# 25

# AGRONOMIC MANAGEMENT OF PERENNIAL WHEAT DERIVATIVES: USING CASE STUDIES FROM AUSTRALIA TO IDENTIFY CHALLENGES

*Richard C. Hayes*[1,3], *Matthew T. Newell*[2,3], *Mark R. Norton*[1,3]

1 Graham Centre for Agricultural Innovation (NSW Department of Primary Industries and Charles Sturt University) Wagga Wagga Agricultural Institute, PMB, Wagga Wagga, NSW 2650. Email: richard.hayes@dpi.nsw.gov.au

2 NSW Department of Primary Industries, Agricultural Research and Advisory Station, Binni Ck Rd, Cowra, NSW 2794

3 Future Farm Industries Cooperative Research Centre, 35 Stirling Highway, Crawley WA 6009

## ABSTRACT

The prospective development of viable perennial cereal crops is as much about developing novel farming systems as it is about developing novel germplasm. Unlike the development of other new crops such as triticale which could be quickly deployed into existing farming systems with only minimal adjustment, a perennial crop will require a substantial re-engineering of the farming system to take advantage of the production and ecosystem service benefits it potentially has to offer. Australia is a country in which pasture and crop production systems rely heavily on exotic species. Farming systems to utilize these species have therefore been developed over many decades and often differ markedly from production systems elsewhere around the world. The objective of this paper is to assess relevant case studies to identify likely challenges in the deployment of perennial cereal crops, with particular reference to perennial wheat. Perennial wheat crops are likely to be dual purpose crops used for grain and forage. They are likely to be for lower input systems that will require appropriate companion species for biological $N_2$ fixation and possibly to perform pest control functions in a perennial crop polyculture. Adequate nitrogen supply from biological sources will be a key challenge in viable perennial crop systems; the perennial forage grass experience in Australia highlights the chronic nitrogen deficiency that inhibits grass production in a conventional system that relies almost entirely on biologically-fixed sources of N. This paper provides examples of forage species which were developed in Australia that could present as useful templates in the development of a more biological production system based around perennial wheat. It also shows that different countries have different technologies and different perspectives that will potentially add value to the development of novel farming systems. The challenge to develop such novel farming systems will not be met easily and will likely require a multi-disciplinary, multi-institutional and probably global approach.

**Keywords:** farming systems, low input, monoculture, perennial grains

## INTRODUCTION

A recent evaluation of available germplasm has established the feasibility of the concept of perennial wheat (Hayes *et al.* 2012). That study quantified longevity and grain yield for up to three years and demonstrated an association between the capacity to regrow post-harvest and the presence of at least one whole genome equivalent (14 chromosomes) from the perennial donor species. A subsequent study (Larkin and Newell, 2014) has gone on to explore the ramifications of this finding in the context of progressing perennial wheat germplasm development based on the synthesis of complete amphiploids. Larkin and Newell (2014) liken this approach to the development of triticale; the hybridisation of wheat (*Triticum* spp.) and cereal rye (*Secale cereale* L.), and therefore establish that the genetic improvement of perennial wheat germplasm using this approach has a precedent from which knowledge and experience can be drawn.

However, while the genetic improvement of perennial wheat might be able to draw upon the triticale experience, the integration of the novel perennial wheat technology into commercial farming systems has no such precedent upon which to draw. Few perennial cereal crops currently exist in commerce. triticale, once developed, was able to be incorporated into existing annual crop rotations reasonably seamlessly. The availability of perennial cereal crops will present a unique challenge to develop a farming system that is sufficiently flexible to utilize its grain (Cox *et al.* 2010; Hayes *et al.* 2012) and grazing potential (Jaikumar *et al.* 2012; Newell *et al.* 2013), while at the same time allowing the crop to undertake the essential ecosystem services that have ultimately spurred their development in the first place (Glover and Renagold, 2010; Glover *et al.* 2012; Culman *et al.* 2013). Perennial wheat development therefore not only requires refining the genetics of the germplasm but also the development of suitable farming systems.

This review paper uses examples from existing Australian production systems to identify likely similarities and differences between management strategies required for a commercial perennial cereal crop in the future compared with various existing production systems. The emphasis on Australian farming systems is due to: i) similarity in emphasis on 'mixed' livestock and cropping production systems which have been previously identified as key targets for perennial crop technologies (such as in parts of Africa, see Glover *et al.* 2012), ii) Australia's ancient and inherently infertile soils, again a key target for perennial crop technologies, and iii) Australia's long history of development of novel farming systems based on the need to adapt exotic species to agricultural production in a unique and variable landscape/soil/climate matrix (Bell *et al.* 2013). Using examples and with a particular emphasis on perennial wheat, this paper highlights the importance of considering the end use of novel perennial grain technologies to inform priorities in germplasm development programmes and the way in which the germplasm is evaluated along its pathway to market. We assume a perspective of developing perennial wheat for the Australian market, but suggest many examples cited will have a broader relevance beyond the Australian context.

## THE AUSTRALIAN CONTEXT

Indigenous Australians were a hunter/gatherer civilization prior to European settlement in 1788. Agricultural production, in the European sense, is therefore relatively new to Australia. European livestock and cropping production systems needed to be adapted to Australian conditions due to the continent's inherently infertile soils (Hubble *et al.* 1983) and one of the most variable rainfall regimes on Earth (Love, 2004). As a result Australia's modern agricultural production systems are based predominantly on exotic species, notwithstanding a small number of exceptions – rangeland production systems being perhaps the most notable (Harrington *et al.* 1984).

Grain cropping in Australia is predominantly carried out in conjunction with grazing and livestock production – so called 'mixed farming' (Bell and Moore, 2012). Although it adds to the complexity of farm business management (Casburn *et al.* 2013) the mixed farming model offers a number of advantages over a single enterprise model. Firstly, a diversified business is more able to manage economic risk associated with inherently variable weather and commodity prices to which Australian farmers are routinely exposed (Hutchings and Nordblom, 2011). Secondly, a diversity of enterprises increases the capacity to utilize different soil types or landscapes that may exist within a given farm (Bell *et al.* 2013). Thirdly, there is the opportunity for synergistic effects between enterprises, such as fixed atmospheric nitrogen from a pasture phase becoming available during a subsequent cropping phase (Dear *et al.* 2004) thus reducing the need for fertilizer inputs. Notwithstanding, external factors such as reduced availability of labour relative to capital (Bell and Moore, 2012) exert significant pressure on Australian farmers to specialize, similar to their counterparts in other developed nations (Russelle *et al.* 2007; Wilkins, 2008).

The importance of pasture legumes to agricultural production on the infertile soils of Australia has been long recognised (Donald, 1965) and well described (e. g. Angus and Peoples, 2012; Peoples *et al.* 2012). However, very few herbaceous legumes native to Australia exist and many of those are toxic to livestock and unsuited to conventional production systems (Cocks, 2001). As a consequence and particularly post Second World War, Australian agriculture has embraced legume development perhaps more than any other country (Nichols *et al.* 2012) with programmes that have culminated in the release of many novel legume cultivars (Nichols *et al.* 2007). Nicholls *et al.* (2012) identify 30 different legume species that are all exotic to Australia but were first commercialised in Australia. Biological $N_2$ fixation from pasture legumes was the primary source of N for cereal crops prior to 1990 when the broadscale use of synthetic fertilizer N accelerated (Angus, 2001). Despite this management change, biological $N_2$ fixation remains important to contemporary Australian grain production systems (Angus and Peoples, 2012).

