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REVIEW

A Perennial Green Revolution to address 21st-century food insecurity and malnutrition

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Abstract

Farming practices of the past century have dramatically increased annual crop yields to unprecedented levels but have consequentially created increasing ecological and public health concerns, posing a long-term threat to global food security. Soil tillage and chemical inputs perpetuate soil erosion, biodiversity loss, wetlands eutrophication, carbon emissions, and other farming stressors. Concomitantly, accompanying poor dietary patterns and malnutrition increase the risk for chronic diseases, such as cardiovascular diseases, obesity, type 2 diabetes, and cancer, which account for greater than 70% of global mortality per annum. Altogether, such annual monocropping systems exacerbate food insecurity, necessitating action across the fields of public health, agriculture, nutrition, medicine, and environmental ecology, that is, a transdisciplinary approach. Herein, we argue that the perennialization of crops creates an opportunity to address the challenges of environmental sustainability and nutritional adequacy economically. Unlike annuals, perennial crops have deeper roots for increased drought tolerance and reduced needs for fertilization and irrigation. Adopting perenniality can result in greater drought tolerance and improved soil health while reducing erosion, farming labor, and seed purchasing. Furthermore, perennializing novel staple crops may offer a superior and diverse dietary profile of phytochemicals, fiber, and macronutrients compared to conventional annuals. Instead of traditional perennial tree crops, we focus on intermediate wheatgrass Kernza® (*Thinopyrum intermedium*) and sunflowers (*Helianthus tuberosus*, *H. maximiliani*, and *Silphium integrifolium*) as exemplars of perennial staple food crops for grain and oil, respectively, at different stages of perennial crop commercialization. Ultimately, we discuss how integrating perenniality has the potential to revolutionize global agriculture and address food security concerns for the remainder of the 21st century.

KEYWORDS

food insecurity, Green Revolution, malnutrition, perennial food crop

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1 | INTRODUCTION

The prevalence of food insecurity has been increasing globally as documented since the inception of data collection by the Food and Agriculture Organization of the United Nations in 2014 (FAO et al., 2022, 2023). USDA recognizes the definition of food insecurity as *the limited or uncertain availability of nutritionally adequate and safe foods, or the limited or uncertain ability to acquire acceptable foods in socially acceptable ways*. The combination of its major drivers, such as conflict, climate extremes, economic slowdowns and downturns, and growing inequality, has been exacerbated of late, especially owing to global warming, the COVID-19 pandemic, and the escalation of war in Ukraine (FAO et al., 2023). In 2022, 2.4 billion people of the global population (29.6%) were moderately or severely food insecure. Consequently poor dietary quality further aggravates not only undernutrition and the hidden hunger syndrome (Lowe, 2021), that is, inadequate intake of micronutrients, but also the development of obesity (Tumas & López, 2024). This double burden of malnutrition further encompasses diet-related noncommunicable chronic diseases, particularly type 2 diabetes (T2D), metabolic dysfunction-associated fatty liver disease (MAFLD), cardiovascular diseases (CVDs) and stroke, and cancer, as well as various types of mental illnesses. Collectively, their global mortality accounts for 74% per annum (WHO, 2023) with an estimated cost reaching $47 trillion worldwide by 2030 (Hacker, 2024). The severity of such circumstances prompted FAO of the United Nations to set Sustainable Development Goals (SDGs) to end food insecurity and all forms of malnutrition by the year 2030 (FAO et al., 2022, 2023), but progress so far has been limited. Thus, we emphasize the paramount importance and urgency of all sectors of the agricultural community to join biomedical and public health to renew a long-term vision and collective effort to tackle these unceasing global challenges.

The global threat to four dimensions of food security—food availability, food access, food utilization, and stability thereof—has been exacerbated by climate change. Global warming of the atmosphere, ocean, and land, fluctuating weather patterns, extreme temperature stresses, and more frequent ecological disasters, create constant uncertainties about the stability of food production and livelihoods. Conversely, agriculture is one of the major segments of human-induced activities that can magnify irregular climatic patterns. Despite the globality of climatic challenges for food security, this narrative review will explore mitigation and adaptation approaches for threatened crop productivity using Untied States-centric examples with brief conjectures about global implications.

2 | FROM GREEN REVOLUTION TO CRISIS

By the year 2050, it is estimated that farmers will need to feed 9.7 billion individuals—nearly 2 billion more than present day (United Nations DESA/PD, 2022). Meanwhile, the amount of virgin lands available for crop cultivation is limited, creating unprecedented demands for larger yields on existing limited farmland (Jacobo, 2021). Nevertheless, crop yields today have never been greater. Beginning in the 1960s and stretching through the rest of the 20th century, Norman Borlaug and other scientists championed the genetic progression of agricultural crops for larger yields and greater vigor (John & Babu, 2021). These global agricultural advancements, both genetic and mechanical, redefined modern-day farming, commencing the Green Revolution (GR). Many farmers began specializing in one or two crops within a monocropping system using advanced machinery. Monocropping (or monocultivating) is the farming practice of growing one specific crop over an entire field (Balogh, 2021). This technique allows for streamlined mechanization of tilling, fertilizing, planting, pesticide applications, and harvesting. Borlaug's approach quickly gained traction worldwide, allowing developing nations to nearly triple crop yields (John & Babu, 2021). Moreover, new crop hybrids became highly responsive to synthetic fertilization (John & Babu, 2021). Today in the United States, over 400 million farm acres are monocropped in the Borlaug style (Jacobo, 2021). However, despite the progress in yields, annual intensive monoculture has created novel burdens for both the environment and the farmer.

