Perennializing Grain Crop Agriculture: A Pathway for Climate Change Mitigation & Adaption

A white paper for the philanthropic community

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Perennial grain crops deliver dramatic amounts of carbon to the soil, as illustrated by the extensive root system of intermediate wheatgrass (left) compared to annual wheat (right). Intermediate wheatgrass produces Kernza® perennial grain. Photo: Jim Richardson

Authors: Fred Iutzi, MS and Tim Crews, PhD

Contact:
Rachel Stroer,
Acting President, The Land Institute
stroer@landinstitute.org

Timothy Crews, PhD
Director of Research, The Land Institute crews@landinstitute.org

The Land Institute, 2440 E. Water Well Rd., Salina, KS 67401
785-823-5376 www.landinstitute.org

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EXECUTIVE SUMMARY

- Soil carbon sequestration is the most beneficial source of negative emissions for the global climate change mitigation portfolio, and current grain crop production acreage is the prime candidate for major sequestration opportunities.
- Global grain crop agriculture is based on crops that are shallow-rooted annual plants grown in low-diversity monocultures that have lost the majority of the soil carbon that existed pre-settlement. The native grasslands that sequestered that carbon to start with were composed of deep-rooted perennial plants growing in high-diversity mixtures of multiple species.
- While discussions of soil carbon sequestration often emphasize uncertainty, it is unambiguous in the scientific literature that the highest levels of carbon sequestration achievable occur when lands previously planted to annual crops are converted to continuous perennial vegetation.
- In other words, we now have actionable knowledge that perennializing the agricultural landscape is the single most effective thing we can do for carbon sequestration.
- Perennial grain crops produced in high biodiversity have now emerged as a pathway for simultaneously abundantly provisioning both food and ecosystem services.
- In addition to providing a major carbon sequestration opportunity, perennial polyculture grain cropping systems have the potential to substantially reduce emissions of the potent greenhouse gas (GHG) nitrous oxide from agricultural soils, and to reduce carbon dioxide emissions from farm equipment operations and the synthesis of inputs, especially nitrogen fertilizers.
- In addition to their climate change mitigation benefits, perennial grain crops can also make major contributions to increasing agriculture's adaptation to climate change, as well as reducing soil degradation, reducing negative water quality impacts, and reducing agricultural pesticide use.
- The Land Institute and its network of global research collaborators have recently achieved proof of concept with their perennial grain crops research efforts. The world's first two perennial grain crops are now in pilot scale commercial production: Kernza® perennial grain and perennial rice. Other perennial grain crops are under development.
- Results achieved to date demonstrate that a suite of perennial grain crops can be developed to replace the bulk of current global grain crop production, resulting in transformational increases in carbon sequestration – but at current levels of investment, full deployment is decades away.
- Decisive action by funders is now warranted to accelerate perennial grain crop research and development while hastening adoption of perennial crops that already exist. A detailed strategy to this end is presented on page 8.

CLIMATE CHANGE MITIGATION & ADAPTATION THROUGH PERENNIAL GRAIN CROPS – NON-TECHNICAL NARRATIVE

Any credible portfolio of measures for mitigating climate change requires a negative emissions component, and soil carbon sequestration is arguable the most effective and beneficial source of negative emissions. Current grain crop production acreage should be a priority setting, because it has the most soil carbon to regain and because the most effective soil carbon sequestration method likely also will serve to reduce GHG emissions from agriculture. We argue that fully developing perennial grain crops and deploying them to replace current annual grain crop production is the path forward.

<u>Perennializing grain crops is a major untapped carbon sequestration opportunity</u>

Global grain crop agriculture is overwhelmingly based on crops that are annuals (plants that need to be reseeded every year) grown in single-species monoculture plantings. In contrast, the native ecosystems that preceded grain crop agriculture, such as native grasslands and forests, consisted of perennials (plants that regrow from year to year) growing in multi-species polycultures. It is well known that major losses in soil carbon were in all cases an immediate consequence of conversion of native ecosystems to grain crop fields early in history, and that in many farming systems these losses have continued over time. We now know that native grasslands were able to accumulate high levels of soil carbon precisely because of their perenniality and biodiversity – functions that current annual grain crops are unable to replicate. Developing perennial grain crops suitable to be grown in high biodiversity would be a decisive intervention to substantially increase soil carbon sequestration under grain crop farming, bringing it closer to pre-settlement carbon levels.

