CHAPTER FOUR

From concept to crop: Kernza perennial grain is a work in progress

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Advances in Agronomy, Volume 193
ISSN 0065-2113, https://doi.org/10.1016/bs.agron.2025.05.004

Abstract

Intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey) is a perennial grass that has been explored for use as a perennial grain since the 1980s. With growing recognition of the potential for perennial grains to improve soil quality, sequester carbon, and reduce nitrate leaching, research with the species has expanded rapidly since 2010. However, introducing a new crop requires coordination across a wide array of research fronts and commercial development activities. The grain, sold under the registered trade name Kernza, has been used to develop commercial products, but high prices for the grain and intermittent supply have limited use. Market growth depends on increased yields through breeding and agronomic improvements, combined with development of cost-effective regional processing. Therefore, we reviewed the current knowledge base surrounding intermediate wheatgrass as a grain crop to summarize available information and suggest future directions. Evidence for the environmental benefits of Kernza on water quality and soil health is growing. While perennial grasses generally increase stored soil carbon, long-term cropping system experiments are required to accurately predict landscape-scale impacts of this new crop on soil carbon stocks, in interaction with crop rotation and pedoclimatic parameters. Studies have revealed the importance of soil nitrate availability in determining grain yield, and fertilizer recommendations are

available for some regions. However, the role of other nutrients and the potential for legume intercropping to supply nitrogen remains uncertain. Improved techniques are urgently needed to sustain seed yields in aging stands across diverse environments. Expanding markets will be essential for success.

Abbreviations

ADF	acid detergent fiber.
CP	crude protein.
DM	dry matter.
DON	deoxynivalenol.
FDA	Food and Drug Administration.
FNBs	food and beverage companies.
FSU	floret site utilization.
GEBVs	genomic estimated breeding values.
GDD	growing degree day.
GHG	greenhouse gas.
GRAS	generally recognized as safe.
IWG	intermediate wheatgrass.
KSA	Kernza Stewards Alliance.
LCA	life cycle assessment.
LTL	less than truckload.
MAOC	mineral-associated organic carbon.
NDF	neutral detergent fiber.
NDFD	NDF digestibility.
OP	optimal price.
PMC	point of marginal cheapness.
PME	point of marginal expensiveness.
POC	particulate organic carbon.
RFV	relative feed value.
RRC	Rodale Research Center.
SOC	soil organic carbon.
TDN	total digestible nutrients.
TLI	The Land Institute.
TTNDFD	total tract NDFD.
WUE	water use efficiency.

1. Domestication: From grass to multipurpose grain

Thinopyrum intermedium (Host) Barkworth & D.R. Dewey (intermediate wheatgrass – IWG) is an outcrossing allohexaploid (2 n = 6x = 42) cool-season temperate grass native to steppe and hilly environments of Eurasia, from the western regions of the Middle East to the southern parts of the former Soviet Union (Bajgain et al., 2022). It is a rhizomatous grass, although rhizome production is variable depending on genotype. It was introduced to North America for erosion control and forage production in the first half of the 20th century, and several cultivars were bred and used as forage, often in association with alfalfa, in the northern half of the United States and Canada (Hitchcock and Chase, 1951; Flora of North America Editorial Committee, 1993; Schwendiman, 1956).

At the end of the twentieth century, the first breeding initiatives were undertaken to improve grain production and to use populations of IWG as perennial grains. These initiatives were mainly motivated by the ambition to protect and improve soils, and to limit the operating costs associated with seeds, tillage and sowing. The first domestication efforts began at the Rodale Research Center (RRC, Pennsylvania, USA). After a comparative study of about one hundred perennial grasses, IWG was selected for domestication because of its favorable traits for grain production (vigorous perenniality, easy threshing, larger seed, synchronous maturity, shatter resistance, lodging resistance, seed heads above foliage for easy harvest, and potential for mechanical harvest) (Wagoner, 1990). From about 250 accessions evaluated over two years of cultivation, about 20 accessions, mostly from the former Soviet Union (Stavropol region), were selected in the fall of 1989 and crossed in the greenhouse (Crain et al., 2024). Seed from the crosses was used to seed the first space-planted nursery at the Big Flats Plant Materials Center in New York. A second nursery was established in 1995 using seed from crosses of the 11 best individuals from the first nursery, evaluated over four years of cultivation, to which 3 new accessions from the RRC were added. A second selection cycle was initiated in 1997 using a similar methodology. Seed from the best performing plants in cycles 1 and 2 was transferred to The Land Institute (TLI, Salina, Kansas, USA), which then initiated the breeding programs from which all current populations were derived and improved for grain production with the intention of providing IWG suitable for human food (DeHaan et al., 2018).

The development and selection methods at TLI have been presented and detailed in several publications (Bajgain et al., 2022; Crain et al., 2021; DeHaan et al., 2018). Between 2003 and 2015, TLI conducted 6 selection cycles using space-planted nurseries and evaluated a large number of traits, including seed yield per spike, seed mass, percent naked seed, short stature, shattering resistance, and floret site utilization (FSU), seed width, seed area, and seed plumpness. From 2017, the breeding program incorporated genomic selection, enabling one-year breeding cycles by genotyping genets and predicting the best genets based on genomic estimated breeding values

(GEBVs). Approximately 4000 genets were genotyped each year. About 100 of these were selected based on genomic predictions for spike yield, free threshing, shattering, and seed mass, and crossed to form the next generation. At the same time, about a thousand genets were selected and planted in the field for phenotypic evaluation and validation of the genomic predictions. In 2011, breeding programs were also initiated at the University of Minnesota (USA) and the University of Manitoba (Canada), based on selection cycles 3 and 4 conducted at TLI. In 2018, breeding programs also started at USDA-ARS, Utah (USA), and in Sweden at the Swedish University of Agricultural Sciences, Uppsala (Bajgain et al., 2022). This expansion of breeding programs was also associated with agronomic and environmental quality research as well as concerted efforts at commercialization and on farm trials (Reilly, 2023).

In 2023, improved IWG varieties were grown by U.S. farmers on approximately 973 ha (Crop Stewardship, 2023). Grain harvested from improved varieties is marketed under the trade name Kernza, through licensing with TLI, which owns the Kernza trademark. Here, we will use the name Kernza to refer to both the grain and the crop more generally. Kernza food products have come from pioneering food processing companies that are experimenting with processes using Kernza whole grain, rolled grain and flour, and developing products for value-added industries in marketing segments that highlight the challenges of agricultural transformation and environmental preservation (www.kernza.org). Outside of the USA, Kernza production is not yet licensed, and cultivation is confined to research plots in countries such as in France, Belgium, Italy, Sweden, Denmark, Uruguay, Russia, Norway, Finland, Poland, Argentina, and Ukraine. In France and Sweden, a few hectares have been planted in on-farm experimentation, with the aim of providing a learning experience and experimental support for farmers wishing to design crop management strategies for future adoption (Ginot et al., 2024).

2. Ecosystem services

A primary motivation for the development and adoption of perennial grains broadly and IWG specifically is to improve both economic and environmental benefits (Lanker et al., 2020). Given the varying degree to which ecosystem services can be influenced by plant growth over space and time with local climate and soil characteristics, early indicators of how

IWG influences services are similarly varying. Ecosystem functions that are a direct response to plant growth such as water quality and reduced nitrogen (N) loss are consistently and dramatically improved by IWG compared to annual crops (Culman et al., 2013; Jungers et al., 2019; Reilly et al., 2022a). Other functions such as improved soil health and systemic goals like reduced greenhouse gas (GHG) emissions and climate-resilient crops take longer periods of time to realize and assess given the complexity of factors influencing these outcomes and rate that these services can respond. Here we review the current evidence of how IWG influences core ecosystem functions such as improved water quality, soil aggregation, microbial activity, soil organic carbon (SOC), net GHG as well as fruitful future research directions.

2.1 Influence on water use and water quality

Water use and water quality are critical issues in agricultural lands. Excess fertilizer not taken up by plants can leach from the soil in the form of nitrate, polluting drinking water and causing issues such as eutrophication or hypoxia of downstream waters (Brender et al., 2013; Erisman et al., 2013). In addition, the bare ground present for much of the year in annual cropping systems, without roots to hold the soil in place, can be associated with water pooling, flooding, and erosional loss of topsoil. For example, it has been estimated that 8 Pg, or 10 %, in total of SOC stocks in the US have been lost from annual cropping systems (Drewniak et al., 2015).

IWG has a consistent ability to reduce soil water nitrate concentrations to levels close to that of native tallgrass prairies, with 60 to over 98 % reductions compared to corn (Jungers et al., 2019), unfertilized soybean (Reilly et al., 2022a), or annual wheat (Culman et al., 2013; Huddell et al., 2023). In all these studies, IWG most effectively reduces soil water nitrate beginning roughly in summer of the first growing season after planting. The most impactful soil water nitrate reductions occur in the winter and shoulder seasons when there is no plant coverage in annual cropping systems and IWG still reduces soil water nitrate by over 90 % on average (Huddell et al., 2023). When soil water nitrate estimates and hydrologic properties are used to model potential reduction in nitrate loads in IWG compared to annual crops, there is likewise a reduction by 90 % or more, with loads ranging from 0.1 to 3 kg ha^{-1} yr^{-1} (Huddell et al., 2023; Jungers et al., 2019; Mulla et al., 2023) compared to estimates of 15–67 kg ha^{-1} yr^{-1} in corn and a range of 5–70 kg ha^{-1} yr^{-1} in annual wheat (Huddell et al., 2023; Mulla et al., 2023; Pugesgaard et al., 2014; Randall et al., 1997). This could be a result of IWG's ability to take up and use nitrogen effectively, reduce soil available N pools compared to annual crops (Dobbratz et al., 2023; Huddell et al., 2023; Sprunger et al., 2018a), as well as its ability to reduce soil moisture or deep water percolation (Clément et al., 2022; Huddell et al., 2023; Mulla et al., 2023) through increased evapotranspiration and water use efficiency (WUE) (de Oliveira et al., 2020; Mulla et al., 2023; Vico and Brunsell, 2018). IWG's water use characteristics may change depending with seasonal and annual changes in plant physiology (Vico et al., 2023) and its high WUE (de Oliveira et al., 2020) could imply that the reduction of deep water percolation depends on the context of rainfall amount in a given region or season.

When these results are modeled across watershed and landscape situations, similarly impactful reductions in leached nitrate have been observed (Wilson et al., 2023), with estimates that converting approximately 34 % of a typical upper midwestern watershed to IWG would achieve regional goals of a 30 % reduction in overall leached nitrate to waterways.

Another metric of IWG's ability to improve water quality and soil conservation is its ability to reduce erosion. Little work on this topic has been done, but results to date are promising, demonstrating that IWG and other similar perennial grasses decrease soil erosion by 68 % (Fasching and Bauder, 2001) and decrease surface nutrient and sediment runoff by approximately 30 % compared to winter wheat (Ashworth et al., 2022; Katuwal et al., 2022).

2.2 Influence on soil carbon

The source, depth of input, and frequency of disturbance are the main differences in how perennial grains affect soil differently than annuals. Under perennial grain cultivation, the majority of the soil C input comes through roots, while under annuals it comes predominantly from litter at the soil surface that may be incorporated into the soil through tillage (Anderson-Teixeira et al., 2013). Perennials may allocate as much as 750 % more belowground biomass compared to annual grass crops, have less (20–45 %) aboveground litter, and a slightly higher soil respiration (~30 %) despite the greatly enhanced belowground growth (Anderson-Teixeira et al., 2013). Given that root-derived C is preferentially retained as SOC (Austin et al., 2017; Kätterer et al., 2011; Rasse et al., 2005; Sokol and Bradford, 2018), the enhanced and deeper root growth of perennial grasses tends to lead to the deeper and greater SOC in grasslands (Jobbágy and Jackson, 2000) as is frequently observed (Acharya et al., 2012; Beniston et al., 2014; Christensen et al., 2016; Culman et al., 2010; Gamble et al., 2019).

A recent meta-analysis studying the effects of cover cropping and perennials found that the change in SOC was primarily explained, and potentially limited by, the change in increased root inputs to the soil (King et al., 2024). Since studies comparing IWG and annual grain crops have consistently found IWG has three to fifteen times greater root biomass across all depths studied (0–120 cm) (Duchene et al., 2020; Rakkar et al., 2023; Sainju et al., 2017; Sprunger et al., 2018b; Woeltjen et al., 2024b), this suggests that IWG as a crop would enhance SOC as has been found with perennial crops broadly (Ledo et al., 2020).

SOC can be in two main forms: particulate organic carbon (POC) or mineral-associated organic carbon (MAOC). Each type of SOC has a different formation pathway and distinct protection mechanism. POC forms primarily from structural inputs and has minimal protection beyond soil aggregation resulting in faster turnover rates (Cotrufo et al., 2015; Lützow et al., 2006; von Lützow et al., 2007). MAOC forms primarily from low-molecular weight compounds that chemically bind to minerals, leading to protection from the soil matrix (Cotrufo et al., 2015; Keiluweit et al., 2015; King et al., 2023). King et al., (2024) comparing perennial and annual agricultural systems, found that increases in POC were best explained by average annual increases to root C input, though constrained by decomposition, while increases in MAOC were best explained by the cumulative increase in root C input to a system, supporting the understanding that increasing root inputs to soil leads to changes to SOC both as POC and MAOC.

Studies that have examined perennial root growth over time have found that perennial root biomass doubled in the second year of growth (0–45 cm), with much of the increased growth occurring within the upper 15 cm (Bolinder et al., 2002) and root biomass greater at four than seventeen years (Acharya et al., 2012). A study of root growth rates of IWG suggested that root growth rates may slow with stand age but that they remain plastic and reflect plant growth aboveground (Woeltjen et al., 2024a). This same study found that decomposition rates (0–15 cm) were higher under a 2 year old IWG stand compared with a younger stand, implying root turnover may spur increased microbial activity. Overall, these studies suggest that IWG often has greater biomass production and net C uptake at higher levels than annual crops in part owing to the greater root growth.

