

Review Article

Cite this article: Olsson L *et al.* (2024). What is the prospect of a perennial grain revolution of agriculture? *Global Sustainability* 7, e35, 1–17. <https://doi.org/10.1017/sus.2024.27>

Received: 22 December 2023

Revised: 28 May 2024

Accepted: 3 June 2024

Keywords:



agriculture; policies; politics and governance

Corresponding author:

Lennart Olsson;

Email: lennart.olsson@lucsus.lu.se

What is the prospect of a perennial grain revolution of agriculture?

Lennart Olsson¹ , Elina Andersson¹, Jonas Ardö², Timothy Crews³, Christophe David⁴, Lee DeHaan³ , Axel Hilling⁵, Aubrey Streit Krug³, Michael Palmgren⁶, Sergio Rey⁷, Torbern Tagesson², Anna Westerbergh⁸ and Patrik Vestin²

¹Lund University Centre for Sustainability Studies (LUCSUS), Box 170, 22100 Lund, Sweden; ²Department of Physical Geography and Ecosystem Science, Lund University, Sweden; ³The Land Institute, Salina, KS, USA; ⁴Department of Agroecology and Environment, ISARA, Lyon, France; ⁵Department of Business Law, Lund University, Sweden; ⁶Department of Plant and Environmental Sciences, University of Copenhagen, Denmark; ⁷Department of Geography, San Diego State University, CA, USA and ⁸Department of Plant Biology, Swedish University of Agricultural Sciences, Uppsala, Sweden

Abstract

Non-technical summary. Agriculture has been dominated by annual plants, such as all cereals and oilseeds, since the very beginning of civilization over 10,000 years ago. Annual plants are planted and uprooted every year which results in severe disturbance of the soil and disrupts ecosystem services. Science has shown that it is possible to domesticate completely new perennial grain crops, i.e. planted once and harvested year after year. Such crops would solve many of the problems of agriculture, but their development and uptake would be at odds with the current agricultural technology industry.

Technical summary. Agriculture is arguably the most environmentally destructive innovation in human history. A root cause is the reliance on annual crops requiring uprooting and restarting every season. Most environmental predicaments of agriculture can be attributed to the use of annuals, as well as many social, political, and economic ones. Advances in domestication and breeding of novel perennial grain crops have demonstrated the possibility of a future agricultural shift from annual to perennial crops. Such a change could have many advantages over the current agricultural systems which are to over 80% based on annual crops mainly grown in monocultures. We analyze and review the prospects for such scientific advances to be adopted and scaled to a level where it is pertinent to talk about a perennial revolution. We follow the logic of E.O. Wright's approach of Envisioning Real Utopias by discussing the desirability, viability, and achievability of such a transition. Proceeding from Lakatos' theory of science and Lukes' three dimensions of power, we discuss the obstacles to such a transition. We apply a transition theory lens to formulate four reasons of optimism that a perennial revolution could be imminent within 3–5 decades and conclude with an invitation for research.

1. The many problems of annual grain production

The Neolithic Revolution 12,000 to 7000 years ago, during which humans shifted from hunting and gathering to farming, was arguably the most decisive social transition in human history in terms of path dependency. This profound shift in the provision of food marked the rise of civilizations and the beginning of political organizations (Weisdorf, 2005), and was by some proposed as the onset of a new geological Epoch, the Anthropocene (Lewis & Maslin, 2015). Its most important characteristic was the domestication of the annual grasses and forbs that still comprise the mainstay of our food, such as wheat, rice, maize, soya (together representing 50% of world croplands), barley, beans, millet, oat, rye, sesame, sorghum, and sunflower. It is hard to overstate the importance of agriculture for the development of civilization, but now agriculture and the world's food supply have reached a critical crossroad (Olsson *et al.*, 2023).

The history of domestication has so far resulted in that most humans today depend on a few high-yielding staple crops in agricultural systems that are unsustainable (McIntyre *et al.*, 2009), climate vulnerable (Bezner Kerr *et al.*, 2022), nutrient poor (FAO *et al.*, 2020; Gillespie *et al.*, 2017), and inequitable (Krug *et al.*, 2023). The global demand for food is projected to continue to increase because of a burgeoning population, shifting dietary preferences, over-consumption, and food wastage (van Dijk *et al.*, 2021). The size of the demand for food by 2100 is contested, from a doubling, as argued by agroindustry (Steenland, 2021) to 40–55% as assumed by the FAO (FAO, 2019), and as low as 30% as suggested by some integrated models (van Dijk *et al.*, 2021). Climate change, water scarcity, and land use change are expected to

Copyright © The Author(s), 2024. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution-NonCommercial licence (<http://creativecommons.org/licenses/by-nc/4.0>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original article is properly cited. The written permission of Cambridge University Press must be obtained prior to any commercial use.

make it difficult to meet even the lowest of increased demands (Bezner Kerr *et al.*, 2022; Mbow *et al.*, 2019; Olsson *et al.*, 2019). Moreover, agriculture is already one of the most polluting sectors of society (Breitburg *et al.*, 2018; Foley *et al.*, 2011; Ramankutty *et al.*, 2018), and dominant trends in the sector are at odds with social goals such as health (Clark *et al.*, 2019), employment (White, 2012), livelihood diversity, and social cohesion (Losch *et al.*, 2012). Most people living in extreme poverty are rural and employed in agriculture, a sector characterized by inequality and gender disparities (World Bank, 2018). In high-income countries farmers suffer from high and increasing debts, decreasing returns, and high levels of stress (Rudolphi, 2019; Rudolphi & Barnes, 2019). At a very different level, agriculture is also the main culprit of the 400+ marine dead zones in coastal waters (Bailey *et al.*, 2020; Foley *et al.*, 2011). These challenges combined make a radical change in the agricultural sector imperative, and such a change must also respond to the increasing demands and expected deteriorating productivity due to climate change (Bezner Kerr *et al.*, 2022; Challinor *et al.*, 2014; Mbow *et al.*, 2019; Porter *et al.*, 2014) and the nutritional quality of food (Zhu *et al.*, 2018).

Modern agriculture is unsustainable first and foremost because of the reliance on low diversity annual cropping systems that require severe disruption of soil ecosystems every year to restart the production cycle (Baker, 2017; Crews *et al.*, 2018; Crews & Rumsey, 2017; Eislser, 2019; Lubofsky, 2016; Rasche *et al.*, 2017; Soto-Gómez & Pérez-Rodríguez, 2022). This is arguably a root cause of both environmental damage (erosion, nutrient leaching, greenhouse gas emissions, deteriorating soil biodiversity, and spreading of toxic substances) and many social predicaments, such as the high dependence on an industry of external inputs (seeds, agrochemicals, machinery, and fossil fuel). This makes agriculture a cost to society through a complex system of subsidies totaling about \$600 billion per year worldwide (Laborde *et al.*, 2021), or in the EU, about 35% of its total budget (Head, 2019; Scown *et al.*, 2020).

In order to attribute these predicaments to one specific factor, the reliance on annual grains, we turn to the concept path dependence for understanding the historical evolution of agriculture (Mahoney, 2000). One reason why annual crops are favored in commercial plant breeding, is the opportunity to use patent protection as a way of reaping future benefits. Even if plants were exempted from the original patent legislation in 1836, the discovery of methods for creating hybrid seeds in the 1920s paved the way for patentability of seeds, and in 1930 the first patent of a seed was granted. The arguments for patentability of plants were primarily industrial (Seay, 1988). Even if crops superior to the hybrids could have been achieved through selection of (not patentable) open-pollinates (Kloppenburger, 2005; Paul, 1989), the plant breeding industry focused on hybrids because of their patentability and hence commercial potential. Therefore, we can consider the 1930s decision to allow patents on plants as a contingent moment initiating a self-reinforcing sequence of plant breeding techniques (Mahoney, 2000).

Agriculture has historically developed in both radical leaps (revolutions) and incremental changes. In the last 150 years we have distinguished at least four technological breakthroughs, sometimes referred to as revolutions, but with very different political and economic implications. The first was the invention and mass manufacture of the moldboard plow in the 1850s. With the steel plow it was possible to plow deeper into heavy soils, and to turn the soil over. This facilitated the expansion of agriculture into

new areas. The second was the Haber Bosch process to manufacture plant-available nitrogen from atmospheric nitrogen in the 1910s (Smil, 2004). The third was the Green Revolution in the 1960s which was primarily driven by advances in plant breeding supported by massive use of agrochemicals for the purpose of eradicating hunger (Evenson & Gollin, 2003). The fourth agricultural revolution was the transgenic revolution primarily oriented towards producing new crops with agronomic traits to make cropping more cost effective – nearly all the commercially released transgenic crops are either herbicide tolerant or insect resistant varieties (van Acker *et al.*, 2017). These four revolutions have increased food production, averted famine, increased food security, and improved lives in many farming communities. Yet, over a longer time perspective the legacy of these agricultural revolutions is increasingly contested both in terms of the environmental trade-offs and social ramifications (Stone, 2019). All four agricultural revolutions also contributed to creating the economic conditions that drive agriculture towards productivism, as will be elaborated below. In sum, modern agriculture is increasingly unable to generate desired benefits without negative costs, and its viability is increasingly undermined by climate change.

2. The many calls for a new agricultural vision

There is growing momentum in the UN (FAO *et al.*, 2020), EU (Kelly & Naujokaityte, 2020), and USA (USDA, 2021) of the necessity for agriculture to change in order to better balance production of goods with conservation of natural resources. However, most of the proposed changes are incremental without addressing a root cause of unsustainability, namely the reliance on annual crops. Below we briefly review some of the most common discourses of sustainable agriculture, many of which overlap.

- **Climate-smart agriculture** is a broad approach for transforming and reorienting agricultural systems to support food security under the new conditions expected from climate change and water scarcity. Even if climate-smart agriculture is loosely defined and interpretations differ among stakeholders, three pillars are foundational: sustainably increase food production; adapting and building resilience to climate change; reducing emission of greenhouse gases and/or remove emissions where possible (Alexander, 2019; Lipper *et al.*, 2014).
- **Sustainable/ecological intensification** is a related umbrella term for various ways of changing agricultural practices to increase crop yield while reducing the environmental impact of agriculture (Pretty, 2018). It is often emphasizing crop diversity (Bommarco *et al.*, 2013), and includes the debate on land sharing/sparing (Phalan *et al.*, 2011).
- **Smart Farming** is an umbrella term that includes ‘precision agriculture’ for harnessing the exponentially increasing use of information and communication technologies (ICT) for optimizing and automatizing farming to deliver water, nutrients, and pesticides at targeted locations, rates, and timings (Walter *et al.*, 2017).
- **Organic agriculture** is a term used explicitly for production systems that do not allow use of synthetic fertilizers and pesticides and instead rely on animal manure, biological fixation, and biological pest control practices, or naturally derived biopesticides (Howard, 1947; Reganold & Wachter, 2016). Organic agriculture is a holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity.

This production system is primarily consumer driven and supported by international regulation standards.

- **Regenerative agriculture** is a broad term generally used to describe practices that improve soil quality through 1) minimal disturbance, 2) continuous cover by mulch and cover crops, 3) diversity in terms of crop rotation and intercropping (Giller et al., 2021; Montgomery, 2017; Rhodes, 2013). This term is increasingly adopted by disparate groups ranging from grass roots farmer and rancher organizations to governmental and development agencies, as well as corporations (Tiftonnell et al., 2022).

Importantly, these discourses have particular institutional links, both private and public. Climate Smart Agriculture is a concept primarily promoted by international organizations such as FAO, World Bank and the CGIAR. Smart Farming is heavily promoted by agricultural technology companies (agrochemicals and machinery). Organic agriculture originated as a biophilic philosophy that has since the early 1990s been codified as a business concept based on third party certification of products. Regenerative agriculture started as a social movement among farmers that is rapidly spreading to other sectors, and risks losing its original meaning (Bless et al., 2023).

A fallacy, however, of all these approaches, at least from a soil carbon perspective, is the assumption that reversing degradation will restore soil carbon levels. It is well known that frequent and deep tillage in combination with leaving the soil surface exposed for long periods of time releases soil carbon to the atmosphere (Chi et al., 2016). But this does not mean that the soil carbon will come back if these detrimental practices are reversed. The soil carbon that accumulated in soils prior to cultivation were built by a diversity of perennial plants with dense and deep root systems. Only by reintroducing a diversity of deep-rooted plants can we hope to rebuild that soil carbon (Guan et al., 2016; Ledo et al., 2020).

3. A perennial revolution as a new radical alternative

We argue that the agricultural systems that hold the greatest promise for improving on all unsustainable dimensions of annual grain agriculture are systems that feature **perennial grains cultivated in mixtures** – here called perennial polycultures (Baker, 2017; Chapman et al., 2022; Crews et al., 2018; de Oliveira et al., 2019; Duchene et al., 2019; Ryan et al., 2018; Soto-Gómez & Pérez-Rodríguez, 2022). We argue that a perennial revolution is essential for long-term sustainable agriculture.

In envisioning this alternative to current agriculture, we take inspiration from Erik Olin Wright's framework for social change, 'envisioning real utopias' (Wright, 2010). This involves a three-pronged approach:

- A theoretically profound and systematic analysis of the current state-of-play. This means that we need to go beyond discussing the problems as such and ask the more fundamental question of why modern agriculture developed into the current system. What were the conditions and drivers of agriculture?
- The formulation of an alternative to the current situation that is desirable (i.e. that it can generate the benefits we envision without negative side effects in terms of environment, agricultural communities, and society at large); viable (i.e. that it can be sustained over long periods of time without shifting problems into

the future); and achievable (i.e. that it can be achieved in a reasonable timeframe).

- A strategy for change by which the current system can be transformed into the new alternative. Such a strategy may have to first undermine or erode the power of the incumbent systems in order to pave the way for the new alternative (Wright, 2019).

The realization of diverse, perennial grain agricultural systems would be revolutionary for both ecological and social reasons. Ecologically, novel agroecosystems of perennial polycultures could help repair the ecosystem harms of industrial annual agriculture and could help restore and retain vitally necessary natural ecosystem services while producing food for humans (Crews et al., 2018). Socially, a perennial revolution could fundamentally challenge the power structures that drive current agriculture by rendering much of the current agricultural inputs industry less important, or in some cases even superfluous, through agroecological transitions balancing production and environmental protection (Duru et al., 2015). The more sustainable ecological, economic, and energetic infrastructure provided by perennial agriculture opens ethical possibilities for more just human cultures and relationships; while a 'social perennial vision' is not inevitable, it can be intentionally pursued (Krug & Tesdell, 2021).