Of the monocultivated crops grown in the United States, corn (maize, *Zea mays*) is the king. For decades, corn has dominated production, exhausting more than 90 million acres and constituting 95% of all grown feed grains (Environmental Protection Agency, 2023; Economic Research Service, 2023). Unfortunately, only 10% of the corn grown in the United States feeds people directly—the rest is fed to livestock or used in ethanol production (Environmental Protection Agency, 2023). More broadly, 36% of all global crop yields are partitioned for livestock feed (Cassidy et al., 2013). Though current production partitioning may satisfy growing demands for animal proteins, it may be an inefficient use of finite resources while perpetuating climate concerns. In beef cattle production specifically, 6 lb of feed is required to yield 1 lb of beef (Byrne, 2018). Furthermore, beef production is one of the leading perpetrators of greenhouse gas emissions in the form of methane, which is 25 times more potent than carbon dioxide in the atmosphere, accelerating the warming and changing climate (Environmental Protection Agency, 2022).

2.1 | The farm

Conventional annual monocropping systems, with fields tilled and replanted year after year, by many accounts, have generated crises of biodiversity loss, topsoil erosion, increased carbon emissions, and polluted waterways (Asselin et al., 2018; Kantar et al., 2018; Vilela et al., 2018), all of which destabilize the potential for long-term food security. When annual crops are removed from fields in the off-season, exposed soils are vulnerable to wind and rain erosions. Thaler et al. (2022) estimate that the Midwestern U.S. croplands have lost 57.6 billion metric tons ([MT]; SE ± 37.8 billion MT) of topsoil since first cultivated in the mid-1800s. Despite large variations in topsoil loss estimations, agricultural erosion rates remain substantial compared to pre-agricultural erosion rates (Quarrier et al., 2023). Heavy inputs of fertilizers (largely nitrogen and phosphorus) can leach from disturbed fields causing eutrophication in nearby bodies of water. Eutrophication—when a body of water is in a state of nutrient excess—can harm or kill aquatic life through hypoxia and algal blooms (Environmental Protection Agency, 2023). Seasonal tilling perpetuates biodiversity loss, especially of the soil biota. Bacteria, fungi, nematodes, earthworms, and more are the underpinnings of soil health (Tibbett et al., 2020). Because soil health directly affects the creation of new biomass, nutrient cycling, water movement, and other climate factors, maintaining a biodiverse community is imperative to preserve the resiliency of soil for generations to come (Tibbett et al., 2020). Additionally, soil tilling can release sequestered soil organic carbon (SOC) in the form of carbon dioxide, exacerbating concerns about climate change (Ogle et al., 2019). Increasing SOC through reduced tillage is a proposed means of attenuating the climate crisis. In a systematic review ($n = 351$) on farming and SOC, no-tillage fields contained on average 4.6 Mg/ha more SOC than high-tillage fields over 10 or more years (0.78–8.43 Mg/ha, 95% CI) (Haddaway et al., 2017).

2.2 | The farmer

In conventional row crops, following the GR principles to reap large harvests, farmers must purchase expensive seeds, fertilizers, herbicides, and pesticides each season and allocate many hours of labor devoted to soil preparation and planting. Almost paradoxically, many of these conventional farming practices, designed to increase crop yields, correlate with the decline in well-being scores of farmers themselves. In a recent systematic review of 167 relevant publications across the United States, the United Kingdom, and Australia, Yazd et al. (2019) outline "pesticide exposure" (in 43 articles), "financial difficulties" (in 39 articles), "climate variabilities/drought" (in 25 articles), and "poor physical health/past injuries" (in 22 articles) to be the four most cited detriments to farmers' mental health and well-being. Reducing pesticide exposure and choosing climate-resilient crops may ease many physical, mental, and financial stressors associated with the profession. Until then, however, farm stressors are exhausting an already aging farmer population ($\mu = 57.5$ years old), while financial and climate barriers dissuade young adults from choosing the profession (Buys et al., 2023; Halvorson, 2023; USDA NASS, 2019). This places greater pressure on the aging population of farmers striving to feed a growing planet (Buys et al., 2023).

3 | ALTERING THE TRAJECTORY OF FOOD SECURITY DECLINE: PERENNIALITY

With the scientific community in consensus on perilously rising global temperatures perpetuated by human activities, slowing the rate of warming is imperative to global health and food security (Filho et al., 2023; Shindell et al., 2021; World Health Organization, 2023). The food system at large should become a cog in slowing greenhouse gas emissions by sequestering carbon. While a multipronged plan of attack is required, we propose that an underutilized complement to conventional row crop is the widespread cultivation of perennial staple food crops as a component in crop rotation patterns, a concept that we dub the 21st-century "Perennial Green Revolution" (PGR) for sustainability, conservation, food security, and human health. The perennialization of annual crops is an essential component in sustaining global health without further exploitation of precious—and fleeting—lands. Perennial crops are a climate-smart choice: their deep roots capture and store carbon while enhancing drought tolerance (Evangelista et al., 2023; Vilela et al., 2018). Additionally, in perennial systems, the burdens of tilling, fertilizing, and seed purchasing are considerably diminished, while soil biota flourish and nutrient leaching is greatly curbed through phytoremediation (Asselin et al., 2018; Vilela et al., 2018). When properly managed, many perennial crops are long lived and can be grown organically. While it is common to focus consideration of perenniality on the food crops shown in Table 1, this narrative review considers the potential contributions of perennial staple food crops—cereal grains and oilseed crops: perennial intermediate wheatgrass Kernza® (*Thinopyrum intermedium*) and perennial sunflowers (*Silphium integrifolium*, *Helianthus tuberosus* × *H. annuus*, and *H. maximiliani* × *H. annuus*), respectively. The review on Kernza® illustrates how a more developed perennial cultivar begins to reach

TABLE 1 List of existing perennial food crops.

