Progress Towards Perennial Grains for Prairies and Plains

K.G. Cassman and D.J. Connor

Abstract
Perennial grain crops have been proposed as environmentally sustainable alternatives to annual grain crop systems that currently dominate the world’s major breadbaskets. Proponents emphasize the potential of perennial grains to mimic natural systems and thereby reduce soil erosion, nutrient losses, and degradation of soil quality although need for adequate grain yield is also recognized as a prerequisite for success. Here we assess progress since 2005 (16 y) towards development of perennial grain systems with sufficient productivity to be seen as competent alternatives to annual wheat on the prairies and plains of North America and Australia. Based on reports published in refereed journals, we see little evidence that yield of Intermediate Wheatgrass or perennial wheats have improved to the point they are viable alternatives. Slow progress is attributed to lack of minimum grain yield targets for economic viability, lack of designated target regions where perennial grains are most likely to be competitive against annuals, selection methods that focused on components of yield rather than yield per se (i.e. on an area basis), and relatively small R & D investment compared to resources given to genetic and agronomic improvement of major annual grain crops. Given current status, we conclude that perennial grains will require substantial R & D investment and several decades if they are to achieve sufficient yield potential and yield persistence to become more than a niche crop for upscale health food markets in wealthy countries.

Keywords
Intermediate wheatgrass, Kernza, perennial wheat, benchmark yield, persistence

Introduction
Prospects for perennial grains date back at least to Tsitsin and Lubimova (1959) who demonstrated successful hybridization between various wheat (Triticum spp.) and Agropyron spp. and the formation of a new perennial grain species Triticum agropyrotriticum perenne from common wheat (Triticum aestivum). Now, other perennial grain hybrids are promoted as providing solutions to weak links in environmental sustainability of current annual grain production systems that represent the bulk of our human food supply. Proponents argue that sufficiently productive perennial grain systems can be developed to better mimic the structure and function of natural ecosystems and thus greatly reduce soil erosion, nutrient losses, and degradation of soil quality associated with annual grain systems. These arguments were advanced in a series of four articles published in the March 2005 issue of Renewable Agriculture and Food Systems (RAFS) (Glover, 2005; De Haan et al., 2005, Cox et al., 2005; Crews et al., 2005). Since then, perennial grain proponents continue to extol the virtues of natural ecosystem mimicry and improved environmental performance of perennial crops as justification for research and development investment in perennial grains (FAO, 2014; FAO, 2019). A 2005 paper titled “Perils of Production with Perennial Polycultures”, written by our deceased colleague Robert (Bob) S. Loomis to provide a critique of the four 2005 pro-perennial grain RAFS papers, was never published for reasons described below. Fortunately, this 2021 Special Issue on Biomimicry and Nature-Based Solutions provides an opportunity to publish it. In addition, we see an opportunity to evaluate progress towards the goal of developing productive perennial grain crops capable of replacing annual grains over the 16 years since the four RAFS papers were published. But first some historical context about the Loomis paper.

Brief history
In late 2004, Bob was invited by Wally Wilhelm (RAFS Editor at that time) to review and comment on four perennial-promoting RAFS papers to be published in that journal the first quarter of 2005. Because Bob’s paper was

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Progress towards perennial grains

The four pro-perennial RAFS papers put forth a number of hypotheses about how to overcome challenges to developing improved perennial grains that are sufficiently productive to be widely grown as replacements for annuals. Without adequate yielding ability in several consecutive years to replace a substantial proportion of annual grain production, perennial grain systems would be limited to niche health-food markets in wealthy countries. As stated by Glover (2005): “All recognize that high seed yields are a basic requirement for successful widespread adoption of perennial grain crops.” And while nutrient supply, insect and disease management are seen as challenges that can also be overcome through R & D (Cox et al., 2005; Crews, 2005), these factors are secondary to the challenge of achieving high-yielding perennial grains. Moreover, Loomis also provided strong arguments about inherent vulnerabilities of perennial grain systems to insects and diseases, as well as difficulties in meeting nutrient requirements of productive perennial grain crops with indigenous resources.