When the idea of shifting from annual crops to perennial crops was first expressed some 40 years ago (Eisler, 2019; Jackson, 1980) it was regarded by many as utopian. However, advances in plant breeding across subsequent decades have shown that it is possible to rapidly develop new perennial crops through wide hybridization of existing annual plants with wild perennial relatives (Cox et al., 2018; Cui et al., 2018; Zhang et al., 2019) and an alternative strategy, *de novo* domestication of wild plants now also seems possible (Chapman et al., 2022; Luo et al., 2022). However, in a situation where most of the plant breeding is funded by the private sector looking for a return on investment, there is little economic incentive to develop perennial grains (Clancy & Moschini, 2017; Coe et al., 2020).

Doubts about and even objections to the idea of domesticating perennial grain crops (Denison, 2012; Loomis, 2022; Smaje, 2015), are sometimes raised by referring to the phenotypic trade-off theory (or the 'Y-model') in ecology, popular in the 1980s and 90s (Roff & Fairbairn, 2007; Roff & Gelinias, 2003). According to this theory perennial plants do not allocate enough energy to producing large seeds, but instead prioritize other plant functions, such as vegetative growth and soil exploration through an extensive root system. However, observed phenotypic trade-offs are not always supported by evolutionary theory because it is possible that natural selection in a competitive environment never favored the development of both longevity (large root system of perennials) and reproductive capacity (many spikes and large seeds) (Garland, 2014). More recent research suggests that a quantitative genetic theory is a more appropriate for understanding trade-offs, and according to this theory plant breeding can promote both longevity (roots) and reproductive capacity (seeds). Evidence exists that the trade-off between perenniality and reproductive allocation is not fixed, for example, herbaceous perennial crops that produce 20 tons (plantain) to 50 tons (banana) of fruit per ha in the tropics (Kreitzman et al., 2020). Olive trees, domesticated about 6000 years ago, sustain their yields for 300 to 500 years (Camarero et al., 2021). Wild perennial plants produce fewer or smaller seeds because of natural selection in a competitive environment where longevity is favored rather than because of physiologically optimized allocation (DeHaan et al., 2005). So

even if most existing agricultural crops are annuals, there is no biological reason preventing the domestication of perennial grain crops (Bajgain et al., 2022; Chapman et al., 2022; Ciotir et al., 2019; DeHaan et al., 2005, 2016; DeHaan & Van Tassel, 2014; Van Tassel et al., 2020). However, if we use a political ecology lens the phenotypic trade-off theory can justify and support a continuation of conventional annual crops.

That a perennial revolution is possible can be illustrated by two recent developments: Kernza® grain, which is the result of domestication and traditional breeding of the wild perennial grass intermediate wheatgrass (hereafter called IWG; *Thinopyrum intermedium*) (Bajgain et al., 2020), and perennial rice which is the result of species-wide hybridization of Asian cultivated rice (*Oryza sativa* ssp. *indica*) with the African wild perennial relative *Oryza longistaminata* (Zhang et al., 2023). The evidence from IWG is that grain yield and other domestication traits such as seed size, shatter resistance, and free threshing ability (i.e. that the seed separates cleanly from the chaff when threshing) can be increased rapidly in a previously wild perennial species using traditional breeding and modern genetic tools such as genomic selection (Fagnant et al., 2023; LeHeiget et al., 2023). The evidence from perennial rice is that wide hybridization of an existing annual crop and a perennial wild relative can generate a high yielding perennial crop. These proofs-of-concept are major and significant achievements, but many more perennial grain crops and cultivars are in the pipeline (Chapman et al., 2022; Crews et al., 2016). Within one to three decades we expect to see a wide range of perennial grain crops making inroads into agriculture and becoming operational, such as barley, oil seeds, sorghum, wheat and legumes (Baker, 2017; Ciotir et al., 2019; Crews et al., 2018; DeHaan et al., 2016, 2020; Luo et al., 2022; Westerbergh et al., 2018). Doubts about the lack of progress in breeding perennial grains were raised recently by Cassman & Connor (Cassman & Connor, 2022), but are contradicted by recent research showing rapid improvements in yield and other agronomic traits (Altendorf et al., 2022; Bajgain et al., 2022; DeHaan et al., 2023).

A fundamental difference between annual and perennial plants is the root system (Roumet et al., 2006). Annuals develop roots just for one season whereas perennials build and accumulate typically deeper and wider root systems over numerous years (Culman et al., 2010; Duchene et al., 2020; Monti & Zatta, 2009; Sainju et al., 2017). In Figure 1 we show the difference between the annual winter wheat ready to be harvested (left) compared with the newly domesticated perennial grain IWG after two seasons. One study has shown that root systems of IWG in its fourth year of growth were 15 times larger by weight and size than wheat (Sprunger et al., 2018). Eddy covariance measurements have demonstrated that IWG can act as a strong carbon sink – the mean annual flux from the atmosphere was about 14 tons CO₂ ha⁻¹ year⁻¹ (370 g C m⁻²) over a five-year period (de Oliveira et al., 2018, 2019). Exactly how much of the assimilated carbon that remains in the soil for long periods of time is still a matter of discussion (Gregory, 2022; Peixoto et al., 2022). The extensive root system is also the reason why perennial crops reduce nutrient leaching to ground water, streams, lakes and ultimately oceans to virtually zero (Cosentino et al., 2015; Culman et al., 2013; DeHaan et al., 2005; Huddell et al., 2023; Jankauskas et al., 2011; Vallebona et al., 2016). Hence, shifting from annuals to perennials would have a tremendous effect on water quality and eventually ocean health (Beman et al., 2005; Beusen et al., 2016).

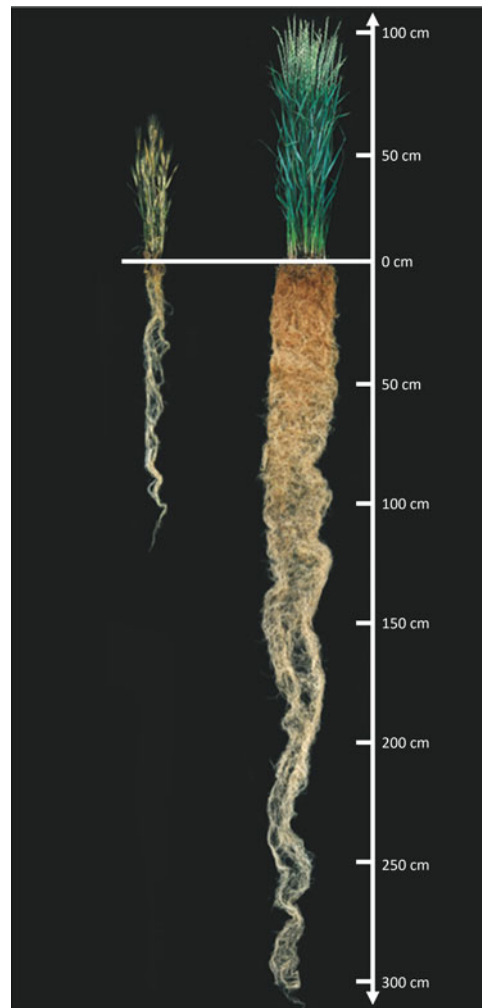


Figure 1. Intermediate wheatgrass in its second year (right) compared with winter wheat ready to be harvested (left). Photo: The Land Institute.

Weeds have been a persistent problem in agriculture since its beginning, indeed they are both an ecological response of, and a reason for clearing the land with tillage every year. More recently, herbicide use has increased substantially (Damalas & Koutroubas, 2024), e.g., the most widely used herbicide (glyphosate) has increased almost 15-fold globally since the introduction of glyphosate resistant crops (Benbrook, 2016). One could hope that the increasing use of glyphosate could be balanced by reduced use of other more toxic herbicides, such as paraquat, but does not seem to be the case (Olsson et al., 2023). As a result, we experience an exponential increase in the number of weeds that are resistant to glyphosate, often called ‘superweeds’ (Bain et al., 2017; Damalas & Koutroubas, 2024). Contrary to cropping systems based on annuals, perennial cropping systems, once they are established, can effectively suppress weeds by more fully utilizing the plant resources of sunlight, water, and nutrients. In a controlled experiment during three years, weed biomass decreased by 88% in an IWG field without any weed removal (Zimbric et al., 2020). Therefore, IWG could also reduce weed development and species abundance over time through year-round soil cover and longer growing seasons (Duchene et al., 2023). Lanker et al.

(2020) confirmed that weed suppression was considered by farmers as one of the most important benefits.

Crop rotation is a common practice for reducing the risk of agricultural pests in annual cropping systems, and pathogen pressure is often used as a counterargument against perennial cropping systems. Deploying crop diversity in time (crop rotation) can effectively disrupt insect or disease pest populations and thus reduce crop losses. However, inbred annual cultivars with low genetic diversity and cultivated in monocultures are always susceptible to pests. Strategically deploying crop diversity (inter and intraspecific) in space (intercrops/polycultures) has also been widely recognized as an effective strategy for regulating insect and disease populations (Deguine et al., 2021; Ratnadass et al., 2012). In addition to interspecific diversity, genetic diversity within crop species in agroecosystems (as seen in outcrossers such as IWG and other perennials, or among mixtures of cultivars) reduces pest and disease pressures and enhances yield production (Wan et al., 2022).

Even if perennial grains are used, they are likely to be renewed at intervals of 3–7 years. Reasons for this could be to remove weeds or that plant breeding has resulted in new and higher yielding cultivars. Studies have also suggested the possibility of rejuvenating old perennial cultures through thinning, burning, grazing or other treatments, but more research is needed (Law et al., 2021; Pinto et al., 2021).

The application of nutrients, either in the form of mineral fertilizers or as manure is another costly and labor-intensive part of growing annual crops. Nitrogen is a problem, often added at a rate of 120 to 250 kg ha⁻¹ year⁻¹, and the manufacture of synthetic nitrogen fertilizers comprises the greatest fossil energy input into agriculture, and a significant source of greenhouse gas emissions. It is well-documented that typically <50% of the fertilizer-N applied to annual grains is used by plants (Ladha et al., 2005, 2016) while the rest is lost to the environment as water soluble nitrate or in various gaseous forms including ammonia and nitrous oxide (Cameron et al., 2013; Sharma & Bali, 2018). Cropping systems that feature deep-rooted perennial grains cultivated in mixed cultures or rotations with nitrogen (atmospheric N₂) fixing legumes, such as clover or alfalfa, hold promise to drastically reduce or perhaps even replace the need for synthetic nitrogen applications (Huddell et al., 2023; Pugliese et al., 2019). Fewer inputs through natural nitrogen fixation are needed when N losses are greatly reduced in an N-use efficient perennial cropping system. Phosphorous is another essential nutrient for crop production which is added in large quantities, typically 10–40 kg ha⁻¹ year⁻¹ in annual cropping systems. The known minable resources are finite and may be depleted in less than 100 years (Cordell et al., 2009). However, agricultural soils commonly contain substantial reserves of phosphorus that are unavailable for our annual crops with shallow root systems. New perennial crops with deep and extensive root systems can potentially utilize such reserves (Stutter et al., 2012), and hence substantially reduce the need for external inputs of phosphorous. Also, with deeper roots natural reserves of phosphorus can be acquired from a larger soil volume, held in forms that are more plant-available, and prevented from contaminating water supplies due to soil erosion (Crews & Brookes, 2014). The ability of perennial grain crops to harness mycorrhiza for improved nutrient cycling is another potential major benefit (Duchene et al., 2020; Gregory, 2022; Strohm, 2021).

From a farming point of view, perennial grains could be described as a farmer's dream – a cultivar that is planted once and then harvested every season for several years with a minimum

of land management in between. Instead of 4–10 tractor passes per year as with annual cultivars, only 1–5 for harvesting and nutrient, pest, and weed management, would be required. From a farm economics point of view, farming perennial grains could translate into a significant reduction in production costs, resulting in increasing total factor productivity. From a regional economic perspective, it could mean that a larger share of farmers' income would remain in the local economy as the need for purchased inputs such as seeds, agrochemicals, synthetic fertilizers, fuel, and machinery from external (often transnational) corporations are reduced. The retained income may stimulate local economic development through the creation of new businesses (Low et al., 2015; Persky et al., 1993) that service the emerging perennial sector. Such local growth could play an important role in offering opportunities to workers in seasonal employment (i.e. tractor drivers) who may be displaced in the short run during this transition. In the long term, the transition to perennial grains could provide a basis for more diverse and thriving rural economies. Comparisons with existing perennial crops, e.g. sugarcane or horticulture, may be difficult to learn from because of their very different means of production and market structures.

While perennial grains hold considerable promise for addressing a wide range of ecological and social challenges in the future, the perennial crops, and cultivars themselves are in early stages of development relative to the annual grains and much research in plant breeding and in cropping systems is needed in the decades to come before the 'utopia' becomes a 'real utopia' (Wright, 2010). But a strong momentum exists among plant breeders operating outside of the commercial seed industry around the world, and over 150 research groups on all continents are currently participating in research on perennial grain crops, cropping systems, sociocultural engagement, and supply chain and product development (DeHaan et al., 2023). Rapid advances in molecular biology and genetics are facilitating accelerated progress in breeding of perennial crops (Chapman et al., 2022; DeHaan et al., 2020; Luo et al., 2022; Van Tassel et al., 2020). Perennial rice is already competitive in terms of yield compared with annual rice (Huang et al., 2018; Zhang et al., 2023). For eight breeding cycles of IWG, yield has been increasing by 9% per cycle and is expected to match annual wheat in about 20 years if progress continues with genomic selection as a breeding tool (Bajgain et al., 2022) along with other improvements of crop management (Fagnant et al., 2023). Finally, tools and technologies for new crop domestication can be integrated with methods that engage humans, as people are essential for plant domestication processes and cultural valuation and awareness can help drive support for crop development and adoption (Krug et al., 2023; Van Tassel et al., 2020).