The science of soil carbon sequestration is notoriously complex, and emphasis is often placed on the difficulty of precisely estimating sequestration rates under different agricultural practices. But the reality that carbon accumulation under continuous perennial cover, like native grasslands or permanent pasture, greatly exceeds carbon accumulation under current annual grain crop production has been well characterized for many decades. And soil and plant science research in recent decades has given us a greatly improved understanding of the linkages between carbon sequestration and specific functional characteristics of perennial vegetation (e.g. large root systems). We can therefore predict with high confidence that crops and cropping systems that closely mimic the functional characteristic of native grasslands will be able to come closer to pre-settlement carbon sequestration levels than crops and cropping systems that do not. This prediction is strongly supported by empirical work on perennial pasture crops and the first emerging perennial grain crops. In other words, **we now have actionable knowledge that perennializing our agriculture landscape is the single most effective route to increased soil carbon sequestration.** Perennial grain crops are the centerpiece of a strategy for getting there.

How perennial grains can sequester large amounts of carbon in the soil

The carbon sequestration benefits of a grain crop agriculture based on perennial polycultures are delivered through several mechanisms. Key among them is the deep, massive root system produced by perennial crops. As roots release organic exudates and as individual root strands die and are constantly replaced, these large root systems allow perennial plants to act as highly efficient carbon pumps, taking carbon pulled out of the air during photosynthesis and placing it deep underground in chemical forms likely to persist in the soil. Compared to perennial species, annual plants typically produce less total biomass every year and allocate far less of it to underground roots. Total biomass productivity of the species chosen for domestication into perennial grain crops is high enough that grain yields can be increased by reallocating excess aboveground vegetative biomass (leaves and stems) into grain biomass.

Another critical mechanism by which perennial grain crops increase carbon sequestration is eliminating the frequent soil-disturbing tillage associated with annual grain crop production, resulting in less oxidation of soil organic matter and consequent loss from the soil. Low soil disturbance and permanent vegetative cover also overwhelmingly reduces soil erosion compared to annual cropping systems, and the associated losses of organic compounds attached to soil particles. Several of the factors mentioned so far – large root structures, elimination of tillage, and presence of a diversity of crop species in a polyculture – combine to create a healthier, higher functioning soil microbiota. This increased soil health contributes to carbon sequestration both directly through the microbial biomass produced and indirectly through improved plant health and productivity, as well as through more efficient conversation of root biomass inputs into stable forms of soil carbon. Finally, combining nitrogen-fixing legumes in the same polyculture with non-legume perennial grain crops will serve to reduce the need for synthetic nitrogen fertilizer, in some cases drastically. Drastic reductions in nitrogen fertilizer requirements could lead in turn to drastic reduction in nitrous oxide emissions compared to fertilized annual monocultures – an effect that is supported by a growing body of research.

Transformational benefits for more than climate

While the focus of this white paper is on the high level of benefits perennial grain crops provide for soil carbon sequestration and GHG emissions reduction, perennials also provide transformational benefits for a host of other ecosystem services. The same nitrogen fertilizer uptake advantage that sharply reduces GHG emissions also sharply reduces nitrate contamination of ground and surface water. The same deep root systems that sequester soil carbon also sharply reduce soil erosion, and in the process reduce phosphorus contamination of surface waters – and they may also result in increased yield stability in the face of drought. The physiology and production ecology of a perennial serves to reduce weed competition and the need for herbicides, while future polyculture systems are likely to reduce the need for insecticides and fungicides – all serving to reduce off-target impacts of pesticides.

Developing the world's first perennial grain crops

Replacing annual grain crops with perennial vegetation is the best opportunity for increasing soil carbon sequestration because of the large share of cropland acreage occupied by these crops and because they have the most soil carbon to regain. But because we rely on this grain crop production acreage directly or indirectly for more than 70% of the calories we consume, there are distinct limits to the proportion of cropland that can be shifted to the perennial vegetation options that have historically existed: perennial pasture and hay crops, native grasslands, and forests. Because all current major and minor grain crops were originally domesticated as annuals, development of the world's first perennial grain crops is the keystone innovation priority for perennialization of agriculture.

