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Perennial grains: from moonshot to farmers' fields

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1 Introduction: why perennials?

From the standpoint of both species diversity and net primary productivity, the vegetation of natural ecosystems is overwhelmingly perennial. Globally only an estimated 6% of all plant species and 15% of herbaceous plant species are annuals (Poppenwimer et al., 2023), and in most natural terrestrial ecosystems, the percentage of plant productivity (net primary production) from annuals is even less. The composition of terrestrial ecosystems becomes perennial because of their ability to outcompete annuals for soil resources and light (McLendon and Redente, 1992; Tilman, 1988). Annuals can play an important role in colonizing and stabilizing exposed soil following severe floods, fires, landslides, and other ecological disturbances, but in a matter of years to decades, perennials regain prevalence through ecological succession (Connell and Slatyer, 1977).

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An underrecognized but highly consequential feature of perennial vegetation is the role that it plays in soil formation. American soil scientist Hans Jenny and Russian soil scientist Vasily Dokuchaev independently identified five "soil forming factors" whose interactions result in the development of different soil types. The factors are parent material (original rock or sediment), climate, topography, organisms, and time (since soil formation began) (Jenny, 1941; Dokuchaev, 1880 [as cited in Amundson and Jenny 1997]). As part of the organism "factor" perennial vegetation plays an outsized influence on the development of fertile functioning soils, as perennials stabilize soils in place and help build soil organic matter as well as structural components such as aggregates and macropores. It is noteworthy that the soils we farm today were developed under the influence of perennial vegetation, and arguably could not have formed under continuous cycles of annuals.

The conversion of forests, grassland, savannahs, and other native ecosystems to agriculture during what some have called the Anthropocene has substantially increased the global cover of annuals both as crop and weed species that appropriate disturbed habitats (Poppenwimer et al., 2023; Mohler, 2001). In natural systems, the prevalence of annual species tends to be a fleeting, early successional ecological response to natural disturbance regimes. In agriculture, annuals persist over very large areas due to human design and work, or in recent decades, the combustion of fossil fuels—natural vegetation needs to be cleared and cleared again for the seeds of annual crops to germinate, establish, and produce seed. Annual cereals, pulses, and oilseeds, or collectively grains, are of particular importance as they are grown on around 70% of croplands globally, and provide a similar percentage of human calories either consumed directly or through consumption by livestock (Glover et al., 2010). The ecological consequences of frequent, repeated disturbances to maintain land in annual grain production are so significant that they threaten the long-term viability of agriculture itself (Amundson et al., 2015). Soil erosion, loss of soil carbon, leaching of nutrients, and reduced precipitation infiltration are among the ecosystem disservices that result from arresting land in a disturbed, early successional stage (Crews et al., 2018).

1.1 Unforeseen consequences of annual grains

The domestication of annual grains took place on multiple continents often in different millennia (Harlan, 1995). It is widely believed that the early stages of converting a wild plant into an agricultural crop—that is, the repeated act of collecting and sowing seeds and raising plants through sexual cycles in which they cross-pollinate—resulted in rapid crop evolution and were unintentional (Cox, 2009). One of the most important domestication traits is "shatter resistance". Shattering is the tendency for the seed of wild plants to detach and disperse away from parent plants. As with most traits, there is typically genetic variation for the shattering trait with some mutants exhibiting little tendency to drop their seed. People in the transition from gathering to farming logically collected the seeds of plants that did not drop their seeds (shatter-resistant genotypes), and by re-sowing these seeds, and caring for them through cycles of sexual selection, shatter resistance became dominant, making it possible to harvest much more grain from a given area of land. Several traits made wild annuals more likely to garner the attention of early farmers than wild perennials (Van Tassel et al., 2010), but maybe none greater than the fact that annuals die at the end of each growing season whereas perennials quite obviously persist. Even though there is ample evidence that Neolithic people gathered seeds from perennial grasses, it doesn't seem there would have been reason or incentive for early farmers to terminate stands of healthy perennials and replant them to fulfill the required sexual cycles needed for crop evolution (Cox, 2009). In fact, the challenge of killing perennials without metal tools would have been daunting.

The implications of humans adopting a food-producing ecosystem predicated on annual crops have been amongst the most consequential defining elements of our species. With smaller human populations, Indigenous peoples all around the world successfully developed highly sustainable agricultures in which the norms and expectations of communities were in relative synchrony with the ecological processes underlying annual crop productivity in specific geographical contexts. In part, this was possible because annual cropping frequently was constrained to landscape positions that were resilient in the face of frequent disturbances such as river floodplains, valley bottom wetlands, or shifting dune soils (Mazoyer and Roudart, 2006). But history is replete with dramatic exceptions in which soil degradation from annual agriculture, especially excess erosion, contributed to the collapse of societies or entire civilizations (Hillel, 1991).

Events of the last two centuries have greatly escalated the impacts of annual cropping. The eight-fold increase in the human population coupled with the extensive harnessing of fossil fuel energy has allowed annual monocultures to be planted on vast landscapes, year after year, with heavy reliance on fossil fuel-derived inputs such as N fertilizers and herbicides to maintain production. Meanwhile, soils continue to erode well beyond replacement rates (Amundson et al., 2015; Olsson et al., 2023), unacceptable losses of nutrients from farmscapes eutrophy water bodies (Bailey et al., 2020), pests develop resistance to pesticides (Jørgensen et al., 2020), and extreme weather events become more frequent affecting crop yields in many farming regions (Hasegawa et al., 2021; Schmitt et al., 2022). For decades, agricultural sciences including agroecology have worked to improve annual cropping systems, but with little acknowledgment that our food-producing ecosystem that depends on vegetation-clearing disturbance to maintain annual crops may simply not be sustainable or even desirable. It is noteworthy, however, that the USDA's Natural Resource and Conservation Service and organizations such as the Soil Health Institute have come close to making such an acknowledgment with their widely touted principles of regenerative agriculture summarized as *minimizing soil disturbance, and maximizing living roots, soil cover and biodiversity* (NRCS, 2024).

1.2 Why perennial grains?

In the last two decades, there has been growing recognition of the ecological functions and benefits of growing perennial crops or integrating wild perennial species into cropping systems (Table 1) (Asbjornsen et al., 2013; Lehman et al., 2015; Scott et al., 2022; Sprunger et al., 2024; Mosier et al., 2021). Interest in perennials has been especially pronounced amongst farmers and organizations promoting soil health and regenerative agriculture (Brown, 2018). This interest includes perennial cereals, pulses and oilseeds, or collectively grains (Crews

Table 1 Commonly reported soil health benefits of perennial species

Ecosystem attribute	Mechanisms of improvement with perennials	References
Soil organic matter/carbon	Greater physical and chemical protection of organic matter with reduced tillage and greater allocation of C belowground via perennial roots	Lavallee et al., 2019 Diederich et al., 2019 Paustian et al., 2019 Siddique et al., 2023
Soil erosion	Continuous living cover and live roots protect and stabilize soil	Gyssels et al., 2005 Cosentino et al., 2015 Nearing et al., 2017 Olsson et al., 2023
Nutrient retention	Root uptake activity is greater for more time per year and frequently to greater soil depths coupled with reduced surface runoff	Sprunger et al., 2018 Hussain et al., 2019 Jungers et al., 2019 Fontaine et al., 2023
Water infiltration and uptake efficiency	Improved soil structure including macropores increases infiltration. Deep roots may access large volumes of soil water	Bharati et al., 2002 McCallum et al., 2004 Basche and DeLonge, 2019 Vico et al., 2023
Functional soil foodweb/ microbiome	Greatly reduced soil disturbance coupled with greater soil C inputs can result in more structured food web and microbial communities	Neher, 2010 Culman et al., 2010 Duchicela et al., 2012 Sprunger et al., 2024

and Cattani, 2018); perennial grasses such as switchgrass or miscanthus for use in producing cellulosic biofuels (Robertson et al., 2017); rotations of annual crops with perennial forages such as alfalfa (Sprunger et al., 2024; Prairie et al., 2023); agroforestry alley crop plantings in which rows of tree crops like hazelnuts, or trees with unique functions such as N fixation, are planted at regular intervals across fields of mainly annual grains (Wolz and DeLucia, 2018); planting of diverse mixtures of native perennial prairie species in "prairie strips" adjacent to croplands on erodible landscapes or adjacent to riparian areas (Mayer, 2023); and perennial pasture rangeland that largely substitutes for corn and soy produced for feedlots (Mosier et al. 2021).