There are few long-term studies with IWG and annual crop comparisons, but the studies that do exist show substantially higher SOC under IWG than annual crops. Several of these studies were conducted with IWG as a forage or bioenergy crop rather than varieties selected for increased grain yield. As biomass production for early varieties (TLI-Cycle 2, first harvested 2010) of IWG for grain and forage are similar (Jungers et al., 2017), these forage and bioenergy studies seem relevant to the varieties of IWG grown for grain and forage today. Most agronomic studies with IWG have been with a few early varieties of IWG which were most available at the start of experiments: TLI-Cycle 5 (first harvested 2014, retired in 2022) and MN-Clearwater (publicly released 2019). In a 10-year study contrasting SOC under several perennial grasses grown for bioenergy (including IWG) with annual spring wheat in Froid, MT, USA, researchers found that SOC under IWG was 11 % higher 0–120 cm and 16 % greater 0–30 cm than the annual wheat comparison, showing even greater SOC gains than the other perennial grasses in the study (Sainju et al., 2023). Sampling a 16-year old experiment with replicated blocks of IWG (RRC-developed materials) and annually tilled and fertilized wheat (0–15 cm in Salina, KS) revealed SOC (measured as soil organic matter) concentrations that were 38 % greater under IWG (Means et al., 2022). The only on-farm field study with TLI-Cycle 5 IWG compared to annuals (near Salina, KS) found that fields under IWG (~5–17 yrs) had an average of 11.4 Mg C ha^{-1} more SOC than adjacent annual fields 0–100 cm which would translate to a SOC accrual rate of 0.4 Mg C ha^{-1} yr^{-1}, presuming annual and perennial fields were similar prior to planting IWG. This study further found significantly greater POC at all depths, accounting for roughly 40 % of the enhanced SOC under IWG (van der Pol et al., 2022). Finally, a comprehensive study of IWG grown for hay over 18 years in the Northern Great Plains (AB, Canada) found that fertilized IWG had SOC 7.8 Mg C ha^{-1} greater than the annual crops (0.43 Mg C ha^{-1} yr^{-1}) (Bremer et al., 2011). Thus, while studies are limited, the general principle that long-term perennial plant communities support higher SOC (Guo and Gifford, 2002; Prairie et al., 2023) can be applied to IWG.

Short term (≤4 yrs) studies of IWG effects on SOC and GHG flux have primarily relied on measurements argued to be early indicators of SOC change: POC, permanganate-oxidizable carbon (POXC), 24-hour C mineralization assays, and eddy covariance flux towers. These studies have had mixed results where some studies have found higher POC (Duchene et al., 2020) and POXC (Sprunger et al., 2019) under IWG than annuals, while others have observed no change (Link et al., 2023; Sprunger et al., 2018b) or the opposite (Taylor et al., 2024). While POC may be a soil pool more likely to detect short-term management changes given it is a smaller pool of SOC compared to bulk or MAOC (Lavallee et al., 2020), most changes in SOC require at least 6–10 years to be detectable with 90 % confidence, presuming soil C inputs increase ~20 % (Smith, 2004). Thus, we would not expect to see a substantial increase in POC for a short term study as acknowledged in Sprunger et al. (2018b). POXC has often been described as a method responsive to management and short-term changes (Culman et al., 2012; Weil et al., 2003), though measurement variability is highly dependent on grind size, SOC concentration, and soil mass used in analysis, making this measurement problematic as an indicator of soil health (Pulleman et al., 2021).

2.3 Greenhouse gas emissions

Perennial grains have potential to reduce net greenhouse gas (GHG) emissions associated with management by serving as a net sink for atmospheric carbon dioxide (CO_2), reducing conditions likely to produce nitrous oxide (N_2O), and reducing the emissions associated with more frequent heavy equipment and synthetic inputs (Crews, 2024). To understand the net C exchange balance with IWG as stands age compared to annual grains, eddy covariance flux towers provide insights into the net photosynthetic C-uptake and water-use efficiency over time. These studies have found that IWG has a net C-removal from the atmosphere of 370–500 g C m^{-2} yr^{-1} – substantially greater than annuals, which range from 200 g C m^{-2} yr^{-1} net removal to net C losses from soil as high as 320 g C m^{-2} yr^{-1} (de Oliveira et al., 2018; Wiesner et al., 2022). The greater net C-removal is attributed to the longer growing season of IWG as well as the increased WUE and ability of deep roots to maintain higher soil moisture availability and sustain photosynthesis even during very dry periods of the growing season (de Oliveira et al., 2020; de Oliveira et al., 2018; Sutherlin et al., 2019; Thorup-Kristensen et al., 2020). In this regard, the WUE and C-uptake of IWG more closely resemble mixed C3/C4 grasslands than annual cropping systems (Sutherlin et al., 2019). Studies with IWG as forage or bioenergy have similarly shown net C removal with IWG (Bremer et al., 2011; Sainju and Allen, 2023) and reduced GHG (N_2O, CH_4, CO_2) compared to annuals (Liebig et al., 2021; Liebig et al., 2020).

Perennial grains have the potential to reduce nitrous oxide (N_2O) emissions by reducing the frequency and duration of conditions likely to promote N_2O production, which are high concentrations of soil N, especially NO_3^-, and soil water, which leads to pockets of anaerobic conditions (Daly et al., 2022; Daly and Hernandez-Ramirez, 2020). Many of the studies comparing N_2O emissions from perennials and annuals have found inconsistent, site-specific, or year-to-year variability given the sporadic and weather-driven nature of N_2O emissions (Daly et al., 2022; Johnson and Barbour, 2016; McGowan et al., 2019; Oates et al., 2016; Smith et al., 2013), and there have been few studies comparing IWG to annuals. Bremer et al., (2011) described above, is the one recent study that found IWG compared to the annual reduced GHG (CO_2, N_2O) by 20−29 Mg CO_2 equivalent ha^{-1} over 18 yr and lost only 3 % of synthetic N applied compared with 32 % under annual cultivation. A two-year study comparing an unfertilized IWG stand to one intercropped with alfalfa and one with added N and phosphorus (P) found that the IWG intercrop had similar N_2O emissions as the unfertilized monoculture in a field in central Kansas, USA (Crews et al., 2022). Management that optimizes synchrony of N availability with crop demand, such as with a legume intercrop or timed fertilization, may minimize N_2O emissions from IWG and other perennial grasses (Crews et al., 2022; Johnson and Barbour, 2016) and mitigate potential N_2O priming from the greater root growth and exudation under perennials than annuals (Daly and Hernandez-Ramirez, 2020).

2.4 Soil health and climate resilience

While SOC is the most commonly measured soil health indicator (Bünemann et al., 2018) and is often considered synonymous with soil health (Liptzin et al., 2022) given its effect on soil physical, biological, and chemical functions, other soil indicators such as microbial activity elucidate how IWG interacts with soil. Studies comparing grassland microbial biomass and food web complexity tend to find greater microbial biomass, activity, and more complex food webs in perennial grasslands than annual cropping systems 0–100 cm (Beniston et al., 2014; Culman et al., 2010; Glover et al., 2010). While studies comparing microbial biomass and activity for IWG are limited to short term studies, many have found higher microbial biomass and increased fungal abundance under IWG compared to annual crops (Audu et al., 2022; Duchene et al., 2020; Rakkar et al., 2023; Taylor et al., 2023). A 4-year study that analyzed nematode trophic complexity under IWG and annual wheat (Michigan, USA) found that trophic complexity increased 55 % under IWG compared to the annual (Sprunger et al., 2019). Unsurprisingly, greater microbial biomass tends also to be linked to higher soil mineralization rates as some studies with IWG have demonstrated (Means et al., 2022; Taylor et al., 2024; Woeltjen et al., 2024b). Whether the increased microbial activity coupled with increased root growth from introducing IWG into a formerly annual system results in net SOC gains or losses may depend on the context, especially for short timeframes (<10 year) (Dijkstra et al., 2021; Keiluweit et al., 2015; Liang et al., 2018; Shahzad et al., 2018) and is an area where greater research is needed. Soils with complex clay minerals and tendency to form aggregates may have the greatest potential to see short-term SOC gains (Dijkstra et al., 2021), and while not many studies have compared soil aggregation under IWG and annual crops, a couple two-year studies (MN, USA) that did so found that the mean weight diameter of water stable aggregates increased by 22 % (Link et al., 2023) or more (Rakkar et al., 2023) under IWG. Thus, given the many ways to examine soil health, studies to date reflect favorably on IWG improving soil health beyond annual cropping systems.

As the effects of global climate change intensify and have consequences for food production systems, a key strategy for adaptation is to adopt agroecological systems that confer both stability and resilience (Sanford et al., 2021). Stable cropping systems are those that have consistent yields year to year when facing normal variability (Bowles et al., 2020), while resilient systems are those that remain productive and recover quickly after a significant perturbation such as drought or flooding event (Paut et al., 2020). No study to date has specifically examined the stability or resiliency of IWG systems, though studies contrasting perennial and annual systems for these traits have found that perennials promote system stability while diversity promotes resiliency (Sanford et al., 2021). Perennial systems have the potential to enhance the stability and resiliency of agricultural systems (Asbjornsen et al., 2014; Jungers et al., 2023) in part through their ability to enhance ecosystem services which have been demonstrated for IWG compared to annual grains as detailed in this section. Breeding, managing, and assessing IWG crop stability and resiliency across a range of climate and environmental conditions is a research priority that should include intercropped systems and annual comparisons.

3. Management for grain yield

3.1 Overview of grain yield

In terms of grain production, the best performance is achieved in the first or second year of harvest, before declining in subsequent years. The best production is between 0.7 and just over 1 Mg ha^{-1} of dehulled grains (Culman et al., 2023; Duchene et al., 2023; Fagnant et al., 2024a; Hunter et al., 2020a; Fernandez et al., 2020; Law et al., 2021; Tautges et al. 2018), with a harvest index generally around 10 %. Furthermore, the yield values are not always comparable from one situation to another, depending on the proportion of naked or in-hulled grain considered in the batches of harvested grain. After the first or second year of harvest, a decline in yields is often observed in the plots, with yields fluctuating within a range of 200–400 kg grain ha^{-1} and very low harvest indices (~5 % and below). Yield performance depends mainly on the fertility of the tillers to ensure sufficient spike production per m^2 and on the fertility of the florets to ensure a sufficient number of grains per spike (Altendorf et al., 2021; Fagnant et al., 2024a; Fernandez et al., 2020; Hunter et al., 2020).

3.2 Crop cycle and growth context

As a cool-season perennial, IWG can grow in a wide variety of contexts, as evidenced by the wide distribution of collected populations (Bajgain et al., 2022). The high genetic diversity of populations (Crain et al., 2023; Crain et al., 2024; Jensen et al., 2016) implies phenotypic variability and that many ecotypes can be selected for specific contexts, as was the case with the selection of particularly cold-hardy populations in Canada (Cattani and Asselin, 2018). Nevertheless, breeding is now directed towards increasing the overall performance of populations to achieve a minimum of 'domesticated' behavior (minimum yields, threshability, processability), before focusing on specific breeding strategies for this or that growing context. It is generally discussed that IWG is better adapted to well-drained soils and perform better in situations where annual rainfall ranges from 500 to over 1300 mm (Duchene et al., 2023; Fagnant et al., 2024a; Hunter et al., 2020; Jungers et al., 2018; Jungers et al., 2017; Zimbric et al., 2020). Productivity and WUE are difficult to characterize in absolute terms because they depend on the products harvested (grain and/or forage) and the age of the crop. Due to lower grain yields than annual cereals, the water productivity of IWG is also lower, but yields appear to be more stable due to the ability to buffer periods of drought through a deeper root system (Vico and Brunsell, 2018). In terms of nitrogen requirements, IWG has a moderate need due to its low tissue nitrogen content compared to other grain crops and forage grasses (Fagnant et al., 2023), low reproductive effort (Vico et al., 2016), and ability to store nitrogen in roots, tillering crowns, and stem bases (Sprunger et al., 2018a; Fagnant et al., 2024b). Optimal nitrogen fertilization is now considered to be between 90 and 100 kg nitrogen per hectare per year (Jungers et al., 2017; Fagnant et al., 2023). Nitrogen applications are commonly made in the spring, but it may also be beneficial to split them in the fall to promote tillering and tiller size before the winter period (Fagnant et al., 2024a).

IWG can be sown in spring or late summer/early fall. Induction of reproductive growth requires a winter vernalization period (cold temperatures between 0 and 7 °C) followed by initiation of stem elongation by increasing day length and temperature (Duchene et al., 2021a; Locatelli et al., 2022). The need for vernalization means that seedlings sown in spring will not achieve reproductive growth until the following year (Jungers et al., 2022). Depending on climatic region, GDD accumulation up to flowering is variable due to the cross influence of photoperiod, and flowering is generally observed between mid-June and early July in North American and European situations and between mid-December and January in Uruguay (Duchene et al., 2021a; Jungers et al., 2018; Locatelli et al., 2022). Depending on the region, this flowering period is considered relatively late compared with the phenology of annual grains and forage grasses in temperate situations. From flowering onwards, a further 1000 to 1500 GDD are needed to reach physiological grain maturity and proceed to harvest. Depending on moisture and nitrogen availability, IWG produces regrowth after harvest, and provides green ground cover the following fall.

3.3 Grain yield decline

Intermediate wheatgrass grain yields decline with stand age under certain conditions (Zhen et al., 2024). The problem of declining yields is not new to perennial grasses, and the same observations are made in plots dedicated to forage seed production, where harvests are only possible during two to four years, even with reduced seeding densities and increased inter-row spacing to limit canopy closure and promote tillering (Canode and Law, 1975; Fulkerson, 1972). However, for yields up to about 5OO kg seed ha^{-1} (in-hull), research into forage seed production has shown that it is possible to maintain IWG yields by using cover renovation techniques involving burning and mechanical destruction (Canode, 1965). At the moment, unprecedented breeding efforts for grain yield and the originality of IWG phenotypes e.g. higher root diameters and tissue silica contents, lower specific leaf area and specific root length (Duchene, unpublished) compared to conventional temperate forage grasses suggest that IWG's physiological adaptation and response to cultural practices and environmental conditions may not be fully extrapolatable from past observations on these other forage grasses.