Crop category	Crop examples
Cereals	Kernza® (a perennial wheatgrass), Perennial *Sorghum* spp., Perennial Rice (*Oryza* spp.), Wheat (*Triticum aestivum*)
Pulses	Perennial Beans (*Phaseolus* spp.), Sainfoin (*Onobrychis viciifolia*), Lima Bean (*Phaseolus lunatus*), Runner bean (*Phaseolus coccineus*), Thicket bean (*Phaseolus polystachios*)
Roots and tubers	Yacon (*Smallanthus sonchifolius*), Air Potato (*Dioscorea bulbifera*), Cassava/Yuca (*Manihot esculenta*), Potato (*Solanum tuberosum*), Taro (*Colocasia esculenta*), Enset (*Ensete ventricosum*), Jerusalem artichoke (*Helianthus tuberosus*), sweet potato (*Ipomoea batatas* (L.) Lam), Horseradish (*Armoracia rusticana* G. Gaertn., B. Mey. & Scherb.), Oca (*Oxalis tuberosa* Molina)
Sugar crops	Cane sugar (*Saccharum* spp.), Date (*Phoenix dactylifera L.*), Sugar palm (*Arenga pinnata*), Honey Locust (*Gleditsia tricanthos*), Sugarcane (*Saccharum officinale*)
Oil-bearing crops	Rosinweed (*Silphium integrifolium*), Kapok (*Ceiba pentandra*), Olive (*Olea europaea*), Coconut (*Cocos nucifera* L.), Oil Palm (*Elaeis guineensis* Jacq.), Brazil Nut (*Bertholletia excelsa*), Buffalo Gourd (*Cucurbita foetidissima*), Inche (*Caryodendron orinocense*), Okra (*Abelmoschus esculentus*), Pequi (*Caryocar brasiliense*), Sunflower (*Helianthus annuus*), Maximilian sunflower (*Helianthus maximiliani*), Avocado (*Persea americana*), Macauba palm (*Acrocomia aculeata*), Buriti palm (*Mauritia flexuosa*), Pecan (*Carya illinoiensis*), Macadamia (*Macadamia* spp.), Babassu (*Attalea speciosa*), Hazelnut (*Corylus avellana*), Pistachio (*Pistacia vera*), Walnut (*Juglans regia*), Almond (*Prunus dulcis* [Mill.] Rchb.)
Vegetables	Bamboo shoot (*Bambusa vulgaris* Nees), Asparagus (*Asparagus officinalis* L.), Moringa Leaf (*Moringa oleifera* Lam.), Grape Leaf (*Vitis* spp.), Chipilin (*Crotolaria longirostrata*), Okra (*Abelmoschus esculentus*), Chayote (*Sechium edule*), Olive (*Olea europaea*), Asparagus (*Asparagus officinalis*), Avocado (*Persea americana*), Artichoke (*Cynara scolymus*), Moringa (*Moringa oleifera*), Daylily (*Hemerocallis fulva*), Jujube (*Zizyphus jujuba*), African Eggplant (*Solanum aethiopicum*)
Fodder crops	Mesquites (*Prosopis* spp.), Chestnuts (*Castanea* spp.), Honey locust (*Gleditsia triacanthos* L.), Persimmon (*Diospyros kaki* Thunb.), Mulberries (*Morus* spp.)
Fruits and berries	Apple (*Malus domestica*), Peach (*Prunus persica* [L.] Batsch), Orange (*Citrus sinensis* Pers.), Banana (*Musa acuminata*), Plantain (*Musa paradisica*), Marula (*Sclerocarya birrea*), Pequi (*Caryocar brasiliense*), Butterfruit (*Dacryodes edulis*), Lucuma (*Pouteria lucuma*), Sweet Cherry (Prunus avium L.), Papaya (*Carica papaya* L.), White Sapote (*Casimiroa edulis* La Llave), Date Palm (*Phoenix dactylifera* L.), Fig (*Ficus carica* L.), Grape (*Vitus vinifera* L.), Pomegranate (*Punica granatum* L.), Guava (*Psidium guajava* L.), Pear (*Pyrus communis* L.), Kiwifruit (*Actinidia deliciosa*), Cherimoya (*Annona cherimola* Miller), Jackfruit (*Artocarpus heterophyllus* Lam.), Breadfruits (*Artocarpus* spp.), Pawpaw (*Asimina triloba* (L.) Dunal), Starfruit (*Averrhoa carambola* L.), European Chestnut (*Castanea sativa* Mill.), Mexican lime (*Citrus aurantiifolia* (Christm.) Swingle), Clementine (*Citrus clementina* Hort. Ex Tan), Persimmon (*Diospyros kaki* Thunb.), Mango (*Mangifera indica* L.), Carob (*Ceratonia siliqua* L.)
Nuts	Chestnut (*Castanea sativa* Mill.), Cashew (*Anacardium occidentale* L.), Hazelnut (*Corylus avellana* L.), Walnut (*Juglans regia* L.), Pecan (*Carya illinoinensis*), Tahitian Chestnut (*Inocarpus fagifer*), Breadnut (*Artocarpus camansii*), African Breadnut (*Treculia africana*), Ramon or Mayan Breadnut (*Brosimum alicastrum*), Nut Pines (*Pinus spp.*), Oaks (*Quercus* spp.), Almond (*Prunus dulcis*), Canarium Nuts (*Canarium* spp.), Macadamia (*Macadamia integrifolia*), Marula (*Sclerocarya birrea*), Oyster Nut (*Telfairia pedata*), Screwpines (*Pandanus* spp.), Pistachio (*Pistacia vera*)
Other	Spices, condiments, aromatic herbs, Coffee (*Coffea* spp.), Cocoa (*Theobroma cacao*), medicinal plants

markets, despite challenges. Complementarily, the review on sunflower perennialization provides insight into existing sunflower oil markets, early-stage cultivar selections, and perennial developmental efforts. Both Kernza® and perennial sunflowers are transformative, pioneering crops in the pursuit of cultivating a PGR for greater environmental and human health.