## THE TRITICALE EXPERIENCE

Triticale (*Triticosecale* Wittm.) provides a model for the development of a viable cereal crop through wide hybridisation. This wheat × rye hybrid is the most successful synthetic crop species produced (Ammar *et al.* 2004). Compared with wheat, triticale demonstrates superior adaptation to acid soils, drought, cold, infertile soils and has improved disease resistance (Giunta *et al.* 2003; Erekul and Kohn, 2006; Motzo *et al.* 2011). The intergeneric hybrid between hexaploid wheat (*T. aestivum*) and rye (2n =14 = RR genome) produces octoploid triticale (2n =56 = AABBDDRR genome), while using tetraploid wheat (*T. durum*) as a parent produces hexaploid triticale (2n = 42= AABBRR genome). Although the aim of hybridisation in this case was not for perenniality, the same principles can be applied to develop perennial cereals (Larkin and Newell, 2014).

Since the synthesis of triticale, most breeding efforts and improvement programmes have focused on hexaploid types which dominate world utilisation, mainly in animal feeding, both as a forage and grain (Ammar *et al.* 2004). Triticale production in Australia is approximately 0.75 million tonnes annually (J. E. Roake, 2013, personal communication). By comparison the average wheat production is 25 (USDA, 2013), making triticale only a minor component of cereal grain production in this country. triticale fits seamlessly into current cropping rotations, as basic agronomic practices such as seeding, fertiliser management, pest control and harvesting are similar to other cereals. As a dual purpose cereal, triticale offers an alternative to other grains in mixed farming enterprises. The nutritional characteristics of triticale are superior to wheat in terms of amino acids (particularly lysine, Mergoum *et al.* 2004) which makes it a sought after grain in ruminant and monogastric animal industries. However, the higher ash content, lower milling yields and inferior loaf volume and texture are detrimental for use in commercial baking (Salehi and Arzani, 2013). Many of the gene loci responsible for bread making quality (glutenin-encoding genes) are located on the 1D chromosome, which is lacking in hexaploid triticale. However, techniques exist which can identify greater proportions of glutenin content in hexaploid triticale, which would allow selection for improved bread making quality (Salmanowicz and Dylewicz, 2007). A high proportion of alpha-amalayse activity is also common in triticale grain which further limits dough quality and predisposes triticale to preharvest sprouting (Martinek *et al.* 2008). Addressing these grain quality issues will be important for improving market access of triticale into the future. So too, end use capability and market access will be important attributes for the success of perennial cereal crops. Some attention must be given to grain quality and target area of adaptation when developing perennial cereals to prevent these crops becoming "just another" feed grain or forage species.

## THE GRAZING CROP EXPERIENCE

Dual purpose crops (wheat, oats, barley, triticale and more recently canola) to produce both forage and grain, have been an integral part of mixed farming enterprises for many years, both in Australia and elsewhere (Dann *et al.* 1983; Virgona *et al.* 2006; Kirkegaard *et al.* 2012; Tian *et al.* 2012). The ability of annual crops to produce large quantities of herbage during autumn and winter offers an opportunity to rest pastures during this key period (McMullen and Virgona, 2009). The ability to graze dual purpose crops and produce harvestable grain, also improves the gross margin of the farming system and acts as insurance against harvest failure in a poor season and fluctuating commodity prices. This enables increased flexibility in decision making for the farm manager (Virgona *et al.* 2006; Moore, 2009).

Production from dual purpose crops requires a higher level of management as it requires earlier autumn sowing and then grazing in the winter. Earlier sowing takes advantage of warmer autumn temperatures for better crop establishment and crop vigour (Harrison *et al.* 2011). However, earlier sowing can predispose cereal crops to disease because of increased activity of fungal pathogens in warmer temperatures (Virgona *et al.* 2006). Effective break crops and resistant varieties are important to combat these issues, as are the use of pesticides. Similar issues are faced with canola as a grazing crop and the use of resistant varieties and careful grazing management are required to reduce disease incidence (Kirkegaard *et al.* 2012). While spring type cultivars can be used as dual purpose crops, winter types are favoured because of their longer period of vegetative growth. Grazing needs to be managed so that animals are removed before stem elongation. Once the crop matures to the reproductive stage, apical meristems rise quickly with stem elongation, increasing the possibility of removal by grazing and subsequent reduction in grain yield. Inputs of nitrogen (N) fertiliser are required following grazing to replace N removal by animals and to improve grain protein, especially in cultivars with higher grain quality (Virgona *et al.* 2006). While there are many factors that influence grain yield in dual purpose crops, grazing generally reduces grain yield (Harrison *et al.* 2011). However, with precise management grazing can have a positive effect on grain yield of grazed crops compared with their ungrazed counterparts. Grazing lengthens development and delays water use in crops (Virgona *et al.* 2006; McMullen and Virgona, 2009). This water can be conserved and used more effectively after anthesis, when assimilation is directed toward grain yield, thereby increasing water use efficiency. Earlier sowing also leads to deeper roots, increasing access to moisture in the soil profile. The delayed development can allow crops to respond to late season rain in favourable seasons and greater water use efficiency can improve yields under drier conditions.

Cereal forages are known to have extremely high nutritive value and to support high growth rates in sheep (Moore, 2009). However there is concern that the nutrient content of these forages may limit growth rates of grazing animals and lead to nutritive disorders (Berger, 1992; Dove and McMullen, 2009), particularly regarding the ratios of potassium (K), magnesium (Mg), sodium (Na) and calcium (Ca). All cereals contain sufficient Ca for ruminant dietary requirements but K contents can be up to ten times the required intake, while the Mg and Na content for wheat in particular, is generally below dietary requirements (Dove, 2007). Winter grazing of grass monocultures that have high levels of protein and K with relatively low quantities of Mg and Na causes reduced Mg adsorption in the rumen. This inhibits weight gain in animals and can lead to the hypomagnesaemia (grass tetany) disorder (Brightling, 1994). Mineral Supplements are required to correct these deficiencies. Indices of cation ratios can be helpful in deciding the supplement requirements from different forages. Cation ratios K/(Mg + Ca) exceeding 2.2 indicate the need to supplement diets with Mg. Cation ratios for wheat have been reported as high as 3.7 (Dove and McMullen, 2009). By comparison cation ratios for subterranean clover (*Trifolium subterraneum* L.) range from 0.9-1.3 (Dove, 2007). Indices for K:Na have not been quantified, however Na supplementation is also recommended when grazing winter wheats (Dove, 2007). These findings suggest that adverse animal health implications of grazing a perennial cereal crop could be reduced where the crop is grown as part of a polyculture in which grazing animals are exposed to different forages.

## THE PERENNIAL FORAGE GRASS EXPERIENCE

Associated with Australia's extensive breeding, development and commercialisation of annual forage legumes from the Mediterranean Basin was the early realisation that these legumes had to be grown in a mixture with a productive companion species. This was necessary because pure annual legume swards tend to be prone to weed invasion and thus not very productive. Growing these legumes with a grass companion greatly increased overall productivity and because the N fixed by the legume would be used by the grass companion the botanical stability of the sward was also improved. The most common grass companion during the early stages of development of this pasture technology was annual ryegrass (*Lolium rigidum*; Oram, 1990). This species is rarely recommended now because of several disadvantages including (a) weed potential to cereal crops, (b) alternative host of several cereal diseases and (c) the annual habit may exacerbate soil problems including erosion, waterlogging and acidification. Perennial pasture grasses, such as phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*) are broadly utilised in Australian farming systems because they do not have the disadvantages of ryegrass or other annual grasses and have been shown to enhance farming system sustainability (Dear *et al.* 2007).