Based on thorough review of the literature, Loomis (2022) identifies several reasons why yields of perennial grain crops are so much lower than yields achieved by well-managed annual grains. In contrast, Glover (2005) argues that it is possible to overcome these challenges if the power of recent advances in genetics and computational sciences are brought to bear: “Modern plant breeders, unlike those earliest plant breeders, have recent advances in plant breeding, unprecedented computational power and a greater understanding of ecology, cytogenetics and molecular biology to make high-yielding perennial grain crops possible.” De Haan et al. (2005) provide more detail about specific approaches to overcome physiological “tradeoffs” between perenniality and grain yield.

Here we evaluate progress since 2005 towards development of higher-yielding perennial wheats (Triticum aestivum) and Intermediate Wheatgrass (Thinopyrum intermedium) grain crops as the first step in subsequent development of stable polycultures. Because the time from a hypothesis about a new breeding strategy to having farmer-ready wheat cultivars typically takes 15–20 years in existing, well-funded genetic improvement programmes at major national and international research institutions (Hall and Richards, 2013), it would likely take somewhat longer to achieve high-yielding perennial grains which attract less support, even if the goal were achievable in principle. Wes Jackson was a leading proponent of perennial grains in the 1980s and 1990s while at the Land Institute, a private agricultural research centre in Salina, Kansas. In 1996 Jackson stated that it would take 25 years or more of basic research and field testing to have farmer-ready cultivars (Moffat, 1996). Nine years later, Grover (2005) suggested a 25-yr timeframe to achieve productive perennial grain systems, “If, in 25 growing seasons, there are productive agricultural systems in place that provide adequate yields, support vital ecosystem functions and are highly energy efficient, the time required for success will have seemed short.” At this writing, in late 2021, 16 years have passed since the RAFS papers were published, which is time enough to expect some measurable progress towards higher yields of perennial grains with adequate grain quality to replace annual wheat if it is possible to overcome grain-yield tradeoffs due to perenniality. We therefore focus on published reports since 2005 (a period of 16 y) that evaluate yields of improved IWG and perennial wheats based on field studies conducted in North America and Australia.

While, for comparison, there appears to be substantial progress towards perennial rice in lowland irrigated systems in China and southeast Asia, it is notable that current rice varieties and hybrids already have the capacity to produce “ratoon” crop yields that are 80% of an annual irrigated rice double-crop system with 32–42% lower energy input, production costs, and global warming potential (Yuan et al., 2019). More recent work has shown additional promise of perennial rices (Zhang et al., 2021; Fukai and Wade, 2021). But irrigated rice is produced in level, bunded fields with little erosion risk such that reduced input and labour costs are the primary motivations for ratooning of annual rice and introduction of high-yielding perennial rices in highland valleys of southern China (personal communication, Shaobing Peng and Len Wade). In contrast, promoters of perennial grains in upland, rainfed systems of North America and Europe emphasize environmental benefits in terms of reduced erosion and nutrient losses and improved soil quality as primary justification. Hence our focus on rainfed perennial wheats and the underpinning narrative that perennial grain polycultures can be seen as a viable alternative to current annual wheat systems in wheat-producing regions of North American and Australia. For example, with annual wheat harvest of 47 Mha in the USA and Canada (mean harvested area, most recent five years), replacement of a substantial portion of annual wheat area by less-polluting and natural resource-conserving alternatives would provide considerable scope for reducing negative per-hectare impacts of these systems. But if less grain is produced per
hectare, shortage-driven price increases will encourage environmentally destructive practices elsewhere, from overfertilization to converting natural grasslands and draining wetlands for crop production. Therefore, as noted by Glover (2005), high perennial grain yields are essential for success. For the purpose of assessing progress towards this goal, benchmark target yields for productive perennial systems are required that are sensitive to contributions to net income from grain and forage production plus the value of ecosystem services that can be attributed to the system, all balanced by the need to avoid a large increase in land requirements elsewhere to meet global grain demand if perennial yields are too low.

**Progress on intermediate wheatgrass in North America**

In North America, IWG has received greatest attention as a potential perennial-grain crop because of its agronomic properties, nutritious and palatable grain, synchronous seed maturity, moderate shattering and reasonable threshability (Waggoner, 1990, 1995; Becker et al., 1991).