Today, two different, but not contradictory, hypotheses are proposed to explain the decline in IWG grain yields over time. On the one hand, the yield decline could be explained by resource limitation at the tiller and plant levels. Intraspecific competition would be detrimental to grain production and would imply managing tillering toward an optimal situation, i.e. maximizing resource capture and use efficiency and minimizing competition among ramets (Chapman et al., 2022; Fagnant et al., 2024a; Hjertaas et al., 2023). This hypothesis is based on the fact that investment in reproduction is limited by morphogenetic regulation (e.g. light signals) coupled with resource availability. A second hypothesis explains the decline in yield by a change in the ecological strategy of the plant with age and stress gradient. Individuals would switch from a "seed" to a "resprout" strategy to ensure their longevity. As the plant ages, it stops producing seeds and favors vegetative and perennating organs, thus limiting the number of sink organs and the possibility of allocating photosynthates to them. The effect of plant aging on plant physiology and growth strategy needs further research but change in photosynthetic efficiency and carbon and nitrogen allocation in plant tissues has been documented (Fagnant et al., 2024b; Jaikumar et al., 2013; Jaikumar et al., 2016; Woeltjen et al., 2024b). Both hypotheses refer back to the question of drivers and balances between reproductive and vegetative growth in perennial herbaceous plants (Lundgren and Des Marais, 2020), and imply that plant growth strategy is the expression of a genetic-environmental interaction, never just one or the other.

Either way, breeding advances in IWG grain productivity are essential to maintain populations with sufficient reproductive behavior that is stable over time in a range of environmental conditions. However, the role of agronomic practices in limiting yield decline may also be considerable and needs to be studied in depth. How can we limit intraspecific competition within a canopy to optimize yield per unit area? And can specific practices be used to maintain individuals reproductive growth? Today, several pieces of information provide useful avenues for thought and work. First, observations of space-planted plants in nurseries or in the field indicate that reproductive effort can be maintained over years, suggesting a behavioral plasticity on which selection can act. On the other hand, field experiments have shown that reducing canopy density (by mechanical disturbance or reducing plant density) can limit yield losses (Canode, 1965; Fernandez et al., 2020; Hunter et al., 2020; Law et al., 2020). Another experiment showed a stable field yield of about one ton of grain per hectare for 4 years and points to the importance of regulating the population of tillers and the availability of resources for them (Fagnant et al., 2024a). Recent experiments even show that very low densities (10 plants per m^2 or less) result in higher grain yields per plant and per unit area. Observations like these raise a number of questions about the goals and cropping systems we're trying to achieve (dense stands that favor group performance at the expense of individual fitness, facilitate weed control, and limit the risks associated with planting, or sparse stands that favor individual fitness and vegetative growth?).

The issue of declining yields therefore requires a major research effort to identify the interactions between plant growth strategy and growth conditions. Despite the considerable scope for breeding progress that remains unexplored (Bajgain et al., 2022; DeHaan et al., 2005; Van Tassel et al., 2010; Van Tassel et al., 2020; Van Tassel et al., 2022), physiological trade-offs will be inevitable under limiting resource conditions, and these trade-offs will need to be arbitrated and discussed in the light of production and ecological objectives in the field.

3.4 Burning and thinning

Earlier studies with forage cultivars of IWG showed a positive effect of burning and thinning on seed production (Canode, 1965). Both mechanical (inter-row cultivation or tillage) and chemical (banded herbicide applications) practices have been studied in Kernza (Pinto et al., 2021; Law et al., 2021; Bergquist et al., 2022). Strip tillage in the fall increased grain yield by 61 % the following year compared to the control in an experiment in New York, due to an increase in the number of fertile tillers per area (Law et al., 2021), but spring strip-tillage did not affect grain yields. In another study in Minnesota, fall inter-row cultivation and spring band-applied herbicide did not affect grain yields in second and third years (Bergquist et al., 2022). In one experiment in Wisconsin, several post harvest management practices were tested, including burning, mowing, mechanical and chemical thinning. All practices increased light penetration on the canopy but they did not increase grain yield in the subsequent year (Pinto et al., 2021). Fall mechanical or chemical thinning reduced lodging and increased yield components per row, but not per area due to reduction in number of rows (Pinto et al., 2021). Thinning a stand and opening the canopy may increase weed competition. Another study in multiple sites in Wisconsin observed no differences in grain yields after spring thinning with herbicides (Shoenberger et al., in prep.). More research is needed to recommend optimal post-harvest management practices because results of various methods have so far been inconsistent. Better understanding of underlying mechanisms could allow for application of optimal renovation strategies in diverse environments.

4. Cropping systems

4.1 IWG in farming systems

To date, much of the research on Kernza IWG has focused on germplasm development, evaluating its environmental benefits, and refining agronomic management approaches for both grain and forage production. As such, little to no research has focused on how it fits within current farming systems or even within future cropping systems scenarios. Part of the challenge lies in that there are only a few farmers who have experienced Kernza cultivation, and Kernza production fields total less than three thousand hectares. Therefore, discussing the integration of IWG in regional and broader cropping systems context is a very fresh topic that requires further exploration and refinement. One effort to fill this knowledge gap is work being conducted by researchers within the USDA's Agricultural Research Service to evaluate how IWG fits within various crop production systems across various ecoregions and soil types of the US. As new fields and farmers bring new experiences that contribute to the design of new cropping systems and as new research findings emerge such as the work being done by USDA and elsewhere, systems-level recommendations on how to optimally integrate IWG within various crop production systems contexts will follow.

The implementation of IWG on farms requires the development of crop management in line with farmers' strategies and objectives within a given pedoclimatic and socioeconomic situation. Given the diversity of potential socio-technical scenarios on farms, there is no single, universally applicable solution, and farmers are key stakeholders in determining the extent to which the proposed IWG management can be considered generic. In fact, the introduction of IWG is derived from a set of decisions made by farmers associated with targeted goals and financial returns (Ginot et al., 2024). Surveys and interviews have underlined that improving the biophysical functionalities of fields were driving farmers' interests in perennial grains, with a major interest in enhancing soil structure and soil organic matter content (Adebiyi et al., 2016; Ginot et al., 2024; Lanker et al., 2020; Wayman et al., 2019). Further, farmers anticipated future climatic and legal constraints, especially regarding drought and pesticide usage in France, and saw IWG as a potential solution (Ginot et al., 2024). Economic profitability was then seen as a prerequisite for farm survival rather than a primary objective, and farmers further adopted a broad and farm-scale vision of profitability that included all direct and indirect benefits associated with IWG (Ginot et al., 2024). However, it should be noted that farmers testing IWG in the US and in France could be described as first adopters, so that they were also driven by their vision for agriculture's role in society, beyond food production (environment, education, art, etc.) and both their motivations and definition of profitability may not be widely representative.

Beyond a common interest in improving soil functioning, the multiplicity of agricultural products and expected services associated with IWG make the crop attractive in a variety of farming systems and pedoclimatic conditions. In France, three farm ideotypes described the links between existing farming systems, expected ecosystem services and IWG marketable products (Ginot et al., 2024). One represented organic grain farms targeting the production of human-consumed grains and focused on diversifying crop rotations and foodstuffs. A second type represented conventional grain farms, also focused on grain production but looking for a low-input crop for non-treatment and protected zones. In both cases, easy-to-manage and productive fields would be used for cash crops, while IWG, expected to be less demanding, was seen as a means to value marginal lands. A final type included farms that were primarily interested in producing forage, typically already had a hay outlet, and were particularly interested in drought tolerance, with grain as a possible secondary product. The decline in IWG grain yield over time suggests that the duration of IWG cultivation should not exceed 3 years, unless there is continuity of viable forage use and recovery, which this ideotype would provide.

Farmers' willingness to grow IWG was also a function of their ability to manage risks and uncertainties (Ginot et al., 2024). As a novel crop, much uncertainty surrounds this crop both on the production side (lack of references and experiences about agronomic management) and on the market and processing side, so that any farming system would need to tolerate this lack of information. Technical and economic certainties associated with grain storage, cleaning and processing were consistently discussed by farmers in the Midwest, US, revealing the embedding of farming systems into a broader regional socio-technical food system (Ginot & Schoenberger, personal communication Sept 10, 2024). Introducing IWG in farming systems necessitates strategic and tactical flexibility (Cowan et al., 2013), i.e. the ability to change outputs or the use of inputs to absorb variability, without changing the whole farm structure.

Farmers who had the clearer link from the strategic (long-term and the farm-level) to the tactical (daily, mid-term and field-level) decisions were those who had developed a specific strategy to deal with risks and uncertainties (Ginot et al., 2024). As Leeuwis (2003) explained, "farmers' decisions may involve perceptions about the consequences of practices in a large number of different domains, and are linked with an even higher number of perceptions regarding (un)certainty, likelihood and risk". Considering that farm behavior is not deterministic, uncertainty becomes a core element of the dynamics, and resilience a criteria for assessing system performance (Prost et al., 2023).

4.2 Crop rotation and management

Farmers' perspectives regarding date of IWG sowing and its place in rotations is variable and site-specific. In France, farmers proposed a variety of crops to precede IWG such as legumes (alfalfa, peas) for fixing N, winter cereals (wheat, barley, meslin; i.e. mix of grain crops for animal feed) because their cycle is compatible with early sowing in autumn and are major cash crops, or spring oil crops (sunflower, flax, rapeseed) because they are broadleaf crops so that it should be easier to control regrowth with herbicides (Ginot et al., 2024). These general considerations remain theoretical ideas and have not been tested due to the novelty of this crop on only a few farms. However, research from the US suggests that due to vernalization and growing degree day (GDD) requirements, the ideal time to plant Kernza IWG to maximize grain and biomass yield in its first year is between mid-August and early September in northern latitudes (Jungers et al., 2022). This typically limits preceding crop selection to early-maturing or winter cereal such as oats, winter wheat, or other crops that can be harvested or terminated by late summer. What remains clear is that a large number of creative possibilities remain to be explored, including seeding under cover or in mixtures and innovative establishment methods in a standing cash crop, etc.

Though IWG's many benefits stem from its perennial nature and deep root system, grain yield declines, low yields, and other uncertainties may necessitate a reevaluation of how practitioners and researchers think about IWG in a cropping systems context. While researchers continue to advance the science, a shorter-term approach that may facilitate greater integration of IWG would be to fit it within a crop rotation much like systems that include three to four years of an alfalfa phase. Understanding optimal rotations, i.e., which crops should follow IWG to maximize total dry matter and grain production, optimal perennial phase duration, and termination methods to preserve the benefits accrued during the IWG phase, are areas of research that remain under-explored. From work conducted in the US on integrating IWG and other perennials in an annual crop production system, 4- and 5-yr stands of an IWG-alfalfa mixture resulted in both near-surface soil benefits as well as yield benefits to the subsequent cash crop (spring wheat), with yield benefits persisting for 5 yr following conversion from perennial to annual (Franco et al., 2018; Liebig et al., 2018). Research in Wisconsin, USA and Sweden showed that tillage and herbicides can effectively terminate IWG, but repeated mowing is not enough (Olugbenle et al., in prep.) Ongoing research in Wisconsin, USA is evaluating IWG termination methods, i.e., interactions between tillage and chemical termination, for their impacts on subsequent silage corn production and preservation of soil benefits. However, much more research is needed to evaluate a number of other cash crops following IWG under varying climates, soils, and termination methods for optimal outcomes.

Additionally, prototyping of IWG crop management by pioneer farmers has focused mainly on sowing methods, fertilization and weed management (Ginot et al., 2024). Sowing was seen as the most critical operation for IWG success, for the establishment year and later on. Although the prototypes may differ widely, Ginot et al. (2024) summarized the underlying rationales for the choice of crop management practices. One rationale concerned grain cropping based on external inputs (fertilization, weeding) which mostly aims at using or adapting practices commonly used for managing winter cereal in conventional or organic systems. Another rationale concerns grain cropping based on ecosystem services to manage crop nutrition, protection and weeding. Diversification and intercropping practices are then importantly used. A final rationale concerns crop management choices aimed at reducing workload. Interestingly, the farm system limits the type of crop management rationale that could be applied, but does not strictly determine it. This may open up a variety of possibilities for each farmer to integrate IWG into their existing cropping system.

4.3 Intercropping

Intercropping IWG with legumes can provide multiple benefits to farmers. Legumes have the ability to fix N from the atmosphere through their association with N-fixing bacteria. While legumes can compete with IWG for other resources (such as water, light, other nutrients), they generally are good companions, improving overall cropping system performance. Little is known about growing legumes with IWG from on-farm data or experiences but several legume species were tested in field experiments.

Most studies have included alfalfa or red clover intercropped with IWG (Dick et al., 2018; Favre et al., 2019; Mårtensson et al., 2022; Pinto et al., 2024; Reilly et al., 2022b; Tautges et al., 2018), but other legumes such as Kura clover (*Trifolium ambiguum* M.Bieb), Berseem clover (*Trifolium alexandrinum* L.), sweet clover (*Melilotus officinalis* L.), and white clover (*Trifolium repens* L.) have also been tested (Dick et al., 2018; Pinto et al., 2024; Reilly et al., 2022b).

Legume intercropping effects on IWG grain yields are variable, showing both higher and lower grain yields than IWG monoculture. This variability is largely influenced by the IWG stand age and the legume biomass production. In the first grain production year, which is typically the year with the highest grain yield, intercropping with legumes usually does not affect grain yield (Dick et al., 2018; Law et al., 2022b; Pinto et al., 2024; Reilly et al., 2022b). In the second year, intercropped systems often have lower grain yields than IWG monocultures, particularly when legume forage biomass is high (Pinto et al., 2024; Reilly et al., 2022b). However, the proportion of revenue coming from Kernza grain decreases after the first year and lower grain yields could be compensated with higher total harvested forage added by legumes (Law et al., 2022a; Pinto et al., 2022). In the third year, legume intercropping may have higher grain yields than IWG monocultures, as seen with red clover (Reilly et al., 2022b) and alfalfa (Pinto et al., 2024). This is likely due to N provided by legumes in the first year, which can take two or more years to cycle through legume tissues, soil microbes, and other organic matter before being assimilated and detectable in IWG tissues (Reilly et al., 2022b).