The temperate perennial grasses that are important in the mixed farming zone of southern Australia, phalaris, cocksfoot and tall fescue all contain a wide degree of genetic variability associated with the fact that all their zones of origin encompass large tracts spreading from Eurasia, across the Mediterranean Basin to the verges of the Sahara in North Africa (Anderson, 1961; Borrill, 1972; Lumaret, 1988). Indeed, a key element of the development of appropriate adaptation in these grasses for Australia has involved germplasm discovery in Eurasian and north African isoclimes (Neal-Smith, 1955). Because the zones of adaptation of these species cover such large regions, the range of climates to which adaptation within any one of these species is found is also large. Thus populations from the cool to cold temperate, summer rainfall dominant zones in north-western Europe typically are summer active while those from arid Mediterranean climates of North Africa with summer dry periods of four months or more are winter active and summer dormant (Cooper, 1963). Indeed, some of the grass cultivars best adapted to Australia's drier mixed farming zones, e.g. Sirocco phalaris, Kasbah cocksfoot and Resolute tall fescue, trace their parentage back to populations collected during expeditions to Africa and the Near East. Ideally, perennial donor species for perennial cereal crops intended for Australian environments would also be sourced from Eurasian and/or north African environments, if no suitable native species could be identified.

Perennial grasses able to survive the hot, dry summers which are typical of southern Australia generally have to express one or a combination of traits including summer dormancy (Volaire and Norton, 2006), dehydration avoidance (Norton *et al.* 2012), or dehydration tolerance (Volaire and Conejero, 2001) to ensure survival. In addition lenient grazing over the summer may also be required because the joint stresses imposed by defoliation and drought, which threaten both plant carbohydrate reserves and water status, are important in reducing survival of perennial pasture grasses (Volaire, 1995; Hacker *et al.* 2006). In addition, some species, e.g. cocksfoot, typically shed many roots over dry summers and this may make them susceptible to being pulled out of the soil by livestock if grazing occurs before replacement roots have regrown sufficiently (Ridley and Simpson, 1994). It will be important to understand the nature of the perennial cereal crop rooting structure in order to develop a grazing system that maximises productivity but does not compromise plant persistence.

The length of time that a sown perennial grass based pasture is likely to persist is a key determining factor that the farmer must consider when deciding whether or not it is economic to sow a new pasture. The decision will also be influenced by the costs associated with pasture improvement and the extra income that the farmer will likely obtain from the improvement. Decision support tools are increasingly being used to assist in the making of these decisions (e.g. www.evergraze.com.au/tools.htm). However, in any case there will be a minimum amount of time over which the newly sown pasture must persist and produce for the farmer to recoup his investment (break-even period) and this will be influenced by the genetic makeup of the new pasture (i.e. how well it is intrinsically adapted to the environment), and the management that the pasture experiences. Commonly break-even periods of 6-10 years are quoted for pasture resowing although depending upon the rate of return required on investment this may even increase to 20 years (Scott *et al.* 2000). As a consequence persistence is acknowledged as an important attribute that any successful cultivar should possess. Longevity of a perennial cereal crop will too be an important factor in determining its economic viability, though income received from grain yields would likely reduce its required persistence, compared with a perennial forage grass.

When the agronomic practises used for the various types of grasses are considered, the perennial grass crop which is maintained primarily for seed production is the closest analogue we have which mimics a perennial, dual-purpose, forage/grain cereal. The management of any perennial grass will, by necessity be quite different depending upon whether it will be used solely for forage or have a dual purpose as a forage and grain/seed crop. The practise absolutely essential to maximise grain/seed yield is to protect the reproductive tillers from defoliation. This necessitates the removal of grazing animals or the cessation of cutting prior to when reproductive tiller elongation commences. Similarly management practises, e.g. sward renovation, fertilisation, plant protection etc. to maximise the density of fertile reproductive tillers which are initiated will optimise yield potential. In the same way reducing the likelihood of lodging, perhaps by application of straw shortening hormone, during the late reproductive growth stage is increasingly recommended to improve seed yield recovery.

In contrast, for a grass whose primary function is forage production the protection of the reproductive tillers is generally not particularly essential. This is especially so because for most perennial forage grasses recruitment of young plants from seed is not the primary means of sward perenniation but rather the long term survival of adult plants. Perennial grasses grown for forage in Australia are almost always sown with a companion legume the aim being two-fold, to improve sward forage quality and enhance soil nitrogen status through biological $N_2$ fixation. In contrast, perennial grass seed crops are rarely grown with a companion legume as the seed is usually of high value so that seed producers are able to absorb fertilisation costs. Moreover, the agronomy required for maintaining a mixed grass/legume sward is more complicated than pure grass culture and the favourable returns make additional complexities unnecessary. In contrast, the value of grain produced by a perennial cereal will certainly be much less than seed produced by a perennial forage grass. Consequently the forage produced by the perennial cereal will assume an important part of the overall value of the crop, particularly if as demonstrated in a previous modelling exercise, it is produced, 'out-of-season' in autumn in southern Australia (Bell *et al.* 2008). Whether substantial 'out-of-season' autumn forage production will be achievable from a cool season perennial grass at a time of the year normally quite dry remains to be seen.

## MONOCULTURES VERSUS POLYCULTURES

Various authors have suggested that a move toward perennial crops may also represent a move away from the reliance on monocultures (Cox *et al.* 2006; Glover *et al.* 2007; Glover and Renagold, 2010; Glover *et al.* 2012). Recent research in forage species would support the notion that perennial crop-based polycultures could be commercially feasible to the extent that increased species richness on average increases total biomass productivity and weed suppression in perennial herbaceous polycultures (Tracey and Sanderson, 2004; Picasso *et al.* 2008; 2011). However, this is in a pure forage production system – what negative impacts could we anticipate on grain production of perennial cereals grown in a mixed sward?

The fundamental basis for targeting a polyculture system is to enhance resource utilisation through complementarity of companion species (Glover and Renagold, 2010; Picasso *et al.* 2011). The most obvious example of complementarity is the synergy between a $N_2$-fixing legume providing N to non-legume species growing in the same sward. In designing perennial crop-based polycultures, it would seem the integration of appropriate companion legumes would be an obvious place to start. Nitrogen is a critically important macro-nutrient for forage and grain-crop species alike, and a farming system that reduced or eliminated the need for synthetic nitrogenous fertiliser would quickly achieve many of the fundamental imperatives of a perennial crop, such as reduced nutrient leakage and lower input requirement (Glover *et al.* 2007, 2012; Glover and Renagold, 2010). Yearly nitrogenous fertiliser consumption for annual cereals grown in Australia totals $702 \times 10^6$ kg/ha, the highest use of any agricultural enterprise (Chen *et al.* 2008). A great proportion of the applied nitrogen is lost, with efficiencies of uptake for cereals such as wheat quoted at 41 percent (Chen *et al.* 2008). The loss of nitrogen represents a significant business inefficiency for farmers as well as having negative implications for the environment and human health. Perennial grains grown in polyculture could provide a way of reducing synthetic nitrogenous fertiliser use in cereal grain production systems.