In addition to environmental benefits, consuming grain and oilseed perennial crops through a plant-focused dietary pattern (whole grains, vegetables, fruits, and unsaturated fats) may actively promote a healthy lifestyle in reducing rates of obesity, CVD, T2D, MAFLD, and cancer (Centers for Disease Control and Prevention, 2022; Gibbs & Cappuccio, 2022; Wang et al., 2023), contributing to the benefits of improved food security. Over 60% of Americans are living with at least one chronic disease (Centers for Disease Control and Prevention, 2023b). Not only do chronic diseases impact the well-being of millions, but disease states reduce economic productivity and constitute 90% of all healthcare-related expenditures at $3.7 trillion annually (Centers for Disease Control and Prevention, 2023a). Reducing preventable chronic diseases through dietary interventions benefits human health and economic interests alike. When compared to their annual

crop counterparts suffering from domestication bottlenecking, many novel perennial crops contain a wider nutritional profile of phytochemicals in addition to a richer gene pool for increased environmental vigor (Allaby et al., 2019; Cetiner et al., 2023; Herman, 2022; Pour-Aboughadareh et al., 2021; The Land Institute, n.d.-e). In developing new perennials for staple crop supplementation, breeders must continue to target and improve both nutritional and agronomic attributes (e.g., phytochemical and fiber content [and their bioavailability], drought tolerance, pest resistance, and yield) to address both chronic disease burden and food supply concerns worldwide.

4 | PERENNIAL KERNZA®

Perennial intermediate wheatgrass (*Thinopyrum intermedium*) is a Eurasian perennial grain crop first selected by the Rodale Institute in 1983 (The Land Institute, n.d.-c). Funding from this institute and the USDA began breeding research for better agronomic traits. In 2003, research on this crop transferred to The Land Institute, where oversight remains to date, and it was trademarked under the name Kernza®.

Kernza®'s wheat-like grains can be harvested and used for human foods, replacing conventional wheat and wheat flour. Its perenniality is desirable since crops returning yearly reduce farmer planting and tilling demands. Kernza® is incredibly drought tolerant and well-suited to semi-arid climates. The deep roots of Kernza® (often 10 feet or more into the soil) make this crop highly water efficient and water resilient against drought while capturing and storing carbon deep into the soil (Clément et al., 2022; Culman et al., 2013). High-drainage soil is necessary for long-term success, and clay soils should be avoided (Tautges et al., 2023). Consequently, it is not recommended to plant this crop in wet or lowland fields. Hillside fields prone to erosion may be suitable candidates for this perennial. Annual weeds are tolerable, as mature Kernza® can dominate and prevent weed seed germination (Tautges et al., 2023). Modern robotic weeding of specialty crops, as reviewed by Fennimore and Cutulle (2019), may aid in establishing new organic fields of Kernza®. Further crop improvements of Kernza® may expand growing regions and soil compatibilities, for example, regions with clay soils and/or prone to flooding.

A study by Culman et al. (2013) witnessed reduced soil moisture at lower soil depths, signaling Kernza®'s ability to reach deep water reserves. Additionally, the perennial crop's root system reduced nitrate (NO_3^-) fertilizer leaching by 85.8% in high-nitrogen plots, by 98.2% in medium-N plots, and by 99.4% in organic plots compared to annual wheat plots with the same N applications (during second-year plantings) (Culman et al., 2013). While alfalfa—a commonly grown perennial forage crop—has slightly longer roots, Kernza® utilizes less water on average, as noted by Clément et al. (2022). For example, between 1.0 and 1.5 m below the soil surface, Kernza® utilized 28–123 mm of water, whereas alfalfa used 68–157 mm (Clément et al., 2022). Another study examined Kernza®'s potential to store carbon and nitrogen as particulate organic matter (POM) deep in soils (van der Pol et al., 2022). While this crop was successful in increasing POM carbon ($t = 19.26$, $p < 0.001$) and POM nitrogen ($t = 4.51$, $p < 0.001$), the study was unable to determine how long the POM would remain before natural breakdowns (van der Pol et al., 2022). However, perennial crops, such as Kernza®, are superior to annual crops in water hardiness, reduction of nutrient leaching, and carbon sequestration. Thus, Kernza® is a robust perennial candidate for extensive cultivation.

4.1 | Nutritional attributes

In addition to environmental benefits, Kernza® production is especially exciting due to its direct impact on consumers. The harvested grain can be substituted in most scenarios currently using wheat. This includes, but is not limited to, cereals, breads, crackers, pastas, and beers. Nutritionally, Kernza® surpasses wheat, quinoa, rice, and others; per 100 g, Kernza® grains have 18 g of fiber and 19.2 g of protein (Table 2) (AURI, 2020). It is well accepted and advised that 25–42 g of fiber be consumed daily (Cleveland Clinic, 2023; Kleintop et al., 2013; Thompson & Brick, 2016). Appallingly, less than 5% of Americans meet these guidelines (Quagliani & Felt-Gunderson, 2017). Consequently, a low-fiber diet leads to gut microbial imbalances, increased inflammation, increased risks of chronic disease, and even has links to worsened mental health (Herman, 2022; McManus, 2019; Swann et al., 2019). Thus, the adoption of Kernza® grains into the diet, in addition to other high-fiber grains and pulses, will help close the dietary fiber gap. Kernza® products should be marketed as high-fiber and heart-healthy choices by filing with the U.S. Food and Drug Administration (FDA)

TABLE 2 Fiber and protein content comparison (per 100 g serving) between Kernza® and other grain crops (per 100 g serving) (AURI, 2020; USDA, 2020a, 2020b, 2023).

Grain crop	Fiber (g)	Protein (g)
Kernza® (whole flour)	18	19.2
Wheat (whole flour)	10.6	15.1
Quinoa (whole flour)	6.3	11.9
Brown rice (whole flour)	4.6	7.2

for an approved packaging health claim (compliant with The Nutrition Labeling and Education Act of 1990 [NLEA] and/or The Food and Drug Administration Modernization Act of 1997 [FDAMA]) (FDA, 2022). A study by Cetiner et al. (2023) compares breadmaking outcomes between Kernza® flour and conventional wheat flour. In addition to highlighting the increased fiber and protein contents, the authors observed a higher carotenoid content of $23.09 \pm 0.085\,\mu g$ compared to $2.78 \pm 0.021\,\mu g$ in the control (Cetiner et al., 2023). Thus, by increasing Kernza® flour amounts in the bread from 0% (100% wheat flour) to 60% (40% wheat flour), there was a correlated increase in visible yellow coloration and overall carotenoid content, a potential bioactive food component ($p < 0.05$).