Sociologist Erik Olin Wright wrote extensively on pathways for social transformation invoking a three-step framework consisting of diagnosis and critique, envisioning alternatives, and elaborating strategies of transformation (Wright, 2010). Work on perennial grains has gradually taken shape by advancing through these steps over the last century, starting with many broad critiques of conventional, industrial agriculture (e.g. Howard, 1945; Carson, 1962; Berry, 1977), followed by the emergence of the novel alternative idea to develop perennial grains and grow them in polycultures to capture a wide range of functions that undergird the productivity of natural ecosystems (Jackson, 1980; Cox et al., 2002; Glover et al., 2007; Crews et al., 2016). In recent decades, exploring processes of transformation to perennial grain agriculture involving a wide range of natural and social science disciplines has garnered increasing attention (Streit Krug and Tesdell, 2022; Olsson et al., 2024). In this chapter, we introduce a model of transformation by a transdisciplinary group of researchers starting with plant breeding and expanding to include ecological intensification of cropping systems, farmer adoption, and cultural adoption. We adopt the definition of transdisciplinary proposed by Harris and colleagues (2024) as "research conducted with actors from different sectoral and disciplinary backgrounds to work together on a common mission" (Fig. 1).

2 Perennial crop breeding and improvement

Breeding perennial species involves many unique technical challenges (Van Tassel et al., 2010) but for years, theoretical challenges about whether high-yielding perennial grain crops might be an energetic impossibility were at least as significant amongst the agricultural and ecological research communities. The reasoning was that asking a plant to regrow would mean reduced allocation of resources to grain. This idea has been reinforced by the observation that among wild plants, those that live longer tend to allocate fewer resources to reproductive tissues (Smaje, 2015). However, others have argued that trends in nature do not necessarily provide guidance regarding what can be achieved through plant breeding (Crews and DeHaan, 2015). While perenniality will have

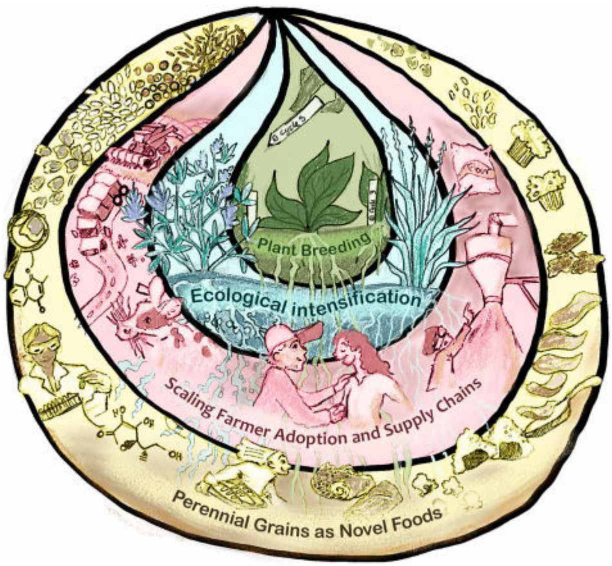

Figure 1 Concentric transdisciplinary research realms supporting a transformation to perennial grain agriculture. The first realm on which the rest depend is breeding and improving perennial grain crop species. As crops become viable, subsequent realms expand to include work on ecological intensification, farm scaling, and cultural adoption of novel foods. Figure by Lydia Nicholson.

a cost of overwintering tissues, perennials might save the cost of rebuilding root systems every year, and more photosynthesis early and late in a growing season could allow perennials to capture more sunlight and water.

2.1 Methods to breed perennial grains

Herbaceous perennials that produce abundant seeds might be achievable through breeding precisely because nature had no mechanism for their creation (Denison, 2015). In wild ecosystems, natural selection tends to either favor herbaceous plant species which live briefly and produce abundant propagules prior to their early death, or it favors species that establish competitive dominance over a patch of soil, live many years, and produce relatively few seeds. Through artificial selection, humans have the capacity to modify the rules governing the "survival of the fittest." While in nature, the rare plants producing the most abundant seed are the annual weedy sort that thrive briefly in disturbed environments and spread their copious propagules far and wide to persist for periods of time in soil seed banks in anticipation of a rare soil disturbance, plant breeders can create a new set of rules (DeHaan et al., 2005). They can measure both longevity and seed production, and only select individuals that are outstanding for both traits. Just as plants that hold onto their seed until harvest would go extinct in the wild but are highly favored for farming, modern plant breeders are able to select dramatically new types of plants, those that are suited to thriving in modern perennial grain cropping systems.

2.2 Wide hybridization between closely related annual and perennial species

There are three general methods that plant breeders are using to develop perennial grains, shaped by the genetic structure of the starting plant materials and their evolutionary histories. The first approach is to use wide hybridization between closely related crops and wild perennial species. When the perennial and annual crop species are close enough relatives, their chromosomes can align with each other during meiosis and genetic information originating from the annual and perennial parents can be exchanged. The result is that genes from the perennial parent that might reduce yield can be freely swapped with the good yield genes from the annual crop, while other genes on the chromosome that are essential for perenniality can be retained.

A clear example of this wide hybridization approach is perennial rice. Because the relatively few essential genes for perenniality that were scattered throughout the genome could be retained while most of the genome is restored to a state very similar to annual rice via back-crossing, perennial rice that yields similarly to annual rice over eight consecutive harvests was developed within decades (Zhang et al., 2022). This achievement is the first high-yielding perennial grain crop and is evidence that theoretical concerns about the possibility of perennial grains were unfounded. Perennial grain sorghum is another crop that is under development using similar methods. Although initially perennial sorghum breeding utilized tetraploids, recent efforts have begun to focus on diploids which allow the exchange of genes between the annual and perennial chromosomes (Cox et al., 2018). Also similar to rice, perennial sorghum could be introduced first in tropical environments where the challenge of winterhardiness is avoided.

2.3 Wide hybridization between distantly related annual and perennial species

The second method for breeding perennial grains is to hybridize distantly related annual and perennial species whose chromosomes are too greatly differentiated to properly pair during meiosis. These projects require some method of chromosome doubling following the wide hybridization step. Through the doubling step, every chromosome obtains a partner derived from its own parental species, with which it pairs during meiosis. The result is that although fertility is restored, there is no built-in reproductive mechanism that can be used to remove yield-reducing genes from the perennial or eliminate longevity-reducing genes from the annual.

Perennial wheat is a clear example of the second major approach. Although efforts to breed perennial wheat began nearly a century ago, the best varieties produced so far have had insufficient survival paired with lower yields than annual wheat (Hayes et al., 2012; Scheinost et al., 2001). Progress of perennial wheat breeding so far may have been limited by existing variation within the annual and perennial parents, since recombination between annual and perennial chromosomes is extremely rare. Therefore, success may depend on generating new variation. One approach is to treat plants with chemical mutagens that induce random changes in DNA (Chapman et al., 2022). By screening large numbers of mutagenized plants, it may be possible to identify plants carrying beneficial genetic changes. For instance, a gene for excessively late maturity that came from the perennial parent might be knocked out through mutagenesis, producing the required early-maturing phenotype.