Our conclusion is that a perennial revolution would be socially and environmentally *desirable*, economically *viable*, and scientifically *achievable*. However, a perennial revolution will not be achieved overnight but can hopefully be achieved within a time-frame like that of the Green Revolution, about 35 years (Kendall & Pimentel, 1994). Within two to three decades domestication and plant breeding, and other associated fields of research, if sufficiently funded, can probably achieve the necessary increases in yield and other traits that are required for ensuring global food security (DeHaan et al., 2023; Krug et al., 2023; Luo et al., 2022).

Arguments against a shift to perennial grains based on the need for increasing food production in the next few decades are to some extent valid but should not deter us from looking at the longer term. World agricultural output growth rates are

slowing and are now the lowest for at least six decades while the growth rate of Total Factor Productivity has declined in the last two decades (Morgan *et al.*, 2022). Explanations for the declining growth rates are not fully understood but impacts of climate change and degradation of natural resources are frequently invoked. Our current staple food crops will face unprecedented challenges and perhaps even complete failure towards the second half of this century (Liu *et al.*, 2016; Zhao *et al.*, 2017). Therefore, the development of completely new crops that are better adapted to the conditions of the Anthropocene should be an urgent priority (Kreitzman *et al.*, 2020).

4. Obstacles for change

A perennial revolution will challenge politically powerful conventional agriculture supported by economically concentrated agrochemical and seed industries. Inevitably, such radical changes will involve political and economic power struggles, and they are certain to be resisted by existing vested interests. So how can perennial polycultures make inroads into conventional agriculture and ultimately replace annual crops as the mainstay of our food systems? Below we will discuss four broad areas of challenges.

4.1 Interdisciplinary challenges

Competing paradigms are unusual in the core disciplines of the natural sciences, except during short periods of paradigmatic shifts. In many social sciences, however, competing paradigms, or at least perspectives, are the norm and they may persist over generations. In the more applied sciences (e.g. agriculture, energy, environment, and forestry) there are sometimes parallel and competing paradigms, (Persson *et al.*, 2018) each one supported by their vested economic and political interests (MoeSingh, 2012). Most obvious is the situation in agricultural sciences where there are two competing paradigms, often called the Productivism Paradigm (Karimi *et al.*, 2021) and the Ecological Paradigm (Kassam & Kassam, 2021). The paradigms differ both in epistemological approaches (Bösch, 2009), and worldviews (Schurman & Munro, 2010). However, paradigms are not purely epistemic but also part of different, ever competing, food regimes (Friedmann, 1993; McMichael, 2009). Regimes associated with productivism paradigm are tightly integrated with the food industry, which is one of the most globally consolidated production spheres (Howard, 2015). Research and plant breeding within the productivism paradigm is well funded and supported by both state and private sources, while research in the ecological paradigm is substantially less funded and almost exclusively by state funding and philanthropy (Lindner, 2004). In searching for radical change, both paradigms offer necessary insights but neither of them is sufficient (Persson *et al.*, 2018) because neither seriously challenges the very core of agriculture – the overwhelming reliance on annual crops.

For understanding the dynamics of agricultural change, we turn to the concept of a research program by Imre Lakatos, which we believe is more suitable than Kuhn's paradigm (Gholson & Barker, 1985). Lakatos' view of science differed from that of a paradigm influencing (or even ruling) how science is practiced. Lakatos described the existing scientific knowledge as a hard core of central theses that are irrefutable (or at least highly resistant to refutation), and the core is surrounded by a protective belt of auxiliary hypotheses open for testing (Musgrave & Pigden,

2021). An important difference between Lakatos' and our understanding of the world (or agriculture) is that while Lakatos only considered scientific protective belts, we understand the hard core being protected, not only by epistemic protective belts of hypotheses that can be verified or falsified, but protective belts of vested economic and political interests, Figure 2.

In practice this makes change even harder than if the protective belt had been epistemic only. The hard core of agriculture is the annual crops, while the protective belts have multiple dimensions, such as scientific fields (e.g. agronomy, soil science, and plant science), economic (e.g. the agrochemical industrial complex), institutional (e.g. rural advisory services, and industry organizations), ideological (e.g. neoliberalism), and cultural (e.g. beliefs, traditions, and values). A perennial revolution needs to engage with all layers of the protective belts.

4.2 Politics of seeds and agrochemicals

Power over the sources and development of seeds is a key for understanding the evolution of modern agriculture (Kloppenborg, 2005; Mooney, 1983; Peschard & Randeria, 2020). From being a public good, often organized as co-operatives, seeds emerged as the linchpin of a commercialization of the agricultural inputs market in the 20th century (Dale, 2004; Friedmann, 1993; Howard, 2015; Kloppenborg, 2005). Pivotal moments were the granting of patents on Roundup Ready cultivars in the mid-1990s, and the ruling by the US Supreme Court in 2013, *Bowman vs Monsanto* (Haugo, 2015; Lim, 2013). Against a strong industrial trend of increasing market consolidation and power, there is also a counter movement, seed activism (Peschard & Randeria, 2020). Even if seed activism has been around for at least four decades (Mooney, 1983), it has grown stronger recently and is now receiving support from outside of farmers and agricultural activism (Peschard, 2022), to some extent supported by the spectacular legal cases against the agrochemical giant Monsanto/Bayer (Corporate Europe Observatory, 2020; McHenry, 2018). The reason why it is pertinent to talk about a perennial revolution is the profound effect on the seed industry the deployment of perennial crops and cultivars will have. The market for seeds will change dramatically, both in terms of size and in terms of organization, with perennial crops.

Controlling the sources of agricultural seeds has been crucial for achieving dominance of the agricultural inputs market, hence the recent spectacular wave of concentration and control over the seed industry (Bratspies, 2017; Clapp, 2018, 2021; Dale, 2004; Hendrickson *et al.*, 2017, 2020; Kloppenborg, 2005). The agriculture and food sectors are dominated by large firms that sell seeds and agrochemicals, machinery, and data services, and they thrive on the current agricultural model with heavy state subsidies (Bellmann, 2019; Laborde *et al.*, 2021; Lima & Monteiro, 2015; Scown *et al.*, 2020). They have significant political power and a strong advantage over pioneers and niche innovations (Bruckner, 2016; Clapp, 2018; Hendrickson *et al.*, 2017; Howard, 2015). Understanding these dynamics will be crucial for formulating strategies and pathways towards a perennial and more diverse and just agriculture of the future.

In addition to corporate maneuvering of mergers and takeovers, intellectual property rights are an important field for maintaining dominance over the agricultural inputs market. To obtain exclusive rights to a plant variety, it must meet criteria such as being new, distinct, uniform, and stable (Würtenberger, 2017). Except for the US, plant varieties cannot be patented but can

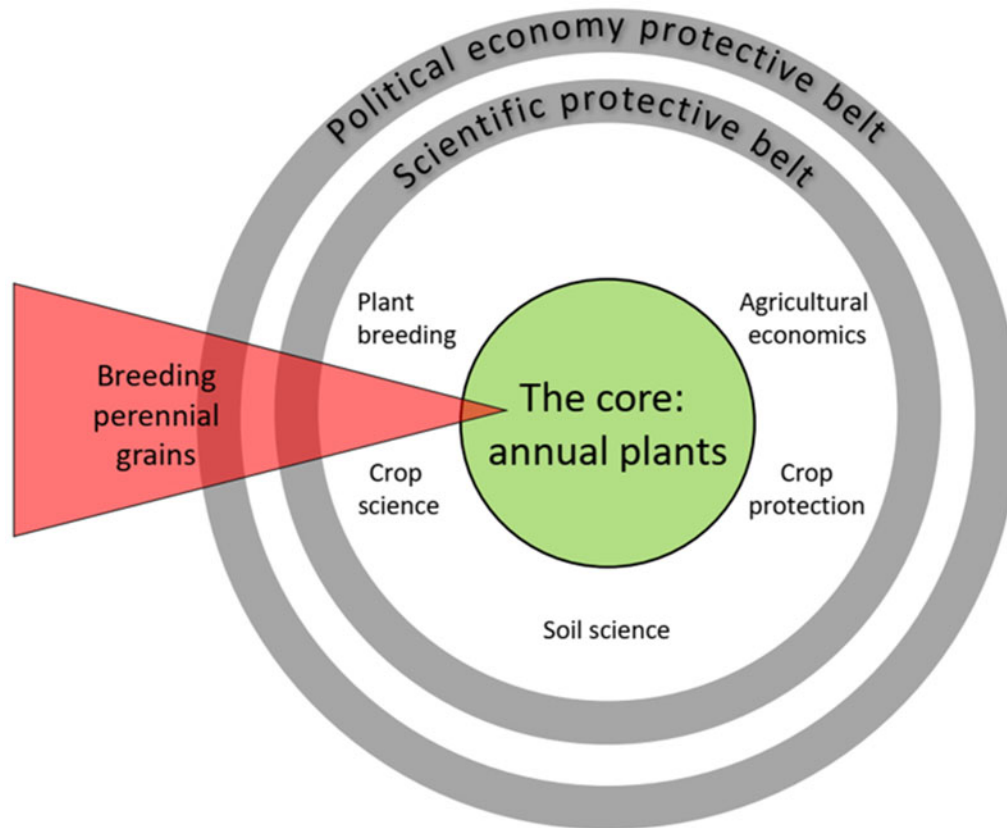


Figure 2. Conceptual view of how agricultural sciences can be understood as a research program with a hard core and protective belts of science and vested economic interests, inspired by Lakatos' concept of Research Program (Lakatos, 1976). A radically different idea, such as domesticating and breeding completely new perennial crops, needs to confront both these protective belts.

be protected under plant breeder's rights. However, a genetically modified plant can be protected by a patent. Both the DNA sequence and the organism into which the sequence has been introduced can be subject to patent protection. Therefore, a genetically modified plant may fall under both plant breeder's rights and a patent. Plant breeder's rights are protected for 25 years, while patent protection lasts for a maximum of 20 years in the USA (Le Buanec & Ricroch, 2021).

Legal protection of varieties and patents in plant breeding is essential for research and development. However, the fact that seeds can reproduce raises questions about whether it violates plant breeder's rights and/or patent protection when the buyer, typically a farmer, produces the seeds themselves. In contrast to patents, plant varieties protected by plant breeder's rights may be freely used for research and further breeding purposes. Thus, a plant breeding company can utilize a competitor's plant variety in its own crossbreeding efforts. However, with patented seeds, regulations are different. In the case of *Bowman v. Monsanto*, the United States Supreme Court argued that allowing simple copying as a protected use would undermine the value of patents and reduce innovation incentives (Simmons, 2013).

Considering that commercially cultivated seeds in modern agriculture are often genetically modified and patented, the *Bowman* case implies that farmers become highly dependent on patent holders, such as Bayer/Monsanto, for their farming operations. Challenging this system, such as saving seeds for future planting, can result in severe economic consequences, as seen in cases like *Monsanto vs Scruggs*. (Savich, 2007).

The rights conferred by patent protection can be used not only to protect one's own inventions, such as GMOs, but also to hinder the development of competing products (Grzegorzczuk & Głowiński, 2020). One conspicuous strategy is acquiring potential rival patents. However, it is also possible to obstruct product development through offensive patent strategies, such as the 'patent picket fence strategy' involving pursuing patents closely related to a competing product, thereby complicating matters for the competitor (Brown & Levitt, 2023). Small organizations with a limited patent portfolio may face challenges in sustaining their existence, as their long-term viability depends on the patents secured by their competitors.

Thus, the development of perennial crops is likely to be significantly delayed if stakeholders who prefer annual crops employ aggressive patent strategies to secure key patents, such as genes that control seed shattering of perennial varieties intended for future commercial use. Various patent strategies employed for commercial purposes can significantly impact innovation and development at the forefront of research. There are numerous examples discussed above that illustrate this effect. These strategies are typically costly, giving larger organizations and companies an advantage over smaller businesses and publicly funded research. This means that individual commercial interests may take precedence over research and development for the greater good. Intellectual property rights and other legislation that can be used (or misused) to acquire and strengthen market power can thus serve as significant protective belts, highlighting the need for international policy actions aimed at enabling innovation

for sustainable transitions (Herrero et al., 2020). However, ideas and initiatives to prevent corporate domination over seeds are frequently discussed, the most advanced initiative so far being the Open Seed Initiative (Kloppenburg, 2014; Kotschi & Horneburg, 2018; Montenegro de Wit, 2019).

There has been a strong trend in the concentration of the seed market globally, and not least in the US where only two firms control over 70% of the US corn seed market after mergers in 2012 (Figure 3).

Vested commercial and scientific interests evidently influence the ways in which science is practiced (Druker, 2015; McHenry, 2018; Schurman & Munro, 2010). This can be described and analyzed aptly by Steven Lukes' typology of three dimensions of power (Lukes, 2005; Scherrer, 2022). The first dimension, being decision making power (also expressed as 'power over' somebody), can be illustrated by several recent and on-going legal processes where market leading companies use their legal power to sue, or threaten to sue, farmers for infringing on patents. The second dimension is called non-decision-making power (also expressed as power to prevent/preempt, or agenda setting). It can be illustrated by the very active role that leading industries take in influencing political agendas about agriculture, e.g. the process of renewal of glyphosate in EU in 2023. The third dimension is called ideological power (also expressed as power to influence people's values, preferences, interests, and perceptions). It can be illustrated by the very active role leading industries take in sponsoring research. A more comprehensive list of examples of Lukes' three dimension is in the supplementary material.

4.3 Beyond seeds, the agricultural treadmill

Even if seeds play a very particular role in the evolution of the current dominant practices in agriculture, we need to look at the broad picture of agricultural technologies. This is best done through the lens of the Agricultural Treadmill Theory (ATM) formulated in 1958 by Willard Cochrane (Cochrane, 1958; Crews et al., 2018). Even if the agricultural sector has changed substantially since its formulation, the ATM theory is still valid. In short,

the ATM explains how technological development drives agriculture towards productivism and increasing use of unsustainable practices. According to ATM theory, agriculture is driven by a self-reinforcing cycle of technological change, which increases the efficiency of agricultural inputs and machinery and suppresses food prices (and farmer income), in turn leading to an impetus to increase farm sizes (corresponding to economic concentration in the farming sector) and further technological innovation (Crews et al., 2018). This process implies that a minority of early non-risk-averse adopters reap the benefits of new agricultural technologies, while the majority of farmers are forced to adopt in order to reduce their costs under increasing competition and falling prices. As an illustration, the majority of small farms in the USA, approximately 90% of all farms, had negative profits in 2016, in sharp contrast to the 3% of large and very large farms (Crews et al., 2018). In theory, one could argue that the treadmill is driving agriculture towards greater resource use efficiency, more narrowly targeted pesticide inputs, and more energy efficiency. However, agriculture as a market is far from the perfect competition often assumed by economists (Sykuta, 2013), instead it is characterized by rapid concentration (Clapp, 2018; Hendrickson et al., 2001, 2017, 2020; Howard, 2009, 2015) that drives agriculture towards higher yields rather than environmental sustainability (Clapp, 2021; Houser & Stuart, 2020).