The Land Institute, a nonprofit agricultural research organization based in Salina, KS, leads a long-term research initiative to develop the world's first perennial grain crops. The initial conceptual and scientific groundwork for this effort was laid in the 1980s and 1990s, and since the mid-2000s the pace of the research outputs has accelerated substantially. **We now have proof of concept that perennial grains are possible.** Over the last three years, the world's first two meaningful perennial grain crops have entered pilot-scale production: Kernza® perennial grain in the U.S. and perennial rice in southern China. The products of a Land Institute-led consortium and a Land Institute-sponsored project, respectively, these two crops are the first two meaningful perennial grain crops in the history of agriculture.

Additional perennial grain crops are in development at various stages of the R&D pipeline: perennial wheat, perennial grain sorghum, perennial oilseed sunflower, and two perennial pulse crops (perennial legumes that produce a protein-rich grain comparable to a bean). These are all edible crops that will be able to functionally replace current food ingredients, including flours, starches, vegetable oils, and vegetable proteins. They will also no doubt be utilized for livestock feed and industrial purposes.

Growing perennial grain crops in biodiversity, especially in multi-species polycultures, will have even greater benefits for GHG-reduction and for other ecosystem services than the considerable benefits already supplied by a single-species stand of perennial grains. Polyculture research to date has focused on simple two-species mixtures of a perennial cereal grain and a perennial legume, because of the disproportionately large ecological benefits provided by this combination. In particular, the presence of the nitrogen-fixing legume has the potential to reduce the amount of synthetic nitrogen fertilizer needed for the cereal grain, thereby reducing emissions of nitrous oxide, a potent GHG. Polycultures of Kernza perennial grain and forage alfalfa are now entering pilot commercial production, while research is underway on intercropping Kernza with prospective edible grain legumes. Future research will address more complex polycultures.

Pathways to full development and deployment of perennial grain crops

The existence of annual grain crops like corn and wheat is the product of 10,000 years of folk plant breeding, and today's high grain yields are the product of 100 years of scientific plant breeding. Full development of perennial grain crops likewise hinges on plant breeding and genetics – but with the considerable advantage of being able to access new plant breeding technologies from the ground floor. Although transgenic methods and other forms of interventional biotechnology attract disproportionate public attention, the innovation that has arguably contributed more to grain crop yield gains is the use of observational biotechnology tools such as marker-assisted selection and genomic selection to greatly accelerate conventional plant breeding. The other "innovation" behind current annual crop performance is scale: billions of dollars of public and private investment each year in plant breeding and genetics.

The proof of concept recently achieved with Kernza perennial grain and perennial rice is a potentially game-changing milestone for perennialization of agriculture. But while perennial rice yields are already achieving comparable yields to annual rice, in most cases even after a new perennial grain is developed and enters its initial small-scale markets, considerable additional years of plant breeding effort will be required to achieve full yield potential and enter truly large-scale production. **Just as it took extensive plant breeding to bring annuals like corn and wheat to current yields, it will also take extensive plant breeding for perennial grains to reach their yield potential.** Substantial agroecology research is also required to successful manage each new perennial grain crop alone and in polyculture.

The Land Institute employs an in-house research staff of 12 PhD scientists and a similar number of non-PhD research personnel, and as of December 2019 coordinates the work of 55 other public and private research institutions (Figure 1), more than half of which are outside the U.S. This growing base of capacity demonstrates the potential to rapidly scale the perennial grains R&D effort. And the important research milestones reached to date are even more impressive in light of the very limited resources available for this work to date: total resources at the direct disposal of The Land Institute are less than $8 million per year and the total global investment in perennial grain crop research has not yet reached $20 million per year. (For comparison, the total global public and private investment in annual grain crops research likely exceeds $10 billion each year.)

We argue that society is not yet investing in perennial grain crop research and development in proportion to its transformational benefits. At current funding levels, full development and deployment of perennial grain crops is still decades away. While no level of funding can bring transformational change to a biological system overnight, a major investment in perennial grain crop research could potentially cut decades from the timeline. This is especially true if an aggressive public investment sets off a virtuous circle of even more aggressive private sector investment.