2.4 De novo *domestication*

The third approach to developing perennial grain crops is to directly domesticate wild perennial species (Fig. 2). This method avoids the complexity that arises from wide hybridization, instead relying on repeated generations of evaluation, selection, and intermating to domesticate the wild species. Key traits that must be identified include shatter resistance, ease of threshing, larger seed, and increased seed yield (Luo et al., 2022). A drawback of this approach is that genetic variation for essential traits may be lacking, or even if present may require an excessive number of generations (and therefore numerous decades) to assemble into viable cultivars.

A promising example of the direct domestication strategy is recent work with perennial "intermediate wheatgrass" or *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey, which is marketed under the trade name Kernza® (Crain et al., 2024). For the remainder of the chapter, we will refer to intermediate wheatgrass as Kernza. While this species has substantial genetic variation for critical domestication traits, allowing for steady improvement, the number of generations required to achieve wheat-like yields is projected to number in the dozens (Bajgain et al., 2022). One exciting development to accelerate breeding has been a method termed genomic selection. With this technique, genetic markers are paired with field data to generate accurate predictions of how genotyped seedlings would perform, were they grown to maturity. Using these predictions, seedlings can be selected and intermated, avoiding years of field evaluations and accelerating the domestication process dramatically (Crain et al., 2021). Another rapid domestication approach that is being investigated with the species is genome editing (DeHaan et al., 2020).

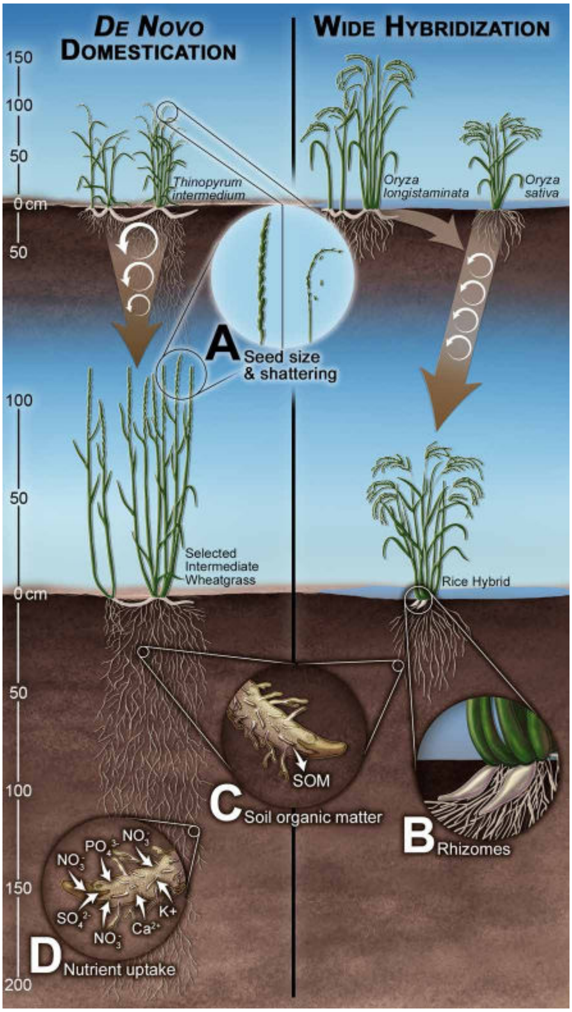

Figure 2 Two approaches to breeding perennial grains and expected soil ecosystem functions. *De novo* domestication is depicted on the left panel using *Thinopyrum intermedium* (intermediate wheatgrass or Kernza®) as an example. Two traits commonly under selection in domestication programs are an increase in seed size and a reduction in shattering (A). Wide hybridization is depicted on the right panel using a cross between *Oryza sativa* and *Oryza longistaminata* to develop a perennial rice. A central objective of the hybrid cross in rice is to create a crop that resembles the preexisting annual species in yield and seed quality while introducing rhizomes from the perennial, *O. longistaminata* (B). The relative contribution of the annual and perennial parent to the genome of the hybrid varies by crop type. There is mounting evidence that root turnover and exudates from the large root systems of perennial grains contribute to soil organic matter accumulation (C) and efficient nutrient uptake (D).

In this method, knowledge of domestication genes in crop species would be used to produce directed mutations that immediately result in domestication phenotypes (Chapman et al., 2022). If gene editing of plants becomes routine, this technique could accelerate the domestication of many perennial plant species.

In addition to the species already mentioned, there is a wide array of potential perennial grain crops (Cox et al., 2006). Perennial sunflower through wide hybridization is a possibility, and direct domestication of *Silphium integrifolium*, a sunflower relative, is underway (Vilela et al., 2018). Perennial flax (*Linum* spp.) is being explored as a perennial food and fiber crop (Tork et al., 2019) as is perennial barley (Westerbergh et al., 2018). Legumes are a critical plant family in agriculture, due to their capacity for symbiotic nitrogen (N) fixation. There are several candidate perennial grains in this family (Cox et al., 2002), with sainfoin (*Onobrychis viciifolia* Scop.) now entering the domestication pipeline (Karabulut et al., 2023).

Recent advances in high-throughput genotyping, genome sequencing, and genome editing, have made high-yielding perennial grains an achievable objective with a timeline of decades rather than a century or more (DeHaan et al., 2023). With rice and Kernza providing proofs of concept for wide hybridization and domestication approaches, there is new interest in exploring other candidates for new crop development (Streit Krug et al., 2023a).

3 The role of perennial grains in promoting ecological intensification

After breeding, the next most important realm of research in advancing new perennial crop species is learning to grow them. Conventionally, this work would fall under the discipline of agronomy, focusing on practices such as row spacing, seeding rates and timing, pest control, and fertility management. Here we subsume these traditionally agronomic considerations under the umbrella of ecological intensification (EI), emphasizing the agroecological objectives of supplanting human labor, mechanization, and purchased inputs with ecological processes to the greatest extent possible (Bommarco et al., 2013). Increasing plant diversity in time and/or space is the most powerful tool for achieving these objectives, but other approaches exist such as burning, grazing, mowing, and relay planting. Below we explore the new possibilities and challenges that perennial grains present for achieving ecological intensification objectives.

3.1 Diversity in perennial grain cropping systems

Millennia of farmer practices and decades of research have shown that increasing biodiversity in agricultural systems, at both field and landscape scales, can help sustain productivity with fewer inputs and environmental externalities (Cappelli et al., 2022; Gliessman et al., 2023). Field-scale diversification can happen in time, with crop rotations, or in space, with mixed or intercropping systems. In the case of perennial grain cropping systems, benefits of diversification can include pest regulation and suppression (Law et al., 2022; Dick et al., 2018), economic revenue diversification (Pinto et al., 2022), floral resources to support higher insect biodiversity (Butters et al., 2022), and N-provisioning via the addition of a legume (Reilly et al., 2022; Mårtensson et al., 2022; Crews et al., 2022).

3.2 Diversity through rotations

Crop rotations are an agroecological management tool commonly used to add diversity in time to improve soils and reduce pests in annual cropping systems. Perennial agriculture by definition precludes the frequent use of rotations to achieve certain EI objectives, such as breaking pest cycles and inducing rapid mineralization of legume cover crop residues. However, longer rotations involving only perennials or perennials and annuals can result in EI benefits such as improvement in soil structure and N fertility (Ryan et al., 2018a). To some degree, when tillage is used to facilitate crop succession, soils experience cycles of regeneration and degradation involving negative and positive net carbon balances and other soil health dynamics (Abraha et al., 2018). Infrequent rotations of perennial grains with annuals involving minimal or no-till methods may preserve some soil quality benefits derived from perennial grains, but the persistence of benefits will vary with crops and locations and will be an active area of research for some time (Ryan et al., 2018a; García-Préchac et al., 2004).