Germplasm evaluation and mass selection for higher seed yield have been underway since the late 1950s (Knowles, 1977), and more specifically as a potential replacement for annual grains since the late 1980s (Culman et al., 2013; DeHaan et al., 2018). In addition to genetic improvement, research on IWG includes development of appropriate agronomic practices to support higher yields. Table 1 includes data on IWG grain yields from all field studies published in peer-reviewed journals since 2005 (as of October 2021) that provide sufficient detail about plot size and harvest methods to determine if reported yields are reasonably representative of production-scale crop stands.

Based on analysis of these results, there is no evidence of progress towards higher IWG grain yields (Table 1). Production plots in these studies were relatively small such that yield measurements were mostly taken from miniature harvest areas of 0.25 to 1.0 m². Small plots benefit from edge effects and more-consistent management, relative to large commercial fields where heterogeneous soils and uneven implementation of crop and soil management practices give rise to relatively high spatial variability in yield. Likewise, there is no evidence of a decrease in the severity of yield decline in the second and third years after crop establishment. Indeed, relatively few studies measure yields over a three-year period to allow robust assessment of yield persistence as a perennial grain crop. Across the five studies in Table 1 with three consecutive years of harvest data, average first-, second-, and third-year IWG grain yields were 24%, 13%, and 8% of comparable annual wheat yields. It is therefore not surprising that, in a recent survey of ten farmers growing IWG, only two found it worthwhile to harvest grain every year (Lanker et al., 2019).

Rapid yield decline in IWG is associated with a large decrease in harvest index, which in turn is associated with a large reduction in the proportion of tillers that produce grain (Fernandez et al., 2020). Even the improved IWG lines produce far too many tillers relative to their capacity to support floral structures and fill grain. These findings have led to the hypothesis that yield decline with age is caused in part by increasing competition amongst too many tillers (Law et al., 2021). Several studies have attempted various types of stand structure and canopy manipulation, including strip-tillage and defoliation, to reduce competition but results have not shown consistent yield improvement (Fernandez et al., 2020; Law et al., 2021; Hunter et al., 2020).

Lack of yield progress in IWG may reflect the fact that genetic improvement efforts were tightly focused on improving ease of harvest and threshing through a selection index based on single-seed weight and grain number per culm as primary selection criteria rather than yield per se (Cox et al., 2010). Selection for these yield components is understandable because large scale commercialization of IWG as a primary staple grain requires larger grain size to reduce harvest losses associated with small-seeded crops and improve grain quality for commodity markets. But selection for seed size and grain number per culm is not a direct proxy for grain yield per se because yield also depends on number of seed-bearing culms. Ignoring this can result in indirect selection for fewer culms, limiting any increase in yield.

Lack of progress may also reflect difficulties in achieving genetic gains with a perennial crop compared to annual grain crops due to longer crop duration, which limits the number of selection cycles and thus the rate of potential genetic gain. Indeed, the relatively small number of field studies reporting IWG yields over a three-year production cycle indicates modest total investment in R & D to develop and establish this perennial grain as a serious contender to replace annual wheat. Slow but steady progress on yield advance is needed to justify hope that the ultimate goal of high-yielding IWG is achievable, but Table 1 lends little support to that view. Instead, these results are best seen as baseline yields against which future progress towards yield improvement can be measured.

Both Cox et al. (2005) and De Haan et al. (2005) cite the potential of modern breeding methods, including cyto genetic and molecular biology, to accelerate yield improvement in perennial grains (Cox et al., 2005, De Haan et al., 2005). The outcome from use of such tools has only recently been published. One study used high-throughput sequencing and genome-wide association mapping to identify genomic regions linked to yield component traits of culms taken from individual plants in an IWG population representing a third cycle of recurrent selection (Bajgain et al., 2019). Another employed genotyping-by-sequencing on IWG populations derived from five cycles of breeding data spanning 8 years in two breeding programmes (University of Minnesota, St Paul, MN, and The Land Institute, Salina, KS) to develop genomic selection (GS) models predicting improvement in what the authors call “domestication traits”, including free-threshing seed, single-seed mass, and non-shattering, and “agronomic traits” including plant
height, spike yield, spike length, and spikelets per inflorescence (Crain et al., 2020). While these studies were successful in identifying genetic loci associated with yield components and other domestication traits of *individual plants* and estimates of associated genotype prediction efficiencies for these traits, they did not evaluate yield *per se*. And there is no strong evidence that selection for yield components of individual plants leads to selection of IWG lines with higher yield potential per ha, which is the same limitation found in studies reporting recurrent selection for yield improvement of IWG (e.g. DeHaan et al., 2018).