Regardless of the effect on grain yield, intercropping is often a profitable opportunity for farmers due to increases in total forage yield and its enhanced nutritional value (Favre et al., 2019; Law et al., 2022a; Pinto et al., 2022). For example, intercropping IWG with red clover has tripled the amount of available forage in the fall, positively affecting the revenue perceived by the farmers (Favre et al., 2019). In fact, it has been seen that higher forage yields achieved by IWG-legume intercropping systems reduce the Kernza grain price required to be profitable (Law et al., 2022a). The nutritional value of the total forage harvested is also enhanced when legumes are intercropped with IWG. Different intercropping systems, depending on legume species, can improve the crude protein and relative feed value of the forage compared to IWG monoculture (Favre et al., 2019; Pinto et al., 2022). These increases in nutritional quality have positive implications for hay quality, leading to higher prices per kilogram of forage (Pinto et al., 2022). For instance, the summer forage from IWG monoculture was classified as "fair," while intercrops with red clover and alfalfa were rated "premium" or "grade 3 – 4" hay, demonstrating superior forage quality when legumes were planted together with IWG in the spring.

5. Establishment

5.1 Site selection and seedbed preparation

Experiments on IWG have been conducted on a broad range of soil types with varying degrees of drainage. IWG is well adapted to arid conditions and can persist relatively well in conditions with limited soil moisture including coarse structured soils. In two multi-site studies, one with five sites in Minnesota and another with six sites across the US, IWG biomass and grain yields were not especially sensitive to soil type. In Minnesota, yields were similar among loams ranging in silt and clay content (Jungers et al., 2017). Across the US, sand and organic matter content did vary across the six sites but weather variables contributed more to yield variability than compared with soil variables (Cassani et al., in revision).

Poor soil drainage can have reduced IWG yields. Black et al. (2024) compared IWG productivity on a hillslope vs. a depositional landscape on the same soil type at two locations and found that biomass yields 64 % and 174 % greater on the hillslope. High soil water content likely limited IWG growth in the depositional areas despite that landscape having greater soil available N than the hillslope.

Crop choice preceding IWG seedings can affect establishment success. Since IWG requires vernalization (Jungers et al., 2022; Locatelli et al., 2022), many producers opt to seed in late summer or early autumn to generate grain yield in the first summer. Crops that reach physiological maturity before the optimal IWG seeding date are best suited to precede IWG when a fall establishment is targeted. Winter small grains typically mature well before IWG seeding dates, yet volunteers can compete with IWG seedlings in the fall and the following spring. Establishing IWG after small grain species that are susceptible to winterkill reduces risks of spring competition with volunteers. To limit risks of soil pathogen buildup from the production of consecutive grass species in a rotation, IWG can be established following legume forages or pulse crops, both of which can offer N credits to subsequent grain crops (Miller et al., 2015). In regions with insufficient fall precipitation to ensure successful fall IWG establishment, spring planting with and without companion crops has been successful (Ehlke et al., 2024).

Seedbed preparation can affect IWG establishment. As with most relatively small-seeded perennial grasses, successful establishment requires that seeds be sown to promote soil-seed contact in a seedbed with minimal weed pressure. Studies on the effects of seedbed preparation on IWG have been conducted using forage varieties, and it's expected that these results would hold true for modern grain-type varieties despite known differences in seed size (Bajgain et al., 2020). King et al. (1989) found that light tillage with a disc improved IWG establishment compared to a no-till approach following a winter rye cover crop. Planting a nurse crop oat that was chemically terminated immediately prior to IWG seeding in spring led to the highest plant population, likely due to weed suppression of the oat crop in early spring. Since IWG seed production is influenced by row spacing, establishment by sowing seeds with a drill is preferred over broadcast seeding. A drill is more effective at placing seeds below the soil surface but shallow enough for successful emergence. A seeding depth between 1.9 and 2.5 cm resulted in the highest establishment rate and seedling biomass when tested in three soil types (Donelan, 2020).

5.2 Seeding dates

Intermediate wheatgrass requires vernalization and day length requirements for reproductive induction (Duchene et al., 2021a). Seeding in late summer allows seedlings to experience the vernalization requirements, which have been reported as 5 C for at least 7 weeks to maximize plant heading (Locatelli et al., 2022). Although the number and size of vegetative tillers prior to vernalization can influence induction for many cool-season grasses (Chastain and Young, 1998), these variables have not been quantified for intermediate wheatgrass. However, plants reaching at least the three-leaf stage respond to vernalization and day length. In a modeling study using field data from sites spanning nearly 12 degrees of latitude, researchers determined that a secondary induction phase of at least 13 to 14 h of daylength maximized intermediate wheatgrass seed yield (Duchene et al., 2021a).

Induction conditions for intermediate wheatgrass based on greenhouse and modeling studies have been verified in field trials (Jungers et al., 2022; Olugbenle et al., 2021). Because of its vernalization requirements, growers in regions with ample fall precipitation prefer to plant in late summer or early fall to ensure grain production the following year. A multi-site fall seeding date study spanning 10 degrees of latitude confirmed the vernalization requirements and found that sowing seeds early enough to accumulate about 900 GDDs prior to the first killing freeze maximized grain yields the following year (Jungers et al., 2022). A field study in Wisconsin, USA also found that seeds yields were greatest in stands established earlier (late August) compared to those closer to the first killing freeze, and that seeding date did not affect grain yields in the second year of grain production (Olugbenle et al., 2021).

5.3 Plant population

As a small seeded species with individuals that can produce many tillers and can expand rhizomatously, it is difficult to quantify the population of an IWG stand based on the number of seeds planted per unit area or by counting individual plants per unit area. The wide range of row spacing used in IWG grain production systems also complicates the quantification of plant population using standard agronomic measures like plants per unit area. Moreover, the plant population can change as stands age - via recruitment from shattered seed and from rhizomatous spread - and this rate of change can vary substantially by weather, soil type, and other management factors, so recommendations of targeted plant populations at establishment may not result in similar production outcomes through time or across sites. However, some studies have been conducted to determine the effects of within-row and between-row plant density on IWG yields, yield components, and weed suppression.

The relatively small and variable seed size of IWG (e.g., thousand kernel weights ranging from 5.6–8.5 for advanced breeding lines) (Bajgain et al., 2020) requires that producers strive to set seeding rates based on seed mass per unit area rather than a targeted plant population. However, the few studies that have investigated the effects of seeding rates on IWG productivity have presented their seeding rates as seeds m^{-2}. Fernandez et al. (2020) found that grain yields were higher in year one in stands seeded at 145 seeds m^{-2} compared to those at 36 seeds m^{-2}. IWG recruitment via tillers and rhizomes in subsequent years led to diminishing effects of seeding rates on grain yields. The higher seeding rate had a greater propensity to lodge during the first two years of the study, presumably due to increased competition for light in more dense environments. Similarly, Newell et al. (2024) reported that IWG grain yield did not vary among three seeding rates (50, 100, and 200 plants m^{-2}). It should be noted that seed size decreased with increasing plant population, but this effect did not manifest into grain yield per area reductions.

Altering the spacing between seeded rows is another method to influence the IWG plant population. Narrow rows (e.g., 15–24 cm) can allow for higher plant populations and thus a potential for higher grain yields. However, reducing the space between rows can increase intraspecific competition for water, light, and other resources, which can have detrimental effects on seed production per plant. These positive and negative effects can offset one another and lead to a grain yield plateau and diminishing returns with increasing plant population. Hunter et al. (2020) found that, averaged over four years, row spacings of 30 or 61 cm yielded more grain than 15 cm. Increasing the space between rows resulted in a greater number of tillers per m of row. The wide row treatments also had more grains per spike, especially in the first two years of the study, which contributed to the variation in yield across treatments. In a study in Wisconsin, USA, researchers did not observe any differences in IWG grain or biomass yields in stands seeded with 38 or 57 cm between rows over two years (Pinto et al., 2022). The study also found that weed biomass was the same in both row spacing treatments in the first year, but weed biomass was greater in the wider row spacing in year two. There are concerns that wide rows will promote weed populations by allowing greater access to space and light; however, wide rows can be advantageous in that producers have more options for mechanical weed control. Further research is needed to evaluate the interaction between plant density and row spacing in IWG, and the respective effect on yields at the stand and individual plant level.

5.4 Weed management

The perennial growth habit of IWG presents both advantages and challenges for weed control. IWG is especially susceptible to competition from annual weeds during the seedling stage. Compared to other perennial forage grasses, IWG can be considered to have an aggressive relative establishment rating (Cattani and Asselin, 2022), but rather low compared to annual weeds and annual grain crops. The relatively slow aboveground dry matter accumulation in the first few weeks after seedling emergence increases the vulnerability of IWG to competition from annual weeds. In fall seeded stands, early competition at the seedling stage can reduce overwintering biomass and thus spring regrowth vigor, which can further result in productivity impacts by weeds. However, well-established IWG after the first full production year is usually competitive with annual weeds. Zimbric et al. (2020) found that weeds decreased 88 % over three years of production. Farmer observations indicate that weeds are more easily managed in the western, drier, climatic regions, particularly after the establishment year. However, coordinated regional studies to examine climatic impacts on weeds have not been conducted.

Commercial interest in IWG grain has been driven by the crop's positive sustainability attributes, thus it is no surprise that markets for certified organic production have been stronger than conventional markets. Research has been conducted to determine the best management practices for managing weeds in organic and conventional IWG grain production systems. Organic producers rely on cultural and mechanical methods to manage weeds. Mowing biomass when IWG is at a vegetative stage can set back annual weeds. This practice could be especially effective if applied in the spring when annual weed growth is greatest and the IWG biomass can be harvested and used as forage. Zimbric et al. (2020) found that mowing in spring, fall, or both spring and fall had no effect on weed biomass after three years of production, while Bergquist et al. (2022) saw an increase in weed biomass in stands mowed in the spring compared to unmowed controls. Differences in weed community species composition and climatic variability likely underlie the variation observed across studies. Bergquist et al. (2022) also found that a fall burning reduced weeds relative to the control, but this practice is not likely to be implemented widely for logistical challenges and concerns with air quality and carbon emissions. Researchers have measured shifts in weed species community composition in IWG. Duchene et al. (2023) measured a reduction in weed species richness through time and a shift from annual broadleaves to perennial grasses, a compositional shift that was also observed by Law et al. (2021).

Although increases in plant species diversity have been shown to suppress weeds in perennial pastures, (Tracy and Sanderson, 2004) researchers have not seen consistent weed suppression benefits from intercropping legumes with IWG for grain production. Dick et al. (2018) did not see any differences in weed biomass in IWG stands grown in monoculture or as bicultures with three different species in Manitoba, Canada over two years. In another two-year study, Pinto et al. (2022) observed similar weed biomass in IWG monocultures and four different legume/IWG bicultures in the first year. In the second year, two bicultures (IWG + Kura clover and IWG + red clover) had lower weed biomass than the IWG monoculture and two other legume bicultures. Law et al. (2021) also found that IWG + red clover reduced weed abundance relative to IWG monocultures. In a multi-site, multi-year trial in Minnesota, two out of three sites showed similar weed biomass among IWG monocultures and five legume/IWG biculture treatments (Reilly et al., 2022b). The third site which had significant variation in weed biomass among treatments showed that one legume intercrop species – birdsfoot trefoil (*Lotus corniculatus* L.) increased weed biomass compared with the control and other treatments, including fertilized monocultures.

Herbicide efficacy and crop safety trials on IWG have been underway to register these products for use on IWG grain production. Shoenberger et al. (2023) measured IWG injury in response to various rates and application timings of three unique Group 4 herbicides over multiple years in four states. The results were used to support potential manufacturer labeling of 2,4-D amine, clopyralid, and MCPA products for use on IWG. Studies are ongoing to evaluate crop safety of groups 1, 2, 3, and 15 herbicides for both pre- and post-emergent control of grass and broadleaf weeds.

6. Disease management

6.1 Diseases limiting grain yield

Kernza has relatively low disease levels compared to typical annual small grains, including wheat and barley. The only diseases currently that have had a measurable negative affect on grain yield are those that occur on the heads of the plants. Lower yields occur when crops are heavily infected by *Fusarium* head blight (Fig. 1) and glume blotch (Treffer et al., in preparation). The most reliable way to avoid toxin production is by growing the crop in drier environments. In the USA, the preferred environments are the Central Plains or Intermountain West; wetter regions of the Upper Midwest, East and West Coasts have had levels of toxins in grain that exceed USA Food and Drug Administration (FDA) safety recommendations. Resistant varieties may reduce toxins to some extent, but a substantial breeding investment may be necessary to eliminate risk of loss in grain value in wet environments. If intermediate wheatgrass is grown in wet regions, extensive research and regulatory approval may be needed to include Kernza on fungicide labels. In research conducted at TLI over multiple years, planting *Fusarium*-infected seed did not result in higher disease or toxin levels in the next crop (Turner, unpublished data). Avoiding harvesting heavily lodged sections of the field can reduce mycotoxins produced by *Fusarium* due to higher toxin levels in lodged plants compared to either standing or swathed plants (Fig. 2). Increasing air flow during harvest or cleaning to remove lighter kernels can also help reduce the presence of *Fusarium* head blight and color or gravity sorting to remove visibly infected kernels due to ergot and *Fusarium* head blight. In cereals, grasses, and forage crops, ergot is caused by multiple fungal

Fig. 1 (A) Bleached spikelets on intermediate wheatgrass spike; (B) pinkish (circled) and grey intermediate wheatgrass seeds infected with *Fusarium* head blight.

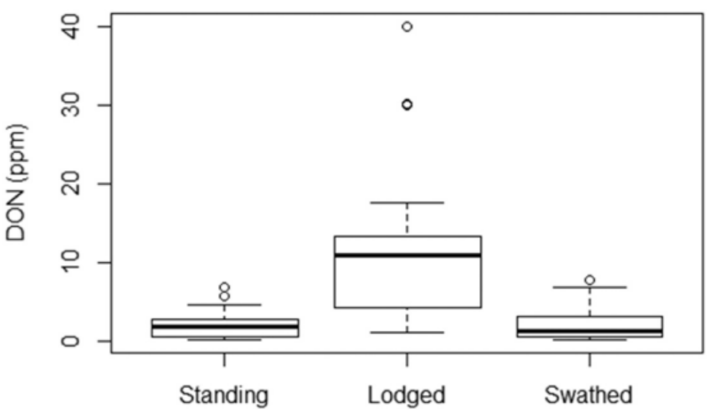


Fig. 2 DON toxin in standing, lodged, and swathed stalks of TLI Cycle 7 intermediate wheatgrass plants.

species of the genus *Claviceps* (Bajgain et al., 2022). Avoiding harvesting the margins of the field, particularly on the windward side, where low pollination can result in higher ergot levels, is advisable when ergot bodies are observed (Fig. 3).