3.3 Diversity through intercropping

Spatial diversification via strip, mixed, or relay intercropping can provide similar benefits to temporal diversification through rotations while retaining the soil health attributes associated with reduced tillage. Non-legume companion crops can offer benefits such as weed suppression or pest reduction (Bybee-Finley et al., 2018); however, to date, research and practice in perennial grain intercrops have largely focused on intercropping with legumes (Reilly et al., 2022; Mårtensson et al., 2022; Crews et al., 2022). Central to the successful practice of intercropping is effective resource complementarity and partitioning, in which companion species utilize different resource niches of water, nutrients, or sunlight, or different quantities of these resources at different times (Brooker et al., 2014). In this way, intercrops can capture a greater quantity or range of resources than sole crops (Duchene et al., 2017).

3.4 N fertility through intercropping with legumes

Legume-grass intercrops have been widely grown in low-input traditional farming systems around the world for millennia, and the multi-year lifespan of perennial grains presents new opportunities and challenges. Legumes can access a pool of N inaccessible to grasses—atmospheric N—and over time contribute to the N-supplying capacities of soils (Crews et al., 2016). Achieving N synchrony—that is the matching of N demand by the non-fixing cereal crop with sufficient N supplied by soil pools that originated from N fixation—will require considerable research in selecting and managing complementary intercrop species for different climates and soil types.

Belowground N transfer from legumes to neighboring plants happens primarily through the decomposition of roots and nodules, the root exudation of N-rich compounds, or the transfer via mycorrhizae of N between plants (Thilakarathna et al., 2016a). Perennial legumes have been found to fix more N or fix N more consistently than annual legumes (Schipanski, 2012), but because perennial legumes enrich the soil primarily through root turnover and exudation, it typically requires more than one year to build up sufficient organic N reserves in the soil to support the N needs of the intercropped cereal (Thilakarathna et al., 2016b). With Kernza-legume intercrops, studies have found a 3–4 year delay in the facilitative effects of the intercrop, perhaps explained by the timing of legume root turnover (Tautges et al., 2018; Reilly et al., 2022; Crews et al., 2022). Possible strategies to manage this early-stand asynchrony include adding N during establishment years or sowing perennial cereal grains into previously established stands of a perennial legume (Fig. 3). Further research is needed to explore these and other N synchronization strategies in perennial legume-cereal intercrops (Crews et al., 2016; 2022).

Beyond provisioning N to cereals, perennial cereal-legume intercrops also provide a source of economic diversification for farmers, as the addition of an N-rich legume increases forage quality that can be harvested in addition to grain (Law et al., 2022). At one or more times per year, depending on the growing season length, precipitation, and timing of grain harvest, perennial cereal and legume biomass can be baled together resulting in increased nutritive value of the forage (Favre et al., 2019).

An additional advantage of intercropping a perennial cereal with a legume is the potential to mitigate grain yield decline which has been found to occur with Kernza after the second year of production (Jungers et al., 2017). Yield decline has been attributed to genetic, physiologic, pathogenic, and agronomic factors, one of which is N limitation (Jungers et al., 2017). There is some evidence suggesting that intercropping alfalfa or other legumes with Kernza can reduce yield decline under certain conditions (Tautges et al., 2018; Crews et al., 2022).

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Figure 3 A four-year-old intercrop of the perennial legume alfalfa (low stature with dark green leaves) and the perennial cereal Kernza (tall stature with light brown seedheads). The alfalfa was sown in a solid stand six years before the photo. In year two, strips of alfalfa were terminated using an undercutting implement or an herbicide and sowed to Kernza. The cropping system includes crop elements of a rotation and an intercrop. Photo by Tim Crews.

While most research to date on perennial grain intercrops has focused on legumes grown with Kernza, intercrops with other developing perennial grains are worthy of exploration. Pulse-cereal intercrops like pigeon pea and perennial sorghum could provide a mix of forages and edible grains (Isgren et al., 2020). Integration of self-seeding winter annuals like vetch into taller stature perennial grain crops like silphium could augment soil N and could minimize exposed soil.

4 The role of perennial grains in sustainable crop protection

As with intercropping for resource use efficiency and fertility management, perennial grain cropping systems present both new opportunities and challenges in insect pest and pathogen management. Many insects and pathogens that damage annual grains are managed through tillage, for example, gray leaf spot (Ward et al., 1999) and wireworms in maize (Saussure et al., 2015), and Hessian fly in wheat (Schmid et al., 2018). Others are managed through crop rotation, such as wheat blotch agent *Pyrenophora triticirepentis* (Jalli et al., 2021), take-all caused by *Gaeumannomyces graminis* in wheat (Paulitz et al., 2010), and the western corn rootworm in maize (Gray et al., 2009). Perennial plants outside of cropping fields can serve as continual reservoirs or "green bridges" by providing overwintering refuges for pathogens such as perennial foxtail barley for Barley yellow dwarf virus (Rashidi et al., 2021) and pests such as European buckthorn for soybean aphids (Heimpel et al., 2010). Reduction or elimination of tillage and rotation in perennial grains could therefore potentially lead to pest and pathogen accumulation, particularly of specialists on that crop.

In Table 2, we compare characteristics of perennial grains with two crop types that already exist on agricultural landscapes—annual crops and woody perennials. Since perennial grains fill a niche that overlaps to a certain degree with annual grains and woody perennial systems, we have the opportunity to draw pathogen and pest management strategies from both. A few examples reviewed here are reduced or targeted non-tillage disturbance, utilizing within-crop genetic diversity, and intercropping.

4.1 Reduced and targeted soil disturbance

We know from research in no-till cropping systems that reduced soil disturbance may benefit some pathogens and pests, but perennial systems present unique conditions of continuous vegetated cover and increased belowground C allocation. Reduced disturbance in perennial systems can increase litter decomposition, which allows saprotrophic microbes to compete with disease-causing organisms. In perennial grasses, beneficial microbes are stimulated by root turnover (Warembourg and Estelrich, 2001; Culman et al., 2010) that promotes disease suppressiveness in the soil due to high microbial activity of antagonists (Weller et al., 2002; Rasche et al., 2017). In Kernza, bacterial leaf streak (*Xanthomonas translucens*) infection decreases over time due to a reduction in rain splash dispersal from exposed soil (unpublished data, Turner). With a robust and diverse microbial community of antagonists, perennial grains have the potential to promote a stable, resilient soil food web (Culman et al., 2010; Sprunger et al., 2024).

Targeted, non-tillage disturbance can be useful in perennial systems for pest management. Controlled burns and grazing can effectively remove

Table 2 General characteristics of annual grain crops, perennial grain crops in commercial production or in development, and woody perennial crops.

Annual grains	Perennial grains	Woody perennial crops
Tilled annually	Tilled every 3+ years	Tilled infrequently or never
Crops rotated annually	Rotation after 3+years	No rotation
Determinate grain set	Determinate or indeterminate	Determinate or indeterminate
Establish quickly and vigorously	Some establish quickly, others take 2 years to bear grain	Can take many years to produce yield
Pathogens and insect pests generally known	Some pathogens and insect pests are known, others are novel	Pathogens and insect pests generally known

residue and decrease detrimental pathogen populations (Cox et al., 2005). Trimming silphium plants to reduce or delay flowering has been found to reduce inflorescence infestations by its specialist pest *Eucosma giganteana*, especially when combined with as little as a single application of insecticide (Vilela et al., 2020; Murrell et al., 2023).

4.2 Crop protection through genetic diversity

Each perennial crop created through recent domestication or hybridization contains vast genetic variation. Kernza is estimated to have many more genes for free threshing than fully domesticated crops like wheat and barley. In Kernza, there are an estimated 304 genetic loci controlling brittle rachis, 187 for shattering, and 251 for controlling seed length (Crain et al., 2022). Within-crop genetic diversity allows for recombination and new combinations of alleles between plants grown in the same field. It limits the abilities of pests and pathogens to evolve virulence or circumvent host defenses by reducing selection pressure (Gould, 1991).