The agrochemical industry has in recent decades forged a strong alliance with the seed industry through mergers and take-overs with enormous legal and political clout. Compared to the 1950s (when the ATM was formulated), we argue that the ATM has intensified because of the unprecedented structural transformation of the agrochemical and seed industry (Howard, 2009, 2015; Lianos, 2019). Hence it is tempting to make an analogy with the Military-Industrial Complex that President Eisenhower warned about in his farewell speech in 1961, i.e., an informal, and to a large extent covert, alliance between a nation's military apparatus and the weapons industry forming vested interests influencing public policy (Adams, 1968). Three conditions for the existence of the military-industrial complex were essential: (i) a commodity of national strategic importance, (ii)

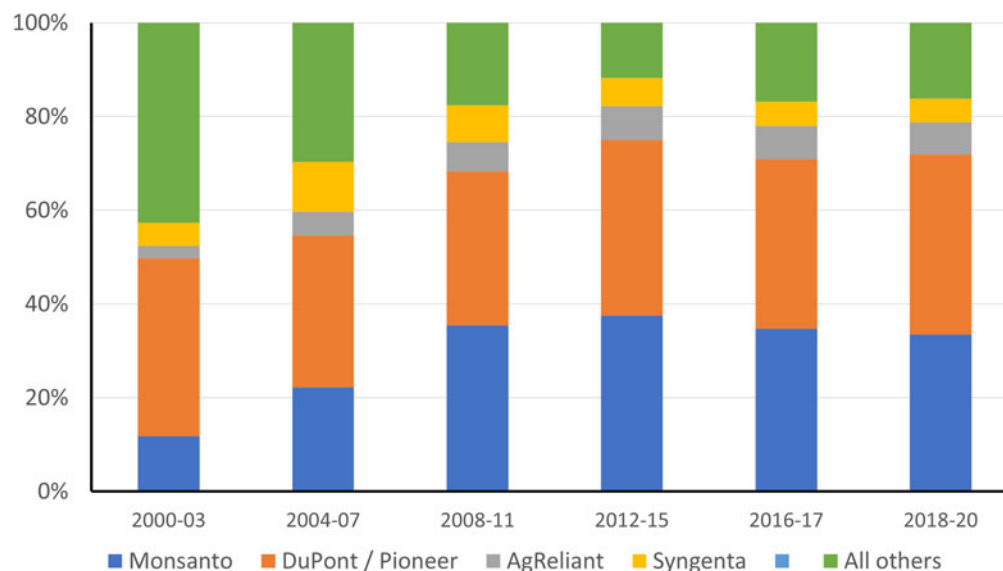


Figure 3. Market share of the US corn seed market. The data for 2018–20 are estimated, and valid for Bayer instead of Monsanto (after the merger in 2018), Corteva instead of DuPont/Pioneer (after the merger in 2018). Source of data (Macdonald et al., 2023).

strong regulatory regime, and (iii) state subsidies. The similarities with agriculture are striking, hence it is relevant to talk about the agrochemical industrial complex as a powerful strategic action field (Fligstein & McAdam, 2011; Olsson & Jerneck, 2018). A relevant example is the lobbying (worth over 45 M€ during 2019 and 2020) by the agrochemical industry to dilute EU's policy for sustainable farming, including the renewal of the license of glyphosate (De Lorenzo & Sherrington, 2021). The prospect of developing perennial grains that would drastically reduce the market for seeds, herbicides, and machinery, may even be seen as an existential threat to the Agrochemical industrial complex.

4.4 Transition theory concerns

Transition theory, here used as an umbrella term including multi-level perspective (Geels, 2019) and transition management (Loorbach et al., 2015), is a middle range theory aimed at understanding the conditions for social change. The strength of transition theory for this purpose is that it links structural conditions with agency (Geels, 2019). Seen through the lens of transition theory, which helps synthesize the epistemic, political, and economic challenges described above, the perennial revolution faces three main barriers:

- A perennial revolution is goal-oriented rather than an emergent transition, generating primarily collective goods (sustainability) rather than private goods (profits). Such transitions struggle to get traction because of the lack of clear and powerful actors to promote change in exchange for benefits. Beneficiaries would primarily be farmers who cannot keep up in the treadmill, because the farms are too small to justify investment in the latest and most efficient technologies, while large farms with high degree of mechanization (i.e. capital-intensive production) would not benefit, at least not in the first place, because of their high sunk costs (Barham & Chavas, 2019).
- The new perennial crops and associated practices may not offer immediate benefits in terms of profit for the early adopters and may not match price/performance of existing technologies. Hence, they may not be able to replace existing systems without policy changes (e.g. taxes, subsidies, regulatory frameworks) that entail politics and power struggles. Powerful vested interests in the agricultural inputs industry may try to resist such changes.
- The agriculture and food sector is dominated by large firms and alliances with many advantages such as access to distribution channels, advertising power, service networks, and complementary technologies (Hendrickson et al., 2001; 2017; 2020; Howard, 2015). The incumbent regime has a strong position vis-à-vis pioneers in terms of knowledge, agricultural advisory services, and experimental farms that can generate evidence-based information.

5. Four reasons for optimism

Despite the many obstacles, we offer four reasons for optimism that a perennial revolution of agriculture is imminent in the next couple of decades. In addition to the rapid advance of plant breeding technologies that make perennial grains scientifically achievable, which is a fundamental priority and prerequisite for agricultural change, we understand the four reasons below as positive signals specifically because of their relevance to begin addressing the main political economy barriers.

5.1 Perennial polycultures are appealing to farmers

Even though the emerging new perennial crops may not yet offer immediate benefits to farmers and have not been promoted to them by powerful actors, there is interest in their adoption. As commercial perennial grain crops are not yet widely available, data on their performance in terms of economy and management is scarce. A few interview or survey-based investigations of farmers' attitudes towards perennial grains in France, Sweden and USA have been published (Adebiyi et al., 2016; Lanker et al., 2020; Marquardt et al., 2016; Wayman et al., 2019). A general conclusion is that information and awareness of perennial grains (particularly IWG and perennial wheat) has already received considerable interest among farmers. Motivations or concerns about adopting new perennial grains vary among farmers, but fall within three main categories:

- Economics: The potential to compete with conventional annual crops was among the most important responses in the on-line survey among farmers in France ($n = 319$) and the US ($n = 88$) (Wayman et al., 2019) and in an interview-based study of farmers who have already adopted IWG (Lanker et al., 2020) in the US. This contrasts with two interview studies in Sweden and USA (Michigan and Ohio) where low yield did not feature as a reason for not adopting the new crops (Adebiyi et al., 2016; Marquardt et al., 2016).
- Environment: In all the studies, the potential of improving soil health and reducing soil erosion was among the top priorities for adopting the new perennial grain crops. In all studies, farmers showed high awareness of the advantages of perennial crops.
- Management: Reducing the time and cost for tillage, weed control, and spraying featured as a strong incentive for adopting (or testing) new perennial crops.

5.2 The legitimacy of contemporary agricultural and food industries is being challenged

Even though the current agriculture and food sector is powerful, its legitimacy is increasingly being questioned by the public due to the previously described problems. However, perennial grains offer new and unique opportunities to address some of these negative consequences.

Agricultural subsidies contribute to push farmers into the agricultural treadmill of productivism (Lima & Monteiro, 2015) and subsidies are increasingly under attack for several reasons. They are accused of distorting the global trade system (Anderson & Martin, 2005; Hopewell, 2019); driving the emission of greenhouse gases from agriculture (Laborde et al., 2021; Scown et al., 2020); excluding small scale producers in the Global South from important agricultural markets (Clapp, 2006); and exacerbating consolidation of the farming sector towards fewer but bigger farms (Bruckner, 2016). By reducing the cost of production, perennial grains offer an opportunity for farmers to break out of the agricultural treadmill, and ultimately the dependence on subsidies.

Consumers are increasingly aware of the negative environmental consequences of agriculture, particularly emission of greenhouse gases (European Commission, 2020). Concerns over the environmental consequences, such as emission of greenhouse gases, loss of biodiversity, eutrophication of coastal waters, and negative impacts on pollinators are increasingly raised. The main benefits of perennial grains are the possibilities to improve on a range of environmental performances as described above, and to reduce

the workload required to grow food whether from human or animal labor, or fossil fuel powered machines. Furthermore, the pandemic and Russia's invasion of Ukraine 2022 have revealed the risks of being dependent on international commodity chains for food, let alone agricultural inputs such as fertilizers.

5.3 There is growing interest in soil health, which could be a collective goal and good

Even though collective goods are undervalued by contemporary societies, there is a complex opportunity at hand for working toward a collective sustainability good and goal in the valuation of soil and the ecological services soil provides. A perennial revolution that offers genuine potential for holding and healing soils aligns with the growing interest in soil health. Powerful actors could promote goal-oriented ecological change in exchange for benefits; however, if not challenged, they could also use this opportunity to retrench current economic systems that feature private profits over public goods.

Kuhnian paradigm shifts are rare, but in soil science we have witnessed a change in the understanding of soils which can be seen as a paradigm shift (Chapin *et al.*, 2009; Dick, 2018; Lehmann & Kleber, 2015), with important implications for agricultural practices and the political economy of agriculture (Chabbi *et al.*, 2017). Before some 20 years ago, soils were primarily understood and modelled as a physical-chemical entity (Chapin *et al.*, 2009; Lavelle, 2000) although early leaders of the nascent organic agriculture movement of the early 20th century (as a competing paradigm) held different viewpoints long before (Howard, 1947). More recently, the understanding of soils as an ecosystem where the dynamics are primarily driven by biological processes have paved the way to the new concept of soil health (Swinnen, 2018) defined as 'the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans' (Swinnen, 2018). Agricultural practices for improving soil health have been concretized as promoting four practices: minimize disturbance of the soil, maximize living roots, maximize soil cover, and maximize biodiversity, as promoted by organic regenerative agriculture (USDA NRCS, 2023). These four practices exactly mirror the functions of the diverse perennial vegetation of natural ecosystems that was responsible for building soil health in the first place.

The shift, subtle as it may sound to lay people, is profound. In a soil health view, soils are living ecosystems of extreme complexity – even more complex than the above-ground interaction of plants and animals. The paradigm shift in and of itself implies a critique of agriculture because most of the practices in conventional agriculture, such as frequent tilling, application of pesticides, excess supply of mineral fertilizers, and monocultures with short rotation, are detrimental to soil health (Olsson *et al.*, 2023). The EU target to 'ensure that 75% of soils are healthy by 2030' (Veerman *et al.*, 2020) is heavily based on promoting soil health, but arguably unrealistic within the <10 years left (Poulton *et al.*, 2018; Schlesinger & Amundson, 2018). However, in a somewhat longer time perspective, a shift to perennial crops would imply a game changer that would significantly improve the chances of achieving, and perhaps going beyond, such a goal.

5.4 There are signs of growing interest in public R&D funding

Public entities are beginning to understand the potential for agricultural research on perennial grains to provide public goods.

While the 1980s to 2010s saw an increasing privatization of agricultural research, both in companies and universities (DeLonge *et al.*, 2016; Fuglie *et al.*, 2012, 2018; Pray & Fuglie, 2015), we are now seeing some signs of a reversal. For example the recent development of perennial rice was heavily supported by public funding (Zhang *et al.*, 2023). Presenting the opportunity to policymakers and voters, we are seeing a growing interest in public funds being used for research that will benefit soil, climate, wildlife, rural cultures, and human health, simultaneously (Minnesota Department of Agriculture, 2022; NIFA, 2020). This win-win opportunity has great potential to ignite a renaissance of public agricultural research. While public agricultural research has been on a downward trend with institutions shrinking their budgets for decades (Nelson & Fuglie, 2022), the opportunity to offer something of great value to society broadly is a great opportunity to reclaim the public-good mission for which some of these institutions were founded centuries ago. Public funding agencies over the past 5 years have just begun to support this research, an indication that democratic ideals may still influence scientific research. Many companies are striving to be at the forefront of climate solutions in agriculture. This presents a whole new array of challenges, for example as discussed above with increased interest in soil health valuation, but it is a clear opportunity to be used.

6. Concluding remark and research priorities

We believe that the time is ripe for the onset of a perennial revolution. The goal of this revolution is the rapid development of entirely new high-yielding perennial grain crops that can replace the current repertoire of annuals. As the diversity of viable perennial pulse, oilseed and cereal crops expands, so will opportunities to experiment with ecologically functional polycultures and other cropping systems thus facilitating the replacement of input intensification with ecological intensification. The result will be cropping systems that preserve the soil, store carbon efficiently, require minimal inputs in terms of commercial energy and machinery, utilize available water effectively, are increasingly self-sufficient in nitrogen and can unlock stores of phosphorous in agricultural soils. Engaging in this endeavor for the benefit of sustainable agriculture will be an exciting research challenge for plant scientists, probably more exciting than incrementally tweaking the existing annual cultivars. It will also foster social science, humanities, and transdisciplinary research on the new sociocultural and economic dynamics of rural societies before, under, and after a perennial revolution. Nevertheless, the revolution is likely to meet strong resistance from the agrochemical industrial complex and societal strategies to address this predicted challenge must be designed.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/sus.2024.27>.

Acknowledgments. We would like to acknowledge The Pufendorf Institute for Advanced Studies at Lund University for providing financial means and intellectual inspiration within the two thematic projects of DOMESTICATION.

Author contributions. LO conceived and designed the manuscript and wrote the first draft. All other authors contributed equally to revising and editing the manuscript.

Funding statement. We acknowledge funding from the following research projects: ERC Advanced Grant No. 101096708 PERENNIAL (LO, EA, TC, CD, ASK, SR, AW). The Swedish Research Council Formas: Capturing

Carbon in Perennial Cropping Systems, Grant No. 2021-00644 and 2022-00228 (JA, TT, PV). The Swedish National Space Agency, Grant No. 2021-00144 (TT)

Competing interests. The authors declare no conflict of interest.