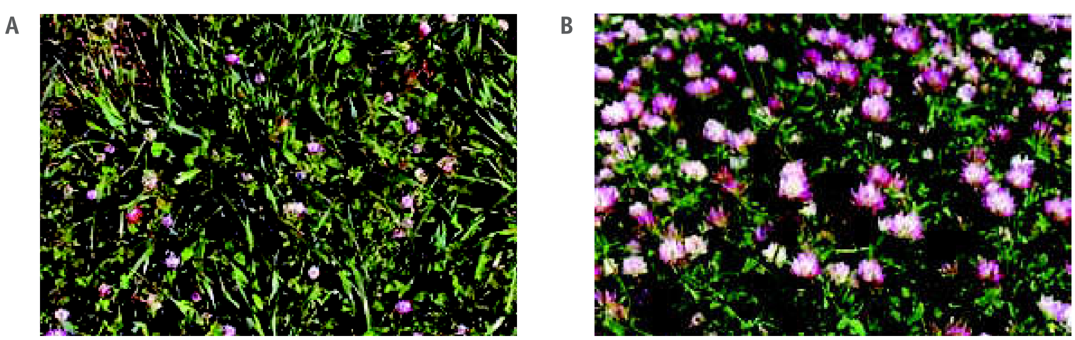
Several surveys conducted across southern Australia (e.g. Fortune *et al.* 1995; Bowman *et al.* 2004; King *et al.* 2006) have commonly found legume composition in commercial mixed pasture swards to be inadequate. The reasons for this are varied but it highlights a practical challenge which is likely to exist if we also expect legumes to coexist with perennial cereal crops. One contributing factor to the Australian experience is the paucity of adapted perennial legume species, particularly in drier cropping-zone environments (Cocks, 2001; Dear *et al.* 2003a; Li *et al.* 2008). Therefore Australian pasture swards are overwhelmingly reliant upon annual legumes such as subterranean clover (*Trifolium subterraneum*) and barrel medic (*Medicago truncatula*). Perennial crops in Australia will also probably be reliant upon annual legume species unless the target environment is the high rainfall permanent pasture zone where white clover (*T. repens*) and Caucasion clover (*T. ambiguum*) are more likely to be adapted (Virgona and Dear, 1996; Lane *et al.* 2000), though seed of the latter species is difficult to obtain at present. Mixtures with alfalfa

(*Medicago sativa*) is a possibility (Boschma *et al.* 2010) in the cropping zone although its supreme capacity to extract soil water in moisture limiting environments (Hayes *et al.* 2010b) is likely to have a negative effect on companion perennial crops similar to its effect on companion annual legumes (Dear and Cocks, 1997) or over-sown cereal cover-crops (Norton and Koetz, 2013).

The nitrogen requirement of perennial cereal crops needs to be determined so that the 'adequate' legume content can be defined. Perennial forage grasses are highly responsive to N fertiliser (e.g. Mills *et al.* 2006) although critical N requirements of common perennial grass forages in Australia are still to be defined. Stork and Jerie (2003) calculated the relative uptake of inorganic N between late autumn and early spring (1 year only) to be 169 kg N $ha^{-1}$ under one year old phalaris. However, Dear *et al.* (1999) demonstrated that a phalaris/subterranean clover mixed sward was only capable of fixing 143-177 kg N $ha^{-1}$ over three years; less than one third the requirement of the perennial grass component, even ignoring the fact that only a proportion of total N fixed in a mixed sward will become available to the grass. Therefore in an Australian system we could expect that perennial grasses grown in mixed commercial swards would typically exist in an almost permanent state of N deficiency. The N-status for perennial cereal crops could be even more constrained due to the elevated N demand for grain production. This needs to be quantified, as does the importance of timing of N supply to a dual purpose cereal crop. The N status of a mixed perennial grass pasture sward in Australia is likely to be better in autumn due to increased mineralisation and reduced N demand over summer, while supply in spring is likely to be much more limiting and it is unclear what implications this would have on grain yield, grain quality and longevity of a perennial cereal crop.

Nitrogen nutrition is more complex than other nutrients because of the strong relationship between plant growth, nitrogen availability and available soil water.

**FIGURE 1.** PERENNIAL GRASS AND ANNUAL FORAGE LEGUME



**A.** **A mixed forage pasture sward containing a perennial grass (*Phalaris aquatica*) and self-regenerating annual legume species ( *Trifolium subterraneum*, *T. michelianum* and *T. glanduliferum* )**

**B.** **Gland clover (*T. glanduliferum*); A self-regenerating annual forage legume released commercially in Australia for its superior insect pest resistance**

Assumptions can be made to calculate the N requirement of conventional wheat. Following Glendinning (2000); if we assume a grain protein content of 11 percent and a protein conversion factor (PCF) of 1.75[1], the estimated grain nitrogen yield is 11×1.75 = 19.2 kg N/tonne grain. The quantity of soil nitrate required is a function of grain nitrogen yield divided by the N-uptake efficiency (NUE). NUE (efficency with which fertiliser N is converted to grain protein) varies according to the physiological state of the plant, but is estimated to range from 50 percent around sowing down to approximately 15 percent at head emergence (White and Edwards, 2008). Assuming a 50 percent NUE, the estimated quantity of soil nitrate required to produce 1 tonne of grain is 19.2/0.5 = 38.5 kg N/tonne. Therefore an average 3 tonnes/ha wheat crop would require 115.5 kg of nitrate N. However, as the grain protein content increases, the NUE decreases, as the crop has difficulty accessing enough water to use the extra nitrogen required for increased protein (Herridge, 2011). Thus at a grain protein level of 14 percent, NUE falls to 34 percent, requiring 75 kg N to produce a tonne of grain.

Assuming 25 kg of atmospheric N is fixed in annual legume shoots for every tonne of DM of legume shoot biomass produced (Dear *et al.* 1999) and making an allowance for an additional 20 kg fixed N/tonne legume DM associated with or derived from legume roots (Peoples *et al.* 2012), total N fixed biologically is equivalent to 45 kg/tonne of total legume DM. Assuming that 50 percent of the total N fixed becomes available to the crop, a wheat crop yielding 3 tonnes/ha at 11 percent protein would require 5 tonnes/ha of legume biomass to supply nitrogen to the system. A number of limitations are acknowledged with the above calculations:

1. the N requirement to produce 1 tonne of grain from perennial wheat may differ to that estimated for annual wheat due to factors such as a different PCF or different grain protein level
2. the proportion of legume N derived from atmospheric $N_2$ will vary according to legume species, seasonal conditions and soil factors
3. the actual proportion of legume N available to the companion crop will be dependent upon factors such as grazing strategy, mineralisation rates and transfer mechanisms between crop and legume plants.
4. in a dual purpose crop, an allowance needs to be made for N removed due to grazing

Nevertheless, the above provides a starting point in determining how much N a perennial wheat polyculture might need, and illustrates the high legume content required if biologically fixed N would be the sole source of N. To put these values into context, total pasture herbage production of various perennial-based pasture swards in two representative Australian field environments ranged from 24-31 tonnes/ha over five years (Hayes *et al.* 2010a) or an average of 5-6 tonnes/ha/year. In such an environment where biomass production can be so low, a major question must be whether a perennial crop grown with the robust companion legume component

1 The PCF for other crops is commonly 1.6; the PCF for perennial wheat is unknown and will need to be determined

necessary to supply the crop's full N requirement can be commercially viable? It is possible that a system that uses legumes in addition to strategic applications of N fertiliser be developed to reduce the legume composition necessary to supply adequate N, although Peoples *et al.* (2012) highlight the negative effect N fertiliser can have on biological $N_2$ fixation.