### Progress on perennial wheats in Australia

The recent Australian experience with perennial grains commenced in September 1997 at an International Workshop "Agriculture as a Mimic of Natural systems" held by the Rural Industries Research and Development Corporation in Williams, Western Australia (Lefroy and Hobbs, 1998). It served to introduce The Land Institute, Kansas, to Australian scientists leading to subsequent collaboration. There were two initial responses. The first was a desk-top analysis using the MIDAS model to evaluate the potential financial benefit of introducing perennial wheat as a dual grain-forage crop into the cropping component (55% of area) on four of eight land-management types comprising a large (2000 ha) mixed annual crop/sheep-for-wool farm in Western Australia, mean annual rainfall 350 mm, 75% winter-spring (Bell et al., 2008). The second, a literature review (Bell et al., 2010) that discussed the potential for perennial wheat to resolve perceived environmental problems that were widely discussed in the Workshop.

The modelling study concluded that, because of extra fodder produced, perennial wheat could be introduced with financial benefit, even with a grain yield only 40% of then-current annual wheats over three consecutive years (L. Bell, pers. comm.). The change to farm management was substantial, however, including increasing pasture area by 200 ha at the expense of land previously devoted to annual crop production, and more sheep to increase stocking rate from 7.6 to 8.9 ha⁻¹ which requires capital investment. The review included discussion of the nonfinancial benefits of perennial fodder production to issues of soil conservation and water and nitrogen balance with reference to alternative management techniques that may achieve the same outcomes. It noted that experimental evidence was needed to support the putative environmental benefits, an issue discussed extensively by Bob Loomis (Loomis, 2022) and advised of the wide range of other germplasm, including Australian native species, that might contribute to breeding of perennial grains. The modelling exercise was important and quantified a perennial benchmark yield for a financially viable perennial grain system (in this case, 40% of annual wheat) dependent on grain and fodder yields, costs, prices of products and assumed persistence of perennial wheat, which has not yet been realized. Further studies in other zones and farming enterprises to evaluate yields, yield persistence, and economic returns under a range of price scenarios for grain, forage, and inputs would be a valuable balance to the current dominance of breeding and selection activities.

Given the large difference in growing conditions between Australia and USA, further collaboration with The Land Institute has been in genetic evaluation of a wider range of perennial grasses and their hybrid derivatives with current Australian wheat cultivars (Hayes et al., 2014; Larkin et al., 2014), in the first instance to develop dual-purpose cultivars. The studies have identified valuable agronomic, disease resistance and grain-quality genes useful for continuing work but have also greatly widened the potential range of activity. For example, it is proposed that the diploid (2n = 14) tall wheatgrass (*Th. elongatum*) could be a better choice for hybridization than the hexaploid (2n = 42) IWG because it follows the previously successful model by which the new crop triticale was developed. At the same time, the difficulties with producing hybrid amphiploids are such that introduction of genes from current wheat cultivars into IWG is proposed as the more productive route for improvement. This work is included in a recent international comparison of early-generation cereals at 21 sites with contrasting rainfall and temperature patterns.
across four continents (Hayes et al., 2018). That analysis reinforces the existence of alternative genetic models for hybridization and the need for individual breeding projects for target areas.

Hayes et al. (2018) also include the suggestion of Bell et al. (2010) to target work on perennial wheat in regions where sown perennial grasses are currently used in paddock-grazing systems and are known to persist. Such areas are identified in the southern Australian wheat belt and its margins, where the introduced, temperate grasses cocksfoot (Dactylis glomerata) or phalaris (Phalaris aquatica) are successfully included in ley pastures with annual sub clover (Trifolium subterraneum). Further guidance is available from experience with lucerne (also called alfalfa, Medicago sativa) introduced as a forage and N source into Australian wheat systems. This focuses attention on the additional drying of soils by the perennial phase that not only reduces growth and survival then, but also subsequent wheat growth and yield until the soil-water deficit is replaced by low and variable rainfall (Angus et al., 2001; McCallum et al., 2001).