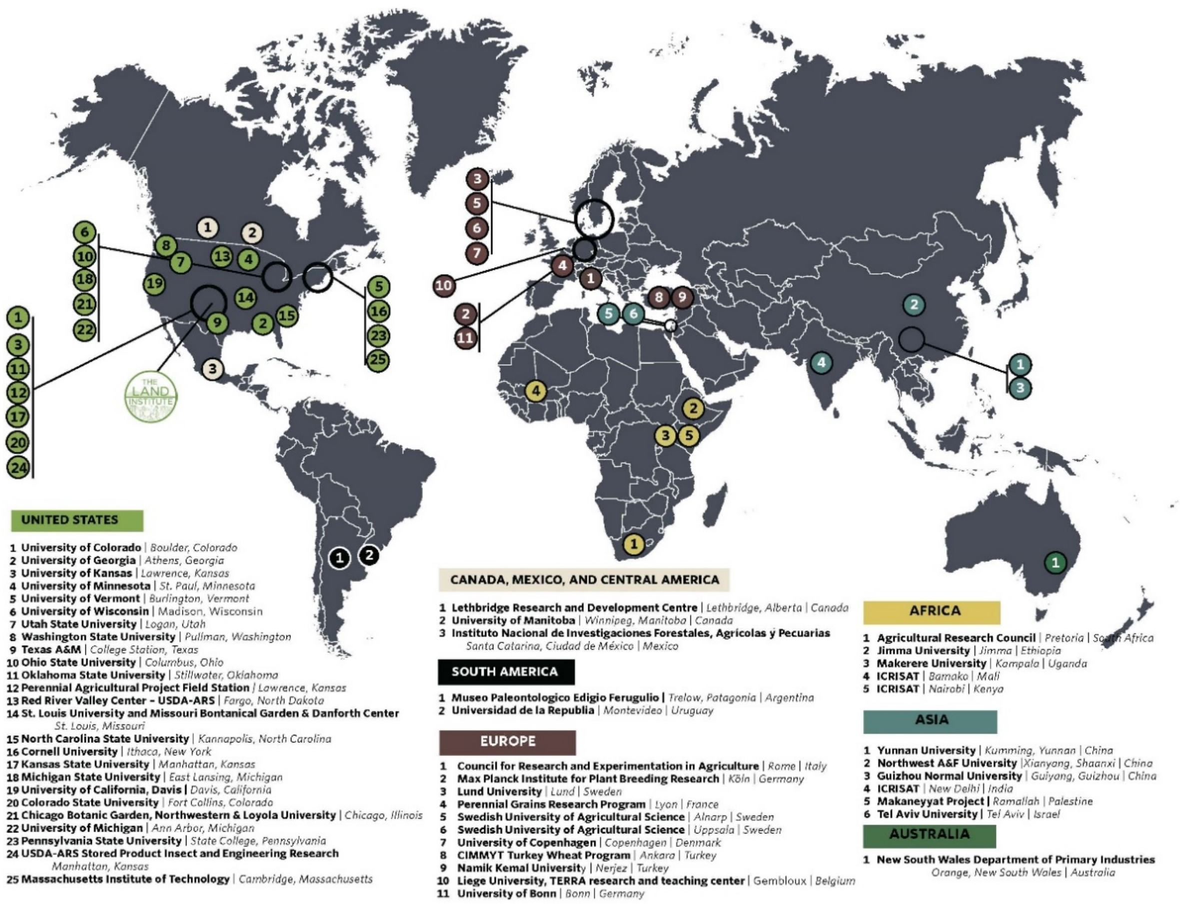

Figure 1. The Land Institute's global perennial grain crops research network as of September 2019.

A philanthropic agenda for perennializing global agriculture

We propose immediate and decisive action by the public and private philanthropic sectors to accelerate perennial grain crops research and development. We believe this is the single most effective measure possible for soil carbon sequestration and reduction of GHG emissions from agriculture – and arguably the single most effective and appropriate negative emissions strategy in any sector.

Specifically, we propose that interested funders:

- Recognize perennialization of the agricultural landscape as their lead strategy for soil carbon sequestration and reduction of GHG emissions from agriculture.
- **Make an immediate commitment to fully fund perennial grain crop R&D**, setting a goal to bring total funding in perennial grain crop research to **at least $100 million per year within five years.** (For comparison, current research investment in perennial grain crops barely exceeds $10 million each year; for annual crops, $10 billion is spent each year on plant breeding and genetics alone.)

- Support The Land Institute's efforts to greatly expand, lead, facilitate, and fund its global coalition of research collaborators, including expansion of agricultural research capacity in the Global South.
- Support a comprehensive vision for perennializing agriculture, including **immediate efforts to convert a portion of current annual grain crop acres to permanent perennial pasture and rangeland**.