6.2 Diseases limiting biomass production

Intermediate wheatgrass is not well suited for waterlogged areas which can cause mortality. Yellow stunted plants are commonly infected by *Colletotricum sp.*

Fig. 3 (A) Intermediate wheatgrass spike with ergot body (circled); (B) actively sporulating ergot body; (C) mixed intermediate wheatgrass healthy brown seeds with dark purple-black ergot bodies.

described as anthracnose disease (Fig. 4). Patches of infection spread to the broader field and typically remain infected and stunted in subsequent years, with limited biomass and head production. Treatment with fungicide or removal of stand and replanting may be necessary to restore productivity, but little research has been conducted on management approaches for anthracnose in intermediate wheatgrass. In greenhouse conditions, intermediate wheatgrass seedling growth can be severely affected by infection from *Pythium* species. Research on anthracnose and other root and crown diseases is one of top priorities for disease management in Kernza.

6.3 Minor diseases

Viral diseases are rare in IWG and occur at low incidence. IWG is occasionally infected with barley yellow dwarf virus, brome mosaic virus, and asymptomatically with wheat streak mosaic virus. Currently, viral diseases are

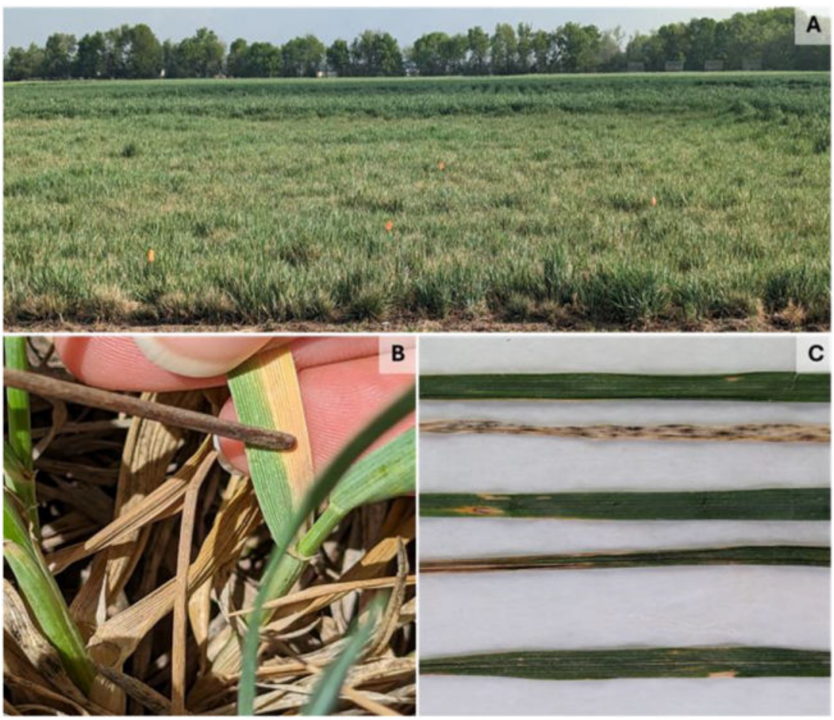


Fig. 4 (A) Yellow-brown patches of a stunted intermediate wheatgrass stand infected with a *Colletotricum* sp.; (B) yellow-brown wheatgrass leaf blade with dead lower leaves due to *Colletotricum* infection; (C) black leaf spots on wheatgrass leaves infected with *Colletotricum*.

so insignificant that they are not considered when developing management strategies. Nematodes species, including the widespread *Pratylenchus neglectus* and the newly described *Pratylenchus smokii,* can colonize IWG, but total counts recorded have been lower than in annual wheat or corn (Fig. 5). Similarly, many leaf-spotting fungal and bacterial diseases are frequently present on the lower leaves of IWG, but are not associated with a yield penalty in the grain and are therefore not currently a target for breeding or management research. These minor fungal and bacterial diseases include: bacterial leaf streak caused by *Xanthomonas translucens pv. undulosa* (Xtu) – the same pathogen that commonly causes BLS of wheat (Bajgain et al., 2022; Curland et al., 2020), spot blotch caused by *Bipolaris sokoriana* (Sacc.) Shoemaker (telomorph: *Cochliobolus sativus* Ito & Kurib), tan spot caused by *Pyrenophora tritici repentis* (Died.) Drechs., and Septoria blotch caused by *Septoria tritici* and *Leptosphaerina nodorum* E. Miiller (Berdahl and Krupinsky, 1987; Farr and Bills, 1989). In a long-term trial with IWG plots maintained for 9 years, burning the plots in early spring before regrowth significantly reduced bacterial leaf streak and spot blotch; plots planted with narrow (30.5 cm) rows had intermediate levels of disease compared to wide (61 cm) rows for bacterial leaf streak and spot blotch (Fig. 6), indicating that burning and possibly narrower rows can reduce foliar diseases as one option for disease control if these diseases need to be more closely managed in the future. Plots that were older generally have less BLS and spot blotch than

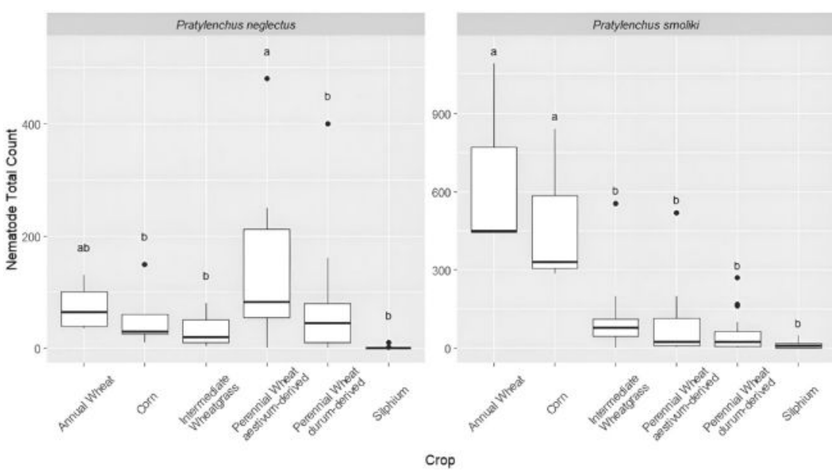


Fig. 5 Total number of nematode species *P. neglectus* and *P. smokii* colonizing IWG, compared to other annual and perennial seed crops. Letters designate significant differences ($p < 0.05$) determined with a Tukey HSD test for mean separation.

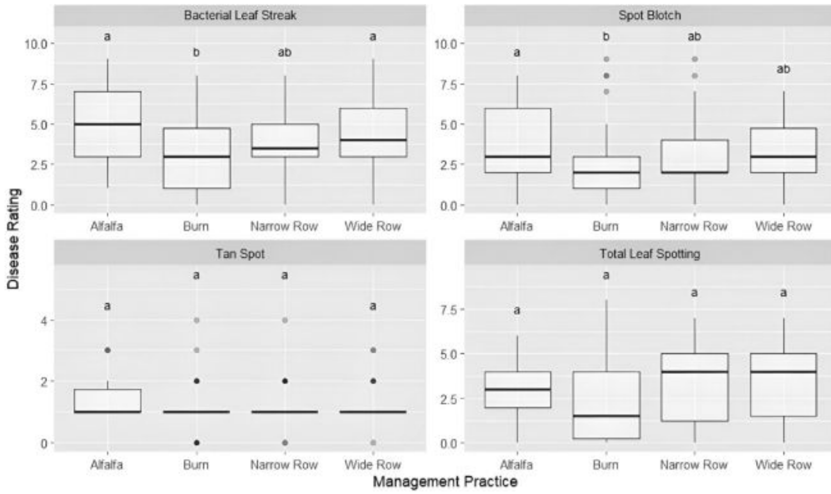


Fig. 6 Disease severity of bacterial leaf streak, spot blotch, tan spot, and a composite of total leaf disease-related leaf spotting in long-term IWG plantings with different management practices. Letters designate significant differences ($p < 0.05$) determined with a Tukey HSD test for mean separation.

newer fields (Fig. 7). While severity of foliar diseases decreases over time, likely due to lower contact with soil as the stand matures and thickens, it is expected that root or crown diseases could increase.

7. Soil nutrient management

7.1 Nitrogen

Integrated nutrient management of IWG is important to achieving target yields while preserving soil health. While IWG is valued for its deep root systems and low input requirements, nutritional requirements need to be met to optimize IWG grain yields. Although research on fertilizer rates specific to IWG is still limited, several studies have revealed differences compared to most annual cash crops, which typically show a saturation response to fertilizer application. Whether because the crop's nutrient requirements are met, or because another yield limitation exists, beyond a certain point, additional fertilizer application does not increase yield. In contrast, IWG seems to have an optimal nitrogen (N) fertilizer which is lower than that typically observed for other crops, with higher rates causing a yield reduction (Fagnant et al., 2023; Jungers et al., 2017). There are two

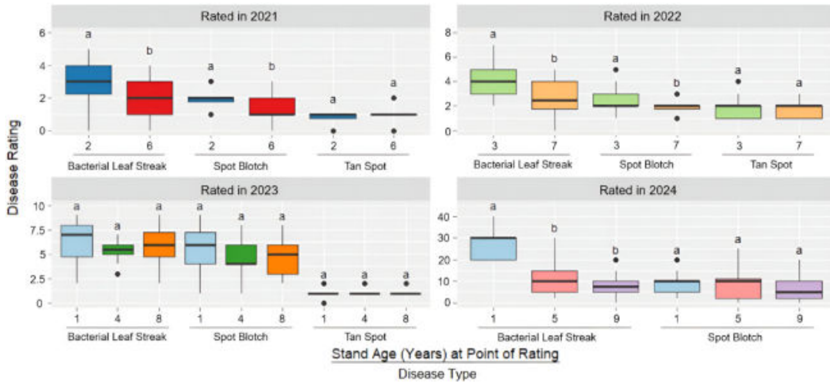


Fig. 7 Disease severity of bacterial leaf streak, spot blotch, tan spot, and a composite of total leaf disease-related leaf spotting in long-term IWG plantings of different ages. Letters designate significant differences ($p < 0.05$) determined with a Tukey HSD test for mean separation.

possible explanations for the decrease in IWG yield at higher N fertilization rates: increased lodging which makes a large proportion of the IWG spikes difficult to harvest (Jungers et al., 2017; Tautges et al., 2023) and decreased tiller fertility (Fagnant et al., 2024b).

Recommended N fertilization rates have been established at 90 kg N ha^{-1} in Minnesota, USA, (Fagnant et al., 2023; Jungers et al., 2017; Tautges et al., 2023) but fertilizer effects on IWG yields (grain or forage) vary by location and stand age (Bowden, 2023; Pinto et al., 2024; Pugliese et al., 2019; Reilly et al., 2022b). In the first grain production year, IWG often does not respond to N fertilizer (Cassani et al., under review, Bianchin Rebesquini et al., under review), but changes in tissue C:N ratios over time suggest that N may limit grain yield in older IWG stands (Crews et al., 2022; Reilly et al., 2022b). In fact, N fertilization has helped mitigate IWG grain yield decline in older stands (Fernandez et al., 2020; Jungers et al., 2017; Tautges et al., 2018), although this has not always been the case in other environments (Pinto et al., 2024). Nitrogen applications are commonly made in winter or early spring, but it may also be beneficial to split them in the fall to promote tillering and tiller size before the winter period (Fagnant et al., 2024a).

7.2 Phosphorus and potassium

The roles of phosphorus (P) and potassium (K) fertility on IWG grain yields has been less explored (Cassani et al., in revision) than N. For seed production, growers have been advised to apply 50 kg ha^{-1} P_2O_5 and/or K_2O prior to planting in dryland fields if P and/or K are deficient in soil testing (Kruger, 2015) In other perennial grasses, P and K fertilization has increased forage yield when applied combined or separately (Frank and Guertal, 2015), but the effect of these nutrients on seed production is limited and inconsistent. For example, in older stands of tall fescue (*Festuca arundinacea* Schreb) both positive effects on grain production (Wheeler and Hill, 1957) and absence of response to P fertilization (Read and Hipp, 1998) have been found. In the first grain production year, IWG seems not limited by P or K, as is often the case with nitrogen. In a study across six locations in the Midwestern USA, no differences were found between fertilization with 90 kg of N ha^{-1} in the spring, 56 kg of P ha^{-1} in the fall and 168 kg of K ha^{-1} in the fall (control) and the absence of P or K (NK or NP) (Cassani et al., under review). Responsiveness of modern Kernza cultivars to mycorrhizal inoculation may help to explain low response to P fertilization (McKenna et al., 2024). The initial P and K contents of the studied locations ranged from 20 to 64 ppm of P ha^{-1} and 91 to 403 ppm of K ha^{-1} (Cassani et al., in revision). In older stands, as with N, K could begin to be limiting. Particularly, when IWG is used as a dual purpose crop, P and K exports from the system within grain and forage may be high, requiring replacement fertilization to maintain soil fertility.

8. Harvest

8.1 Grain harvest

The timing of IWG grain harvest can influence grain yield. Studies documenting IWG growth, development and yield formation have been conducted and can be used to inform the timing of grain harvest. Barriball et al. (2022) and Jungers et al. (2018) recorded IWG development over multiple growing seasons in Kansas and Minnesota, USA, respectively, and produced equations to predict when anthesis would occur based on the accumulation of growing degree days. In three states, researchers tracked grain development and yield components through time (Heineck et al., 2022). Importantly, this study reported moisture loss and grain fill as a function of cumulative GDD after anthesis, which provides growers a benchmark for determining optimum harvest timing. Results indicated that IWG grain yield per spike was maximized between 550 and 750 GDDs (base temperature 0 °C) after anthesis. This estimate accounted for yield penalties associated with incomplete seed fill and dry matter (harvesting too early) and those associated with shattering (harvesting too late). Since IWG seeds partially retain their hulls during harvest, harvesting too early will result in high moisture grain that can promote microbial growth on the grain and hulls. Harvesting early can also lead to a reduced grain size and therefore lower yields. End-users struggle to process the relatively small grains of IWG; thus, reducing them further as a result of early harvest could impact food use applications. Harvesting too late will result in yield loss due to shattering.