While perennial grains will harbor some pathogens, these crops are frequently poor hosts due to strong resistance, plant defenses, and within-crop diversity. For example, perennial grasses are infrequently infected and low rates of transmission are reported for wheat streak mosaic virus vectored by wheat curl mite (Ito et al., 2012). Many resistance genes have been introduced from intermediate wheatgrass into wheat to improve wheat resistance pathogens including stem rust, stripe rust, powdery mildew, barley yellow dwarf, and wheat streak mosaic (Bajgain et al., 2022).

Annual wheat and sorghum are crops that are typically released as inbred lines with a high degree of genetic uniformity; however, perennial sorghum and wheat are examples of crops being developed that will be released and grown in multi-lines to increase the diversity and resilience of the cropping system. This strategy has been demonstrated to be effective in common beans (Botelho et al., 2011) and small grains for a wide range of specific and general pathogens (Mundt, 2002).

4.3 Crop protection through species diversity

As described, annual crop diversity in smallholder farming systems has commonly been deployed both in rotations and intercropped polycultures whereas, in mechanized larger scale production systems, it is mainly achieved through crop rotations (Smith et al., 2023; Ghosh et al., 2019) or planting cover crops in fallow periods between cash crops (Kaye and Quemada, 2017). Diversifying perennial grain agroecosystems relies to a greater extent on intercropping but still features rotations on a semi-decadal timeframe, more closely resembling patterns of plant diversity in natural ecosystems.

Intercropping annual grains has been shown to successfully disrupt and reduce insect herbivore populations (Root, 1973; Yousefi et al., 2024). Ideally, intercrop species combinations simultaneously advance multiple goals of EI (e.g. fertility generation and pest suppression) as well as improve farm economic viability. For example, in Sub-Saharan Africa, annual sorghum is intercropped with *Desmodium intortum* to provide N, suppress *Striga* weeds, and reduce stem borer infestations (Khan et al., 2006). This system could be adopted for perennial sorghum as well.

The use of perennial groundcovers is another intercropping option for managing perennial grain pathogens and pests. Grapes intercropped with exotic grasses can reduce infection by the root pathogen *Ilyonectria liriodendri* (Vukicevich et al., 2018). Groundcovers can also increase natural enemies of insect pests in apple orchards (Judt et al., 2023). In the perennial oilseed silphium (*Silphium integrifolium*), we found that intercropping with foxtail millet significantly reduces rust infection (Murrell and Turner, unpublished).

4.4 Crop protection and weed competition

Weeds establish and thrive in agroecosystems whenever crops fail to fully utilize the resources of sunlight, water, and nutrients (Liebman and Staver, 2001). Tillage is the most common way to temporarily reduce or terminate weed competition to ensure that crops have sufficient resources to establish and close canopy. By eliminating competing vegetation, however, tillage commonly increases future weed pressures by liberating essential plant resources in excess of what immature annual crops can utilize. Compared to annual grains, perennial grains make possible heightened degrees of crop competition with weeds, resulting in weed suppression. For example, many growers have found that once established, the extensive root system and continuous ground cover of the perennial grain Kernza functions as a weed-reducing component of a crop rotation (Lanker et al., 2020).

The role that differential plant resource availability plays in determining weed dynamics of annual and perennial systems is paramount, but the presence or absence of tillage goes beyond plant competition in influencing weed demography and diversity (Meiss et al., 2010). For example, the seeds of many weed species require soil disturbance to break dormancy. The lack of disturbance in perennial systems can result in extended periods of seed dormancy in which seed predation or decay can reduce the soil weed seed bank (Petit et al., 2018). In the absence of regular soil disturbance, perennial agroecosystems may also accumulate litter on the soil surface that can function as a weed-suppressing mulch when sufficiently developed (Meiss et al., 2010).

Challenges can arise with perennial grains during their establishment year as their shoots can be relatively slow to develop, allowing weeds with

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higher aboveground relative growth rates to establish and thrive. Even after establishment, if perennial grain species do not produce abundant tillers or rhizomes, or are planted in wide row spacings that maximize yield but leave some light and soil resources under-utilized, weed populations can become competitive (e.g. Zhang et al., 2022). Another predictable ecological tendency in perennial crops that will require greater attention to attenuate is the shift from annual to perennial weed communities as stands age featuring species such as dandelion (*Taraxacum officinale*) and field bindweed (*Convolvulus arvensis*) (Meiss et al., 2010; Law et al., 2021).

Crop diversity, whether deployed in rotations or in intercrops has been shown to reduce weed competition in annual grains (Smith et al., 2023; Liebman and Dyck, 1993) and especially in crop species that only achieve partial weed suppression in monocultures (Gu et al., 2021). Less work has been carried out evaluating how diversity in perennial grain agroecosystems contributes to weed suppression. Limited research suggests that when care is taken in developing crop rotations or communities with complementary functions (e.g. an N-fixing legume and cereal) and resource partitioning (e.g. deep-rooted crops grown with shallow-rooted crops), diversity can improve significantly on the weed suppressing performance of perennial grains grown in monocultures (Picasso et al., 2008; Law et al., 2021).

Perennial grain crops present a wide range of new possibilities for advancing versions of EI. The potential is great for maximizing the use of soil and light resources in time and space with resource partitioning intercrop designs. Similarly, the potential to develop well-structured and functional microbial communities belowground and beneficial insect communities aboveground is compelling. However new EI opportunities also come with tradeoffs, as time-tested pest and fertility management techniques developed for annual crops such as rotations or tillage are less effective or applicable in perennial systems. The history of new crop introductions and human migrations reminds us that humans have repeatedly demonstrated cultural processes of learning new ways to farm.

5 Increasing farmer adoption and supply chain development

The combined total area of land currently planted to perennial rice and Kernza is under 25 000 hectares (Zhang et al., 2022; Kernza.org, 2024). While this area has grown rapidly in recent years and is expected to continue to grow, it remains a small fraction of the approximately one billion hectares globally planted to annual grains (Monfreda et al., 2008). Perennial grains research has historically focused on breeding and growing new crop species, and these priorities will persist into the future, but if newly developed perennial grains are going to be adopted by farmers on a large percentage of land currently dedicated to annual grains, research into scaling for a perennial transition is essential. We predict that the adoption of perennial grain crops and cropping systems will follow the principles of adoption of other new technologies in agriculture once high-yielding varieties exist and are accepted by consumers as valued foods; namely, scaling out and scaling up (Figure 4) (Seifu et al., 2020). Scaling out primarily relies on farmers to try growing a perennial grain, and then scaling from individual fields to more fields, from few farmers to many farmers, and from small regions to larger regions. Scaling up requires institutional changes that incentivize and reduce risk, promoting systemic adoption through supply chain development, policy change, and institutional support (Seifu et al., 2020; Schut et al., 2020; Sartas et al., 2020). Both types of scaling are critical for perennial grains—on the farm, in food and beverage companies' products, and for consumers.

5.1 Scaling out perennial grains via farmer adoption

Integrating perennial crops is widely understood by farmers and researchers interested in ecological intensification to be one of the most robust and straightforward ways to build soil organic matter and improve soil health in general (Prairie et al., 2023). Still, farmer decision-making around perennial grain adoption is complex because it requires a whole-systems approach to implementation. A framework developed by Han and Niles (2023) uses four elements to understand farmer adoption of sustainable agricultural practices such as perennial grains: entirety, variability, sophistication, and longevity (Table 3). We use this framework for understanding the motivations, innovations and criteria farmers consider in adopting and scaling out Kernza.