An agronomic experiment (Hayes et al., 2017) at Cowra, NSW (mean annual rainfall 600 mm, evenly distributed annually) has evaluated the performance of IWG and two hybrid derivatives from Australian wheat when grown in mixed culture with subterranean clover. This moves research hurriedly to an example of the next step in the "mimicry program" which is to produce self-replicating, mixed populations that provide grain for harvest without need for annual resowing. Proportions of the perennial crops were reduced from the control by sowing sub clover (cv. Coolamon) in the same drill row or spatially separated in every second or third drill row. The hybrid derivatives were more vigorous than IWG in the first year, yielding 1700 and 1106 kg ha$^{-1}$, respectively, but fell to 73 and 277 kg ha$^{-1}$ in the second year when vegetative regeneration was reported as "negligible". That suggests contribution from unharvested seed of the previous year. Yield of IWG was 409 kg ha$^{-1}$ in the first year and despite "adequate" regeneration was only 7 kg ha$^{-1}$ in the second. Yield of IWG, the only assured perennial contributor, averaged 208 kg ha$^{-1}$ over two years. Farm yields for annual wheats in the region commonly exceed 3 t ha$^{-1}$. Measurements of biological N fixation by clover revealed an adequate supply to support continuing removal of 1–2 t ha$^{-1}$ grain. The authors acknowledge, however, that sub clover, being an annual, is unlikely to re-establish in vigorous stands of perennial wheat after the initial sowing.

Progress in conducting agronomic research with perennial wheat derivatives in Australia is hindered because no commercial cultivars are yet available for the establishment of on-farm trials. Meanwhile the objectives and methods for development of perennial wheats remain diverse. Progress is slow in both grain yield and survival such that sequences are short and have rapidly decreasing yield. Persistence is essential for both environmental and economic benefits, as seen in the modelling exercise (Bell et al., 2008) in which perennial wheat yields were held constant for up to 6 y. Subsequent citations of a benchmark target for financial success of 40% yield relative to annual wheat (Bell et al., 2010; Dehaan, 2011; Larkin et al., 2014) are unfortunate because this specific example is not appropriate for wide application. More agronomic work on yield and environmental responses is required, but first some adapted cultivars.

**Commercial production**

In North America, IWG is known as Kernza®. A significant achievement of the past 16 years was release of the first Kernza® cultivar, ‘MN-Clearwater’ (Bajgain et al., 2020), which is the only commercially available IWG seed in North America. A website devoted to information about Kernza® provides current data on commercial production and expectations for further progress in developing the crop and expanding its production (https://kernza.org/the-state-of-kernza/). The website provides an upbeat assessment about prospects for improving domestication traits such as seed size. For example, "If current progress is sustained, Kernza® seed size will be 50% as large as annual wheat seed in the next 10 years. Beyond that, breeders are working on developing shorter plants with improved flavor and functionality that are easier to grow."

The challenge of increasing yield per se, however, is also noted: "Although Kernza® perennial grain currently has low grain yields compared annual production, farmers and consumers can benefit from the ecological impact of producing and consuming Kernza® perennial grain today."

Perhaps most revealing about progress towards establishing IWG as a replacement for annual wheat is the fact that current total USA Kernza production area is less than 1500 ha, consistent with a small niche market willing to pay premium prices without asking tough questions about actual environmental benefits, including need for greater production area to produce adequate grain supply.

**Conclusions**

Wheat is an essential component of the human food supply. Adequate yields and cost to consumers are important determinants of nutrition and quality of life for billions of people, many of low income. At issue is whether perennial wheats could replace a portion of annual wheat production and reduce the negative environmental impacts and greenhouse gas emissions arising from annual wheat systems. Producing adequate supply is only part of the challenge, however, because perennial wheats must also be cost-competitive in terms of resource requirements for land, labour, energy, water, and nutrients. Analysis of economic viability should also include the value of environmental services provided by perennial grain systems vis-à-vis the comparable annual grain so long as they can be reliably quantified.