The gluten quality and content of Kernza® flour is markedly lower than conventional wheat flour, causing a visible decrease in loaf volume (485 mL at 15% Kernza® flour to 360 mL at 60%) (Cetiner et al., 2023). Despite the size decreases, the potential health benefits of Kernza® bread may outweigh the conventionally undesirable physical attributes. Those with gluten sensitivities may benefit from Kernza®-based products with their weaker gluten quality, although this claim needs further investigation. The Land Institute recommends caution for those with gluten allergies when consuming Kernza® (The Land Institute, n.d.-a). Additionally, the high protein content of Kernza® (19.2 g/100 g serving) may supplement future needs for more plant-based proteins as more people divert from environmentally unsustainable animal protein consumption.

4.2 | Current trends and opportunities

Currently, conventional wheat is widely planted in the United States on over 37.2 million acres (Agriculture Marketing Resource Center, 2022). First-year averages are 4.5% of annual wheat with the second-year crop increasing to 33% of annual wheat yields (Culman et al., 2013). Demands for wheat are expected to increase by 26% by 2050; however, climate change—specifically, extreme temperatures in the spring and fall—is expected to reduce wheat yields by 17–31% over the same timeframe (Obembe et al., 2021). Additional drought concerns in the summertime present challenges for most annual crops, let alone for wheat. In contrast, Kernza® exceeds annual wheat crop in climatic resiliency, soil and biodiversity sustainability, and grain content of key nutrients (Clément et al., 2022; Culman et al., 2013; Herman, 2022; KCUR, 2022; The Land Institute, n.d.-c; van der Pol et al., 2022). Nevertheless, only about 4000 acres are devoted to Kernza® production in the United States, with most of it being grown in and between the U.S. states of Kansas and Minnesota, although slowly expanding in new regions (KCUR, 2022; The Land Institute, n.d.-b).

Furthermore, even with grain harvest yields trailing behind annual wheat, Kernza® offers promising markets. Reduced yields could be compensated with additional harvests of forage for animal feed, supplementing farmer incomes with extra harvests (Pugliese et al., 2019). Moreover, harvesting for forage may also increase future grain productivity. In the first three growing seasons, not harvesting for forage decreased grain yields by 25–50% (Pugliese et al., 2019). Current national yield averages for Kernza® are 150 lb per acre, although hypothetical yields could reach 400–900 lb per acre (Spiegel, 2022; The Land Institute, n.d.-d).

The crises facing modern conventional agriculture demand changes like implementing perennial crops. Kernza®, the trademarked cultivar of intermediate wheatgrass (*Thinopyrum intermedium*), is a multipurpose grain and forage that reduces agricultural environmental concerns and complements a healthy human diet. The work is not finished though; continued crop improvements are needed to increase yields and ease the harvesting concerns of toppling and seedhead shattering (Peters, 2021). In persuading more farmers to switch to Kernza® and ease concerns of risk, grower incentives are needed such as federal crop insurance coverage, subsidies, and/or grants (KCUR, 2022). However, its greater drought resiliency may reduce crop insurance payouts. Overall, more research and funding are needed to continue developing Kernza® into a widely cultivated—and consumer-appreciated—perennial crop.

One potential area of research is the use of quantitative trait loci (QTL) for agronomic traits of Kernza® as recently published (Crain et al., 2022). Since Kernza® has a genetic architecture similar to barley, gene-editing techniques are being used to improve barley as well as wheat for agronomic as well as product quality (Elsharawy & Refat, 2023; Křenek et al., 2021; Zhou et al., 2023). Rachis fragility to improve yield and seed shape (increased circularity) to improve milling quality are two inviting avenues for advancement. Relative to product acceptability, not only to the consumer but also to the food producers, the use of traditional approaches to selection may have value in maintaining non-GMO status and a clean label, particularly if product labeling and advertisement are used to promote products made with Kernza® relative to wheat.

The breeding program at the University of Minnesota has been instrumental in the creation of enhanced Kernza® varieties (Tyl et al., 2020) tailored for the Midwestern and Northeastern regions of the United States. Launched in 2011 with The Land Institute–sourced germplasm, the program successfully completed 2019 three cycles of recurrent selection and unveiled its inaugural Kernza®

variety—"MN-Clearwater." The initiative has achieved substantial advancements in augmenting grain yield, seed dimensions, shatter resistance, free-threshing grain, more crop uniformity, lodging, and resistance to diseases (Bajgain et al., 2020; Tyl et al., 2020). The breeding populations undergo a 2-year evaluation process at two separate locations in Minnesota. The data collected from these traits, in conjunction with molecular marker information, are utilized to construct comprehensive genomic selection models that take into account the interaction between genotypes and environments.

Another opportunity that is obvious but not a focus of attention is the distribution of Kernza® seed to developing countries where climate change is driving food insecurity, and differences in the food product quality are of less importance relative to having sufficient food to consume. For example, "Diversification of agriculture and restoration of soil health through the introduction of the perennial grain crop Kernza®" is the ongoing project in Ukraine to study and adapt this perennial crop to Ukrainian agricultural conditions (Kurhak et al., 2024) motivated by its dual economic use as a grain and forage crop, its ability to protect water sources from pollution and siltration, as well as to restore organic matter of Ukrainian black soil (chornozem). Authors emphasize that modest production of Kernza® grain is compensated by a wide range of food industry applications for grain; additional income from the use of summer straw and autumn green mass as valuable forage, cost savings through reduced costs, and benefits from positive impacts on ecology.

5 | SUNFLOWERS: ANNUAL TO PERENNIAL

Although domesticated thousands of years ago by Native Americans, commercial plantings of the annual sunflower, *Helianthus annuus*, did not begin until the mid-20th century. As a result of the cytoplasmic male sterility (CMS) technology, allowing for faster hybridization, a shorter but high-yielding crop emerged with high-oil seeds adapted to mechanization (Vollmann & Rajcan, 2010). Interestingly, despite repeated hybridization and genetic improvements, *H. annuus* remains a non-genetically modified organism (non-GMO) (Roseboro, 2022).