A polyculture is clearly an advantage relative to a monoculture from the perspective of grazing due to: i) the reduced likelihood of adverse animal health conditions and ii) improved forage quality. Grazing ruminants have evolved to ingest a diverse diet, and significant health disorders can ensue if that diversity is not maintained. In general, the ruminant gut relies on an ecosystem of microorganisms to break down food, and the composition of that ecosystem is dynamic and responsive to a changing feed source (Cottle, 1991). Where an imbalance occurs in the diet, there is risk of an imbalance in the gut which can lead to negative effects on health that are sometimes irreversible. These negative effects can occur even when the diet is of high quality, for example, red gut (Gumbrell, 1997) and bloat (FitzGerald *et al.* 1980) from legume pastures or acidosis and lupinosis from grain diets (Brightling, 1994), highlighting the risks to animal health that high quality but imbalanced diets can present to ruminant livestock. The grass tetany example mentioned earlier relating to grazing annual cereal crops is perhaps more indicative of the type of disorder a monoculture perennial cereal crop may present. Regardless, these disorders can usually be managed if there is a balanced diet highlighting a clear advantage of a dual purpose crop grown in a polyculture as opposed to a monoculture.

In addition, a vibrant legume component can improve forage quality for the grazing livestock. Legumes, such as alfalfa, often have a higher protein content and concentration of minerals in their shoots than grasses (e.g. Hayes *et al.* 2008; Hayes *et al.* 2010a). Thus, their presence in a mixed legume/grass sward presents as a high quality component available to browsing livestock. Moreover, the presence of a legume can significantly enhance the quality of the grass herbage through increased N-supply to the grass. Mills *et al.* (2006) showed that the addition of N increased the crude protein of cocksfoot herbage by up to 4-fold and more than doubled the metabolisable energy, in part a reflection of the doubling of pasture growth rates due to additional N. The ability of legumes to substantially enhance the N supply to companion grasses primarily relies on the pasture sward containing a substantial legume content (Peoples *et al.* 2012) and depends upon the efficiency of transfer of N between the legume and grass components.

In its simplest form, a perennial cereal/forage legume polyculture is only a binary mixture and it is acknowledged that production benefits of mixtures may not be fully realized until three or more complimentary species are included (Tracey and Sanderson, 2004). As described above, nitrogen fixation from a legume component is an obvious and easily defined benefit of a polyculture but there are potentially other benefits. Glover *et al.* (2012) describe the 'push-pull' benefits alternative species may offer in controlling pests, particularly in low input production systems. Very briefly the 'push' refers to species that can repel pests thus pushing them away from the valuable crop plant; the 'pull' referring to plants that can attract pests towards them and away from the crop plant. The effectiveness of a push-pull strategy is likely to be site dependant and will vary according to factors such as the type and severity of the pest incursion and the availability of plants with properties capable of pulling or pushing the pest(s) in question. However, there would appear to be enormous potential for research as the push-pull potential of most species is poorly understood.

There are undoubtedly candidates from Australia's various plant development programmes that may have a use in a push-pull context despite this not being the primary motivation for their development. Gland clover (*T. glanduliferum*) was commercialised by Australian scientists for use as a novel alternative in the pastures of mixed farming systems in medium rainfall environments (Nichols *et al.* 2007), particularly on heavier soils (Dear *et al.* 2003b). It has a unique resistance to various insect pests such as redlegged Earth mite (*Halotydeus destructor*), as well as blue green (*Acyrthosiphon kondoi*) and cowpea (*Aphis craccivora*) aphids and although it has been evaluated in forage mixtures (Dear *et al.* 2002; Hayes *et al.* 2008), its potential as a 'push' species was never specifically tested. Biserrula (*Biserrula pelecinus*) is another novel annual legume species also released by Australian scientists as a viable small-seeded legume for pasture crop rotations, particularly where acid soils constrain production (Nichols *et al.* 2007). Sheep tend to avoid grazing this species at certain periods during the year which has fostered its promotion as part of a non-herbicide weed control strategy. It is possible that this species could be incorporated in a non-herbicide weed control perennial crop based system.

These examples highlight two potential opportunities for future perennial grains research. Firstly, they demonstrate that alternative species already exist in commerce around the globe that may have potential to provide complimentary benefits to perennial crops but are yet to be tested in this context. Secondly, it reminds us that germplasm may have existed in previous plant development programmes with similar potential but which were never commercialised because the target market at the time was not focussed on complimentary benefits to other species (certainly not perennial crops) but instead the potential contribution these species could make to production systems in their own right. In a perennial grains context it will be important to define the essential characteristics required of companion species to guide the selection of companion species with which early generation perennial crops should be tested. Both examples above are legume species capable of high rates of biological $N_2$ fixation, highlighting the likelihood that companion species in a perennial crop context will be required to perform more than one function.

## GERMPLASM AND FARMING SYSTEM CO-DEVELOPMENT

The vision for diverse perennial grain cropping systems to replace monocultures of annual crops has been described by various authors previously (e. g. Glover *et al.* 2007; Cox *et al.* 2010). However, in contrast to Cox *et al.* (2010) who suggested that "before such systems can be deployed and tested, new perennial...crops must be developed through breeding", we contend that the process of crop development and farming system engineering should not be separated.

Moreover, the perennial grain crop will ultimately be more successful in commerce and achieve greater environmental impact if the development of both the crop and the farming system occurs concurrently, and better still, if one informs the other in an iterative, multi-disciplinary process.

The temperate perennial forage grass experience in cropping environments of southern Australia provides a useful example highlighting the importance of co-development of the germplasm and the grazing system. Phalaris – another example of an exotic forage species that was primarily developed in Australia (Oram *et al.* 2009) – and cocksfoot are key temperate perennial grass forages in Australia. However, though they are used widely in higher rainfall, permanent pastures, only a few cultivars of either species exist that are suited to drier cropping environments and seed of these cultivars is incredibly difficult to obtain - Australia is currently experiencing market failure in regard to these cultivars. We contend that a major cause of the current market failure was the failure of the local industry to develop the farming system adequately. There is little doubt that the cultivars, primarily Sirolan phalaris (Oram *et al.* 2009) and Kasbah cocksfoot (Oram, 1990), are agronomically suitable to their target environment (Hackney *et al.* 2006 and unpublished data). However, their addition to the phased farming system of southern Australia brought additional complexity to the management regimes which was never adequately explored by the research community and probably explains much of the reason why farmers felt it easier to leave these species out of their rotations. For example, no selective grass herbicides currently exist which are registered for use to control annual grass weeds in establishing perennial grass-based swards (Dear *et al.* 2006) and no integrated weed management strategy has been developed or tested to provide farmers with workable strategies to control their grass weeds in a perennial-grass based sward. Likewise, no previous research has tackled the nitrogen question in relation to perennial grass swards. Farmers require their pasture phase to leave adequate residual soil N for use by subsequent crops (Angus, 2001). Perennial grasses are known to be highly competitive with annual legumes and therefore suppress nitrogen fixation of the total sward (Dear and Cocks, 1997; Dear *et al.* 1999; Dear *et al.* 2000). But no research has yet answered the question of how perennial grasses can be included into cropping rotations in such a way that maintains adequate levels of biological $N_2$ fixation. Due to the lingering questions about management issues such as weed control and N supply, Australian farmers in the mixed farming zone have avoided utilising these grass cultivars, which has sent feedback through the seed supply chain over the last two decades rendering these cultivars commercially unviable and culminating in a situation in which even a progressive farmer would find incorporating these species problematic due to the paucity of commercial seed.