Research transparency and reproducibility. n/a.

References

- Adams, W. (1968). The military-industrial complex and the new industrial state on JSTOR. *The American Economic Review*, 58(2), 652–665.
- Adebiyi, J., Schmitt Olabisi, L., & Snapp, S. (2016). Understanding perennial wheat adoption as a transformative technology: Evidence from the literature and farmers. *Renewable Agriculture and Food Systems*, 31(2), 101–110. <https://doi.org/10.1017/S1742170515000150>
- Alexander, S. (2019). What climate-smart agriculture means to members of the global alliance for climate-smart agriculture. *Future of Food: Journal on Food, Agriculture and Society*, 7(1), 21–30.
- Altendorf, K. R., DeHaan, L. R., & Anderson, J. (2022). Genetic architecture of yield-component traits in the new perennial grain crop, intermediate wheatgrass. *Crop Science*, 62(2), 880–892. <https://doi.org/10.1002/CSC2.20716>
- Anderson, K., & Martin, W. (2005). Agricultural trade reform and the Doha development agenda. *World Economy*, 28(9), 1301–1327. <https://doi.org/10.1111/J.1467-9701.2005.00735.X>
- Bailey, A., Meyer, L., Pettingell, N., Macie, M., & Korstad, J. (2020). Agricultural practices contributing to aquatic dead zones. In K. Baudhdh, S. Kumar, R. P. Singh, & J. Korstad (Eds.), *Ecological and practical applications for sustainable agriculture* (pp. 373–393). Springer. https://doi.org/10.1007/978-981-15-3372-3_17
- Bain, C., Selifa, T., Dandachi, T., & Velardi, S. (2017). ‘Superweeds’ or ‘survivors’? Framing the problem of glyphosate resistant weeds and genetically engineered crops. *Journal of Rural Studies*, 51, 211–221. <https://doi.org/10.1016/j.jrurstud.2017.03.003>
- Bajgain, P., Zhang, X., Jungers, J. M., DeHaan, L. R., Heim, B., Sheaffer, C. C., Wyse, D. L., & Anderson, J. A. (2020). ‘MN-Clearwater’, the first food-grade intermediate wheatgrass (Kernza perennial grain) cultivar. *Journal of Plant Registrations*, 3, 288–297. <https://doi.org/10.1002/plr2.20042>
- Bajgain, P., Crain, J. L., Cattani, D. J., Larson, S. R., Altendorf, K. R., Anderson, J. A., Crews, T. E., Hu, Y., Poland, J. A., Turner, M. K., Westerbergh, A., & DeHaan, L. R. (2022). Breeding intermediate wheatgrass for grain production. In I. Goldman (Ed.), *Plant breeding reviews* (Vol. 46, pp. 119–217). Wiley.
- Baker, B. (2017). Can modern agriculture be sustainable? *BioScience*, 67(4), 325–331. <https://doi.org/10.1093/biosci/bix018>
- Barham, B. L., & Chavas, J.-P. (2019). Sunk costs and resource mobility: Implications for economic and policy analysis. In *Food security, diversification and resource management: Refocusing the role of agriculture?* (pp. 391–400). Routledge. https://doi.org/10.4324/9780429457326_28
- Bellmann, C. (2019). Subsidies and Sustainable Agriculture: Mapping the Policy Landscape. <https://www.chathamhouse.org/2019/12/subsidies-and-sustainable-agriculture-mapping-policy-landscape>
- Beman, J. M., Arrigo, K. R., & Matson, P. A. (2005). Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. *Nature*, 434(7030), 211–214. <https://doi.org/10.1038/nature03370>
- Benbrook, C. M. (2016). Trends in glyphosate herbicide use in the United States and globally. *Environmental Sciences Europe*, 28(1), 1–15. <https://doi.org/10.1186/s12302-016-0070-0>
- Beusen, A. H. W., Bouwman, A. F., Van Beek, L. P. H., Mogollón, J. M., & Middelburg, J. J. (2016). Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. *Biogeosciences (Online)*, 13(8), 2441–2451. <https://doi.org/10.5194/BG-13-2441-2016>
- Bezner Kerr, R., Hasegawa, T., Lasco, R., Bhatt, I., Deryng, D., Farrell, A., Gurney-Smith, H., Ju, H., Lluch-Cota, S., Meza, F., Nelson, G., Neufeldt, H., & P. (2022). Food, fibre and other ecosystem products. In IPCC (Ed.), *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the 6th Assessment Report of the IPCC [Pörtner, H.-O. et al]* (pp. 713–906). Cambridge University Press. <https://doi.org/10.1017/9781009325844.007>
- Bless, A., Davila, F., & Plant, R. (2023). A genealogy of sustainable agriculture narratives: Implications for the transformative potential of regenerative agriculture. *Agriculture and Human Values*, 40(4), 1379–1397. <https://doi.org/10.1007/S10460-023-10444-4/FIGURES/1>
- Bommarco, R., Kleijn, D., & Potts, S. G. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology and Evolution*, 28(4), 230–238. Elsevier Current Trends. <https://doi.org/10.1016/j.tree.2012.10.012>
- Böschchen, S. (2009). Hybrid regimes of knowledge? Challenges for constructing scientific evidence in the context of the GMO-debate. *Environmental Science and Pollution Research*, 16(5), 508–520. <https://doi.org/10.1007/s11356-009-0164-y>
- Bratspies, R. (2017). Owning all the seeds: Consolidation and control in Agbiotech. *Environmental Law*, 47, 583–608. <https://heinonline.org/HOL/Page?handle=hein.journals/envlnw47&id=617&div=23&collection=journals>
- Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G. S., Limburg, K. E., Montes, I., Naqvi, S. W. A., Pitcher, G. C., Rabalais, N. N., Roman, M. R., Rose, K. A., Seibel, B. A., ... Zhang, J. (2018). Declining oxygen in the global ocean and coastal waters. *Science (New York, N.Y.)*, 359(6371), eaam7240. <https://doi.org/10.1126/science.aam7240>
- Brown, R. J., & Levitt, K. E. (2023). An effective patent strategy: What it is, and how to implement it. *Intellectual Property Update*, 3(4), 1–7.
- Bruckner, T. (2016). Agricultural subsidies and farm consolidation. *American Journal of Economics and Sociology*, 75(3), 623–648. <https://doi.org/10.1111/AJES.12151>
- Camarero, J. J., Colangelo, M., Gracia-Balaga, A., Ortega-Martínez, M. A., & Büntgen, U. (2021). Demystifying the age of old olive trees. *Dendrochronologia*, 65, 125802. <https://doi.org/10.1016/j.DENDRO.2020.125802>
- Cameron, K. C., Di, H. J., & Moir, J. L. (2013). Nitrogen losses from the soil/plant system: A review. *Annals of Applied Biology*, 162(2), 145–173. <https://doi.org/10.1111/aab.12014>
- Cassman, K. G., & Connor, D. J. (2022). Progress towards perennial grains for prairies and plains. *Outlook on Agriculture*, 51(1), 32–38. <https://doi.org/10.1177/00307270211073153>
- Chabbi, A., Lehmann, J., Ciais, P., Loescher, H. W., Cotrufo, M. F., Don, A., Sanclément, M., Schipper, L., Six, J., Smith, P., & Rumpel, C. (2017). Aligning agriculture and climate policy. *Nature Climate Change*, 7(5), 307–309. Nature Publishing Group. <https://doi.org/10.1038/nclimate3286>
- Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, 4(4), 287–291. <https://doi.org/10.1038/nclimate2153>
- Chapin, F. S., McFarland, J., David McGuire, A., Euskirchen, E. S., Ruess, R. W., & Kielland, K. (2009). The changing global carbon cycle: Linking plant-soil carbon dynamics to global consequences. *Journal of Ecology*, 97(5), 840–850. <https://doi.org/10.1111/j.1365-2745.2009.01529.x>
- Chapman, E. A., Thomsen, H. C., Tulloch, S., Correia, P., Luo, G., Najafi, J., DeHaan, L., Crews, T. E., Olsson, L., Lundquist, P.-O., Westerbergh, A., Pedas, P. R., Knudsen, S., & Palmgren, M. (2022). Perennials as future crops: Opportunities and challenges. *Frontiers in Plant Science*, 13, 898769. <https://doi.org/10.3389/fpls.2022.898769>
- Chi, J., Waldo, S., Pressley, S., O’Keeffe, P., Huggins, D., Stöckle, C., Pan, W. L., Brooks, E., & Lamb, B. (2016). Assessing carbon and water dynamics of no-till and conventional tillage cropping systems in the inland Pacific northwest US using the eddy covariance method. *Agricultural and Forest Meteorology*, 218–219, 37–49. <https://doi.org/10.1016/J.AGRFORMET.2015.11.019>
- Ciotir, C., Applequist, W., Crews, T. E., Cristea, N., DeHaan, L. R., Frawley, E., Herron, S., Magill, R., Miller, J., Roskov, Y., Schlautman, B., Solomon, J., Townesmith, A., Van Tassel, D., Zarucchi, J., & Miller, A. J. (2019). Building a botanical foundation for perennial agriculture: Global inventory of wild, perennial herbaceous Fabaceae species. *Plants, People, Planet*, 1(4), 375–386. <https://doi.org/10.1002/ppp3.37>
- Clancy, M. S., & Moschini, G. C. (2017). Intellectual property rights and the ascent of proprietary innovation in agriculture. *Annual Review of*