As a food crop, a sunflower mainly lies in either confection or oilseed classifications. Confectionary sunflowers are grown for their edible seeds, often larger and black-and-white striped with an oil content of 30%; this group also contains the markets for birdseed (Myers, 2022). Oilseed sunflowers, as the name implies, are grown for vegetable oil; these cultivars have a smaller, black seed with a much higher oil concentration of around 50% (Myers, 2022; Vollmann & Rajcan, 2010). In the United States, 70–80% of sunflower cultivars grown are oilseed varieties (Myers, 2022). From there, oilseed crops can be sorted by α-linoleic or oleic acid content. As sunflower seed hulls (SSHs) occupy 43.9% of the total seed weight, removal of the lignocellulose hull is often necessary before oil pressing begins. The resulting "enriched kernel" is higher in oil and a good source of vitamin E and omega-6/9 fatty acids (Vollmann & Rajcan, 2010; Warwick, 2020).

Silphium integrifolium, commonly known as silflower or rosinweed, is found in Eastern North America from Ontario, Canada, to New Mexico, USA (Hilty, 2018). Work on *S. integrifolium* domestication began in 2003 by David Van Tassel of The Land Institute (Kansas, USA) (The Land Institute, n.d.-f). Generally, this plant is 3–5 feet tall and unbranched except near the tops, with 2- to 3-inch bloom disks. Opposite of *H. annuus*, *S. integrifolium* has fertile ray florets and infertile disk florets. It is an excellent pollinator attractant, with many native bees and butterflies being frequent visitors. *S. integrifolium* blooms in late summer/early fall for 1–2 months. Like the annual variety, it prefers full sun and grows well in loam or clay loam soils without the need for fertilizer (Hilty, 2018). This plant has excellent winter hardiness with rhizomes and drought tolerance from its 1.5–2 m taproot (Evangelista et al., 2023). This taproot has helped *S. integrifolium* outperform many annual crops that succumb to seasonal drought. Notably, its vigor was recorded by botanists during the 1930s Dust Bowl (The Land Institute, n.d.-f). Over the last two decades, *S. integrifolium* seed yields and biomass have increased through breeding efforts. A few unintended consequences of breeding efforts observed thus far include root shortening (potentially reducing drought tolerance) and attenuating resin content. The resinous sap, once chewed by Native Americans as gum, is evolutionarily designed for pest deterrence; reduction would, therefore, increase pest pressures (Van Tassel et al., 2017; Vilela et al., 2018). Breeding goals for the future include better-synchronized flowering, reduction of seed shattering, reduction of plant height, maintaining genetic diversity (for future improvement), improving the (a)biotic stress tolerance, and increasing bioactive, health-beneficial chemical components (The Land Institute, n.d.-f; Van Tassel et al., 2017; Vilela et al., 2018). Addressing these concerns will make *S. integrifolium* production more competitive against conventional annual vegetable oils. Early commercial production is expected to begin as soon as 2025 (The Land Institute, n.d.-f). Early agronomic trialing of *S. integrifolium* for oilseeds has yielded 312–1319 kg/ha with an average of 192 g of seeds per plant (Evangelista et al., 2023). When chemically analyzed, its seeds were 20% crude fat, 33.5% crude protein, and 22.1% cellulose (Evangelista et al., 2023).

The Jerusalem artichoke or sunchoke (*Helianthus tuberosus*) is another candidate for perenniality by crossbreeding with *H. annuus*. Many know and consume *H. tuberosus* for its edible tubers rich in fiber, B and C vitamins, potassium, and iron (USDA ARS, USDA ARS, 2019; Weg, 2022). Those tubers are what lend *H. tuberosus* its perenniality. An *H. tuberosus* × *H. annuus* cross in early trials has exhibited a 320% increase in phenotypic gains such as seed yields (Kantar et al., 2018). Perenniality is a top priority but is difficult to genetically pinpoint in breeding trials since tuber traits are oligogenic (Kantar et al., 2018; Wyse, 2023). Experimental cultivars may reach farms as soon as 2029, thanks to breeding efforts by organizations, for example, The Forever Green Initiative of the University of Minnesota (Wyse, 2023). Like *S. integrifolium*, perennial *H. tuberosus* × *H. annuus* could be a more sustainable source of vegetable oil production.

The maximilian sunflower (*Helianthus maximiliani*) is a third sunflower candidate for perennialization by crossbreeding with *H. annuus*. Like *H. tuberosus*, *H. maximiliani* is a wild relative of *H. annuus* and a promising candidate for commercial oilseed production. This plant ranges from the southern Canadian prairies through Northern Mexico. Its wild, perennial nature brings excellent resistance to sclerotinia rot and leaf rust—two ailments in *H. annuus* production (Asselin et al., 2018). With high levels of recombination and heterozygosity, *H. maximiliani's* low genetic inbreeding makes it easier to selectively breed for better agronomic traits. As with *S. integrifolium* and *H. tuberosus*, cross-pollination breeding tactics are the best approach for crop improvement.

5.1 | Nutritional attributes

Nutritionally, sunflower seeds and oils contain a healthy source of poly- (PUFAs) and monounsaturated fatty acids (MUFAs), vitamin E, dietary fiber (in seeds) (Adeleke & Babalola, 2020), and numerous bioactive phytochemicals known for antioxidant, anti-inflammatory, and anticancer properties (Table 3). Subsequently, the consumption of sunflower seeds may extend beyond traditional culinary usage and be considered a nutraceutical helping to prevent chronic disease (Adeleke & Babalola, 2020). Sunflower seed oil contains both α-linoleic (ALA, or omega-6) and oleic (OA, or omega-9) PUFAs (precise compositions depend on the cultivar), both of which support a healthy lifestyle and may prevent the onset of chronic diseases (Li et al., 2022; Tallima & El Ridi, 2018; Wang et al., 2021). Occasionally, ALA is metabolized into arachidonic acid (ARA) after consumption. While previous literature has suggested harmful associations from ARA, Tallima and El Ridi (2018) and Wang et al. (2021) outlined its newfound healthful qualities. Circulating ARA levels, albeit relatively low, are observed to have anticancer effects as well as aid brain and muscular functions (Tallima & El Ridi, 2018). Additionally, metabolites of ARA benefit natural inflammatory and immune system responses. Moreover, therapeutic applications for ARA and its metabolites are in further development (Wang et al., 2021). Overall, switching from saturated to unsaturated PUFAs is shown to lower LDL cholesterol and triglycerides while increasing HDL cholesterol (American Heart Association, 2020; Mayo Clinic, 2023; Office of Disease Prevention and Health Promotion, 2016; Warwick, 2020). This metabolomic shift reduces the risk of cardiovascular disease and other chronic diseases (Mayo Clinic, 2023), making sunflower seed products of value in reducing U.S. chronic disease burdens. Thus, the consumption of plant oils high in ALA and OA would support a healthy lifestyle with potential therapeutic benefits.