An existing research project, EverCrop™ (Llewellyn *et al.* 2013), is currently examining the problems around the inclusion of perennial grasses into cropping systems and is trialling the practice of planting mixed swards in monoculture rows. However, an additional problem facing this project is the negative perceptions that some farmers have of perennial grasses in these systems on account of their previous bad experience with the technology. Because the cultivars were developed in isolation from agronomy management research, they failed to meet the expectations of farmers. On account of prejudices which exist with some farmers in relation to these grasses, it is now much more difficult for researchers to achieve meaningful practice change on farm. It is our contention that perennial wheat developers should heed the lessons of Australia's perennial grass experience; perennial wheat technology is likely to be much more successful if a suitable farming system exists at the time the germplasm first becomes commercially available, and the integration and adoption of the new technology will be easier to achieve if bad commercial experiences are avoided.

## REFLECTING UPON INITIAL EVALUATION OF PERENNIAL CEREALS

The initial evaluation of perennial wheat derivatives undertaken in Australia (Hayes *et al.* 2012) established the feasibility of the concept of perennial wheat and helped researchers define a strategy for continued development of the wheat × wheatgrass germplasm (Larkin and Newell, 2014). Despite the constraints of limited seed supply hampering the evaluation, a number of inferences could be drawn from the initial study with regard to the likely farming system required of a perennial wheat crop in Australia. It was established that early-generation perennial wheat derivatives were unlikely to persist unless they were grown in high-rainfall environments. Without the introduction of summer dormancy traits the germplasm is unlikely to be able to persist through the hot and dry summer conditions typical in most conventional Australian cropping environments. This is certainly the experience of temperate perennial forage grasses in Australia (Hackney *et al.* 2006; Hayes *et al.* 2010a) and elsewhere (Malinowski *et al.* 2005; Norton *et al.* 2006a,b). However, as with perennial forage grasses it is acknowledged that zones of adaptation can change with continued plant breeding and development. This insight on zone of adaptation immediately provides direction as to the initial companion species that might be targeted in an Australian context; annual and perennial legume species suited to higher rainfall/permanent pasture regions.

However, the initial evaluation was conducted on monoculture, and in many cases, on single row plantings, neither of which is likely to be relevant to commercial perennial wheat plantings. We acknowledge that there will always be a role for testing germplasm in monocultures and, as with the initial evaluation in Australia, monoculture testing is sometimes unavoidable. But if perennial wheat is ultimately envisaged to be grown in polycultures, we suggest that evaluations of perennial crop technology in polyculture occurs early in the development pathway to ensure that the technology is relevant to the situation for which it is intended and that when a perennial crop technology becomes commercially available, a good body of knowledge already exists as to the appropriate management strategies. Most evaluations of forage species in Australia, both legumes and grasses, assess species and cultivars in monocultures. It is understandable why this occurs in the context of measuring relative performance and eliminating all possible sources of error. However, for species that are never to be used as monocultures commercially, surely it is a failing never to test them in their commercial setting until after release. The case for evaluating perennial grains in polycultures is even stronger than for forage species in Australia because not only does the evaluation process screen germplasm, it also develops and refines management strategies for this novel technology.

One final observation: the initial evaluation of perennial wheat in Australia (Hayes *et al*. 2012) was unexpectedly successful. The project had a relatively small budget, none of the germplasm tested was developed for the Australian environment, and none of the research team had previous experience in growing perennial cereal crops. However, the project was able to establish the biological feasibility of perennial wheat crops in Australian environments and could associate the capacity for PHR with the addition of one extra genome equivalent from the perennial donor, thus paving the way for the development of a breeding strategy for the crop (Larkin and Newell, 2014). The success of the research initiative was in no small way attributable to the collaborative, multi-disciplinary approach the project took. The collaboration first relied upon an institution, the Future Farm Industries Cooperative Research Centre, to invest in genuinely '*blue-sky*' research and on research providers (NSW DPI, CSIRO and Charles Sturt University) to co-invest with infrastructure and the valuable time of their staff. Second, it relied upon generous contributions by partner agencies on the other side of the globe, The Land Institute and Washington State University, to provide free and ready access to their best available germplasm. Third, it relied upon the competency of a research team which collectively possessed a broad range of skills including crop agronomy, pasture agronomy and adaptation, physiology, genetics, molecular biology and cereal chemistry. The Australian team also had an advantage in that they were not constrained to biological methods for conducting experiments. This meant they were free to use herbicides, fungicides and fertilisers as appropriate which no doubt assisted in evaluating the genetic potential of the germplasm. It is likely that future success in the challenging field of perennial grain development will also require a multi-disciplinary, multi-institutional and probably international approach.

## SUMMARY AND CONCLUSION

Triticale, the most successful hybrid crop, establishes a precedent by which genetic improvement in perennial wheat might be achieved. Despite its superior adaptation to a range of biotic stresses triticale is underutilised in Australia due to its inferior grain qualities, particularly properties important to commerce viz. baking and malting, rendering its grain less valuable than other cereals such as wheat and barley. This is a reminder that the end use of the product is an important consideration determining the extent to which benefits of the genetic gain achieved in the breeding of this crop are realized in the commercial world. So too, the end use of perennial crops needs to be defined and articulated early in the development process to facilitate maximum impact of the technology.

Existing grazing crops provide confidence that the dual-purpose attributes of a perennial cereal will likely add to the flexibility and resilience of mixed farming enterprises, capitalising on the financial benefits associated with diversified income streams as well as improved adaptation to variable weather patterns. Avoiding animal health risks associated with grazing monocultures, and meeting the elevated N requirement caused by N-removal from grazing livestock will be key challenges to be met in perennial cereal production systems. However, the use of perennial cereals in polycultures with legumes will potentially overcome both these constraints.

The temperate perennial forage grass experience in southern Australia provides both hope and caution for the development of viable perennial cereal production systems based on polycultures. Perennial forage grasses in Australia typically rely almost entirely on biological $N_2$ fixation from pasture legumes and thereby present as an example of a viable polyculture production system. However, a range of factors such as the paucity of legume species available (particularly perennials), the variability of $N_2$ fixation in the field and the competition between the grass and legumes growing in the same sward mean that perennial grasses likely exist in an almost permanent state of N-deficiency. Using figures from existing industries, early indications suggest that the N-requirements of perennial cereal crops would be even greater than that for perennial forage grasses due to the need to maximise grain yield and grain quality. The suggestion offered in this paper of 5 tonnes of legume DM required in a polyculture to supply adequate N for 3 tonnes of perennial wheat grain could be proven incorrect in time if our various assumptions are wrong, but it paints an ambitious picture of the potential composition of a perennial wheat/ legume polyculture raising questions as to whether a polyculture that supplied 100 percent of the crop's N requirement is commercially feasible. This is a priority area of research in perennial crop development. If a polyculture remains the preferred model for perennial cropping systems, the multiple roles of the companion species need to be defined so that suitable species are identified and tested. This paper highlights the potential of legumes commercialised in Australia to perform multiple functions as companions in perennial cropping systems, but there is a need to screen a wider range of potential species for their suitability.