Funding the next phase of perennial grain crops research worldwide

The drive to develop the world's first perennial grain crops began with a big vision in a small start-up nonprofit in Kansas. The Land Institute has subsequently grown into a highly capable plant science research team, and if there is a global capital for perennial grains research, we see it as Salina, KS. But the acceleration needed to bring this work to full fruition in a timely manner demands a profoundly larger scale of R&D effort. Today we are joined by more than 55 collaborating research institutions across six continents, and this growing international coalition represents the future of perennial grain crops research. The Land Institute aims to grow its own research operations substantially, but the cumulative research capacity brought to bear by our partners must grow far larger and faster. This includes not only US institutions and not only the research community of the Global North, but also the immense latent agricultural innovation capacity of the Global South.

In May 2019 The Land Institute convened representatives of its international research collaborator community for a five-day meeting in Lund, Sweden, drawing 92 researchers from 16 different countries. The outcome was a clear call to The Land Institute for more intensive leadership and coordination of the network – both to support the current 55 collaborators and to drive the substantial growth of the community in the months and years to come. We are now planning this intensified effort, which may be implemented as a new program area of The Land Institute or as a new affiliated organization. We hope to greatly expand four areas of engagement that we are already engaged in now:

- Identifying and recruiting new institutions to join the perennial grain crops research effort.
- Motivating and coordinating effective, efficient collaborations among collaborators.
- Stepping in when research efforts falter to ensure continuity of effort.
- Acting as a direct funder or close advisor to funders to effectively allocate funding among institutions.

A two-pronged transition to perennial agriculture

An immediate investment in perennial grain crops will take decades off the timeline for fully readiness – but no amount of funding will make these new crops ready for full deployment instantly. We believe it is critically important for funders to simultaneously commit to immediate conversion of a portion of global annual grain crop acreage to permanent pasture and rangeland. These perennial pasture crops have similar ecosystem services benefits to future perennial grain crops and are available now. The main strategic limitation to this strategy is that the maximum potential scale of grassfed or semi-grassfed ruminant livestock production is limited by the global food system's total demand for meat, and the minimum scale for grain production (currently supplied by annual crops) is limited by the need for grain. Immediate and simultaneous investments into perennial grain crop R&D and into conversion of current annual grain production to perennial pasture could in principle provide a time sequence in which, just as acreage conversion to perennial grazing is leveling off, new perennial grain crops will come fully online.

This figure illustrates the relationships between current technological readiness and the potential scale of conversions of existing annual crop land to new perennial cropland:

System	Technological readiness	Maximum scale
Pasture & rangeland	Ready now	Moderate*
Perennial grain crops (early prototypes)	Ready now	Very small
Perennial grain crops (fully developed)	Major R&D investment needed	Large to very large

The imperative for immediate and transformative action

Critics of decisive action on climate change sometimes contend that because approaches based on innovation cannot be deployed instantly, only incremental changes to existing practices should be considered. We argue that to disregard the need for serious R&D into transformational change because it cannot be deployed instantly ignores the hard lessons of the last 30 years on climate change. The best time to fund research into transformational technologies like perennial grain crops was decades ago – the second-best time is now. The global climate change mitigation portfolio <u>must</u> include a mix of decisive actions that can be performed now and decisive investments into transformational change – such as developing perennial grain crops.

DETAILED TECHNICAL NARRATIVE

As society confronts the challenge of not only stabilizing greenhouse gas concentrations in the atmosphere, but also reducing them to a significant degree, restoring carbon to the soil that has been released to the atmosphere due to land management practices is by many accounts perceived to be low hanging fruit (Griscom et al. 2017, Sanderman et al. 2017). However, as with many apparently straightforward solutions to difficult problems, altering land management techniques to sequester carbon is fraught with uncertainty and controversy (Schlesinger and Amundson 2019, Amundson and Biardeau 2018). Part of what makes carbon "draw down" approaches challenging from a policy perspective is the difficulty in actually measuring what are often relatively small changes to large pools of soil carbon over short periods of time (Necpálová et al. 2014). Another challenge is that different land management innovations take advantage of different mechanisms for increasing soil carbon. Broadly speaking, there are management approaches that increase the amount of carbon entering the soil in a given year, and then there are approaches that impede the loss of soil carbon back to the atmosphere. One approach to increasing soil carbon that researchers agree is robust, is the replacement of annual vegetation with perennial plants (Reicosky and Janzen 2019). Paustian (2014) illustrates why this is the case (Table 1), since no other approach addresses both mechanisms of improving carbon inputs into the soil while at the same time decreasing carbon loses.