Harvesting IWG grain early enough to prevent shattering can result in grain with high moisture (Heineck et al., 2022). Swathing can expedite grain drying but also increases the risk for microbial contamination and subsequent grain quality degradation. Alternatively, grain can be left to dry within the inflorescence of standing plants and later harvested directly with a grain combine. The moisture content of IWG vegetative tissues at physiological maturity is greater than most annual small grains, and direct cutting can also collect green biomass from living weeds. Therefore, direct harvest without swathing can result in damp foreign material collected with the grain, increasing risk of heating and spoilage if the harvested grain is not immediately aerated until an even moisture content of less than 13%. However, a precise determination of the critical moisture content has not yet been conducted.

8.2 Straw harvest and residue management

At physiological maturity of the seed, the stage necessary for grain harvest, IWG vegetative biomass yields can exceed 12 Mg ha^{-1} (Franco et al., 2021). Leaving the vegetative biomass in the field can smother crowns and limit fall regrowth, which can lead to variability and reductions in grain yields in subsequent years (Culman et al., 2023). The vegetative residue that remains after grain harvest has value as forage (see section 10 for details) or as biofuel feedstock. A study in Minnesota, USA reported land ethanol yields around 4000 liters ha^{-1} from IWG stands ranging in stand age (Jungers et al., 2017). Chopping and distributing residue is a possible practice to retain nutrients and return them to the soil, but studies have not confirmed the effectiveness of this approach with IWG. Burning residue is another option to remove it to facilitate strong regrowth, but can result in volatilization of N and long-term decreases in soil N (Rasmussen and Parton, 1994). Effects of post-harvest burning on subsequent grain yields have been mixed, with some reports showing no significant impact compared to mechanical residue removal (Bergquist et al., 2022) while others have found that, when imposed shortly after grain harvest, burning can significantly increase grain yields the following year (Ehlke et al., 2024). More research is needed to understand the effect of burning on grain production and its environmental consequences.

9. Forage utilization and post-harvest management

9.1 Forage yields

Kernza intermediate wheatgrass is a dual-use crop that can be harvested for forage and grain. In terms of forage production, vegetation reaches heights of up to 180 cm at grain maturity in summer and an average of 5–6 tons of dry matter per ha can be harvested in addition to grain across the US Midwest (Culman et al., 2023; Zimbric et al., 2021). First year Kernza summer forage ranges from 3 to 11 tons of dry matter (DM) ha^{-1}, while older stands range from 2 to 17 tons of DM ha^{-1} across US locations (Franco et al., 2021). If resource availability permits, forage production can exceed 10 tons DM ha^{-1} in dense, vigorous stands (Culman et al., 2023). One or two additional forage harvests may be possible in the fall, or in early spring prior to stem elongation. Depending on growing conditions, these harvests can add 1–2 tons DM ha^{-1} each, ranging from 0.5 to 4 tons ha^{-1} (Culman et al., 2023; Franco et al., 2021). Fall forage harvests can increase the next season's grain productivity, while early spring forage harvests are likely to decrease it (Culman et al., 2023). In more temperate climates, like Uruguay, forage yields in first summer were 10–12 tons DM ha^{-1} in the first year, followed by 2 ton DM ha^{-1} in the fall, and another 1 ton DM ha^{-1} in the winter, with 4–6 ton DM ha^{-1} in the second year (Locatelli et al., 2022).

9.2 Forage quality

The forage quality of IWG is directly related to the phenological development of the crop (Fagnant et al., 2024a; Favre et al., 2019). IWG forage is generally less nutritious than common forage grasses such as *Dactylis glomerata, Lolium perenne, or Festuca pratensis* for equivalent phenological stages (Fagnant et al., 2024a), and like other species it has the best nutritional quality when harvested during the vegetative phase (Fagnant et al., 2024a; Favre et al., 2019). As the quantity of forage increases due to stem elongation, forage quality decreases until it is fibrous and low quality at summer grain harvest. Nevertheless, this forage can be a valuable resource, increasing the forage autonomy of livestock farms in summer, and feeding herds in a non-productive phase, such as dry cows or juvenile animals (Favre et al., 2019).

In a study across multiple sites in North America, forage nutritive parameters were evaluated for spring, summer, and fall forage harvests (Culman et al., 2023). Spring forage was high quality with Crude Protein (CP) ranging from 15 to 21 %, NDF ranging from 51 to 56 %, and ADF ranging from 26 to 29 %, resulting in Relative Feed Values (RFV) of 112 to 127. The summer forage was lower quality, with CP of 4–5 %, NDF 67–70 %, and ADF 38–42 %, resulting in RFV of 75 to 84. Fall forage had CP of 12–15 %, NDF 57 %, ADF 31 %, and RFV 105 (Culman et al., 2023). In Uruguay, forage quality had similar values to those of North America for summer and fall, while winter forage had 20 % CP, 56 % NDF, 30 % ADF, and a RFV of 108 (Locatelli et al., 2022).

The digestibility of the fiber (NDFD) at 48 and 240 h of incubation and total tract NDFD (TTNDFD) was reported by Favre et al. (2019). In the spring, NDFD48 was 63 %, NDFD240 was 88 %, and TTDNFD was 53 %; summer forage values were 35 %, 56 %, and 41 % respectively, and for fall forage values were 48 %, 69 %, and 40 % respectively. Fiber digestibility was lower than for other cool season grasses. However, TTNDFD is a more relevant indicator of the fiber digestibility and it was similar to what has been observed for other cool-season grasses and ruminant forages in the Upper Midwest USA, and much higher than wheat straw (Favre et al., 2019). IWG forage nutritive value is low in summer but could replace straw in high-starch dairy diets to maintain proper rumen function (Favre et al., 2019). Both spring and fall-harvested IWG forage have high nutritive value and are suitable for lactating beef cows, dairy cows, and growing heifers (Franco et al., 2021, Favre et al., 2019).

Forage quality of vegetative Kernza forage in the first summer (when seeed in the spring) has been reported as 17 % CP, 55 % NDF, 30 % ADF, and 111 RFV in Wisconsin (Pinto et al., 2022). Forage quality of Kernza intercropped with legumes can be superior to sole cropping, as described in Section 4.3 (Pinto et al., 2022).

In central Sweden, Kernza intermediate wheatgrass forage was harvested during summer over 4 dates, from stem elongation until full heading (Nadeau and Picasso, 2023): crude protein decreased from 14 % to 6 % of DM, in vitro OM digestibility decreased from 87 % to 66 %, NDF increased from 55 % to 71 %, ADF increased from 29 % to 44 %, and water soluble carbohydrates decreased from 26 % to 15 % of DM. In Canada, stockpiled Kernza intermediate wheatgrass in December had 12 % CP, 51 % NDF, 26 % ADF, and TDN of 70 %, with RFV of 124, suggesting high potential for dual use (Cattani and Asselin, 2017).

9.3 Livestock utilization

Kernza straw can be mechanically harvested and baled after grain harvest to use as forage for beef cows and dairy heifers which require low-energy and high-fiber diets. Minimal information on performance of animals fed Kernza straw is available. Two experiments evaluated the performance of beef cows and dairy heifers fed Kernza straw in Wisconsin, USA (Pizarro et al., 2024). In the first experiment, Angus cows were fed two diets: 100 % grass-alfalfa haylage, and 50 % IWG straw – 50 % grass-alfalfa haylage over two years. IWG straw reduced dry matter intake and average daily gain of beef cows when included as 50 % of their diet. However, cows fed IWG straw maintained their body condition without impacting calf birth and weaning weights (Pizarro et al., in review). In a second experiment, pregnant Holstein heifers were fed three diets containing either 0 %, 20 %, or 40 % of IWG straw. Inclusion of IWG straw reduced dry matter intake of dairy heifers by 10 %. However, heifers maintained their body condition, with average daily gains of 1 kg d^{-1}, considered in the optimal range for replacement dairy heifers (Pizarro et al., in review).

Intermediate wheatgrass forage in dual-use systems can be grazed by livestock. A three-year experiment in Minnesota and Wisconsin, USA compared spring, fall, and both spring and fall grazing over an ungrazed control (Pinto et al., in prep). In the first grain production year, spring grazing reduced Kernza grain yield compared with ungrazed stands. However, fall grazing improved the total annual forage yield and did not affect grain yield in the following year. Legume intercropping increased total annual forage yield but did not affect Kernza grain yield.

10. Development of food and beverage products

10.1 Changes in grain with domestication

From the 1980s when the domestication of Kernza began, it has gone through more than a dozen breeding cycles. Within each breeding cycle, plants with the best traits such as yield, seed size, shattering, and threshability were selected for the next cycle. As these breeding cycles proceeded, the size of the seeds increased (Bharathi et al., 2022). This increase in seed size meant that the proportion of major components in the seeds such as carbohydrates and proteins would be affected. From the some of the earliest forage variety such as Manifest to the first widely grown grain type (TLI-Cycle 5) when analyzed by (Hayek, 2020) and (Luu, 2020), we see an increase in ash, fat and total carbohydrate contents with a decrease in protein content. It was also observed that the content of starch has increased, while total, insoluble and soluble dietary fiber has decreased as the breeding progresses. A significant increase in carotenoid contents (lutein and zeaxanthin) analyzed by Oahe, Beefmaker, Manifest, Rush, Manska, C2, C3, and C5 (Table 3; Hayek, 2020; Mathiowetz, 2018; Tyl and Ismail, 2019) shows significant increases in later breeding cycles. Carotenoids are associated with reduced risk of macular degeneration and cardiovascular diseases (Zaheer, 2017). Increases in ferulic, p-coumaric and sinapic acids have also been observed in more advanced breeding populations.

10.2 Product development

Since the release of the MN-Clearwater variety, there have been numerous efforts to develop ingredients and products from Kernza. At the University of Minnesota, efforts were made to develop a tempering process for Kernza. Tempering, which is a process typically used during wheat milling, involves increasing the moisture content of grains just enough (usually to about 14 %) to toughen the bran layer to increase milling efficiency. Bharathi et al. (2019) recommended Kernza tempering conditions of 14 % moisture content at 30 C for 4 h as the best conditions for the tempering of Kernza grains. Bharathi et al. (2022) explored the use of steam explosion to modify the physicochemical properties of Kernza bran. Their intent was to improve the functionality of Kernza bran after refining the grain. As a hydrothermal treatment, steam explosion significantly increased free phenolic acids, free fatty acids, water-extractable arabinoxylans and browning in Kernza bran, while reducing phytic acid content. Dai et al. (2021) investigated the effects of Kernza bran pre-treated with xylanase on the properties of Kernza bread and concluded that the pre-treatment could facilitate the incorporation of Kernza bran into breads. Extrusion technology has also been used to develop low moisture expanded products from Kernza. Boakye (2022) developed an optimized process to produce expanded Kernza products. A 20 % feed moisture, 200–356 rpm screw speed, and 130–154 °C extrusion temperature were observed to be the optimum processing conditions. These conditions resulted in extruded products with the highest expansion ratios and water absorption index. Extruding Kernza resulted in measured decreases in dietary fiber, fat, starch, and amylose content, but did not change protein and ash contents (Boakye et al., 2023). Current efforts are ongoing to increase the expansion and appearance of extruded Kernza by blending it with starches from different sources. Dana et al. (2024) explored the puffing of Kernza grains by investigating how initial grain moisture and puffing pressure impacted the characteristics of puffed Kernza grains. From that study, it was recommended that Kernza be puffed at 15–20 % grain moisture and at a pressure of at least 160 psi. Dana et al. (2024) also investigated the effects of germination on the characteristics of Kernza grains and recommended treatment for 2 to 4 days at temperatures between 15 °C and 20 °C to produce germinated Kernza as an ingredient.

Kernza has also been explored for the production of Kernza-based bread and baked goods, Kernza granola, Kernza-based cereal products, Kernza pasta, Kernza-based protein bars and Kernza snack chips. The ability of Kenza to be processed into malt makes it suitable for both brewing and distillation. Kernza provides a distinctive flavor profile, marked by a nutty, earthy taste with subtle sweet and spicy notes. When used in whiskey production, Kernza imparts a smoother, slightly nutty character. Several craft breweries and distilleries, particularly those focused on sustainability, have been experimenting with Kernza. In collaboration with TLI and Hopworks Urban Brewery, Patagonia Provisions launched the first Kernza beer in 2016, sold as Long Root Ale (Black, 2016). The product highlighted the grain's sustainable farming practices and offered a nutty, earthy flavor profile. In recent years, more than a dozen beers have been produced and marketed throughout the USA. Distilleries have also been experimenting with Kernza in spirit production. Several Kernza Whiskey products have been developed by distillers in Kansas, Colorado, Minnesota, and California, USA (Brooks, 2023; Iseman, 2024). Additional Kernza products that have been sold in the USA include flour, noodles, waffle mix, cold cereal, muffin mix, whole grain, flaked grain, crackers, breads, and desserts (The Land Institute, 2025).

11. Market and supply chain development

11.1 Trademark ownership and governance

Kernza is the trade name under which the grain or seed of improved varieties of intermediate wheatgrass is sold. Because Kernza is a trademark name with increasing recognition from producers, processors, and consumers, governance of the trade name has potential to impact all actors in the supply chain. TLI owns and currently administers the trademark, including developing and maintaining an identity-preserved program to ensure traceability and quality from the seed source to the final food product. The trademark requires holders to apply, be approved, and submit to annual auditing. Producers, distributors, and companies using Kernza can all enter into licensing agreements in the United States, depending on their role in the supply chain and marketplace. TLI licenses distributors internationally, streamlining the auditing process. TLI approves applications, conducts audits to identify producers with the highest likelihood of production success and provides supply data to the marketplace.