- Resource Economics*, 9, 53–74. <https://doi.org/10.1146/ANNUREV-RESOURCE-100516-053524>
- Clapp, J. (2006). WTO agriculture negotiations: Implications for the global south. *Third World Quarterly*, 27(4), 563–577. <https://doi.org/10.1080/01436590600720728>
- Clapp, J. (2018). Mega-mergers on the menu: Corporate concentration and the politics of sustainability in the global food system. *Global Environmental Politics*, 18(2), 12–33. https://doi.org/10.1162/glep_a_00454
- Clapp, J. (2021). The problem with growing corporate concentration and power in the global food system. *Nature Food*, 2(6), 404–408. <https://doi.org/10.1038/s43016-021-00297-7>
- Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences of the United States of America*, 116(46), 23357–23362. <https://doi.org/10.1073/pnas.1906908116>
- Cochrane, W. W. (1958). *Farm prices: Myth and reality*. University of Minnesota Press.
- Coe, M. T., Evans, K. M., Gasic, K., & Main, D. (2020). Plant breeding capacity in U.S. Public institutions. *Crop Science*, 60(5), 2373–2385. <https://doi.org/10.1002/CSC2.20227>
- Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19(2), 292–305. <https://doi.org/10.1016/j.GLOENVCHA.2008.10.009>
- Corporate Europe Observatory. (2020). *FleishmanHillard's secret lobby campaign for Monsanto*. <https://corporateeurope.org/en/2019/09/fleishmanhillards-secret-lobby-campaign-monsanto>
- Cosentino, S. L., Copani, V., Scalici, G., Scordia, D., & Testa, G. (2015). Soil erosion mitigation for perennial species under Mediterranean environment. *Bioenergy Research*, 8(4), 1538–1547. <https://doi.org/10.1007/S12155-015-9690-2/FIGURES/9>
- Cox, S., Nabukalu, P., Paterson, A. H., Kong, W., & Nakasagga, S. (2018). Development of perennial grain Sorghum. *Sustainability* 10(1), 172. <https://doi.org/10.3390/SU10010172>
- Crews, T., & Brookes, P. C. (2014). Changes in soil phosphorus forms through time in perennial versus annual agroecosystems. *Agriculture, Ecosystems & Environment*, 184, 168–181. <https://doi.org/10.1016/j.AGEE.2013.11.022>
- Crews, T., & Rumsey, B. (2017). What agriculture can learn from native ecosystems in building soil organic matter: A review. *Sustainability*, 9(4), 578. <https://doi.org/10.3390/su9040578>
- Crews, T., Blesh, J., Culman, S. W., Hayes, R. C., Jensen, E. S., Mack, M. C., Peoples, M. B., & Schipanski, M. E. (2016). Going where no grains have gone before: From early to mid-succession. *Agriculture, Ecosystems & Environment*, 223, 223–238. <https://doi.org/10.1016/j.AGEE.2016.03.012>
- Crews, T. E., Carton, W., & Olsson, L. (2018). Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. *Global Sustainability*, 1, e11. <https://doi.org/10.1017/sus.2018.11>
- Cui, L., Ren, Y., Murray, T. D., Yan, W., Guo, Q., Niu, Y., Sun, Y., & Li, H. (2018). Development of perennial wheat through hybridization between wheat and wheatgrasses: A review. *Engineering*, 4(4), 507–513. <https://doi.org/10.1016/j.ENG.2018.07.003>
- Culman, S. W., DuPont, S. T., Glover, J. D., Buckley, D. H., Fick, G. W., Ferris, H., & Crews, T. E. (2010). Long-term impacts of high-input annual cropping and unfertilized perennial grass production on soil properties and belowground food webs in Kansas, USA. *Agriculture, Ecosystems and Environment*, 137(1–2), 13–24. <https://doi.org/10.1016/j.agee.2009.11.008>
- Culman, S. W., Snapp, S. S., Ollenburger, M., Basso, B., & DeHaan, L. R. (2013). Soil and water quality rapidly responds to the perennial grain Kernza wheatgrass. *Agronomy Journal*, 105(3), 735–744. <https://doi.org/10.2134/agnonj2012.0273>
- Dale, P. J. (2004). Public-good plant breeding: What should be done next? *Journal of Commercial Biotechnology*, 10(3), 199–208. <https://doi.org/10.1057/PALGRAVE.JCB.3040075/METRICS>
- Damalas, C. A., & Koutroubas, S. D. (2024). Herbicide resistance evolution, fitness cost, and the fear of the superweeds. *Plant Science*, 339, 111934. <https://doi.org/10.1016/j.PLANTSCI.2023.111934>
- Dequigne, J. P., Aubertot, J. N., Flor, R. J., Lescourret, F., Wyckhuys, K. A. G., & Ratnadass, A. (2021). Integrated pest management: Good intentions, hard realities. A review. *Agronomy for Sustainable Development* 41(3), 1–35. <https://doi.org/10.1007/S13593-021-00689-W>
- DeHaan, L. R., & Van Tassel, D. L. (2014). Useful insights from evolutionary biology for developing perennial grain crops ¹. *American Journal of Botany*, 101(10), 1801–1819. <https://doi.org/10.3732/ajb.1400084>
- DeHaan, L. R., Van Tassel, D. L., & Cox, T. S. (2005). Perennial grain crops: A synthesis of ecology and plant breeding. *Renewable Agriculture and Food Systems*, 20(01), 5–14. <https://doi.org/10.1079/RAF200496>
- DeHaan, L. R., Van Tassel, D. L., Anderson, J. A., Asselin, S. R., Barnes, R., Baute, G. J., Cattani, D. J., Culman, S. W., Dorn, K. M., Hulke, B. S., Kantar, M., Larson, S., David Marks, M., Miller, A. J., Poland, J., Ravetta, D. A., Rude, E., Ryan, M. R., Wyse, D., & Zhang, X. (2016). A pipeline strategy for grain crop domestication. *Crop Science*, 56(3), 917–930. <https://doi.org/10.2135/cropsci2015.06.0356>
- DeHaan, L., Larson, S., López-Marqués, R. L., Wenkel, S., Gao, C., & Palmgren, M. (2020). Roadmap for accelerated domestication of an emerging perennial grain crop. *Trends in Plant Science*, 25(6), 525–537. Elsevier Ltd. <https://doi.org/10.1016/j.tplants.2020.02.004>
- DeHaan, L. R., Anderson, J. A., Bajgain, P., Basche, A., Cattani, D. J., Crain, J., Crews, T. E., David, C., Duchene, O., Gutknecht, J., Hayes, R. C., Hu, F., Jungers, J. M., Knudsen, S., Kong, W., Larson, S., Lundquist, P. O., Luo, G., Miller, A. J., ... Westerbergh, A. (2023). Discussion: Prioritize perennial grain development for sustainable food production and environmental benefits. *Science of The Total Environment*, 895, 164975. <https://doi.org/10.1016/J.SCITOTENV.2023.164975>
- DeLonge, M. S., Miles, A., & Carlisle, L. (2016). Investing in the transition to sustainable agriculture. *Environmental Science & Policy*, 55, 266–273. <https://doi.org/10.1016/J.ENVSCI.2015.09.013>
- De Lorenzo, D., & Sherrington, R. (2021). *Mapped: The Network of Powerful Agribusiness Groups Lobbying to Water Down the EU's Sustainable Farming Targets – DeSmog Report*. <https://www.desmog.com/2021/12/09/network-agribusiness-chemicals-pesticides-lobbying-eu-sustainable-climate-farming/>
- Denison, R. F. (2012). *Darwinian agriculture: How understanding evolution can improve agriculture*. Princeton University Press.
- de Oliveira, G., Brunzell, N. A., Sutherlin, C. E., Crews, T. E., & DeHaan, L. R. (2018). Energy, water and carbon exchange over a perennial Kernza wheatgrass crop. *Agricultural and Forest Meteorology*, 249, 120–137. <https://doi.org/10.1016/j.AGRFORMET.2017.11.022>
- de Oliveira, G., Brunzell, N. A., Crews, T. E., DeHaan, L. R., & Vico, G. (2019). Carbon and water relations in perennial Kernza (*Thinopyrum intermedium*): An overview. *Plant Science* 295, 110279. Elsevier Ireland Ltd. <https://doi.org/10.1016/j.plantsci.2019.110279>
- Dick, R. (2018). Soil health: The theory of everything (terrestrial) or just another buzzword? *CSA News*, 63(11), 12–17. <https://doi.org/10.2134/csa2018.63.1114>
- Druker, S. M. (2015). *Altered genes, twisted truths*. Clear River Press.
- Duchene, O., Celette, F., Ryan, M. R., DeHaan, L. R., Crews, T. E., & David, C. (2019). Integrating multipurpose perennial grains crops in Western European farming systems. *Agriculture, Ecosystems and Environment*, 284, 106591. <https://doi.org/10.1016/j.agee.2019.106591>
- Duchene, O., Celette, F., Barreiro, A., Mårtensson, L. M. D., Freschet, G. T., & David, C. (2020). Introducing perennial grain in grain crops rotation: The role of rooting pattern in soil quality management. *Agronomy* 10(9), 1254. <https://doi.org/10.3390/AGRONOMY10091254>
- Duchene, O., Bathellier, C., Dumont, B., David, C., & Celette, F. (2023). Weed community shifts during the aging of perennial intermediate wheatgrass crops harvested for grain in arable fields. *European Journal of Agronomy*, 143, 126721. <https://doi.org/10.1016/J.EJA.2022.126721>
- Duru, M., Therond, O., & Fares, M. (2015). Designing agroecological transitions: A review. *Agronomy for Sustainable Development*, 35(4), 1237–1257. <https://doi.org/10.1007/S13593-015-0318-X>
- Eisler, R. (2019). Sustainable agriculture--going to the root of the problem: A conversation with Wes Jackson. *Interdisciplinary Journal of Partnership Studies*, 6(1), 2. <https://doi.org/10.24926/ijps.v6i1.1983>
- European Commission. (2020). Public opinion on the common agricultural policy | European Commission. The Eurobarometer Survey. https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance/eurobarometer_en#euagricultureandtheenvironment

- Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science (New York, N.Y.)*, 300(5620), 758–762. <https://doi.org/10.1126/SCIENCE.1078710/ASSET/4B81E052-332D-4728-BF5B-FA7743B5E8BC/ASSETS/GRAPHIC/SE1731473002.JPG>
- Fagnant, L., Duchêne, O., Celette, F., David, C., Bindelle, J., & Dumont, B. (2023). Learning about the growing habits and reproductive strategy of *Thinopyrum intermedium* through the establishment of its critical nitrogen dilution curve. *Field Crops Research*, 291, 108802. <https://doi.org/10.1016/j.FCR.2022.108802>
- FAO. (2019). *The future of food and agriculture | FAO | Food and Agriculture Organization of the United Nations*. <http://www.fao.org/publications/fofa/en/>
- FAO, IFAD, UNICEF, WFP, & WHO. (2020). *The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets*. FAO. <https://doi.org/doi.org/10.4060/ca9692en>
- Fligstein, N., & McAdam, D. (2011). Toward a general theory of strategic action fields. *Sociological Theory*, 29(1), 1–26. <https://doi.org/10.1111/j.1467-9558.2010.01385.x>
- Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., ... Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, 478(7369), 337–342. <https://doi.org/10.1038/nature10452>
- Friedmann, H. (1993). The political economy of food: A global crisis. *New Left Review*, 197, 29–57.
- Fuglie, K., Heisey, P., King, J., & Schimmelpennig, D. (2012). *Rising concentration in agricultural input industries influences new farm technologies*. USDA.
- Fuglie, K. O., Clancy, M., & Heisey, P. W. (2018). Private-Sector research and development. In N. Kalaitzandonakes, E. G. Carayannis, E. Grigoroudis, & S. Rozakis (Eds.), *From agriscience to agribusiness, theories, policies and practices in technology transfer and commercialization* (pp. 41–73). Springer International Publishing.
- Garland, T. (2014). Trade-offs. *Current Biology*, 24(2), R60–R61. <https://doi.org/10.1016/j.CUB.2013.11.036>
- Geels, F. W. (2019). Socio-technical transitions to sustainability: A review of criticisms and elaborations of the multi-level perspective. *Current Opinion in Environmental Sustainability*, 39, 187–201. Elsevier B.V. <https://doi.org/10.1016/j.cosust.2019.06.009>
- Gholson, B., & Barker, P. (1985). Kuhn, Lakatos, and Laudan. Applications in the history of physics and psychology. *American Psychologist*, 40(7), 755–769. <https://doi.org/10.1037/0003-066X.40.7.755>
- Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: An agronomic perspective. *Outlook on Agriculture*, 50(1), 13–25. <https://doi.org/10.1177/0030727021998063>
- Gillespie, S., van den Bold Gillespie, M. S., & van den Bold, M. (2017). Agriculture, food systems, and nutrition: Meeting the challenge. *Global Challenges*, 1(3), 1600002. <https://doi.org/10.1002/GCH2.201600002>
- Gregory, P. J. (2022). Russell review: Are plant roots only “in” soil or are they “of” it? Roots, soil formation and function. *European Journal of Soil Science*, 73(1), e13219. <https://doi.org/10.1111/EJSS.13219>
- Grzegorzczak, T., & Głowiński, R. (2020). Patent management strategies: A review. *Journal of Economics and Management*, 40, 36–51. <https://doi.org/10.22367/jem.2020.40.02>
- Guan, X. K., Turner, N. C., Song, L., Gu, Y. J., Wang, T. C., & Li, F. M. (2016). Soil carbon sequestration by three perennial legume pastures is greater in deeper soil layers than in the surface soil. *Biogeosciences (Online)*, 13(2), 527–534. <https://doi.org/10.5194/BG-13-527-2016>
- Haugo, J. (2015). The future of farming after bowman v. Monsanto. *Journal of Corporation Law*, 739, 739–757.
- Head, J. W. (2019). *A global corporate trust for agroecological integrity*. Routledge. <https://doi.org/10.4324/9780429289293>
- Hendrickson, M., Heffernan, W. D., Howard, P. H., & Heffernan, J. B. (2001). Consolidation in food retailing and dairy. *British Food Journal*, 103(10), 715–728. <https://doi.org/10.1108/00070700110696742/FULL/PDF>
- Hendrickson, M., Howard, P. H., & Constance, D. H. (2017). Power, food and agriculture: Implications for farmers, consumers and communities. *SSRN Electronic Journal*, 1–55. <https://doi.org/10.2139/ssrn.3066005>
- Hendrickson, M. K., Howard, P. H., Miller, E. M., & Constance, D. H. (2020). *The food system: Concentration and its impacts*. Family Farms Action Alliance. <https://www.openmarketsinstitute.org/s/Hendrickson-et-al-2020-Concentration-and-Its-Impacts-FINAL.pdf>
- Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., Bogard, J. R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G. D., Bryan, B. A., Campbell, B. M., Christensen, S., Clark, M., Cook, M. T., de Boer, I. J. M., Downs, C., ... West, P. C. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nature Food*, 1(5), 266–272. <https://doi.org/10.1038/s43016-020-0074-1>
- Hopewell, K. (2019). US-China conflict in global trade governance: The new politics of agricultural subsidies at the WTO. *Review of International Political Economy*, 26(2), 207–231. <https://doi.org/10.1080/09692290.2018.1560352>
- Houser, M., & Stuart, D. (2020). An accelerating treadmill and an overlooked contradiction in industrial agriculture: Climate change and nitrogen fertilizer. *Journal of Agrarian Change*, 20(2), 215–237. <https://doi.org/10.1111/joac.12341>
- Howard, A. (1947). *The soil and health: A study of organic agriculture*. The University Press of Kentucky.
- Howard, P. (2009). Visualizing consolidation in the global seed industry: 1996–2008. *Sustainability*, 1(4), 1266–1287. <https://doi.org/10.3390/su1041266>
- Howard, P. H. (2015). Intellectual property and consolidation in the seed industry. *Crop Science*, 55(6), 2489–2495. <https://doi.org/10.2135/cropsci2014.09.0669>
- Huang, G., Qin, S., Zhang, S., Cai, X., Wu, S., Dao, J., Zhang, J., Huang, L., Harnpichitvitaya, D., Wade, L., & Hu, F. (2018). Performance, economics and potential impact of perennial rice PR23 relative to annual rice cultivars at multiple locations in Yunnan province of China. *Sustainability*, 10(4), 1086. <https://doi.org/10.3390/su10041086>
- Huddell, A., Ernfors, M., Crews, T., Vico, G., & Menge, D. N. L. (2023). Nitrate leaching losses and the fate of 15N fertilizer in perennial intermediate wheatgrass and annual wheat – A field study. *Science of The Total Environment*, 857, 159255. <https://doi.org/10.1016/j.SCITOTENV.2022.159255>
- Jackson, W. (1980). *New roots for agriculture*. University of Nebraska Press.
- Jankauskas, B., Jankauskiene, G., & Fullen, M. A. (2011). Erosion-preventive crop rotations and water erosion rates on undulating slopes in Lithuania. *Canadian Journal of Soil Science*, 84(2), 177–186. <https://doi.org/10.4141/S03-029>
- Karimi, V., Karami, E., Karami, S., & Keshavarz, M. (2021). Adaptation to climate change through agricultural paradigm shift. *Environment, Development and Sustainability*, 23(4), 5465–5485. <https://doi.org/10.1007/S10668-020-00825-8/FIGURES/4>
- Kassam, A., & Kassam, L. (2021). Paradigms of agriculture. In A. Kassam & L. Kassam (Eds.), *Rethinking food and agriculture: New ways forward* (pp. 181–218). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-816410-5.00010-4>
- Kelly, E., & Naujokaityte, G. (2020). *EU lifts lid on its five research moonshots | ScienceBusiness*. Science Business. <https://sciencebusiness.net/framework-programmes/news/eu-lifts-lid-its-five-research-moonshots>
- Kendall, H. W., & Pimentel, D. (1994). Constraints on the expansion of the global food supply. *Ambio*, 23(3), 198–205.
- Kloppenborg, J. R. (2005). *First the seed: The political economy of plant biotechnology*. University of Wisconsin Press.
- Kloppenborg, J. (2014). Re-purposing the master's tools: The open source seed initiative and the struggle for seed sovereignty. *Journal of Peasant Studies*, 41(6), 1225–1246. <https://doi.org/10.1080/03066150.2013.875897>
- Kotschi, J., & Horneburg, B. (2018). The open source seed licence: A novel approach to safeguarding access to plant germplasm. *PLOS Biology*, 16(10), e3000023. <https://doi.org/10.1371/JOURNAL.PBIO.3000023>
- Kreitzman, M., Toensmeier, E., Chan, K. M. A., Smukler, S., & Ramankutty, N. (2020). Perennial staple crops: Yields, distribution, and nutrition in the global food system. *Frontiers in Sustainable Food Systems*, 4, 216. <https://doi.org/10.3389/FSUFS.2020.588988/BIBTEX>
- Krug, A. S., & Tesdell, O. I. (2021). A social perennial vision: Transdisciplinary inquiry for the future of diverse, perennial grain agriculture. *Plants, People, Planet*, 3(4), 355–362. <https://doi.org/10.1002/PPP3.10175>