TABLE 1 | Examples of agricultural management actions that can increase organic carbon storage and promote a net removal of CO_2 from the atmosphere and the main mode of action on the soil C balance (from Paustian, 2014).

Management practice	Increased C inputs	Reduced C losses
Improved crop rotations and increased crop residues	✓	
Cover crops	✓	
Conversion to perennial grasses and legumes	✓	✓
Manure and compost addition	✓	
No-tillage and other conservation tillage		✓
Rewetting organic (i.e., peat and muck) soils		✓
Improved grazing land management	✓	

Undegraded cropland soils can theoretically hold far more soil organic matter (SOM) (which is ~58% carbon) than they currently do (Soussana et al. 2004). We know this deficiency because, with few exceptions, comparisons between cropland soils and those of proximate mature native ecosystems commonly show a 40-75% decline in soil carbon attributable to agricultural practices. What happens when native ecosystems are converted to agriculture that induces such significant losses of SOM? Wind and water erosion commonly results in preferential removal of light organic matter fractions that can accumulate on or near the soil surface (Lal 2003). In addition to the effects of erosion, the fundamental practices of growing annual food and fiber crops alters both inputs and outputs of organic matter from most agroecosystems resulting in net reductions in soil carbon equilibria (Soussana et al. 2004; McLauchlan 2006; Crews et al.

2016). Native vegetation of almost all terrestrial ecosystems is dominated by perennial plants, and the belowground carbon allocation of these perennials is a key variable in determining formation rates of stable soil organic carbon (SOC) (Jastrow et al. 2007; Schmidt et al. 2011). When perennial vegetation is replaced by annual crops, inputs of root-associated carbon (roots, exudates, mycorrhizae) decline substantially. For example, perennial grassland species allocate around 67% of productivity belowground, whereas annual crops allocate between 13-30% (Saugier 2001; Johnson et al. 2006).

At the same time inputs of SOC are reduced in annual cropping systems, losses are increased because of tillage, compared to native perennial vegetation. Tillage breaks apart soil aggregates, which, among other functions, are thought to inhibit soil bacteria, fungi, and other microbes from consuming and decomposing soil organic matter (Grandy and Neff 2008). Aggregates reduce microbial access to organic matter by restricting physical access to mineral-stabilized organic compounds as well as reducing oxygen availability (Cotrufo et al. 2015; Lehmann and Kleber 2016). When soil aggregates are broken open with tillage in the conversion of native ecosystems to agriculture, microbial consumption of SOC and subsequent respiration of CO_2 increase dramatically, reducing soil carbon stocks (Grandy and Robertson 2006; Grandy and Neff 2008).

Many management approaches are being evaluated to recapture soil organic carbon, especially by increasing mineral-protected forms of SOC in the world's croplands (Paustian et al. 2016). The menu of approaches being investigated focuses either on increasing belowground carbon inputs, usually through increases in total crop productivity, or by decreasing microbial activity, usually through reduced soil disturbance (Crews and Rumsey 2017). However, the basic biogeochemistry of terrestrial ecosystems managed for production of annual crops presents serious challenges to achieving the standing stocks of SOC accumulated by native ecosystems that preceded agriculture. A novel new approach that is just starting to receive significant attention is the development of perennial cereal, legume, and oilseed crops (Glover et al. 2010; Baker 2017). Perennial grain crops represent the one approach that could increase carbon inputs and reduce carbon losses, thus potentially approaching the SOC standing stocks of native ecosystems (Crews and Rumsey et al. 2017).

There are two basic strategies that plant breeders and geneticists are using to develop new perennial grain crop species. The first involves making wide hybrid crosses between existing elite lines of annual crops, such as wheat, sorghum, and rice, with related wild perennial species in order to introgress perennialism into the genome of the annual (Figure 2) (Cox et al. 2018; Huang et al. 2018; Hayes et al. 2018). The other approach is *de novo* domestication of wild perennial species that have crop-like traits of interest (DeHaan et al. 2016; DeHaan and Van Tassel 2014). New perennial crop species undergoing *de novo* domestication include intermediate wheatgrass, a relative of wheat that produces grain marketed as Kernza® (Figure 3) (DeHaan et al. 2018; Cattani and Asselin 2018) and *Silphium integrifolium*, an oilseed crop in the sunflower family (Figure 4) (Van Tassel et al. 2017).