Crop institutes or councils often perform these roles for more established grain crops. In 2020, TLI, partner organizations such as the University of Minnesota, and all licensees, developed a strategic plan and revenue model for a Kernza Stewards Alliance (KSA). If created, the KSA would own and administer the trademark, operating similarly to a crop institute or council. However, its proposed legal structure is unique and centered on continuing the multiple-value-proposition which licensees and other stakeholders imagine for Kernza–in this case, the social and economic value. The KSA would be incorporated as a Perpetual Purpose Trust with important non-licensee stakeholders maintaining involvement as Trust Enforcer, Corporate Trustee, or as members of the Trust Stewardship Committee (Bove and Langa, 2021). These roles would be filled based on democratic election by Kernza licensees and any stipulations deemed necessary in the bylaws (for example, that one of these roles be held by a member of TLI staff). Intent to pursue this structure has not changed since 2020, but budgetary constraints have, thus far, prevented the legal incorporation of the perpetual purpose trust.

This structure for governance of the Kernza trademark would ensure that profits from the trademark are reinvested to serve the legally established purpose. Stakeholders involved in the strategic planning process agreed on three key points that should be included in the purpose statement: increasing Kernza production is a priority, Kernza licensees and non-licensees must both benefit from Kernza, and funds generated by trademark license fees should be stewarded responsibly.

Until the initiation of the perpetual purpose trust, TLI retains authority, responsibility, and decision-making power concerning the trademark. The small non-profit sometimes finds it difficult to respond to requests for all activities that licensees and others imagine the trademark holder will take on. TLI has not, for example, directly taken on market development or supply chain creation activities; instead, it has left those to businesses and other institutional partners like the University of Minnesota. The mismatch between capacity, expertise, and expectation sometimes creates tension among licensees, entrepreneurs, other stakeholders, and institutions when commercialization activities begin. Commitment amongst these parties to building strong relationships has helped provide some relief, even as Kernza enterprises traverse the "valley of death" (Frank et al., 1996) that exists between public support and private investment to achieve full commercialization.

11.2 Taking Kernza to market

Despite the early dearth of supply chain infrastructure, the first Kernza products were released in 2016 due to the efforts of individuals who transported sacks of grain in family automobiles and threshed the harvest by hand. The first products were released in a pre-competitive environment in which market pull created a reason for production to expand beyond research stations and onto farms despite the early stages of crop development. Two medium-large food and beverage companies (FNBs) made their intentions to bring Kernza products to the market known. Both were worried about having adequate supply to support the expansion of these products. Even without regional agronomic best management practices or high-yielding varieties, TLI and its partners expanded collaborations with farmers to work toward stable supply for these early product developers. In turn, these early adopter FNBs invested financially in bringing Kernza to market, including pursuing regulatory evidence for Kernza's status as Generally Recognized as Safe (GRAS) for human consumption, developing a Kernza-specific processing line with an ingredient manufacturer, and forward-contracting production with early farmers for premium prices (Reilly, 2023).

Allowing these companies to lead Kernza's go-to-market process resulted in product releases and nascent market development. In 2019, the University of Minnesota added commercialization staff, including market development staff, to concentrate on developing markets and products for Minnesota markets. At the same time, TLI added commercialization staff focused on developing on-farm technical assistance, seed production and quality systems, and trademark management.

A comprehensive go-to-market strategy that pairs bioregional and national/international market development for Kernza has not emerged. Entrepreneurial businesses with a regional focus, supported by public funds and private investment, have had some success in Minnesota. The state has provided risk mitigation and incentive programs for producers and funds used to build out the middle of the supply chain. This regional focus on market development, supported by the state, a large urban population, and a strong local foods movement, is emerging as a model for Kernza and other novel crops (Cureton et al., 2023). The limitations of this approach are that the scale of adoption of Kernza remains small in terms of hectares, reducing its overall ecosystem benefits, and the price of Kernza remains high despite on-farm yield increases, new germplasm, and market efficiencies emerging. Finally, market domination by certified organic products reduces overall market penetration; Kernza remains a niche crop.

11.3 Yields and price

On-farm Kernza yields were not monitored from 2016–2020. TLI launched the first annual survey in 2021 as part of the trademark auditing process. Surveys are collected annually from November to December, and data is analyzed in January. Survey results are delivered between February and early March of the following year. All producers are surveyed and response rates have ranged from 93–100 %.

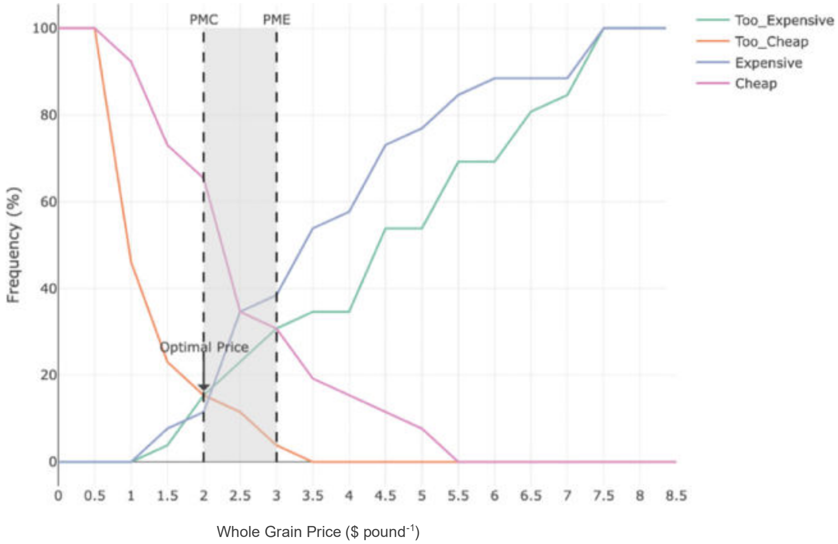
Producers were asked questions about their operations, helping to build an understanding of the number of hectares under production, the stand lifetime, and uses for the crop (including grazing and hay in addition to grain). This data is compiled to provide market partners data about supply, such as how many hectares are being grown and how Kernza fits into a farm's overall operations. From 2021 to 2022, acres in cultivation remained steady, with the total number of hectares increasing from 1601 to 1610. However, in 2023, there was a significant decrease in the number of hectares of Kernza under cultivation. Only 973 ha remained as some fields failed to be established (99 ha), and others were rotated out of production after 3–4 years (468 ha) (Crop Stewardship, 2023). The decrease was also likely due to the overall stagnation of the market. Macroeconomic factors such as the COVID-19 recovery and the invasion of Ukraine by Russia affected global supply chains, food and beverage businesses, and the cost of commodity grains such as wheat. For example, companies distributing Kernza ingredients reported cancellation of contracts due to businesses closing or taking cost-cutting measures as wheat prices skyrocketed to historic highs in May 2022 (USDA NASS, 2022). The lag in price reduction caused companies to reduce the use of high-cost grains such as Kernza, even in organic products, which has, so far, been the most stable market sector for Kernza because the higher price earned on organic products can help businesses recoup some of the high cost of Kernza.

In 2023, TLI undertook the first-ever demand review, surveying 88 businesses about Kernza pricing and other barriers preventing further demand. Of those surveyed, 39 responded, a response rate of 44 %. Most businesses identified price as the top barrier to increasing their use of Kernza. Using the VanWestendorp method (Chhabra, 2015), the survey explored price sensitivity, identifying the Point of Marginal Cheapness (PMC), Point of Marginal Expensiveness (PME) and the Optimal Price (OP) (Fig. 8). The range of acceptable prices (PMC to PME) was \$2.00–\$3.00 per pound for whole grain (Fig. 8A) and \$1.84–\$4.00 per pound for flour (Fig. 8B).

These price points reflect a buyer's perceived willingness-to-pay and are not based on actual purchase data. Results of the Van Westendorp model show a wide perceived acceptable price range for Kernza flour, \$1.84–\$4.00 per pound (Fig. 8B). This wide range shows an inconsistent view of product value among buyers. The wide price range for flour may be due, in part, to the different industry segments and scale of businesses represented by survey respondents. While the perceived acceptable price range of clean, non-organic whole grain Kernza is narrower, \$2–\$3 per pound (Fig. 8A), this price range is still large, making it hard for businesses to determine pricing based on this data alone. The Van Westendorp method also identifies the theoretical "optimal price" which is the price at which there is the least rejection of price. The OP is found at the intersection of "Too Expensive" and "Too Cheap." The OP of whole grain Kernza was \$1.84 per pound and \$2.25 per pound for flour. The difference in OP for each product represents a perceived added value of \$0.41 per pound for Kernza flour (as compared to whole grain Kernza).

The current market pricing of Kernza is variable but generally trended down between 2022 and 2024. While the price to consumers can be more easily found due to online marketplaces, the price to intermediary businesses, such as those surveyed in the Van Westendorp study, is less transparent and varies depending on the ingredient purchased (whole grain, wholegrain flour, sifted flour, flakes) and management system (organic, transitional, or

A



B

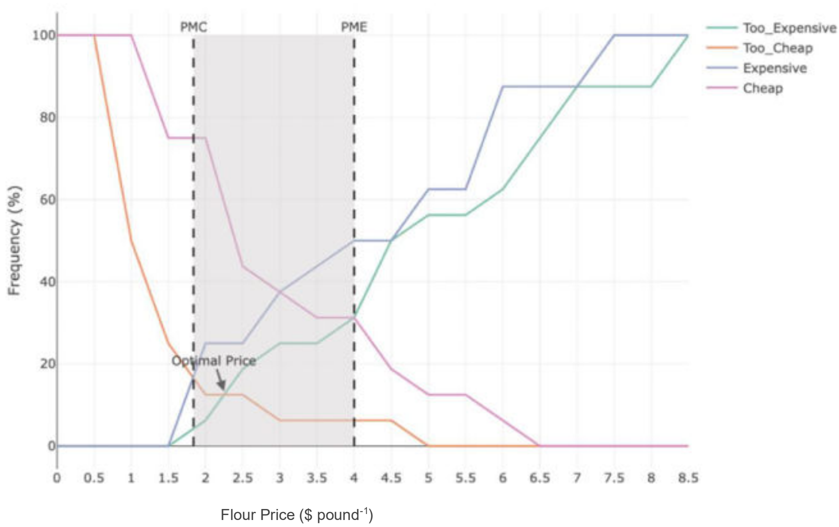


Fig. 8 The Van Westendrop method for estimating price sensitivity provides information on acceptable price ranges for (A) Kernza whole grain and (B) Kernza flour. For whole grain, the range from the point of marginal cheapness (where companies are concerned about quality because of the product's low price) and the point of marginal expensiveness where the product is too expensive to be purchased was \$2.00–\$3.00 per pound. For flour it was \$1.84–\$4.00 per pound. These large ranges indicate confusion about pricing. This model was developed based on survey data from current and historic Kernza grain purchasers.

conventional). Conventional (nonorganic) Kernza ingredient prices can range from $2.75–$9.75 per pound, depending on the product, and organic Kernza ingredients can range from $3.50–$12.65 per pound.

The high costs of Kernza grain are related to the overall yield of the grain on the farm, shipping costs to grain processors, processing costs, and a lack of economies of scale in each production step. In the annual Kernza grower surveys, producers are asked to estimate bin-run grain yield estimates (Fig. 9). Due to edge effects and harvesting techniques, yield estimates are weighted by the corresponding number of harvested hectares. As expected, Kernza grain yield declines with stand age. Still, yield estimates for clean, dehulled grain remain difficult to estimate because of variability in the cleanliness of grain coming off the fields. Forty percent or more loss from cleaning and dehulling is not uncommon.

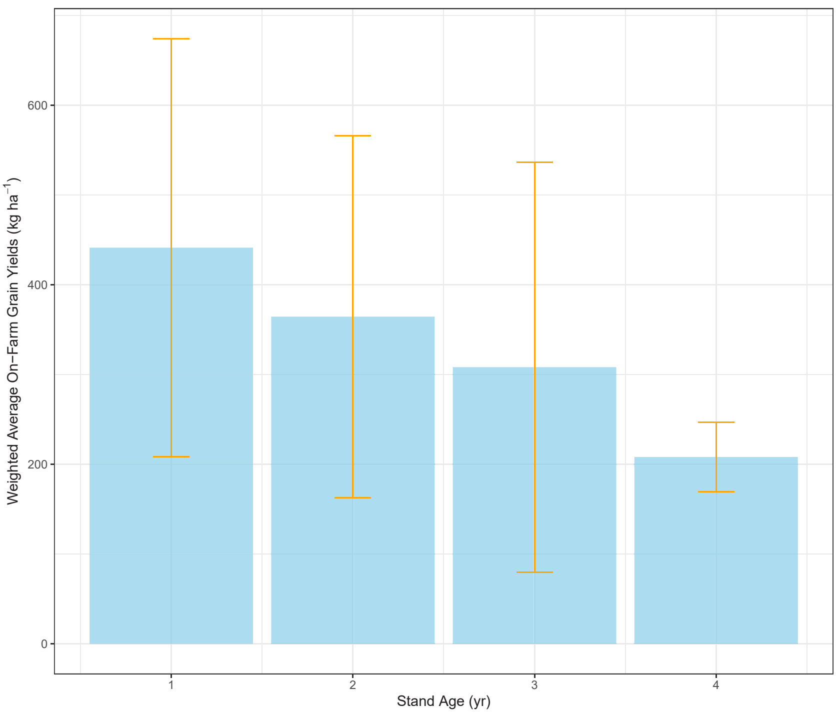


Fig. 9 Yield estimates are weighted by the number of acres that were harvested and by stand age. From year 1 to year 4, yields decrease from just under 400 lbs/acre to just under 200 lbs/acre. Yield decline over the life of the stand is a persistent problem that scientists are working to understand.

Businesses taking the demand survey, in addition to answering questions about pricing, identified six priorities that would help to support market development and stability (Table 1). The subsequent sections will address improvements and projects to address these priorities.

11.4 Supply transparency, quality and grading, and defensible claims

Building supply transparency requires implementation of two separate, but equally important, protocols. First, supply volume monitoring and accurate estimation must be implemented. Second, supply quality must be monitored and reported. Results from these two protocols must then be made

Table 1 Market priorities and summary of actions taken to fulfill determined needs based on the 2023 Kernza demand review.

