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

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## 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 (Steensland, 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 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; Eisler, 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 (Kloppenburg, 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 biocides (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.

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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 (Tittonell 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 & Gelinas, 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

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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 $CO_2$ $ha^{-1}$ $year^{-1}$ (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).

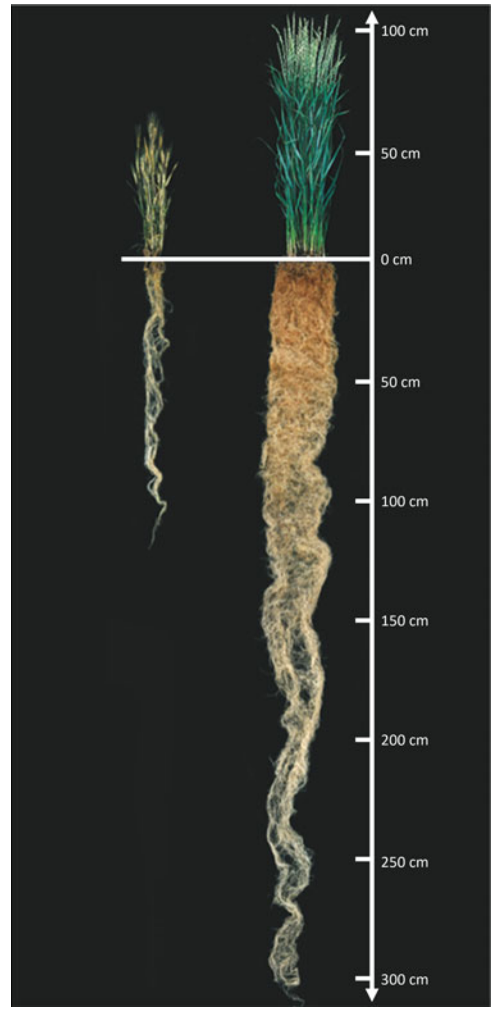


**Figure 1.** Intermediate wheatgrass in its second year (right) compared with winter wheat ready to be harvested (left). Photo: The Land Institute.

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 $N_2$) 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 timeframe 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 (Böschen, 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 (Kloppenburg, 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; Kloppenburg, 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; Kloppenburg, 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

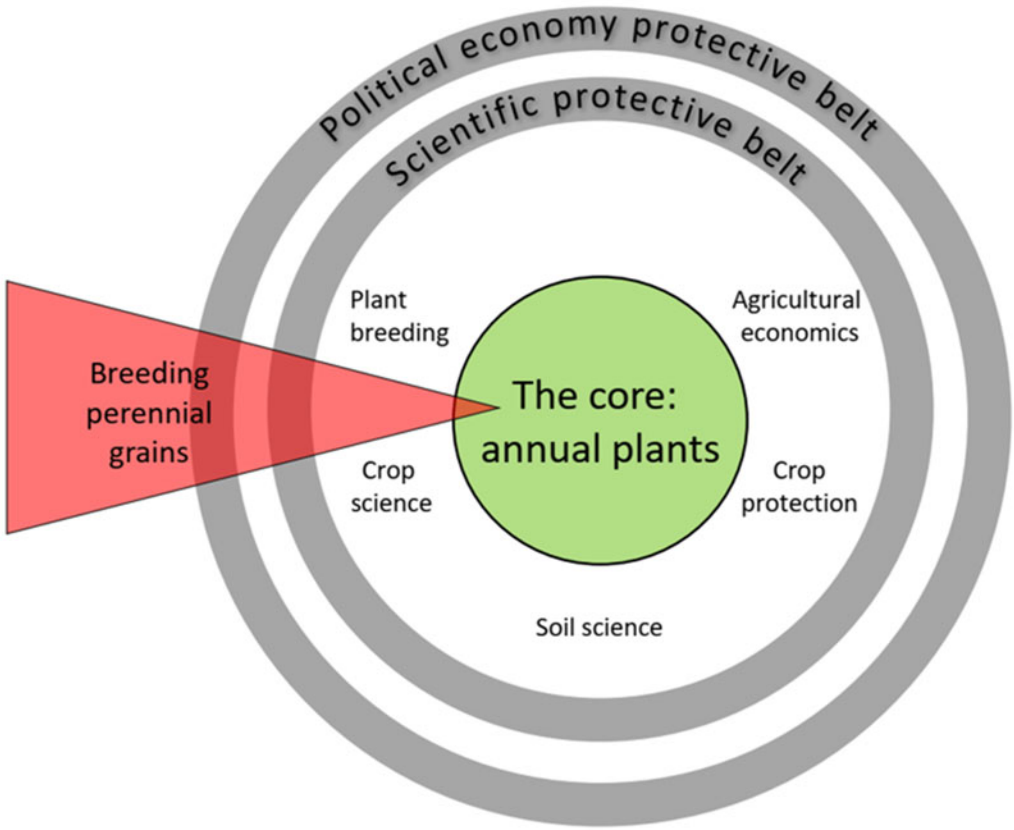


**Figure 2.** Conceptual view of how agricultural sciences can be understood as a research program with a hard core and protective belts of science and vested economic interests, inspired by Lakatos' concept of Research Program (Lakatos, 1976). A radically different idea, such as domesticating and breeding 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 (Grzegorczyk & 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-aversive 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 takeovers 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)

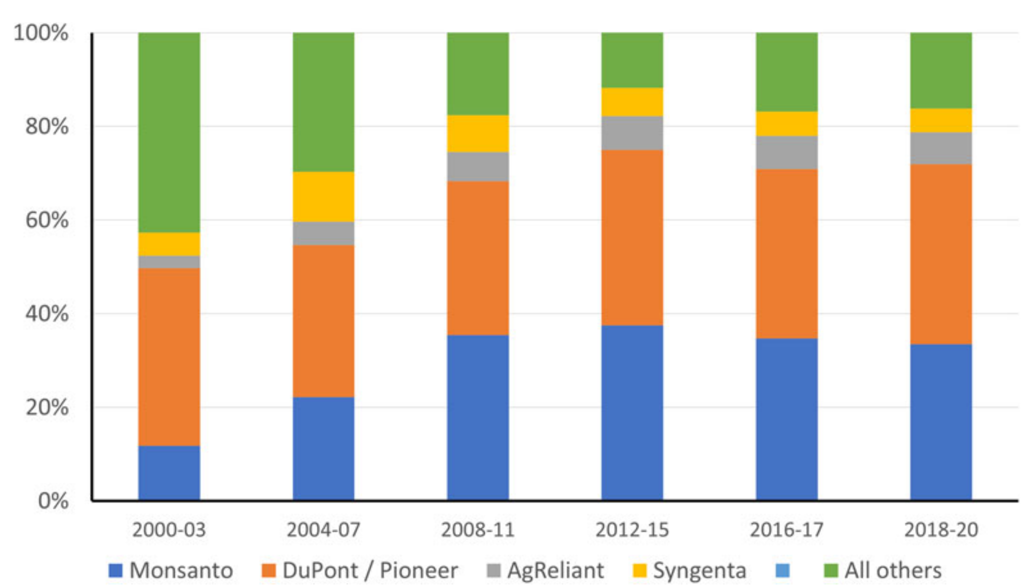


**Figure 3.** Market share of the US corn seed market. The data for 2018–20 are estimated, and valid for Bayer instead of Monsanto (after the merger in 2018), Corteva instead of DuPont/Pioneer (after the merger in 2018). Source of data (Macdonald et al., 2023).

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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 multilevel 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

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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.

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