Many challenges lay ahead on the road to developing a viable perennial crop. Germplasm development itself is not trivial, but the need for novel farming systems adds to the challenge. It is unlikely this challenge will be met by individuals operating in isolation. The *Perennial Wheat Feasibility Study* undertaken in Australia presents as an example of the unexpected success that can be achieved in this challenging field of research particularly where vibrant multi-disciplinary, multi-institutional and global collaboration exists. We contend that future challenges in perennial crop development will be best met by a similar but scaled-up collaborative approach.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Future Farm Industries Cooperative Research Centre, NSW Department of Primary Industries, CSIRO and Charles Sturt University for their vision in supporting the *Perennial Wheat Feasibility Study*.

## REFERENCES

**FAO.** 2004. *The history of evolution of triticale. Triticale improvement and production*, by Ammar, K., Mergoum, S. & Rajaram, S. FAO plant production and protection paper 179.

**Anderson, D.E.** 1961. Taxonomy and distribution of the genus *Phalaris*. *Iowa State Journal of Science.* 36: 1-96.

**Angus, J.F.** 2001. Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture.* 41(3): 277-288.

**Angus, J.F. & Peoples, M.B.** 2012. Nitrogen from Australian dryland pastures. *Crop and Pasture Science.* 63(9): 746-758.

**Bell, L.W., Byrne, F., Ewing, M.A. & Wade, L.J.** 2008. A preliminary whole-farm economic analysis of perennial wheat in an Australian dryland farming system. *Agricultural Systems.* 96: 166-174.

**Bell, L.W. & Moore, A.D.** 2012. Integrated crop-livestock systems in Australian agriculture: Trends, drivers and implications. *Agricultural Systems.* 111: 1-12.

**Bell, L.W., Moore, A.D. & Kirkegaard, J.A.** 2013. Evolution in crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy*. **In press.**

**Berger, L.L.** 1992. *Grass tetany: causes and prevention*. Salt Institute report.

**Borrill, M.** 1972. Studies in *Festuca*. III The contribution of *F. scariosa* to the evolution of polyploids in sections of Bovinae and Scariosae. *New Phytologist.* 71: 523-532.

**Boschma, S.P., Lodge, G.M. & Harden, S.** 2010. Seedling competition of lucerne in mixtures with temperate and tropical pasture species. *Crop and Pasture Science.* 61(5): 411-419.

**Bowman, A.M., Smith, W., Peoples, M.B. & Brockwell, J.** 2004. Survey of the productivity, composition and estimated inputs of fixed nitrogen by pastures in central-western New South Wales. *Australian Journal of Experimental Agriculture.* 44(12): 1165-1175.

**Brightling, A.** 1994. *Stock diseases. Diseases of beef cattle, sheep, goats and farm dogs in temperate Australia*. Chatswood, Australia, Butterworth-Heinemann.

**Casburn, G.C., Burns, H.M., Anderson, M., Nugent, T.M., Sproule, P., Olsen, M. & Hayes, R.C.** 2013. Crops, rumps and woolly jumpers: An innovative extension approach enabling the complexities of mixed farming to be shared and understood. In: *Proceedings of the 22nd International Grasslands Congress.* 15-19 September 2013, Sydney.

**Chen, D., Suter, H., Islam, A., Edis, R., Freney, J.R. & Walker, C.N.** 2008. Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. *Soil Research.* 46(4): 289-301.

**Cocks, P.S.** 2001. Ecology of herbaceous perennial legumes: a review of characteristics that may provide management options for the control of salinity and waterlogging in dryland cropping systems. *Australian Journal of Agricultural Research.* 52(2): 137-151.

**Cooper, J.P.** 1963. Species and population differences in climatic response. *Environmental control of plant growth*. L. T. Evans. New York, Academic Press**:** 381-403.

**Cottle, D.J.** 1991. Digestion and metabolism. *Australian sheep and wool handbook*. D. J. Cottle. Melbourne, Inkata Press**:** 174-211.

**Cox, T.S., Glover, J.D., Van Tassel, D.L., Cox, C.M. & DeHaan, L.R.** 2006. Prospects for developing perennial grains. *BioScience.* 56(8): 649-659.

**Cox, T.S., Van Tassel, D.L., Cox, C.M. & DeHaan, L.R.** 2010. Progress in breeding perennial grains. *Crop and Pasture Science.* 61(7): 513-521.

**Culman, S.W., Snapp, S.S., Ollenburger, M., Basso, B. & DeHaan, L.R.** 2013. Soil and water quality rapidly responds to perennial grain Kernza Wheatgrass. *Agronomy Journal*. 105: 735-744.

**Dann, P., Axelson, A., Dear, B., Williams, E. & Edwards, C.** 1983. Herbage, grain and animal production from winter-grazed cereal crops. *Australian Journal of Experimental Agriculture*. 23: 154-161.

**Dear, B.S. & Cocks, P.S.** 1997. Effect of perennial pasture species on surface soil moisture and early growth and survival of subterranean clover (*Trifolium subterraneum* L.) seedlings. *Australian Journal of Agricultural Research*. 48(5): 683-694.

**Dear, B.S., Cocks, P.S., Swan, A.D., Wolfe, E.C. & Ayre, L.M.** 2000. Effect of phalaris (*Phalaris aquatica* L.) and lucerne *Medicago sativa* L.) density on seed yield and regeneration of subterranean clover (*Trifolium subterraneum* L.). *Australian Journal of Agricultural Research*. 51(2): 267-278.

**Dear, B.S., Moore, G.A. & Hughes, S.J.** 2003a. Adaptation and potential contribution of temperate perennial legumes to the southern Australian wheatbelt: a review. *Australian Journal of Experimental Agriculture*. 43(1): 1-18.

**Dear, B.S., Peoples, M.B., Cocks, P.S., Swan, A.D. & Smith, A.B.** 1999. Nitrogen fixation by subterranean clover (*Trifolium subterraneum* L.) growing in pure culture and in mixtures with varying densities of lucerne (*Medicago sativa* L.) or phalaris (*Phalaris aquatica* L.). *Australian Journal of Agricultural Research*. 50(6): 1047-1058.

**Dear, B.S., Sandral, G.A., Peoples, M.B., Wilson, B.C.D., Taylor, J.N. & Rodham, C.A.** 2003b. Growth, seed set and nitrogen fixation of 28 annual legume species on 3 Vertosol soils in southern New South Wales. *Australian Journal of Experimental Agriculture*. 43(9): 1101-1115.

**Dear, B.S., Sandral, G.A., Virgona, J.M. & Swan, A.D.** 2004. Yield and grain protein of wheat following phased perennial grass, lucerne, and annual pastures. *Australian Journal of Agricultural Research*. 55(7): 775-785.

**Dear, B.S., Sandral, G.A. & Wilson, B.C.D.** 2006. Tolerance of perennial pasture grass seedlings to pre- and post-emergent grass herbicides. *Australian Journal of Experimental Agriculture*. 46(5): 637-644.