Efforts to develop a perennial grain replacement for annual wheat on the prairies and plains of North America have been underway for more than 30 years, and the scientific literature over that period is regularly punctuated by
papers reporting progress towards that goal and promoting the ecological virtues of such systems. A serious initiative to develop economically viable perennial wheat polycultures would begin with an estimate of minimum grain yields required to be cost-competitive against annual wheat systems. The concept of a minimum yield target, however, is absent from the published reports on genetic improvement of IWG in North America. Current first-year yields of IWG average about 25% of comparable annual wheats and yields in subsequent years are much lower still (Table 1). How much further must grain yields rise, and how persistent must these yields be, to approach levels that give adequate net return assuming reasonable values for the grain, harvested forage, and environmental services?

As Glover (2005) states: “By selecting strongly for seed yield in a population of perennial plants, the plant breeder can likely achieve that which is rare in nature—a high seed-yielding perennial plant”. Clearly it has proven to be much more difficult than that and there is no convincing evidence of detectable progress in yield increase over the 16 years since the pro-perennial RAFS publications, let alone their productive combination in polycultures to minimize inputs. The most likely reasons for lack of progress, in addition to the fundamental constraints imposed by perenniality and highlighted by Loomis (2022), are: (1) a focus on domestication traits instead of yield per se, (2) slower breeding progress than for annual grains, and (3) inadequate total investment in R&D relative to magnitude of the challenge. Although it has been suggested that a small increase in an initially low harvest index should be achievable with only minor effects on persistence (Denison, 2012, p. 99), the associated impact on yield would also be small. And if harvest index (reproductive allocation) of IWG were ever to approach that of annual wheat, that would severely limit resources to maintain perennialism.

At present, IWG exists as a tiny niche crop in the USA for those who value novel foods and the putative ecological services attributed to the crop. But commercialization for substantial deployment as replacement for annual wheat across millions of ha in the prairies and plains of North America or elsewhere to improve the environmental performance of grain production systems still remains, if possible, at least 25–50 years away. This timeframe would, unfortunately, be too late to contribute to the urgent goal of securing global food security in the face of increasing world population and changing climate by mid-century. Our assessment suggests that a tighter focus on selection for yield per se, rather than components of yield, and clearer definition of benchmark target grain yields (or yield range) that make perennial wheat systems economically viable in specific agro-ecozones are needed to facilitate genetic and agronomic improvement efforts. Delineation of regions best suited for perennial grains also needs greater emphasis. For example, although much of the agro-nomic and crop improvement research on IWG in North America has been conducted in regions of the Corn Belt with favourable climate and fertile soils, perennial grain polycultures may have greater advantages in regions with less favourable climate and soils. Targeting efforts to these regions may give more promising results when compared to annual grain systems. In Australia, the southern wheat belt and margins have been suggested as target regions (Bell et al., 2010).

At issue is how much to “bet” on perennial grains versus investments focused on improving the environmental performance of existing major grain production systems through sustainable intensification. Sustainable intensification seeks to increase yields on existing cropland while employing ecological principles to conserve soil, water and biodiversity through cover crops, conservation tillage, precision management of inputs and field operations in time and space, modified annual crop rotations, continued genetic improvement of annual grain crops, and strategic retirement of marginal land with high risk of erosion and runoff (Cassman and Grassini, 2020).

Developing a new perennial grain crop sufficiently productive, nutritious, and profitable to achieve widespread adoption in replacing current annual wheat area remains a long-term proposition that requires 25–50 years when starting without competent commercial cultivars, established markets, and supply chains (Cox et al., 2005; DeHaan et al., 2005, 2018). Although IWG geneticists have produced one commercially available cultivar since 2005, and additional improved IWG lines are in late-stage development, our assessment of headway towards higher grain yields during the past 16 years found little evidence of progress in overcoming low yields and rapid yield decline after the first grain harvest. Hence, having competitive perennial grains to supplant a meaningful proportion of annual wheat production continues to be a distant goal, even with an adequately funded R & D programme. And Bob Loomis’ doubts about the potential for productive perennial grains, based on fundamental physiological conflicts between perenniality and productivity, remain unfuted.

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