Market priorities	Summary of action taken
Supply transparency	Merge Marketplace launched in summer of 2024, listing Kernza for KS and NE producers Dockage standard development will happen with 2024 harvest sampling
Quality and grading standards	Pilot project launched in fall 2024
Defensible claims (nutritional and environmental)	Environmental claims developed by The Land Institute (Peters, 2021; Kernza, 2024) Nutritional claims being explored as part of the quality and grading standards development Ecosystems benefits verification through Merge Marketplace
Marketing materials	Materials distributed by The Land Institute developed in 2023–2024 and Perennial Percent concept launch in 2024
Additional pricing research	Enterprise budgets and case studies initiated in 2024
Additional regional processing	Funding for infrastructure investments being pursued by The Land Institute Minnesota Legislature funding to the Minnesota Dept of Agriculture for grants to organizations in Minnesota developing enterprises, supply chains, and markets for continuous living cover crops, including Kernza, in 2022

available widely to meet the transparency requirements of market partners. To monitor supply volume, TLI surveyed producers from 2020–2023, asking them to estimate the bin-run volume that they currently had on-farm from each year's harvest. In addition, in 2023, producers were asked to include estimates of any previous year's harvest they had in storage. This information was reported in the 2023 annual supply report (Crop Stewardship, 2023). In 2024, TLI implemented a sampling strategy to represent the supply more accurately. Producers were sent sample-taking kits and were asked to provide those samples to TLI. Dockage will be estimated using a standard clean-out protocol developed by Northern Crops Institute, and then a grading standard will be developed. Using these dockage estimates for each lot, TLI can then convert grower-reported volumes into more accurate estimates for clean, dehulled grain. Finally, those estimates can also be graded, ensuring quality characteristics are known for grain purchasers.

In July of 2024, collaborating partners, Merge Impact, launched an online marketplace (https://marketplace.mergeimpact.com/) where pilot Kernza producers could list available grain on a blockchain-enabled platform. In 2025, TLI plans to make access to the Merge Impact Marketplace available to all Kernza producers. Each listing will include grain quality (grading), soil carbon, biodiversity, and nutritional information tied to field locations. This dashboard brings together supply volume, supply quality, and transparency for Kernza market partners. It also includes the added result of tying ecosystems benefits to Kernza at the farm scale for partners.

11.5 Marketing and storytelling

Translating the unique benefits of perennial grains to consumers is a challenge for market partners who have limited on-pack space to tell the story. Therefore, TLI has worked to provide storytelling support. For instance, a kit of marketing materials was developed and is available for all Kernza licensees to use in product development and promotion. Additional support has been provided by organizations such as the Forever Green Initiative from the University of Minnesota. Patagonia Provisions and General Mills have both launched national products that are bringing the story to consumers directly on packaging, and they provide more detailed information on their websites. Small food and beverage companies are playing a unique role in communicating the Kernza story to their customers in unique ways that can involve stories in local media, photographs of the plant, or information provided by servers.

In 2024, TLI with numerous collaborators launched the Perennial Percent™ initiative to encourage food and beverage companies to incorporate small percentages of perennial grains into their existing product lines. By focusing on gradual adoption rather than requiring a complete overhaul of product formulations, Perennial Percent provides a practical path for food and beverage manufacturers to contribute to utilizing perennial grains. Companies register products or product lines and then can use the Perennial Percent label on their packaging. The label indicates a company's commitment to perennial agriculture (currently Kernza) and supports marketing and storytelling. Bang Brewing, a small Minnesota brewery, first used the concept to promote their beers. TLI has expanded on the notion, and a baking mix company, Sturdiwheat, is the first company to use the Perennial Percent label.

11.6 Regional processing: The essential middle of the supply chain

Scarce unding for infrastructure investments that would improve supply chain efficiencies remains a factor that limits access to regional processing for Kernza. Currently, processing capacity exists in Nebraska, South Dakota, Wisconsin, and Minnesota, USA. Much of this capacity is proprietary (a business processes grain only for the products they are marketing) or done on a toll basis. There is no distributed or centralized processing widely available that includes Kernza-specific operations and storage (Fig. 10). Lack of redundancy in the processing, storage, and distribution roles in the supply chain has led to shortages of cleaned, dehulled grain and other tertiary processing products such as flour and flakes. The processors often wait until their other grains are completed before bringing in Kernza for processing. Additionally, the lack of competition means that some processors have tripled their prices for cleaning with little notice, leaving Kernza growers with few options but to pay the increased prices. The alternatives of finding a new processor with no experience who is willing to process the grain, or paying high prices to ship long distances to another experienced processor, have obvious downsides. Higher prices, as we've already seen, limit growth of the market. New processors may take up to a year or longer to develop protocols for processing the grain, requiring additional storage time–which is equivalent to additional cost (Fig. 11).

Long distance shipping has its own unique challenges. The disconnect between food production and consumption is a well-documented barrier to sustainable development called the "missing middle" (Veldhuizen et al., 2020).

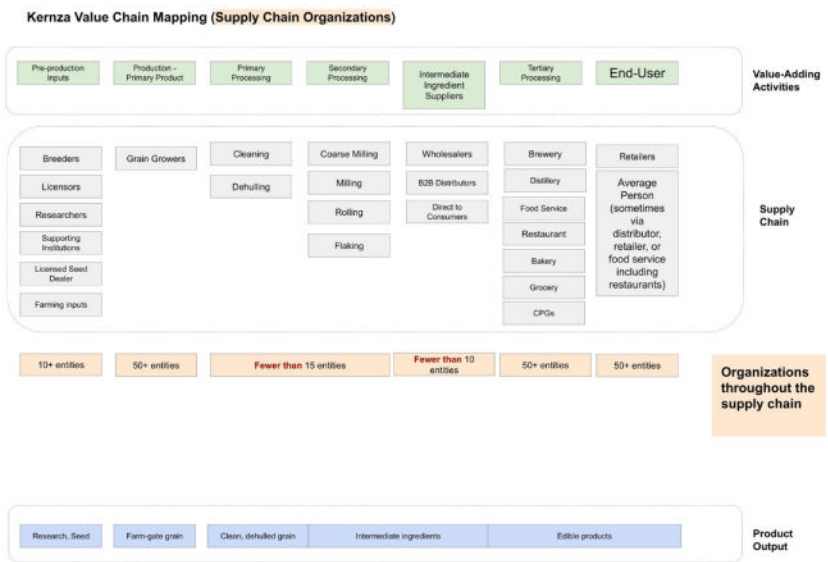


Fig. 10 The middle of the supply chain remains thin, with little redundancy and few entities dedicated to ensuring Kernza has a clear path from farm to food product manufacturer. For primary and secondary processing there are fewer than 15 entities and fewer than 10 entities engaged in ingredient manufacturing.

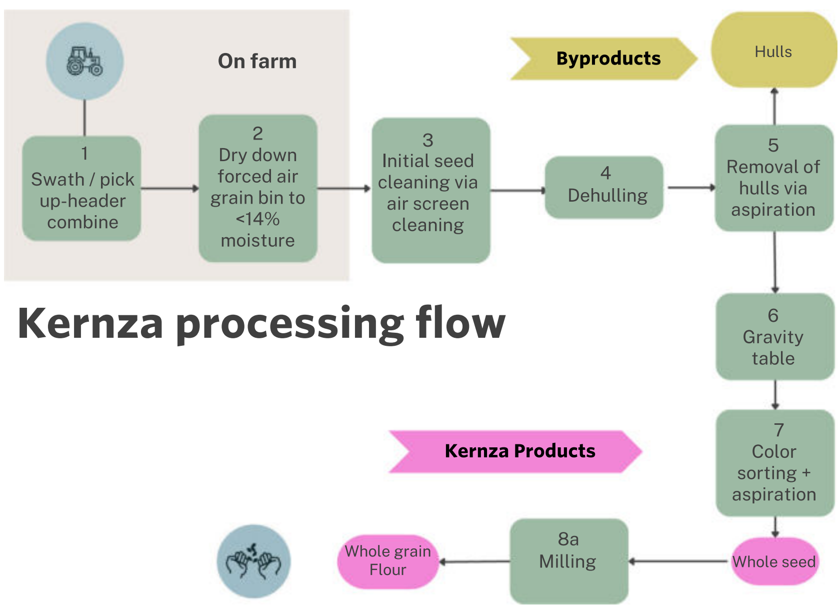


Fig. 11 This flowchart shows the basic processing steps required to take Kernza from the farmers' fields to whole grain and/or flour, including byproducts (Kernza hulls).

For new crops like Kernza that have the opportunity to contribute to global environmental sustainability, infrastructure to get the grain from farms to consumers without increasing emissions due to shipping long distances for cleaning and processing is essential. Fig. 11 shows basic processing flows for Kernza from farm to whole grain and flour. Additional processing may be required for sifted flour, flakes, or other applications. For some farms, the distance between Step 2 (on-farm) and Step 3 (at a processing facility) may require less than truckload (LTL) shipping of grain over 800 miles. Early lifecycle assessments conducted on behalf of specific businesses show that reducing the distance from farm to processing center could improve the overall impact of Kernza on sustainability efforts such as greenhouse gas emissions reduction (Merge Impact, 2024). However, developing regional processing infrastructure that is low-cost is likely to require subsidies, philanthropic investment, or other methods of reducing the price to Kernza producers to ensure end-users are able to obtain the grain for prices that they deem acceptable. As the market grows, the supply will also grow and economies of scale, full truckload or container shipping will become available with reduced environmental impact and reduced cost, stabilizing pricing and access to the grain.

Another way to address the economy of scale conundrum is to increase the yield of Kernza produced in each field. This will require improved varieties to become available through plant breeding and better agronomic management practices to be developed at the regional scale for each variety. While these issues are addressed in other sections, it's important to note that they are directly connected to the economics and environmental benefits of Kernza perennial grain production as it pertains to the entire supply chain.

12. Future directions

Introducing a new crop requires successful coordination of research and development in a wide array of fields, combined with educational outreach to producers and steady investment in processing, product development, and marketing (Jolliff and Snapp, 1988). Given the numerous barriers to successful introduction of a new crop, it is unsurprising that few new crops have entered widespread production in the past century. As productivity of existing crops has increased, introducing new crops has become even more difficult. IWG is remarkable in that the effort has been sustained for 40 years, despite commercial product release only beginning recently.

What separates IWG from most other candidate grain crops is its perennial nature, which is expected to enable improved soil quality, reduced nitrate leaching, carbon sequestration, weed competitiveness, wildlife habitat, etc. These potential ecosystem benefits have provided the rationale to invest in IWG research and development even as success was clearly decades into the future (DeHaan et al., 2023). As commercial production of IWG expands, funders are beginning to demand stronger evidence of the crop's ability to provide ecosystem services, especially in regard to carbon sequestration. A clear priority is for additional on-farm research to understand how the crop performs as it is grown in different regions, with long-term monitoring across crop rotations. Work elucidating the options and consequences to soil for transitioning from IWG or IWG intercrops is urgently needed both to provide informed agronomic recommendations to farmers in different climates as well as understand the tradeoffs involved. Projects that evaluate inputs (time, fuel, fertilizer, etc.) per harvested output (e.g. grain, forage, additional crops) over time within an ecosystem service and climate resilience framework could be especially impactful. Future work should investigate how domestication might impact IWG root investment and interaction with the soil as this may be the main predictor of many enhanced soil functions but also have implications for crop yield and resilience. Another research gap is the suitability of IWG cropping systems as wildlife habitat, since some preliminary work has demonstrated that farming systems including IWG could help provide habitat for ground nesting birds and small mammals.

Increasing yield remains a central concern for the successful introduction of IWG at a scale relevant to positive regional or global impacts (Luo et al., 2022). Breeding is central to domestication of a new crop, such as IWG, so it is appropriate that the first decades of work on the crop focused largely on domestication and breeding, (Bajgain et al., 2022). Now, the newest genetic techniques such as genome editing should be attempted for potential breakthrough advancements (DeHaan et al., 2020). However, improved management has the best-odds potential to improve grain yields of IWG quickly. In the case of wheat in Kansas, about 30 % of historic increases in yield can be attributed to improved management; if similar benefits can be obtained from agronomic studies and extension education with IWG, yields on par with annual wheat might be obtained in 22 years if breeding progress maintained (Bajgain et al., 2022). Agronomic research to increase yields is particularly important because its impact can be realized on farms in the short term, not waiting on the decades-long process of plant breeding. Given the rapid declines in grain yield seen in many aging Kernza stands, agronomic techniques to sustain grain yields over time would have a substantial impact on the viability of IWG.

All new crops will depend on the development of functional supply chains to store, transport, process, and market products from the crop. The success observed so far with Kernza must in part be attributed to the ability to integrate the grain at lower inclusion levels (roughly below 20 %) into existing products with minor adjustment to produce a desirable product. The largest challenges have come from the high cost of storing, processing, and transporting small lots of a specialty grain. Expanded production may be waiting on substantial increases in production within at least one region, allowing efficiencies of scale and the steady supply that is needed for greater market penetration.

Introducing a new crop is a complex multidisciplinary effort, leading Jolliff (1989) to conclude that a center to coordinate the wide array of essential activities should be established to develop new crops. Jolliff (1989) further noted that federal funding typically lags behind new crop development efforts, rather than sponsoring the projects from their beginning. Therefore, he proposed that a central organization should coordinate funds from private and public sectors to ensure that diverse activities happen in an efficient manner. Throughout its 40-year history, work to develop Kernza has been undertaken by an array of institutions, including nonprofit organizations, universities, and private companies. While there has not been a single coordinating organization, there has been a strong spirit of cooperation among diverse entities. If Kernza is to continue on the path to becoming a new crop success story, continued cooperation between diverse parties will be essential, with a focus on steadily growing the levels of private and public investment across essential activities. The necessary enhanced cooperation might be best achieved through the formation of a Kernza Stewards Alliance. Such an organization would be best positioned to acquire essential resources, coordinate stakeholders, rapidly increase the scale of Kernza production, and identify the research needs of most critical importance to producers and the market.

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