Entirety is defined by the extent to which an innovation is adopted (Han and Niles, 2023). For example, no farmers in the United States are growing

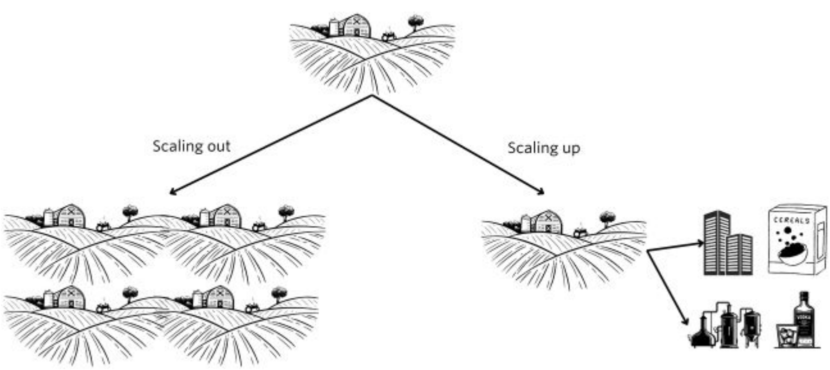

Figure 4 Scaling out requires farmers expanding adoption into new fields and regions. Scaling up requires institutional changes (such as supply chain development) that incentivize change.

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Table 3 Adoption elements and their definitions with examples of how these are realized for Kernza perennial grain. Adapted from Han and Niles, 2023.

Adoption element	Definition	Example in Kernza
Entirety	The degree to which an innovation is adopted	Small plots as trials during BMP development
Variability	Use of variability of a technology	Use of different varieties in different geographies, use of other crops as they enter commercializationIntercropping with legumes
Sophistication	Use of practices that are complementary or enabled by adoption to achieve additional benefits	Grazing and haying Kernza, especially when mixed with legumes
Longevity	Temporal changes in adoption: discontinuation and extent of adoption	New producers begin growing and older stands are rotated out of productionSome producers maintain the number of acres by planting new acres

Kernza on their full acreage. Instead, farmers initially trial the crop, typically beginning with between 5 and 20 acres. This scale of experimentation allows farmers to develop their own versions of best management practices (BMPs). BMPs for established crops exist on county or soil-type bases, usually produced by government agencies or universities. The lack of comprehensive data for new crops like Kernza means that farmers must themselves experiment or work with institutions to determine growing practices.

Variability pertains to the number or types of versions of the innovation under adoption (Han and Niles, 2023). In the case of Kernza, farmers may adopt one or more varieties of the crop. As new perennial grains emerge and are available for on-farm production, farmers will likely vary the species and areas they incorporate into their rotations and management plans.

Sophistication of adoption refers to an evolutionary process by which innovations are bridged with complementary practices or re-imagined to deliver greater benefits and/or functionality (Han and Niles, 2023). In the case of Kernza, for example, 78% of farmers surveyed in 2022 and 62% of farmers in 2023 reported acres that had uses other than grain only (Peters, 2022; Fancher, 2023). In some cases, farmers grazed the fields or harvested hay and/or straw. Some farmers planted Kernza with a companion crop legume (often alfalfa or white clover) as these companions are known to increase the forage value.

Longevity of adoption acknowledges that adoption is not a linear process. It can accelerate, or retard, and can also be discontinued either because the innovation does not meet expectations, or because the broader circumstances surrounding adoption change (Han and Niles, 2023). In the case of new perennial grain crops, longevity is still being understood. It is influenced by on-farm factors such as an individual farmer's success with the crop, soil conditions, or storage infrastructure. Additionally, longevity is influenced by factors that are related to scaling up.

5.2 Scaling up perennial grains via supply chain development

Infrastructure, policy, and marketplace support are necessary to ensure farmers adopt perennial grain crops long-term by creating market pull. Developing the infrastructure for perennial grain crops will require investment in "The Missing Middle," which connects food production to food consumption (Veldhuizen et al., 2020). This common disconnection between producers and consumers happens at different geographical scales, including local, regional, national, and global. For Kernza, entrepreneurs have successfully filled the gap by creating businesses that contract grain from farmers, process that grain (clean and dehull), and create their own consumer packaged goods (CPGs) for sale. These businesses operate at the local and regional scales for grain production and processing, but sell CPGs nationally, giving them access to larger consumer markets.

Consumers must also want to eat and be willing to purchase perennial grains. A small number of consumers interested in climate change and environmental degradation may purchase Kernza, but a larger number of consumers are interested in health claims such as "high in fiber" or "high in antioxidants." Pursuing research that will allow those claims to be made by companies may increase the number of consumers purchasing Kernza. For example, quinoa entered the market, and its popularity expanded because of health claims such as "gluten-free" and "complete protein." This desire on the consumer end helps drive scaling up through market pull. This model may be replicable on the regional scale, but in locations where it is most successful, it is due to friendly public policy at the farm and value chain levels.

5.3 Public support policies to enable adoption and scaling

Publicly funded assistance programs in established crops help incentivize farmers and mitigate production risks. For example, crop insurance and crop subsidies provide safety nets that prevent farmers from economic catastrophe even in the event of complete crop failure. Developing these public assistance programs requires large amounts of on-farm yield data. For novel perennial grains, these data do not currently exist. Additionally, in the United States, Kernza and other perennial grains fall in between categories where public funding is not readily available. They are not commodity crops, but they do not qualify as specialty crops either since specialty crops do not include grains. Farmers, instead of depending on public assistance programs, must rely on research grants or the social responsibility commitments of food and beverage companies to provide favorable contracts for producing the new crop. This relational aspect of new crop adoption could potentially cause re-entrenchment of social norms so that new crops, if successful, could continue to be grown by those with dominant-system privilege. The analysis of this potential is beyond the scope of this work but is worth identifying for further investigation.

Creating public policy to address the Missing Middle is also necessary. For Kernza, the State of Minnesota has created a value chain development fund through legislative appropriations to the Minnesota Department of Agriculture. This fund allows businesses supporting perennial grains and other continuous living cover (CLC) crops to apply for grants for infrastructure creation (Minnesota Department of Agriculture, 2024). This unique program could be replicated in other regions and for other perennial grain crops as they enter the marketplace. Creating an environment for adopting perennial grains over the long term is critical since it helps create pathways to the marketplace.

Ultimately, the adoption of perennial grains by farmers hinges to a signficiant extent on access to markets. To date, the Kernza marketplace has been dominated by specialty market uptake such as organic. Farmers hoping to sell this new grain into readymade markets have been disappointed because of the fickle nature of new crop adoption by businesses and consumers. As friendly policies continue to promote perennial grains, Kernza markets may become more reliable, as has been the case with other new technologies in the sustainability space, such as solar and wind energy.

Kernza provides an example for understanding how perennial grain crop adoption is being realized. Both scaling out and scaling up are necessary and analyzing entirety, variability, sophistication, and longevity gives us an understanding of the complexity of adoption decisions for farmers with regards to scaling out. New crop scaling up requires farmers, policymakers, businesses, and other stakeholders to be aligned toward creating the environment (infrastructure, policy, and markets) for system-wide adoption to occur.

6 Perennial grains as novel foods

A series of interconnected questions spanning the various phases of perennial grain development can help us understand how these new crops can become staple foods. Are they safe to eat? How can they be eaten? How are they taken from the field to the plate? Will people buy them? Answers to these questions can be found from the point of identification of an herbaceous perennial as a viable perennial grain candidate, through the research and development leading up to the release of a commercially viable crop, and beyond to the utilization and adoption in different crop and food systems.