- Krug, A. S., Drummond, E. B. M., Van Tassel, D. L., & Warschefsky, E. J. (2023). The next era of crop domestication starts now. *Proceedings of the National Academy of Sciences of the United States of America*, 120(14), e2205769120. https://doi.org/10.1073/PNAS.2205769120/SUPPL_FILE/PNAS.2205769120.SAPP.PDF
- Laborde, D., Mamun, A., Martin, W., Piñeiro, V., & Vos, R. (2021). Agricultural subsidies and global greenhouse gas emissions. *Nature Communications*, 12(1), 1–9. <https://doi.org/10.1038/s41467-021-22703-1>
- Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, 87, 85–156. [https://doi.org/10.1016/S0065-2113\(05\)87003-8](https://doi.org/10.1016/S0065-2113(05)87003-8)
- Ladha, J. K., Tirol-Padre, A., Reddy, C. K., Cassman, K. G., Verma, S., Powelson, D. S., van Kessel, C., de Richter, D. B., Chakraborty, D., & Pathak, H. (2016). Global nitrogen budgets in cereals: A 50-year assessment for maize, rice, and wheat production systems. *Scientific Reports*, 6(1), 1–9. <https://doi.org/10.1038/srep19355>
- Lakatos, I. (1976). Falsification and the methodology of scientific research programmes. *Can Theories Be Refuted?*, 205–259. https://doi.org/10.1007/978-94-010-1863-0_14
- Lanker, M., Bell, M., & Picasso, V. D. (2020). Farmer perspectives and experiences introducing the novel perennial grain Kernza intermediate wheatgrass in the US Midwest. *Renewable Agriculture and Food Systems*, 35(6), 653–662. <https://doi.org/10.1017/S1742170519000310>
- Lavelle, P. (2000). Ecological challenges for soil science. *Soil Science*, 165(1), 73–86.
- Law, E. P., Pelzer, C. J., Wayman, S., Ditommaso, A., & Ryan, M. R. (2021). Strip-tillage renovation of intermediate wheatgrass (*Thinopyrum intermedium*) for maintaining grain yield in mature stands. *Renewable Agriculture and Food Systems*, 36(4), 321–327. <https://doi.org/10.1017/S1742170520000368>
- Le Buanec, B., & Ricroch, A. (2021). Intellectual property protection of plant innovation. In A. Ricroch, S. Chopra, & M. Kuntz (Eds.), *Plant biotechnology: Experience and future prospects*. (2nd ed., pp. 71–86). Springer International Publishing. https://doi.org/10.1007/978-3-030-68345-0_6
- Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J. L., Qin, Z., McNamara, N. P., Zinn, Y. L., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., & Hillier, J. (2020). Changes in soil organic carbon under perennial crops. *Global Change Biology*, 26(7), 4158–4168. <https://doi.org/10.1111/GCB.15120>
- LeHeiget, P. M., McGeough, E. J., Biliget, B., & Cattani, D. J. (2023). Grain yield potential of intermediate wheatgrass in western Canada. *Agriculture*, 13(10), 1924. <https://doi.org/10.3390/AGRICULTURE13101924>
- Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature*, 528(7580), 60–68. Nature Publishing Group. <https://doi.org/10.1038/nature16069>
- Lewis, S. L., & Maslin, M. A. (2015). Defining the anthropocene. *Nature*, 519(7542), 171–180. <https://doi.org/10.1038/nature14258>
- Lianos, I. (2019). Agricultural mega-mergers and innovation – between competition law, regulation and IP rights. In G. Tavassi & M. Muscolo (Eds.), *The interplay between competition law and intellectual property: An international perspective* (pp. 1–49). Kluwer Academic Publishers.
- Lim, D. (2013). Self-replicating technologies and the challenge for the patent and antitrust laws. *Cardozo Arts & Entertainment Law Journal*, 32, 131–224.
- Lima, T., & Monteiro, R. E. (2015). Agricultural subsidies for non-farm interests: An analysis of the US agro-industrial complex. *Agrarian South*, 4(1), 54–84. <https://doi.org/10.1177/2277976015574799>
- Lindner, R. K. (2004). Economic issues for plant breeding – public funding and private ownership. *Australasian Agribusiness Review*, 12(6). <https://ageconsearch.umn.edu/record/132081/>
- Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., ... Torquebiau, E. F. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068–1072. Nature Publishing Group. <https://doi.org/10.1038/nclimate2437>
- Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, D. B., Martre, P., Ruane, A. C., Wallach, D., Jones, J. W., Rosenzweig, C., Aggarwal, P. K., Alderman, P. D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng, D., ... Zhu, Y. (2016). Similar estimates of temperature impacts on global wheat yield by three independent methods. *Nature Climate Change*, 6(12), 1130–1136. <https://doi.org/10.1038/nclimate3115>
- Loomis, R. S. (2022). Perils of production with perennial polycultures. *Outlook on Agriculture*, 51(1), 22–31. <https://doi.org/10.1177/00307270211063910>
- Loorbach, D., Frantzeskaki, N., & Huffenreuter, R. L. (2015). Transition management: Taking stock from governance experimentation. *The Journal of Corporate Citizenship*, 58, 48–66.
- Losch, B., Freguin-Gresh, S., & White, E. T. (2012). *Structural transformation and rural change revisited*. World Bank Publications. <https://doi.org/10.1596/978-0-8213-9512-7>
- Low, S. A., Adalja, A., Beaulieu, E., Key, N., Martinez, S., Melton, A., Perez, A., Ralston, K., Stewart, H., Suttles, S., & Jablonski, B. B. R. (2015). *Trends in U.S. local and regional food systems: A report to congress*. AP-068, U.S. Department of Agriculture, Economic Research Service. <https://hdl.handle.net/1813/71388>
- Lubofsky, E. (2016). The promise of perennials: Working through the challenges of perennial grain crop development. *CSA News*, 61(11), 4. <https://doi.org/10.2134/csa2016-61-11-1>
- Lukes, S. (2005). *Power: A radical view*. Red Globe Press.
- Luo, G., Najafi, J., Correia, P. M. P., Trinh, M. D. L., Chapman, E. A., Østerberg, J. T., Thomsen, H. C., Pedas, P. R., Larson, S., Gao, C., Poland, J., Knudsen, S., DeHaan, L., & Palmgren, M. (2022). Accelerated domestication of new crops: Yield is key. *Plant and Cell Physiology*, 63(11), 1624–1640. <https://doi.org/10.1093/pcp/pcac065>
- Macdonald, J. M., Dong, X., & Fuglie, K. O. (2023). *Concentration and Competition in U.S. Agribusiness*. www.ers.usda.gov
- Mahoney, J. (2000). Path dependence in historical sociology. *Theory and Society*, 29(4), 507–548.
- Marquardt, K., Vico, G., Glynn, C., Weih, M., Eksvärd, K., Dalin, P., & Björkman, C. (2016). Farmer perspectives on introducing perennial cereal in Swedish farming systems: A sustainability analysis of plant traits, farm management, and ecological implications. <https://doi.org/10.1080/21683565.2016.1141146>, 40(5), 432–450. <https://doi.org/10.1080/21683565.2016.1141146>
- Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Livenga, E., Pradhan, P., Rivera-Ferre, M.-G., Sapkota, T., Tubiello, F. N., & Xu, Y. (2019). Food security. In P. R. Shukla, J. Skea, & E. Al (Eds.), *IPCC Special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 437–550). Cambridge University Press.
- McHenry, L. B. (2018). The Monsanto papers: Poisoning the scientific well. *International Journal of Risk & Safety in Medicine*, 29(3–4), 193–205. <https://doi.org/10.3233/JRS-180028>
- McIntyre, B. D., Herren, H. R., Wakhungu, J., & Watson, R. T. (2009). *Agriculture at a Crossroads*. IAASTD Synthesis Report. Island Press.
- McMichael, P. (2009). A food regime analysis of the ‘world food crisis.’ *Agriculture and Human Values*, 26(4), 281–295. <https://doi.org/10.1007/S10460-009-9218-5>
- Minnesota Department of Agriculture. (2022). *2022-2023 Forever Green Projects*. <https://www.mda.state.mn.us/2022-2023-forever-green-projects#:~:text=The%20MDA%20received%20%244%20million,for%20fiscal%20years%202022%2D2023>
- MoeSingh, E. (2012). Structural change, vested interests, and scandinavian energy policy-making: Why wind power struggles in Norway and not in Denmark. *The Open Renewable Energy Journal*, 5(1), 19–31. <https://doi.org/10.2174/1876387101205010019>
- Montenegro de Wit, M. (2019). Beating the bounds: How does ‘open source’ become a seed commons? *The Journal of Peasant Studies*, 46(1), 44–79. <https://doi.org/10.1080/03066150.2017.1383395>
- Montgomery, D. R. (2017). *Growing a revolution: Bringing our soil back to life*. W.W. Norton & Company, Inc.
- Monti, A., & Zatta, A. (2009). Root distribution and soil moisture retrieval in perennial and annual energy crops in northern Italy. *Agriculture, Ecosystems*

- Environment, 132(3–4), 252–259. <https://doi.org/10.1016/J.AGEE.2009.04.007>
- Mooney, P. R. (1983). *The Law of the Seed – Another Development and Plant Genetic Resources*.
- Morgan, S., Fuglie, K., & Jelliffe, J. (2022, December 3). *World agricultural output growth continues to slow, reaching lowest rate in six decades*. USDA Economic Research Service. <https://www.ers.usda.gov/amber-waves/2022/december/world-agricultural-output-growth-continues-to-slow-reaching-lowest-rate-in-six-decades/>
- Musgrave, A., & Pigden, C. (2021). Imre lakatos. In E. N. Zalta, & U Nodelman (Eds.), *The stanford encyclopedia of philosophy (Spring 2023 Edition)*. Metaphysics Research Lab., Stanford University.
- Nelson, K. P., & Fuglie, K. (2022, June 6). *Investment in U.S. Public agricultural research and development has fallen by a third over past two decades, lags Major trade competitors*. USDA Economic Research Service. <https://www.ers.usda.gov/amber-waves/2022/june/investment-in-u-s-public-agricultural-research-and-development-has-fallen-by-a-third-over-past-two-decades-lags-major-trade-competitors/>
- NIFA. (2020, September 23). Multi-state Coalition Aims to Advance Agriculture by Driving Research, Education, and Adoption of Nation's First Perennial Grain Crop. <https://www.nifa.usda.gov/about-nifa/impacts/multi-state-coalition-aims-advance-agriculture-driving-research-education>
- Olsson, L., & Jerneck, A. (2018). Social fields and natural systems: Integrating knowledge about society and nature. *Ecology and Society*, 23(3), art26. <https://doi.org/10.5751/ES-10333-230326>
- Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., DeLusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Li, D., Sonwa, J. D., & Stringer, L. (2019). Land degradation. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, ... J. Malley (Eds.), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (pp. 345–436). IPCC. <https://www.ipcc.ch/srccl/chapter/chapter-4/>
- Olsson, L., Crews, T. E., Franklin, J., King, A. E., Mirzabaev, A., Scown, M., Tengberg, A., Villarino, S., & Wang, Y. (2023). The state of the world's arable land. *Annual Review of Environment and Resources*, 48, 451–475.
- Paul, D. B. (1989). First the seed: The political economy of plant biotechnology, by Jack Ralph Kloppenburg Jr. Book review. *Business History Review*, 63(4), 959–961. <https://doi.org/10.2307/3115976>
- Peixoto, L., Olesen, J. E., Elsgaard, L., Enggrob, K. L., Banfield, C. C., Dippold, M. A., Nicolaisen, M. H., Bak, F., Zang, H., Dresbøll, D. B., Thorup-Kristensen, K., & Rasmussen, J. (2022). Deep-rooted perennial crops differ in capacity to stabilize C inputs in deep soil layers. *Scientific Reports* 12(1), 1–10. <https://doi.org/10.1038/s41598-022-09737-1>
- Persky, J., Ranney, D., & Wiewel, W. (1993). Import substitution and local economic development. 7(1), 18–29. <https://doi.org/10.1177/089124249300700103>
- Persson, J., Hornborg, A., Olsson, L., & Thorén, H. (2018). Toward an alternative dialogue between the social and natural sciences. *Ecology and Society*, 23(4), 14. <https://doi.org/10.5751/ES-10498-230414>
- Peschard, K. E. (2022). *Seed activism: Patent politics and litigation in the global south*. MIT Press.
- Peschard, K., & Randeria, S. (2020). 'Keeping seeds in our hands': The rise of seed activism. *The Journal of Peasant Studies*, 47(4), 613–647. <https://doi.org/10.1080/03066150.2020.1753705>
- Phalan, B., Onial, M., Balmford, A., & Green, R. E. (2011). Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. *Science (New York, N.Y.)*, 333(6047), 1289–1291. https://doi.org/10.1126/SCIENCE.1208742/SUPPL_FILE/PHALAN.SOM.PDF
- Pinto, P., De Haan, L., & Picasso, V. (2021). Post-harvest management practices impact on light penetration and Kernza intermediate wheatgrass yield components. *Agronomy*, 11(3), 442. <https://doi.org/10.3390/AGRONOMY11030442>
- Porter, J., Xie, L., Challinor, A. J., Cochrane, K., Howden, S. M., Iqbal, M. M., Lobell, D. B., Travasso, M. L., Netra, C., Garrett, K., Ingram, J., Lipper, L., McCarthy, N., McGrath, J., Smith, D., Thornton, P., Watson, J., & Ziska, L. (2014). Climate change 2014: Impacts, adaptation, and vulnerability: Working group II contribution to the fifth assessment report of the inter-governmental panel on climate change. In Christopher B. Field, Vicente R. Barros, David Jon Dokken, Katharine J. Mach, Michael D. Mastrandrea, T. Eren Bilir, M. Chatterjee, Kristie L. Ebi, Yuka Otsuki Estrada, Robert C. Genova, B. Girma, Eric S. Kissel, Andrew N. Levy, S. MacCracken, & Patricia R. Mastrandrea (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects* (pp. 485–533). Cambridge University Press.
- Poulton, P., Johnston, J., Macdonald, A., White, R., & Powlson, D. (2018). Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology*, 24(6), 2563–2584. <https://doi.org/10.1111/gcb.14066>
- Pray, C. E., & Fuglie, K. O. (2015). *Agricultural research by the private sector*. 7(1), 399–424. <https://doi.org/10.1146/ANNUREV-RESOURCE-100814-125115>
- Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science (New York, N.Y.)*, 362(6417), 7. American Association for the Advancement of Science. <https://doi.org/10.1126/science.aav0294>
- Pugliese, J. Y., Culman, S. W., & Sprunger, C. D. (2019). Harvesting forage of the perennial grain crop kernza (*Thinopyrum intermedium*) increases root biomass and soil nitrogen cycling. *Plant and Soil*, 437(1–2), 241–254. <https://doi.org/10.1007/s11104-019-03974-6>
- Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M., & Rieseberg, L. H. (2018). Trends in global agricultural land use: Implications for environmental health and food security. *Annual Review of Plant Biology*, 69(1), 789–815. <https://doi.org/10.1146/annurev-arplant-042817-040256>
- Rasche, F., Blagodatskaya, E., Emmerling, C., Belz, R., Musyoki, M. K., Zimmermann, J., & Martin, K. (2017). A preview of perennial grain agriculture: Knowledge gain from biotic interactions in natural and agricultural ecosystems. *Ecosphere (Washington, D.C.)*, 8(12), e02048. <https://doi.org/10.1002/ecs2.2048>
- Ratnadass, A., Fernandes, P., Avelino, J., & Habib, R. (2012). Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review. *Agronomy for Sustainable Development*, 32(1), 273–303. <https://doi.org/10.1007/S13593-011-0022-4/TABLES/3>
- Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants* 2(2), 1–8. <https://doi.org/10.1038/nplants.2015.221>
- Rhodes, C. J. (2013). Feeding and healing the world: Through regenerative agriculture and permaculture. *Science Progress*, 95(4), 345–446. <https://doi.org/10.3184/003685012X13504990668392>
- Roff, D. A., & Fairbairn, D. J. (2007). The evolution of trade-offs: Where are we? *Journal of Evolutionary Biology*, 20(2), 433–447. <https://doi.org/10.1111/J.1420-9101.2006.01255.X>
- Roff, D. A., & Gelinas, M. B. (2003). Phenotypic plasticity and the evolution of trade-offs: The quantitative genetics of resource allocation in the wing dimorphic cricket, *Gryllus firmus*. *Journal of Evolutionary Biology*, 16(1), 55–63. <https://doi.org/10.1046/j.1420-9101.2003.00480.x>
- Roumet, C., Urcelay, C., & Díaz, S. (2006). Suites of root traits differ between annual and perennial species growing in the field. *New Phytologist*, 170(2), 357–368. <https://doi.org/10.1111/j.1469-8137.2006.01667.X>
- Rudolph, J. (2019). Diversity of mental health issues in agriculture. *Journal of Agromedicine*, 25(1), 1. <https://doi.org/10.1080/1059924X.2020.1694821>
- Rudolph, J. M., & Barnes, K. L. (2019). Farmers' mental health: Perceptions from a farm show. *Journal of Agromedicine*, 25(1), 147–152. <https://doi.org/10.1080/1059924X.2019.1674230>
- Ryan, M. R., Crews, T. E., Culman, S. W., DeHaan, L. R., Hayes, R. C., Jungers, J. M., & Bakker, M. G. (2018). Managing for multifunctionality in perennial grain crops. *BioScience*, 68(4), 294–304. <https://doi.org/10.1093/biosci/biy014>
- Sainju, U. M., Allen, B. L., Lenssen, A. W., & Ghimire, R. P. (2017). Root biomass, root/shoot ratio, and soil water content under perennial grasses with different nitrogen rates. *Field Crops Research*, 210, 183–191. <https://doi.org/10.1016/J.FCR.2017.05.029>
- Savich, J. (2007). Monsanto v Scroggs: The negative impact of patent exhaustion on self-replicating technology. *Berkeley Technology Law Journal*, 22, 115–136.