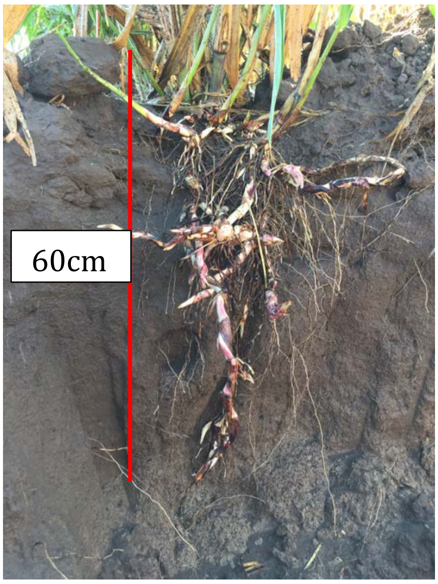

Figure 2. Perennial rhizome. A novel aspect of the newly developed perennial sorghum hybrid.

Figure 3. Comparison of root systems between the newly domesticated intermediate wheatgrass (left) and annual wheat (right). Intermediate wheatgrass produces the grain Kernza®. Photo and copyright: Jim Richardson

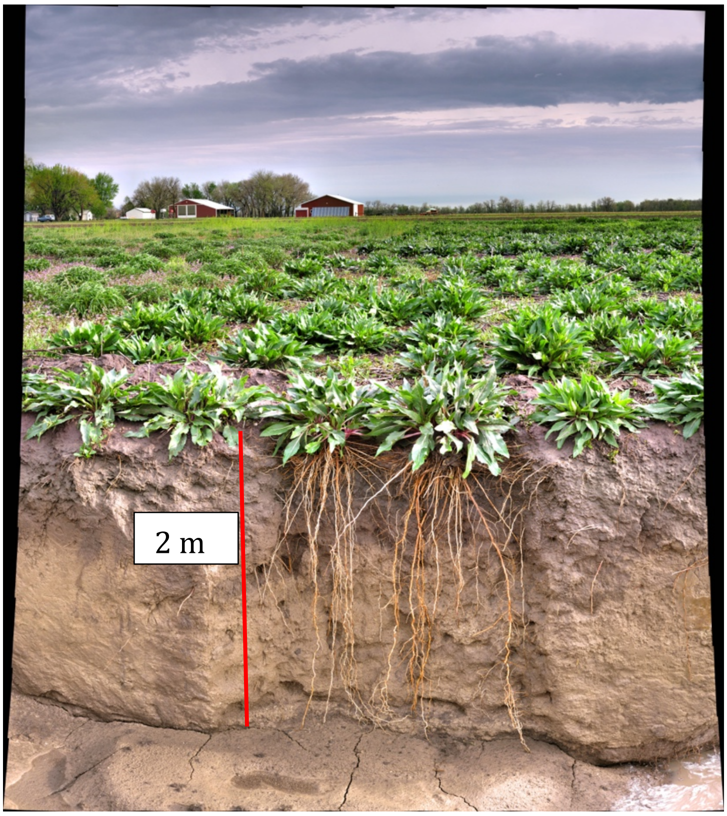

Figure 4. Deep roots of *Silphium integrifolium*. A native prairie species related to sunflower under domestication as a perennial oilseed crop.

Other perennial grain crops receiving attention include pigeon pea, barley, buckwheat, and maize (Batello et al. 2014; Chen et al. 2018) and a number of legume species (Schlautman et al. 2018). In most cases, the seed yields of perennial grain crops under development are well below those of elite modern grain varieties. In the time that it takes intensive breeding efforts to close the yield and other trait gaps between annual and perennial grains, perennial proto-crops may be used for purposes other than grain, including forage production (Ryan et al. 2018). Perennial rice stands out as a high-yielding exception, as its yields matched those of elite local varieties in the Yunnan Province for six growing seasons over three years (Huang et al. 2018).