6.1 What makes a new food edible and desirable

Plants possess and express an enormous diversity of chemical compounds to discourage everything from animals to microbes from eating them. Domestication has not been halted by the presence of toxic compounds (Gepts, 2003). Several crop species have retained toxic or unpalatable compounds, although at reduced levels in most cases, as evidenced by cyanogenic glycosides in cassava (Ndubuisi and Chidiebere, 2018), saponins in quinoa (Otterbach et al., 2021), and alkaloids in lupines (Ohmiya et al., 1995). Genetic changes to remove these compounds would, in general, render the plants vulnerable to attack by insects and pathogens (Mithöfer and Boland, 2012). Therefore, various techniques, such as roasting, fermentation, leaching, and drying, have necessarily been adopted for detoxification and are also often used to increase the palatability of plant foods (Johns and Kubo, 1988). In certain cases, these techniques allowed for the consumption of the plant prior to domestication, thus supporting initial human and plant interactions that could then lead to starting a selection process. Ethnobotanical literature provides a useful reference point from which to investigate the questions of whether a perennial grain is safe to eat and how might it be eaten. Traditional and modern processing techniques will likely be required to take a perennial grain from field to plate, and the extent and intensity of processing may change in response to advances through breeding during further domestication.

Balancing the beneficial nutrients and undesirable compounds that may be present in perennial grains can be achieved through both breeding and processing techniques to make them safe to eat, more palatable, or more nutritious. Using lupines as an example, leaching with water is used to remove bitter alkaloids, while selective breeding has produced cultivars with reduced alkaloid content. The complexity of defining nutritional quality can be organized through different categories, with each category possessing an increasing depth. For example, each of the macronutrients (e.g. fat, minerals, protein, carbohydrates) can be broken down into their constituents, such as amino acids, fatty acids, and micronutrients. Exogenous (e.g. mycotoxins) and endogenous compounds (e.g. phytic acid) may also be present and could have health-beneficial or detrimental effects. Layered on top of the depth of nutritional quality is the reality of how the perennial grain has been processed and how it has been prepared in the resulting food matrix, which may impact the availability of nutrients and how easily they can be digested and absorbed by the body. A robust understanding of nutritional quality must therefore explore each of these dimensions over time to untangle the overall complexity, which can be a daunting task and exciting endeavor if little is known and there is much to discover.

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6.2 Regulations and policies governing new foods

In many countries, government regulations are in place to provide a comprehensive and thorough framework for assessing the safety of new foods like perennial grains. For Kernza, the first commercially available perennial grain in the United States, the Food and Drug Administration's Generally Recognized as Safe (GRAS) status has been secured. The GRAS dossier, as well as the review by Bharathi et al. (2022), provide a comprehensive, although not exhaustive, summary of what is known of Kernza's nutritional quality and food science. At the time of writing, Novel Food status is being pursued for Kernza® through the European Food Safety Authority. In most countries, similar regulatory requirements must be met to bring Kernza, or other novel grains, to market. The development of hairless canary seeds provides another example of bringing a new human food crop to market. Innovations in breeding, to remove carcinogenic silica fibers from the seeds, combined with innovations in processing and food science led to successful market introduction in the United States and Canada (Mason et al., 2018).

The Land Institute is currently pursuing GRAS status for perennial Baki bean™, a novel pulse crop domesticated from sainfoin (*Onobrychis viciifiolia*). Several articles have been published recently to demonstrate the potential of Baki bean as a novel pulse crop (Craine et al., 2024a, 2024b, 2023). While navigating governmental regulations can be resource and time intensive, evidence-based demonstrations of safety are essential for proper due diligence and to confidently bring a new human food to market. This is one part of the answer to the question of how to get perennial crops from field to plate, and essential prior to asking the question of if people will buy it.

7 Challenges and opportunities for improving adoption of perennial grains

We know of no newly developed grain that has been broadly introduced into the human diet in hundreds if not thousands of years (Cox, 2009). Thus, there is little previous experience to inform how best to facilitate the adoption of a novel grain, and which group of people is most likely to adopt it. A perennial transformation of agriculture also rests on farmers adopting novel cropping systems that differ substantially from what they have historically employed. There is a recent and dramatic example of farmers in several major grain-producing countries rapidly adopting a novel cropping system—herbicide-tolerant crops (Bonny, 2009). While it is tempting to consider the remarkable adoption rate of herbicide-tolerant technologies as a relevant model for future perennial grain cropping systems, the historical roots of herbicide tolerant seeds suggest otherwise.

7.1 Inertia from the seed and agrochemical input industry

The technologies needed for cultivation of annual crops have been a focus of industrial interest since at least 1796 when the iron moldboard plow was first patented, and then further improved by several patents by John Deere (Lal et al., 2007), still the world's leading manufacturer of agricultural machinery.

Seeds were long seen as a non-commercial good because farmers could select the best kernels from their harvest to use as seeds for future cultivation, the very mechanism of domestication and breeding. In economic terms, seeds were largely considered a public good (Halewood, 2013) until the first commercial hybrid corn seeds emerged in the 1920s. This was an outcome of what has been described as "one of genetics' greatest triumphs" (Crow, 1998). The plant breeder Henry A. Wallace (later US Vice President under FDR) was the first to take commercial advantage of this and established the Hi-Bred Corn Company in 1926. (It later changed its name to Pioneer Hi-Bred and is now part of Corteva).

The chemical industry has been inextricably linked to the evolution of agriculture, particularly since the invention of the Haber-Bosch process of synthesizing ammonia from atmospheric nitrogen gas (N_2) in the early twentieth century. The first commercial factory was opened in 1913 (although mainly used for making explosives until the end of WWI). Because annual grains have a very low nutrient uptake efficiency, about 50% only, the possibility to add large amounts of plant available N boosted crop yields substantially.

Weeds have always been a serious problem in agriculture as they represent a logical ecological response to the field preparation required to grow annual crops (Mohler, 2001). Chemicals for killing weeds (e.g. sea salt) have been applied for a long time but became a major commercial commodity in the 1940s with the invention of 2,4-D herbicide, still on the market under various brands. The most widely used herbicide, glyphosate, was invented in 1970 and became commercial in 1974 by Monsanto under the brand Roundup. The last patent for glyphosate held by Monsanto expired in 2000. But long before that, already in the 1970s, Monsanto and other agrochemical companies had started to experiment with crops that had been engineered to be resistant to herbicides. This was a technology that promised to increase the profits for herbicide manufacturers substantially and was even seen as essential for companies, as expressed by the Calgene vice president, "If you have herbicide tolerance, you're going to expand market share. If you don't, you're going to lose" (Gladwell, 1988).

From the above short history, it is clear that annual crops have provided a range of business opportunities that have become the foundation of very large and influential industries—many of which maintain an oligopolistic status today. A more recent restructuring of the agricultural inputs industry involves the agrochemical companies acquiring most of the world's seed industry (Howard, 2015). This has enabled industry to take a firm grip on the world's agriculture. A particular strategy is to develop "integrated solutions", which means that several products are offered as a bundle to farmers. This can be seeds and chemicals combined (as in the case of herbicide-resistant crops) and sometimes machinery, chemicals, and data services as a package. This serves to weave a network of dependencies around farmers. For an example of how this plays out in real-world corn production, see Stuart and Houser (2018). From this perspective it is obvious that perennial grains would run contrary to the interests of the highly concentrated and consolidated agrochemical industry's "integrated solutions."

7.2 Innovation and the valley of death

Even if domestication is much faster today than for any of the existing crops, it is much slower than most innovations in the agricultural sector that are based on the modification of long-existing plants. As an example, it took only five years for 98% of soybean growers in Argentina to adopt the herbicide-resistant seeds (Green, 2012).

The traditional view of innovation, in which the gap between public and private support creates an "innovation valley of death" (VoD), is problematic for the domestication and breeding of entirely new crops. Bridging the VoD is often invoked as an argument for concentration and consolidation of the industry—only very large firms have sufficient resources for developing new crops. However, domesticating perennial crops is at odds with the core principle of the consolidated seed-and-agrochemical industry because the annual crop is their linchpin. Not only does perennial agriculture face formidable challenges related to the adoption of novel crops by the public and cropping systems by farmers, but it also faces the headwinds of an entrenched industry that has a powerful interest in maintaining the status quo of high-input annual agriculture.