Gentle low-heat applications are favored ALA and mid-OA sunflower oils, for example, salad dressings, margarine, or stir frying, as repeated high-heat applications may lead to aldehyde production. Nonetheless, high-oleic sunflower oils with greater thermo-oxidative stability can be used for higher-temperature frying (Myers, 2022; Vollmann & Rajcan, 2010). Interestingly, compared to *H. annuus*, *S. integrifolium* sunflower seed oil contains much higher amounts of ALA at 62.32%. Given the growing demand for sunflower seed oils in the United States and abroad, the potential nutritional benefits of consuming sunflower seed products, and the environmental and

TABLE 3 Sunflower seed (*Helianthus annuus*) phytochemical constituents and their corresponding biological effects (Adeleke & Babalola, 2020).

Biological effect	Biological constituents
Antioxidant	Enzymes (catalase, glutathione reductase, guaiacol peroxidase, and glutathione dehydrogenase), phenolic compounds (flavonoids, phenolic acids, and tocopherols), carotenoids, ascorbic acid, and peptides
Anti-inflammatory	Helianthosides, triterpene glycosides, and α-tocopherol
Antidiabetic	Quinic acid, glycosides, chlorogenic acid, caffeic acid, and phytosterols
Antimicrobial	Alkaloids, glycosides, tannins, saponins, and phenolic compounds
Antihypertensive	11S globulin peptides

physiological burdens of conventional farming, developing domesticated perennial sunflower cultivars could revolutionize vegetable oil production for a more sustainable future.

5.2 | Current trends and opportunities

As the fourth most important vegetable oil in the world, with an industry leading 7% growth each year (since 2011), *H. annuus* sunflower oil approaches 20 million MT in annual production (Sandbakken, 2023). Currently, Ukraine, the R.F., the E.U., Argentina, Türkiye, and the United States are the largest producers accounting for nearly 86% of all production worldwide (Sandbakken & Kandel, 2020). Ongoing war against Ukraine (2014–) prompted the nation to fall to #2 in rankings, now behind R.F. (Sandbakken, 2023). Compared to other global leaders, production of sunflower seeds in the United States is modest but respectable—last forecasted to approach 1.04 million MT or 2.3 billion lb (Sandbakken, 2023). Export demands remain high, with the United States primarily exporting to Canada and Mexico; however, the highest importing countries/regions include the EU, Iran, China, India, and Türkiye (Sandbakken, 2023). Sunflowers are heavily cultivated in North and South Dakotas (85% of all U.S. production), followed by Kansas, Colorado, Nebraska, and Texas (USDA, 2023). In contrast, consumption of sunflower-seed oil in the United States is on the rise with 335,000 MT reportedly consumed as of 2022 (Wunsch, 2023). Sunflower market growth is likely explained by consumers seeking healthier cooking oils and food industries desiring oils that remain stable under high heat or frying applications (Myers, 2022; Singh, 2021; Vollmann & Rajcan, 2010). Thus, expanding markets for sunflower oil create opportunities and economic incentives for new, perennialized cultivars.

While more agronomic and nutritional research is needed, perennial sunflowers capitalize on sunflower oil's health qualities for chronic disease prevention while addressing the conventional farming concerns of topsoil erosion and biodiversity loss from repeated tillage, eutrophication of waterways, reduction of SOC and carbon emissions, pesticide and herbicide exposures, financial and labor stressors, and drought (Asselin et al., 2018; Kantar et al., 2018; Vilela et al., 2018; Yazd et al., 2019). Domestic cultivation reduces dependencies on foreign importation of sunflower and other vegetable oils. The Land Institute and other researchers continue to develop *S. integrifolium*, *H. tuberosus*×*H. annuus*, and *H. maximiliani*×*H. annuus* into commercially viable oilseed cultivars. Although widespread consumer availability of perennial sunflower seed oil may be decades away (The Land Institute, n.d.-f), the current literature reveals the necessitous, but arduous, work required for developing new perennial cultivars.

6 | ADVANCING THE FIELD AND FUTURE DIRECTIONS

Despite the benefits of perennialization for greater environmental and human health, limitations for widespread adoption remain. Although advanced genetic technologies have the potential to progress new crops much quicker than historical standards, the many decades required for trait improvements delay the widespread commercialization of perennial sunflowers, Kernza®, and other perennial crops. Current markets for perennial Kernza® remain niche and limited. Farmers interested in planting Kernza®, for instance, must first apply to be a registered grower through The Land Institute and acknowledge the risks of the experimental crop. Limited seed availability, land requirements (≥20 acres) (Forever Green Initiative, 2022a), and proximity to grain mills that can process Kernza® are additional deterrents. Additionally, yields must continue to improve, especially after year 3, for Kernza® to better compete with annual wheat and feed growing populations. As reported by Forever Green Initiative (2022b), present-day cultivation of Kernza® may exceed many annual row crops in average net returns per annum, which may financially incentivize skeptical farmers (given a conservative market price of $1/lb, dual harvests for forage, $60/acre seed costs, 466 lb/acre average yields over three seasons, and no herbicide applications) (Table 4).