In a perennial agroecosystem, the biogeochemical controls on SOC accumulation shift dramatically and begin to resemble the controls that govern native ecosystems (Crews et al. 2016). When erosion is reduced or halted, and crop allocation to roots increases by 100-200%, and when soil aggregates are not disturbed — thus reducing microbial respiration — SOC levels are expected to increase (Crews and Rumsey 2017). Deep roots growing year-round are also effective at increasing nitrogen retention (Culman et al. 2013; Jungers et al. 2019). Substantial increases in SOC have been measured where croplands that had historically been planted to annual grains were converted to perennial grasses, such as in the Conservation Reserve Program (CRP) of the U.S., or in plantings of second-generation perennial biofuel crops. In a recent study, researchers assessed the carbon balance of intermediate wheatgrass bred to produce the grain Kernza® in Kansas USA over 4.5 years using eddy covariance observations (de Oliveira et al. 2018). They found the net C accumulation rate of about 500 g C m^{-2} yr^{-1} in the first year of the study corresponding to the biomass of Kernza increasing, to about 120 g C m^{-2} yr^{-1}in the final year, where CO_2 respiration from the decomposition of roots and soil organic matter approached new carbon inputs from photosynthesis. Based on measurements of soil carbon accumulation in restored grasslands in the central U.S., the net carbon accumulation in stable organic matter under a perennial grain crop might be expected to fall in the range of 30-50 g C m^{-2} yr^{-1} (Post and Kwon 2000) until a new equilibrium is reached. Paustian et al. (2014) recently estimated that perennial grain crops planted on croplands previously sown to annuals could sequester 100 g C m^{-2} yr^{-1}, or 1 ton ha^{-1} yr^{-1}.

When compared to annual grains like wheat, single species stands of deep rooted perennial grains such as Kernza are expected to reduce soil erosion, increase nitrogen retention, achieve greater water uptake efficiency, and enhance carbon sequestration (Crews et al. 2018) (Figure 2). An even higher degree of ecosystem services should at least theoretically be achieved by strategically combining different functional groups of crops such as a cereal and a nitrogen-fixing legume (Soussana and Lemaire 2014). Not only is there evidence from plant diversity experiments that communities with higher species richness sustain higher concentrations of soil organic carbon (Hungate et al. 2017; Sprunger and Robertson 2018; Chen et al. 2018; Yang et al. 2019), but other valuable ecosystem services such as pest suppression, lower greenhouse gas emissions, and greater nutrient retention may be enhanced (Schnitzer et al. 2011; Culman et al. 2013).

Similar to perennial forage crops such as alfalfa, perennial grain crops are expected to have a definite productive life span, most likely in the range of 3-10 years. A key area of research on perennial grains cropping systems is to minimize losses of soil organic carbon during conversion of one stand of perennial grains to another. Recent work demonstrates that no-till conversion of a mature perennial grassland to another perennial crop will experience several years of high net CO_2 emissions as decomposition of copious crop residues exceeds ecosystem uptake of carbon by the new crop (Abraha et al. 2018). Most, if not all, of this lost carbon will be recaptured in the replacement crop. It is not known whether mineral-stabilized carbon that is protected in soil aggregates is vulnerable to loss in perennial crop succession.

The ability of perennial polycultures to sequester carbon has important potential for climate change mitigation. Perennial crops also hold significant promise for adaptation as they address multiple manifestations of soil degradation that are predicted to worsen with climate change. First, soil erosion is a very serious consequence of annual cropping, with median losses exceeding rates of formation by 1-2 orders of magnitude in conventionally plowed agroecosystems, and while erosion is reduced with conservation tillage, median losses still exceed formation by several fold (Montgomery 2007). More severe storm intensity associated with climate change is expected to cause even greater losses to wind and water erosion (Nearing et al. 2004). Secondly, the periods of time in which live roots are reduced or altogether absent from soils in annual cropping systems allow for substantial losses of nitrogen from fertilized croplands, averaging 50% globally

(Ladha et al. 2005). This low retention of nitrogen is also expected to worsen with more intense weather events (Bowles et al. 2018). A third impact of annual cropping is the degradation of soil structure caused by tillage, which can reduce infiltration of precipitation, and increase surface runoff. It is predicted that the percentage of precipitation that infiltrates into agricultural soils will decrease further under climate change scenarios (Basche and DeLonge 2017; Wuest et al. 2006).

Perennial grains hold considerable promise to reduce soil erosion and nutrient leakage while sequestering carbon. When cultivated in mixes with nitrogen-fixing species (legumes) such polycultures also reduce the need for external inputs of nitrogen — a large source of GHGs from conventional agriculture. The potential to accelerate the development of perennial grain species and eventually perennialize large percentages of global croplands is proportionate to society's investment in moving research forward, especially in the areas of genetics, plant breeding, and ecological intensification.

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