Prospects for perennial grains in Australian farming systems – An overview

Richard C. Hayes[1], Matthew T. Newell[2], Philip J. Larkin[3], Lindsay W. Bell[4] and Rick S. Llewellyn[5]

[1] NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, Pine Gully Rd, Wagga Wagga, NSW 2650, richard.hayes@dpi.nsw.gov.au
[2] NSW Department of Primary Industries, Cowra Agricultural Research and Advisory Station, Binni Creek Rd, Cowra, NSW 2794
[3] CSIRO Agriculture and Food, GPO Box 1700, Canberra, ACT 2601
[4] CSIRO Agriculture and Food, PO Box 102, Toowoomba, QLD 4350
[5] CSIRO Agriculture and Food, PMB 2, Glen Osmond, SA 5064

Abstract
Over the last 10 years, perennial crop research in Australia has demonstrated the potential whole-farm economic benefits, the potential of a range of breeding lines over multiple years, and examined various aspects of perennial crop and cropping systems development. This paper provides a brief summary of the collective research effort, with a view to describing how research has progressed and the key challenges that still lie ahead. The Australian focus has been almost exclusively on perennial crops derived from wheat and/or wheatgrass parentage. The biological feasibility of harvesting grain off a so-called 'perennial wheat' crop for up to four consecutive years has been demonstrated, and has highlighted significant potential to add value to grain and graze production systems, particularly in higher rainfall environments. The ecological benefits of perennial cropping systems would be substantial, but will likely be dependent upon being able to develop farming practices that can accommodate perennial crops sown in mixtures with a legume. With some niche markets already demanding perennial grain products, the pressure is on researchers to continue to develop this transformative technology. However, a number of technical challenges remain, such as a requirement for consistent survival and grain yields over 3 - 4 years, and a better understanding of management practices that could improve the profitability of a genuinely novel cropping option. Future research efforts might also consider the potential of other perennial crops, such as sorghum, for Australian environments.

Keywords
Perennial wheat, longevity, monoculture, ecological intensification.

Introduction
There has long been interest around the world in developing viable perennial grain crops to maximise resource-use efficiency and reduce the soil degradation associated with intensive cropping practices based on annual species (Wagoner 1990). Initial research into perennial wheat in Australia was a pre-experimental modelling analysis which determined that perennial wheat could be feasible under Australian conditions if the crop could produce at least 40% of the grain yield of conventional wheat in addition to at least 800 kg/ha of biomass in autumn/winter for grazing (Bell et al. 2008). Subsequently, initial evaluations of early generation breeding material determined that a genuinely perennial crop derived from wheat was biologically feasible under Australian conditions (Hayes et al. 2012), with grain harvested from some lines for up to 4 consecutive years (Larkin et al. 2014). Research has continued since those initial studies to assess the potential of perennial wheat for Australian conditions. This paper summarises those results with a view to identifying the opportunities and future challenges in progressing perennial wheat towards commercialisation.

Perennial crop breeding and development
Two possible pathways to develop perennial wheat have been examined; interspecific hybridisation between annual wheat and a perennial relative, or 'direct domestication' of perennial species with selection for larger seed size and grain attributes (Cox et al. 2010). The majority of hybrid perennial wheat material so far evaluated in Australia was developed in the USA, and mostly derived either from tall wheatgrass (*Thinopyrum ponticum*: $2n = 10x = 70$) or intermediate wheatgrass (*Th. intermedium*: $2n = 6x = 42$), crossed with various annual wheats. Earlier selections from the domestication program of intermediate wheatgrass, marketed as Kernza, have also been included in most perennial grain field experiments in Australia. These were found to be much longer lived than the hybrid lines, but much less vigorous during the establishment year and with grain size of only a sixth of wheat.

Despite some success with US derived material, it was speculated that large gains in adaptation could be made if locally sourced parent lines were used in the primary wheat x wheatgrass crosses. A native Australian perennial relative of wheat, common wheatgrass (*Elymus scaber*: $2n = 6x = 42$), was identified as a broadly adapted and drought tolerant perennial relative of wheat, and so its summer survival mechanisms and capacity to be hybridised with wheat was examined (Newell et al. 2015). However, due to its short-lived nature and difficulties crossing this species with wheat it was concluded that the hexaploid *E. scaber* was not a priority candidate for future breeding efforts.