Unlike Kernza®, perennial sunflower development remains in its early developmental stages. However, once sunflower cultivars are improved, new markets are needed for perennial vegetable oils. Increasing consumer demands for healthy and sustainable vegetable oils may incentivize *H. annuus* farmers to switch their cultivation to perennial. Furthermore, most consumers are willing to pay slightly more for sustainable and organic foods, as

TABLE 4 Average annual gross revenues, total expenses, and net returns reflected in USD per acre (Forever Green Initiative, 2022b).

	Gross revenue	Total expenses	Net returns
Corn	754.19	517.84	236.35
Soybeans, monocropped	497.69	276.92	220.77
Wheat, spring	362.76	245.11	117.65
Oat	268.77	183.04	85.73
Alfalfa hay	615.09	309.50	305.59
Kernza® ($1/lb)	626.67	106.45	520.22

noted in Cook et al.'s (2023) narrative literature review. Thus, capitalizing on consumers' growing sustainability and health interests while persuading growers with financial and ecological benefits is a pertinent perspective that surely will aid in perennial sunflower and Kernza® market expansions.

Extensive implementation of perennial grain and oilseed crops for a PGR depends on transdisciplinary action; increased consumer awareness, acceptance, and demand; improved policies at federal, state, and local levels; and additional financial resources and grant opportunities for farmers (Figure 1):

1. *Transdisciplinary action*: uniting farmers, crop breeders, environmental ecologists, public health officials, nutritionists, physicians, policymakers, and community advocates to each offer expertise and guidance for greater advancements in the perennial crop movement.
2. *Consumer awareness, acceptance, and demand*: increasing the public's knowledge of perennial crops, their benefits for environmental concerns, and their human health attributes to support a healthy lifestyle. Campaigns, presumably from large food companies, must market new perennial crop products to increase consumer demand. Likewise, supply must increase to improve access to products in more communities. Access and affordability greatly improve the chances of consumer acceptance and greater perennial demands.
3. *Federal, state, and local policy*: expanding "agricultural safety nets," such as federal direct payment programs and crop insurance which largely exclude experimental perennial agriculture (Scott et al., 2022). New policies can incentivize switching to perennial cultivation by granting farmers direct payments or crop insurance coverage. Local policy could provide tax incentives for farmers who perennialize fields, considering the environmental benefits for the surrounding ecosystem.
4. *Financial resources and grants*: increasing funding for scientific research for perennial crop development, both in situ and ex situ. Kernza®, perennial sunflowers, and other perennial crops depend on continuing financial resources to perpetuate progress to reach greater cultivation and commercialization. Additionally, expanding grants, such as the Conservation Stewardship Program's E3280 grant for perennial grain crops (USDA, USDA, 2021), may financially persuade more farmers to cultivate perennials by offsetting new equipment and seed costs.

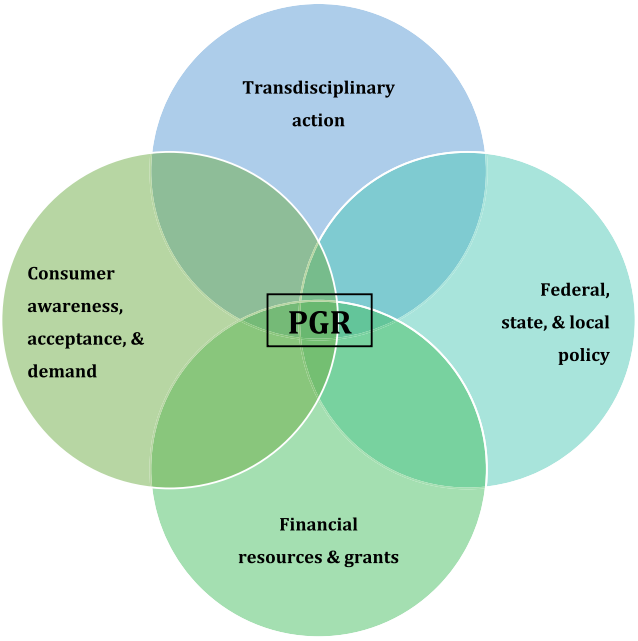


FIGURE 1 Four elements for success of crop perennializations in achieving the goals of a Perennial Green Revolution.

Implementing these four critical elements to advance the perennial crop movement, while addressing and resolving current limitations, has the potential to reform conventional agriculture, environments, and food systems alike (i.e., an effort described as a PGR). As reviewed, the pioneering and ambitious development of perennial sunflower oil and perennial Kernza® grain (for widespread commercialization and the eventual replacement of annual monocropping systems) carry the transformative power to not only revolutionize agricultural practices but also ignite a greater transdisciplinary pursuit towards a sustainable and healthy future for generations to come.

7 | CONCLUSION

Agricultural advancements over the last century have boosted crop yields to unprecedented levels. Feeding and nourishing a growing global population remains an utmost priority for farmers and public health officials alike; however, many annual monocropping systems are perpetuating detrimental soil erosion, biodiversity loss, carbon emissions, chemical exposures, and wetland eutrophication from repeated field tillage and chemical applications (Asselin et al., 2018; Environmental Protection Agency, 2023; Kantar et al., 2018; Ogle et al., 2019; Thaler et al., 2022; Tibbett et al., 2020; Vilela et al., 2018). The development of perennial grain and oilseed crops to supplement conventional annual crops provides a vision for advancing industries for the remainder of the 21st century by tackling many ongoing socio-environmental state events. Unlike annuals, perennial crops have deeper roots for increased drought tolerance, reduced needs for fertilization and irrigation, and

improved soil health, which has recently been linked to human health as codified in the National Academies of Sciences, Engineering, and Medicine (2024). Perennials also can reduce net expenditures for farmers and time spent preparing fields. Lastly, there may be opportunities within grain and oilseed perennialization to address many public health concerns through dietary, staple food crop interventions. In all, the perennial cultivars emphasized in this narrative review offer a focused and promising glimpse into general perennial development and commercialization as a means to address ongoing concerns about global food security.

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