- Scherrer, C. (2022). Embeddedness of power relations in global value chains. In C. Teipen, P. Dühaupt, H. Herr, & F. Mehl (Eds.), *Economic and social upgrading in global value chains* (pp. 121–143). Palgrave Macmillan. https://doi.org/10.1007/978-3-030-87320-2_5
- Schlesinger, W. H., & Amundson, R. (2018). Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology*, 25(2), gcb.14478. <https://doi.org/10.1111/gcb.14478>
- Schurman, R., & Munro, W. A. (2010). *Fighting for the future of food: Activists versus agribusiness in the struggle over biotechnology*. University of Minnesota Press.
- Scown, M. W., Brady, M. V., & Nicholas, K. A. (2020). Billions in misspent EU agricultural subsidies could support the sustainable development goals. *One Earth*, 3(2), 237–250. <https://doi.org/10.1016/j.ONEEAR.2020.07.011>
- Seay, N. J. (1988). Protecting the seeds of innovation: Patenting plants. *AIPLA Quarterly Journal*, 16, 418–441. https://heinonline.org/HOL/Page?public=true&handle=hein.journals/aiplaj16&div=27&start_page=418&collection=journals&set_as_cursor=0&men_tab=srchresults
- Sharma, L. K., & Bali, S. K. (2018). A review of methods to improve nitrogen use efficiency in agriculture. *Sustainability (Switzerland)*, 10(1), 51. MDPI. <https://doi.org/10.3390/su10010051>
- Simmons, W. J. (2013). Bowman v. Monsanto and the protection of patented replicative biologic technologies. *Nature Biotechnology*, 31(7), 602–606. <https://doi.org/10.1038/nbt.2625>
- Smaje, C. (2015). The strong perennial vision: A critical review. *Agroecology and Sustainable Food Systems*, 39(5), 471–499. <https://doi.org/10.1080/21683565.2015.1007200>
- Smil, V. (2004). *Enriching the Earth: Fritz Haber, Carl Bosch, and the transformation of world food production*. MIT Press.
- Soto-Gómez, D., & Pérez-Rodríguez, P. (2022). Sustainable agriculture through perennial grains: Wheat, rice, maize, and other species. A review. *Agriculture, Ecosystems & Environment*, 325, 107747. <https://doi.org/10.1016/j.AGEE.2021.107747>
- Sprunger, C. D., Culman, S. W., Robertson, G. P., & Snapp, S. S. (2018). Perennial grain on a Midwest Alfisol shows no sign of early soil carbon gain. *Renewable Agriculture and Food Systems*, 33(4), 360–372. <https://doi.org/10.1017/S1742170517000138>
- Steenland, A. (2021). 2021 Global Agricultural Productivity Report: Climate for sustainable agricultural growth. <https://globalagriculturalproductivity.org/wp-content/uploads/2021/10/2021-GAP-Report.pdf>
- Stone, G. D. (2019). Commentary: New histories of the Indian green revolution. *The Geographical Journal*, 185(2), 243–250. <https://doi.org/10.1111/GEJ.12297>
- Strohm, T. N. (2021). Possibilities & Potential of Perennial Wheat: A Comparison of Arbuscular Mycorrhizal Fungi Diversity and Abundance between Winter Wheat and Kernza. *Senior Projects Spring 2021*. https://digitalcommons.bard.edu/senproj_s2021/158
- Stutter, M. I., Shand, C. A., George, T. S., Blackwell, M. S. A., Bol, R., MacKay, R. L., Richardson, A. E., Condron, L. M., Turner, B. L., & Haygarth, P. M. (2012). Recovering phosphorus from soil: A root solution? *Environmental Science and Technology*, 46(4), 1977–1978. https://doi.org/10.1021/ES2044745/ASSET/IMAGES/LARGE/ES-2011-044745_0003.JPEG
- Swinnen, J. (2018). *The political economy of agricultural and food policies*. Palgrave Macmillan.
- Sykuta, M. E. (2013). The fallacy of “competition” in agriculture. In H. S. James Jr. (Ed.), *The ethics of economics of agrifood competition* (Vol. 20, pp. 55–73). Springer Science and Business Media B.V. https://doi.org/10.1007/978-94-007-6274-9_4
- Tittonell, P., El Mujtar, V., Felix, G., Kebede, Y., Laborda, L., Luján Soto, R., & de Vente, J. (2022). Regenerative agriculture – agroecology without politics? *Frontiers in Sustainable Food Systems*, 6, 844261. <https://doi.org/10.3389/FSUFS.2022.844261/BIBTEX>
- USDA. (2021). *Action Plan for Climate Adaptation and Resilience*.
- USDA NRCS. (2023, November 1). *Soil Health*, NRCS. Soil Health. <https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/soils/health/?cid=stelprdb1048783>
- Vallebona, C., Mantino, A., & Bonari, E. (2016). Exploring the potential of perennial crops in reducing soil erosion: A GIS-based scenario analysis in southern Tuscany, Italy. *Applied Geography*, 66, 119–131. <https://doi.org/10.1016/J.APGEOG.2015.11.015>
- van Acker, R., Rahman, M. M., & Cici, S. Z. H. (2017). Pros and cons of GMO crop farming. *Oxford Research Encyclopedia of Environmental Science*, 1–23. <https://doi.org/10.1093/ACREFORE/9780199389414.013.217>
- van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nature Food* 2(7), 494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- Van Tassel, D. L., Tesdell, O., Schlautman, B., Rubin, M. J., DeHaan, L. R., Crews, T. E., & Streit Krug, A. (2020). New food crop domestication in the age of gene editing: Genetic, agronomic and cultural change remain co-evolutionarily entangled. *Frontiers in Plant Science*, 11, 11. <https://doi.org/10.3389/fpls.2020.00789>
- Veerman, C., Pinto Correia, T., Bastioli, C., & Biro, B. (2020). *Caring for soil is caring for life: ensure 75% of soils are healthy by 2030 for food, people, nature and climate: report of the Mission board for Soil health and food*. <https://op.europa.eu/en/publication-detail/-/publication/4ebd2586-fc85-11ea-b44f-01aa75ed71a1/>
- Walter, A.S., Finger, R., Huber, R., & Buchmann, N. (2017). Smart farming is key to developing sustainable agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 114(24), 6148–6150. National Academy of Sciences. <https://doi.org/10.1073/pnas.1707462114>
- Wan, N. F., Fu, L., Dainese, M., Hu, Y. Q., Pødenphant Kær, L., Isbell, F., & Scherber, C. (2022). Plant genetic diversity affects multiple trophic levels and trophic interactions. *Nature Communications*, 13(1), 1–12. <https://doi.org/10.1038/s41467-022-35087-7>
- Wayman, S., Debray, V., Parry, S., David, C., & Ryan, M. R. (2019). Perspectives on perennial grain crop production among organic and conventional farmers in France and the United States. *Agriculture*, 9(11), 244. <https://doi.org/10.3390/AGRICULTURE9110244>
- Weisdorf, J. L. (2005). From foraging to farming: Explaining the neolithic revolution. *Journal of Economic Surveys*, 19(4), 561–586. <https://doi.org/10.1111/J.0950-0804.2005.00259.X>
- Westerbergh, A., Lerceteau-Köhler, E., Sameri, M., Bedada, G., & Lundquist, P.-O. (2018). Towards the development of perennial barley for cold temperate climates – evaluation of wild barley relatives as genetic resources. *Sustainability*, 10(6), 1969. <https://doi.org/10.3390/su10061969>
- White, B. (2012). Agriculture and the generation problem: Rural youth, employment and the future of farming. *IDS Bulletin*, 43(6), 9–19. <https://doi.org/10.1111/J.1759-5436.2012.00375.X>
- World Bank (2018). *Poverty and Shared Prosperity 2018: Piecing Together the Poverty Puzzle*. Washington, D.C.: World Bank Group. <http://documents.worldbank.org/curated/en/104451542202552048/Poverty-and-Shared-Prosperity-2018-Piecing-Together-the-Poverty-Puzzle>
- Wright, E. O. (2010). *Envisioning real utopias*. Verso. <https://www.versobooks.com/books/463-envisioning-real-utopias>
- Wright, E. O. (2019). *How to be an anticapitalist in the twenty-first century*. Verso.
- Würtenberger, G. (2017). Protection of plant innovations. In D. Matthews, & H. Zech (Eds.), *Research handbook on intellectual property and the life sciences: Research handbooks in intellectual property series* (pp. 121–131). Edward Elgar Publishing Limited. <https://doi.org/10.4337/9781783479450.00015>
- Zhang, S., Huang, G., Zhang, J., Huang, L., Cheng, M., Wang, Z., Zhang, Y., Wang, C., Zhu, P., Yu, X., Tao, K., Hu, J., Yang, F., Qi, H., Li, X., Liu, S., Yang, R., Long, Y., Harnpichitvitaya, D., ... Hu, F. (2019). Genotype by environment interactions for performance of perennial rice genotypes (*Oryza sativa* L./*Oryza longistaminata*) relative to annual rice genotypes over regrowth cycles and locations in southern China. *Field Crops Research*, 241, 107556. <https://doi.org/10.1016/j.fcr.2019.107556>
- Zhang, S., Huang, G., Zhang, Y., Lv, X., Wan, K., Liang, J., Feng, Y., Dao, J., Wu, S., Zhang, L., Yang, X., Lian, X., Huang, L., Shao, L., Zhang, J., Qin, S., Tao, D., Crews, T. E., Sacks, E. J., Wade, L., ... Hu, F. (2023). Sustained productivity and agronomic potential of perennial rice. *Nature Sustainability*, 6, 28–33. <https://doi.org/10.1038/s41893-022-00997-3>

- Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J. L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., ... Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, 114(35), 9326–9331. <https://doi.org/10.1073/pnas.1701762114>
- Zhu, C., Kobayashi, K., Loladze, I., Zhu, J., Jiang, Q., Xu, X., Liu, G., Seneweera, S., Ebi, K. L., Drewnowski, A., Fukagawa, N. K., & Ziska, L. H. (2018). Carbon dioxide (CO₂) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Science Advances*, 4(5), eaaq1012. https://doi.org/10.1126/SCLADV.AAQ1012/SUPPL_FILE/AAQ1012_SM.PDF
- Zimbric, J. W., Stoltenberg, D. E., & Picasso, V. D. (2020). Effective weed suppression in dual-use intermediate wheatgrass systems. *Agronomy Journal*, 112(3), 2164–2175. <https://doi.org/10.1002/AGJ2.20194>