Perennial wheats, derived from interspecific hybridisation, are genetically stable when seven pairs of chromosomes are added from perennial parents to a complete wheat genome. In reviewing the genomic composition of the most promising wheat x wheatgrass hybrids, Larkin et al. (2014) concluded that the best near term breeding strategy may be achieved by using diploid perennial species, such as *Thinopyrum elongatum* (EE). In this way complete amphiploids are formed when crossed with wheat. This is analogous to Triticale development in which a hexaploid (AADDEE) is formed using a durum wheat or an octoploid (AABBDDEE) in the case of bread wheat. Primary perennial amphiploids could be intercrossed and advanced with selection, more easily than using partial amphiploids formed when polyploid perennial parents are used. Furthermore, perenniality might be enhanced if the wheat parent was a tetraploid. It is postulated that the genes conferring perenniality in this cross may be expressed more strongly compared to a cross from hexaploid wheat which contains 3 genomes from the annual parent and only one from the perennial. Despite the triticale experience offering something of a blueprint for this approach, no previous perennial wheat breeding effort to date has followed this model. It would therefore seem to be an obvious avenue to pursue to complement existing breeding initiatives internationally.

Agroecosystem function and the nitrogen (N) economy

The primary motivation for developing perennial grain crops is the environmental sustainability concerns of annual grain production. Annual-based cropping systems experience among the greatest frequency, extent and magnitude of disturbance regimes of all land-based ecosystems. This ‘disturbance’ is generally in the form of tillage and the use of herbicides, and leads to negative consequences through degraded soil structure, soil erosion, losses of soil organic matter, low nutrient and water retention, severe weed challenges and a less diverse or functional population of micro-organisms. Despite advances in minimum tillage technologies which have reduced some hazards such as soil erosion, annual based cropping systems remain compromised with respect to eco-system functions such as water and nutrient uptake and carbon sequestration/retention compared to other less disturbed ecosystems (Crews et al. 2016). The potential of a new species is never completely understood until it is fully developed and available for testing across multiple environments, and commercial deployment of perennial wheat still remains some years away. Nevertheless, a comprehensive review of agronomic and ecological literature suggests that perennial grain agriculture should feature several ecological functions that could greatly improve the synchrony between N supply and crop demand, leading to production efficiencies and reduced negative consequences for the environment. Those features include larger active soil organic matter pools, a more complex and stable microbiome to facilitate greater turnover of available N, greater N retention due to greater assimilation by deeply rooted perennial plants and greater microbial immobilisation, compared to annually cropped fields. The perennial cropping system would still require additions of N from external sources, in large part to balance product removal and to facilitate N-accrual in depleted soils. Synthetic fertiliser could make up this deficit, but it would seem that in order to fully capture the ecological benefits that a perennial crop has to offer, the N-deficit should be met through biological fixation from companion legumes (Crews et al. 2016). This raises the question of whether it is practical to plant a grain crop in mixtures with other species.

Mixtures or monocultures

A pilot field experiment was established at Cowra, NSW, to test the impact on crop yield, total biomass and nitrogen fixation in swards sown to experimental perennial wheat lines grown in mixtures with subterranean clover (Hayes et al. 2016). Results showed that clover biomass and regeneration was substantially reduced where it was grown amongst a vigorous crop canopy, leading to reduced inputs of fixed N. Spatially separating the perennial crop from the legume in alternate drill rows increased legume biomass by up to 128% and reduced weed incursion by 47% compared to where the two species were sown in the same drill row. However, spatial separation more than halved grain yields compared to where the crop was grown in every drill row. When estimates of the total inputs of fixed N from the clover were compared with the amounts of N removed in grain by the different perennial wheat treatments, it appears feasible that a companion legume could fix sufficient N to maintain the N balance of a perennial cropping system producing 1.5-2.0 t grain/ha each year. There is much research still to be done to refine management strategies and define the yield potential of perennial crops grown in mixtures with a legume. Research is presently hampered by under-developed perennial crop germplasm that is too short-lived to test competition dynamics over a longer timeframe. It is likely that the perennial wheat material will become more favourable compared to annual wheat if it was to survive and produce acceptable grain and dry matter yield for 3-4 years compared to the 1-2 years experienced with most of the current lines. A range of management strategies should also be tested in future research to manipulate competition dynamics between crop and legume species to optimise production, including choice of companion species, seeding density of both species and row spacing/spatial arrangement.

Prospects as a dual purpose crop

From the earliest economic analysis undertaken in Australia (Bell et al. 2008), the dual purpose grain and graze potential of a perennial cereal was identified as a crucial ingredient if the crops were to be financially viable at a commercial scale. This is further supported by the initial field evaluation which concluded that early generation perennial wheat was likely to be best adapted to higher rainfall environments in SE Australia (Hayes et al. 2012), where grazing is the dominant enterprise. An initial field study was undertaken to assess the suitability of four promising experimental lines of perennial wheat to defoliation, compared to one line of kernza and a commercial annual winter wheat, cv. EGA Wedgetail that was re-sown annually (Newell and Hayes 2017). The study also examined the forage quality and mineral composition of the breeding lines in order to establish their suitability for animal production. A key finding of the study was that there was no significant difference in grain yield between Wedgetail wheat and three of the four hybrid lines in the second year of experimentation, with one line actually yielding 60% more than the annual wheat control. This result highlights the importance of being able to monitor perennial crop performance over a longer timeframe, because in contrast to annual plants, the relative performance of perennials is not usually favourable in the establishment year. Newell and Hayes (2017) grew the treatments as spaced plants and could account for changes in plant density, concluding that much of the decline in perennial wheat yield over time previously reported is likely to be attributed to plant mortality rather than reduced yield potential.

