropland than maize, in part because it can be grown in some environments for which maize is not well suited. Similarly, lower-yield perennial crops could be options where higher-yield annuals cannot reliably achieve full yields. In semiarid regions of sub-Saharan Africa, annual crops often use less than 30% of rainfall owing to high rates of water draining below root zones, evaporation, and runoff, which partly explains the meager 1 metric ton/ha yields of annual grains common in such regions (*8*). Perennial crops can reduce surface and subsurface water losses (*8*, *10*) and be grown on highly erodible sites (fig. S1). For example, perennial types of pigeon peas, important food crops and sources of biologically fixed nitrogen, are grown on steep slopes in regions of Malawi, China, and India (*16*).

Second, because they intercept sunlight over long periods of the year and their roots take up deep-soil water and nutrients, many perennials can sustain greater aboveground production per unit land area than our most widely grown annual crops on fertile land-

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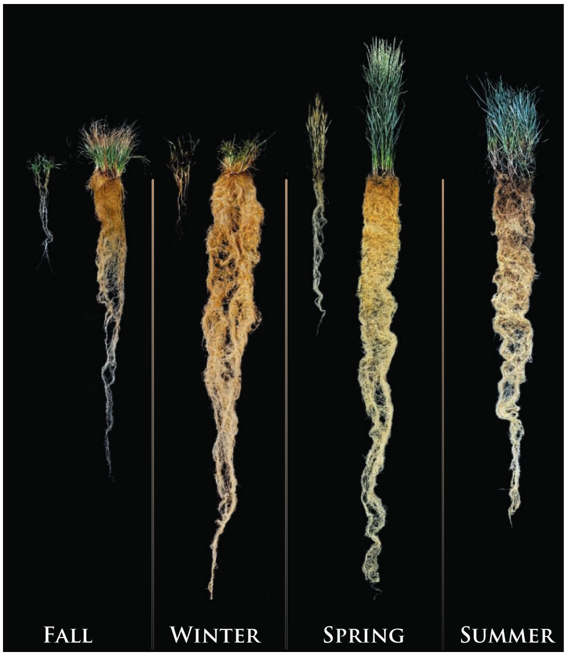

Annual wheat versus perennial intermediate wheatgrass. Seasonal development of annual winter wheat (left of each panel) and its wild perennial relative, intermediate wheatgrass (right of each panel). Plant breeding programs are working to domesticate intermediate wheatgrass (*Thinopyrum intermedium*) and to develop perennial wheat by crossing it with wheat (*11*, *13*).

scapes (*7*, *9*). For example, with no fertilizer inputs and without the benefits of centuries of domestication, the perennial grass *Miscanthus* has 61% greater annual solar radiation interception efficiency by the plant canopy and can produce 59% more aboveground biomass than heavily fertilized, highly domesticated annual maize (*7*, *17*). Regrowth of perennial crop stems and leaves after seed harvest may allow for additional harvests of biomass for livestock feed or biofuels (*13*).

Plant breeding programs must combine multiple desirable traits in perennial grain crops, including (i) reliable regrowth and high grain yield and quality over multiple years; (ii) adaptation to abiotic stresses, such as water and nutrient deficiencies; and (iii) resistance to pests and diseases. Management practices, such as use of fertilizers to minimize nutrient deficiencies, can decrease some pressures. Perennial grain crops could expand opportunities to rotate perennial and annual crops or to grow multiple crops together (*16*), important strategies in reducing pests and diseases. For some traits, perennial crops have advantages over annual counterparts. Wild perennials are often used as sources of disease resistance in annual crop breeding. Offspring from crosses between annual wheat and its perennial relatives are often resistant to diseases to which annual wheat is susceptible (*18*).

Use of molecular markers associated with desirable traits can accelerate breeding programs by allowing plant breeders to characterize and exploit plant genetic variation more effectively (*19*). The ability to determine genotypes of large numbers of plants, covering the entire genome rapidly and inexpensively, can facilitate the combining of desirable genes without the need for field evaluation over many years and in every selection cycle. Naturally occurring genes that permit exchange of DNA between chromosomes of different species or genera can be used to obtain offspring with desirable traits from both parents (*20*). Plant breeders can use genetic modification to introduce new genes, to modify existing genes, or to interfere with gene expression in specific cases. Classically trained plant breeders and agronomists will be needed to fully realize opportunities offered by these innovations.

Additional Needs

Plant breeding innovations can accelerate development of perennial grains. Greater progress, though, requires (i) the initiation and acceleration of breeding programs around the world, with more personnel, land, and technological capacity; (ii) expansion of ecological and agronomic research of improved perennial germplasm; (iii) coordination of global activities through germplasm and scientific exchanges; (iv) prioritization of global regions for introduction of perennial grains; and (v) training of scientists and students in the breeding, ecology, and management of perennial crops.

Perennial grain crops could help meet a wide array of domestic and international challenges (e.g., food security, climate change, and energy supply) (*21*) addressed by U.S. federal agencies, including the Departments of Agriculture and Energy and the Agency for International Development. State agricultural institutions, agencies, and commissions could support perennial grain breeding programs to meet regional needs. International organizations and national governments can assist plant breeding programs in regions of the world most in need of agricultural advancement. The International Rice Research Institute, for example, initiated perennial rice research (*12*) that was subsequently transferred to scientists in China with funding from China's National Natural Science Foundation. As happened during the Green Revolution, private philanthropies can play key roles in supporting transformative plant breeding programs.

Large investments have been committed to developing technologies for biofuel conversion of perennial crops because of their ecological advantages over annual sources, despite their potential to displace food crops. With similar commitments for developing food-producing perennial grains, we estimate that commercially viable perennial grain crops could be available within 20 years.

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