Exactly how the seed-and-agrochemical industry maintains the status quo varies. Apart from controlling much of the agricultural R&D, the industry is highly active in influencing regulatory regimes, public policy, and public perceptions. One area of contention is the expected need to increase food production in the decades to come. The higher the projections for future food demands, the more focus there is on production and less on the ecological consequences of agriculture. Current estimates of the future demand vary substantially from a doubling by 2050 (Agnew and Hendery, 2023) to as low as 30% by 2050 (van Dijk et al., 2021). There is a clear pattern of the agricultural inputs industry stressing this "institutional fact" (MacCormick, 1998) for very high increases in food output (Fig. 5).

Quote	year	Organisation	Link
"we conclude that the assumption of needing to double agricultural production from 2010 to 2050 is still valid"	2023	The GAP (Global Agricultural Productivity) Initiative at Virginia Tech. supported primarily by large AgTech and food industries.	https://globalagriculturalproductivity.org/wp-content/uploads/2024/04/2023-GAP_Executive-Summary_FINAL.pdf
"total food consumption will likely rise by more than 50%, and possibly by 70% by 2050."	2023	HSBC bank report on the future of food.	https://www.research.hsbc.com/C/1/1/320/WgCK7Wv
"in 2050" … "overall food demand is on course to increase by more than 50 percent, and demand for animal-based foods by nearly 70 percent."	2019	World Resources Institute, an international think tank	https://research.wri.org/wrr-food
"Global ag production must grow by 70 percent by 2050" … " said Mary Boote, executive director of an industry group called the Truth About Trade and Technology. "Biotechnology has to be one of the tools we use."	2009	An organization called Truth about Trade and Technology (discontinued) promoting the AgBiotech industry.	https://www.reuters.com/article/idUSTRE5AA055/
"by the year 2050" … "To provide enough food so that – at least in theory – nobody on the planet would have to live with hunger, agricultural production would need to rise by at least 70%"	2018	BASF a major provider of agrochemicals and seeds.	https://www1.basf.com/we-create-chemistry/article.combatting-hunger-with-innovation.en.html
"in the next 30 years" … "farm output will have to increase by about 70 percent to satisfy food demand."	2024	CORTEVA a major provider of agrochemicals and seeds.	https://www.corteva.com/who-we-are/outlook/farmers-future-food-agriculture-challenges.html
"we will need to produce 70% more food in the next 30 years to feed the world's growing population."	2022	Syngenta, a major provider of agrochemicals and seeds. Currently ownde by CHEMCHINA	https://www.syngenta.com/sites/syngenta/files/2023-03/Paraquat/Ensuring_the_Security%2C_Safety%2C_Sustainability_and_Abundance_of_America%27s_Food_System_2022.pdf

Figure 5 Examples of statements from seed and input industry-associated representatives suggesting that global food production must be doubled by 2050.

8 The future: advancing adoption of perennial grains through community learning

A perennial transformation of agriculture faces critical obstacles in the years ahead, particularly given the contemporary political economy of seeds and agrochemicals (Olsson et al., 2024). However, the story so far also illustrates how change has been seeded and is beginning to germinate.

Over the last several decades, a relatively small number of people have imagined the possibility of perennial grains, conceptualized the benefits of perennializing grain agricultures, identified crop candidates, gathered germplasm, and initiated domestication and hybridization. Motivated individuals have connected with each other in community and catalyzed networks, programs, and institutions. Despite the difficulties of finding funding, researchers and visionaries from around the world have sought and secured basic resources to move forward, sharing their questions, knowledge, and iterative results to teach more people about the potential value of perennial grains and to invite them to act to support or join the effort (Land Institute International Initiative Map 2025).

8.1 Community learning with perennials

Human cultural and social learning—learning in community—has long shaped the way we procure food and other necessities to allow our survival and reproduction (Boyd et al., 2011). Learning involves gaining new knowledge and skills, including and especially in social contexts, and social learning is demonstrated when those knowledge and skills are applied through changed behaviors and actions (De Felice et al., 2022). People have had to learn what is safe, nutritious, delicious, and meaningful to eat, and how to find and prepare food, through interacting with each other and our environments.

Across our species' history, people have eaten the seeds of grasses and trees, and a variety of perennials in various places (Wu et al., 2022; Clarkson et al., 2017; Kreitzman et al. 2020). And in more recent millennia, people learned to domesticate annual plants, acquiring and transmitting knowledge and skills across generations and locations to build cultures and ways of life that rely on annual grains as staple foods, with increasing crop yields and food production and distribution systems reliant on fossil fuels (Cox et al., 2002; Crews et al., 2018).

Annual grain agricultures have shaped the landscapes and societies in which people are now seeking to grow and regrow food systems that feature perennial plants. Human communities continue to try to learn. Perennial grain crop development and ecological intensification of cropping systems provide evidence of human learning and its relevance to advancing positive agricultural change.

8.2 Accelerating and diversifying community learning for perennialization

But for diverse, perennial grain agricultures to be realized at both broad and deep scales—for perennial grain crops and cropping systems to be widely adopted, nourishing people, and generating timely and enduring social-ecological benefits—many more people will need to engage in the ongoing work of learning. More knowledge and skills about why and how to develop, care for, eat, and fairly value perennial grains needs to be gained, actually demonstrated, and put into practice (to advance crops, intercropping systems, supply chains, and more, building on early advancements described in this chapter), and transmitted to next generations of researchers, producers, makers, and eaters of all kinds.

In the context of climate change and social-ecological crisis, community learning and crop development processes need to be accelerated and diversified to build resilient food systems (Streit Krug et al., 2023b). Efforts to hold onto and revitalize soils, plant biodiversity, and ethnobotanical knowledge and relationships can be coupled with contemporary scientific inquiry, tools, and methods to support perennialization.

More accessible and widespread community learning processes could help build durable legitimacy for perennial grain agricultures in the face of scientific, political, economic, and ethical credibility tests (Montenegro de Wit and Iles, 2016; Streit Krug and Tesdell, 2022). Formal educational institutions, informal educational networks, advocacy and policy coalitions, agricultural innovation centers and businesses, and place-based and international movements for food and data sovereignty, climate justice, and agroecology are just some examples of the range of potential leaders and partners in community learning.

One participatory method being tested for its effectiveness and impact in engaging more people in community learning that advances agricultural research is citizen science (van de Gevel et al., 2020; Ryan et al., 2018b). In Land Institute civic science efforts in the United States, volunteer civic scientists grow and tend garden-scale plots of future perennial grains, in some cases alongside their annual crop counterparts. These civic scientists participate in research by collecting and sharing scientific data about plant performance and ecological interactions in their specific locations. They contribute observations, images, and measurements across a range of environments.

Educational materials, digital platforms including an app, and peer learning opportunities support civic scientists' data collection skills and knowledge about perennial grains. Civic scientists bring different background experiences and interests to projects, which shape how they build relationships and stories with perennial plants and how they may be inspired to engage their families, neighbors, and communities (Streit Krug et al., 2023b). From social science, arts and humanities, and transdisciplinary research perspectives, civic scientists' engagement in hands-on, multi-year projects provides an opportunity to study if and how interaction with future crops increases near-term community learning and, in the longer term, the social adoption and cultural valuation of perennial grains (Van Tassel et al., 2020).

The staple foods and energetic, ecological, and economic benefits provided by perennial grain crops and cropping systems can help sustain human communities. Where and how—and how quickly and deeply—processes of perennialization unfold will shape the social distribution of these benefits, including the potential of perennial agricultures to support more just perennial cultures (Streit Krug and Tesdell, 2022). Ongoing and increased human learning is vital to the growing scientific and sociocultural effort to perennialize diverse grain agricultures in geographies around the world.

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