Digestibility, metabolisable energy and fibre content of the perennial lines during autumn and winter were similar to that of annual wheat, with crude protein observed to be 62% and 25% greater in the Kernza and the perennial wheats, respectively, compared to Wedgetail. In some cases, cumulative biomass of the perennial lines over a 12 month period was in excess of 3 times greater than that of annual wheat, largely attributed to post harvest regrowth observed during summer and autumn. The winter herbage of the perennial lines generally had a higher proportion of Ca, Mg, K and P but lower proportion of Na compared to annual wheat. The study concluded that perennial wheat would provide valuable feed for livestock over a longer grazing window compared to annual wheat. However, due to the imbalance in forage mineral content, livestock grazing perennial wheat during winter are likely to still require Ca/Mg mineral supplementation to mitigate the risk of nutritional disorders in late pregnant or lactating ewes, as recommended in annual grazing wheats. Future research should consider the implications for the grazing enterprise of growing perennial crops in mixtures with a legume, rather than in pure swards.

Adoptability analysis

Using the ADOPT decision support tool (https://research.csiro.au/software/adopt/) estimations of the level and time to achieve peak adoption were made based on assumptions that perennial wheat would be used as a dual purpose cropping option for growers in the high rainfall permanent pasture zone of SE Australia. This zone represents in excess of 17.0 M ha spanning NSW, Victoria and Tasmania. The analysis suggested that the technology would take over 25 years from the first commercial release of a well-adapted perennial wheat cultivar to reach 80% adoption, reflecting the long-term nature of this field of research and the large changes required at the farm level to accommodate this genuinely novel species and production system. The key benefits to farmers in this region were associated with having a low input grain crop, and the flexibility to switch between grain or grazing according to seasonal conditions or the needs of their particular enterprise. There was little emphasis given to the projected environmental benefits in this zone because benefits would be expected to be small where a perennial grain crop replaced a mixed perennial forage grass/legume sward. As perennial grain technology is advanced further and becomes better adapted to more traditional cropping environments, environmental and financial benefits are likely to be significantly enhanced where they are replacing or augmenting annual cropping systems and where there is substantially more potential to reduce input costs. The current adoptability analysis also takes little account of novel grain quality attributes identified in existing material. Opportunity exists to exploit the diversity of the current material for particular quality attributes or for specific niche markets, such as the boutique Patagonia Long Root Ale (http://www.patagoniaprovisions.com/pages/long-root-ale), recently released and marketed as being made with Kernza grain. Such market developments could change predicted patterns of adoption considerably and would warrant additional analysis.

Conclusion

Research to date suggests that perennial grains are a genuine prospect for Australian farmers in the medium-long term. The proof of concept, both that a genuinely perennial cereal crop is biologically feasible and that the perennial crop is suitable for grain and grazing, has been established under Australian field conditions. Estimated adoption of a new perennial crop by farmers is predicted to be slow. However, a dynamic market environment where perennial grain products are already beginning to be marketed in the USA and elsewhere is a reminder that ultimate adoption will be heavily influenced by developments in perennial grain technology. The question of farmer adoption will need to be re-visited frequently along the path to commercialisation. There are several technical aspects requiring further research to progress perennial wheat towards commercialisation. Foremost is the need to further develop breeding material in order to increase the longevity of the crops presently available, particularly using locally adapted material. Following the triticale approach of developing complete wheat x wheatgrass amphiploids is recommended and will contribute to existing breeding efforts abroad. Global collaboration and material sharing between organisations will be important in the advancement of perennial crops for particular environments. Concurrent development of a novel cropping system is also necessary, and in particular, defining thresholds and management strategies to profitably move away from crop monocultures and accommodate mixed swards of cereals and legumes. It is also prudent to recognise that almost all the research in Australia to date has focussed on wheat derivatives. Alternative crops, such as perennial sorghum, may also offer promise for Australian crop and livestock producers.

Acknowledgements

Part of this work was undertaken within the GRDC-funded CRC Future Farm Industries EverCrop project, a collaboration between DAFWA, CSIRO, NSW DPI and regional partners. Earlier research to which this paper refers was conducted in collaboration with CSIRO, NSW DPI and Charles Sturt University, with financial support from the Future Farm Industries CRC.

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