**Dear, B.S., Virgona, J.M., Sandral, G.A., Swan, A.D. & Orchard, B.A.** 2007. Lucerne, phalaris, and wallaby grass in short-term pasture phases in two eastern Australian wheatbelt environments. 1. Importance of initial perennial density on their persistence and recruitment, and on the presence of weeds. *Australian Journal of Agricultural Research*. 58(2): 113-121.

**Dear, B.S., Wilson, B.C.D., Rodham, C.A., McCaskie, P. & Sandral, G.A.** 2002. Productivity and persistence of *Trifolium hirtum*, *T. michelianum*, *T. glanduliferum* and *Ornithopus sativus* sown as monocultures or in mixtures with *T. subterraneum* in the south-eastern Australian wheat belt. *Australian Journal of Experimental Agriculture*. 42(5): 549-556.

**Donald, C.M.** 1965. The progress of Australian agriculture and the role of pastures in environmental change. *Australian Journal of Science*. 27(7): 187-198.

**Dove, H.** 2007. Mineral nutrition of sheep grazing dual-purpose wheats. GRDC-sponsored Grains Research Technical Update. D. Kaminskas and S. Rawlings. Wagga Wagga, NSW, Jon Lamb Communications: ST Peters, SA**:** 71-75.

**Dove, H. & McMullen, K.G.** 2009. Diet selection, herbage intake and liveweight gain in young sheep grazing dual-purpose wheats and sheep responses to mineral supplements. *Animal Production Science*. 49(10): 749-758.

**Erekul, O. & Kohn, W.** 2006. Effect of weather and soil conditions on yield components and bread-making quality of winter wheat (*Triticum aestivum* L.) and winter triticale (*Triticosecale* Wittm.) varieties in north-east Germany. *Journal of Agronomy and Crop Science*. 192: 452-464.

**FitzGerald, R.D., Wolfe, E.C., Laby, R.H. & Hall, D.G.** 1980. Beef production from lucerne and subterranean clover pastures. 2. Bloat occurrence and effect of anti-bloat capsules. *Australian Journal of Experimental Agriculture and Animal Husbandry*. 20(107): 688-694.

**Fortune, J.A., Cocks, P.S., Macfarlane, C.K. & Smith, F.P.** 1995. Distribution and abundance of annual legume seeds in the wheatbelt of Western Australia. *Australian Journal of Experimental Agriculture*. 35(2): 189-197.

**Giunta, F., Motzo, R. & Pruneddu, G.** 2003. Comparison of temperate cereals and grain legumes in a Mediterranean environment. *Agricoltura Mediterranea*. 133: 234-248.

**Glendinning, J.S.** 2000. *Australian Soil Fertility Manual*, revised edition. Collingwood, Vic, CSIRO Publishing.

**Glover, J.D., Cox, C.M. & Reganold, J.P.** 2007. Future of farming: a return to roots. *Scientific American*. 297(2): 82-89.

**Glover, J.D. & Renagold, J.P.** 2010. Perennial grains - food security for the future. *Issues in Science and Technology*. Winter (41-47).

**Glover, J.D., Reganold, J.P. & Cox, C.M.** 2012. Plant perennials to save Africa's soils. *Nature*. 489 (September): 359-361.

**Gumbrell. R.C.** 1997. Redgut in sheep: A disease with a twist. *New Zealand Veterinary Journal*. 45(6): 217-221.

**Hacker, R.B., Hodgkinson, K.C., Melville, G.J., Bean, J. & Clipperton, S.P.** 2006. Death model for tussock perennial grasses: thresholds for grazing-induced mortality of mulga Mitchell grass (*Thyridolepis mitchelliana*). *Rangeland Journal*. 28(2): 105-114.

**Hackney, B., Dear, B. & Hayes, R.** 2006. Summer dormant temperate grasses are productive and persistent in the medium - low rainfall cropping region of New South Wales. *Ground-breaking Stuff - 13th Australian Society of Agronomy Conference*. Perth, The Regional Institute.

**Harrington, G.N., Freidel, M.H., Hodgkinson, K. & Noble, K.C.** 1984. *Vegetation ecology and management. Management of Australia's rangelands*. G. N. Harrington, A. D. Wilson and M. D. Young. Australia, CSIRO**:** 41-61.

**Harrison, M.T., Evans, J.R., Dove, H. & Moore, A.D.** 2011. Dual-purpose cereals: can the relative influences of management and environment on crop recovery and grain yield be dissected? *Crop and Pasture Science*. 62(11): 930-946.

**Hayes, R.C., Dear, B.S., Li, G.D., Virgona, J.M., Conyers, M.K., Hackney, B.F. & Tidd, J.** 2010a. Perennial pastures for recharge control in temperate drought-prone environments. Part 1: productivity, persistence and herbage quality of key species. *New Zealand Journal of AgriculturalResearch*. 53(4): 283-302.

**Hayes, R.C., Dear, B.S., Orchard, B.A., Peoples, M.B. & Eberbach, P.L.** 2008. Response of subterranean clover, balansa clover, and gland clover to lime when grown in mixtures on an acid soil. *Australian Journal of Agricultural Research*. 59(9): 824-835.

**Hayes, R.C., Li, G.D., Dear, B.S., Conyers, M.K., Virgona, J.M. & Tidd, J.** 2010b. Perennial pastures for recharge control in temperate drought-prone environments. Part 2: soil drying capacity of key species. *New Zealand Journal of Agricultural Research*. 53(4): 327-345.

**Hayes, R.C., Newell, M.T., DeHaan, L.R., Murphy, K.M., Crane, S., Norton, M.R., Wade, L.J., Newberry, M., Fahim, M., Jones, S.S., Cox, T.S. & Larkin, P.J.** 2012. Perennial cereal crops: An initial evaluation of wheat derivatives. *Field Crops Research*. 133: 68-89.

**Herridge, D.** 2011. *Managing legume and fertiliser N in northern grains cropping*, Grains Research and Development Corporation.

**Hubble, G.D., Isbell, R.F. & Northcote, K.H.** 1983. *Features of Australian soils. Soils: an Australian viewpoint*. Melbourne, Division of Soils, CSIRO**:** 17-47.

**Hutchings, T.R. & Nordblom, T.L.** 2011. A financial analysis of the effect of the mix of crop and sheep enterprises on the risk profile of dryland farms in south-eastern Australia. *Australian Farm Business Management Journal*. 8(1): 19-42.

**Jaikumar, N.S., Snapp, S.S., Murphy, K. & Jones, S.S.** 2012. Agronomic assessment of perennial wheat and perennial rye as cereal crops. *Agronomy Journal*. 104(6): 1716-1726.

**King, W.M., Dowling, P.M., Michalk, D.L., Kemp, D.R., Millar, G.D., Packer, I.J., Priest, S.M. & Tarleton, J.A.** 2006. Sustainable grazing systems for the Central Tablelands of New South Wales. 1. Agronomic implications of vegetation–environment associations within a naturalised temperate perennial grassland. *Australian Journal of Experimental Agriculture*. 46(4): 439-456.

**Kirkegaard, J.A., Sprague, S.J., Hamblin, P.J., Graham, J.M. & Lilley, J.M.** 2012. Refining crop and livestock management for dual-purpose spring canola (*Brassica napus*). *Crop and Pasture Science*. 63(5): 429-443.

**Lane, L.A., Ayres, J.F. & Lovett, J.V.** 2000. The pastoral significance, adaptive characteristics, and grazing value of white clover (*Trifolium repens* L.) in dryland environments in Australia: a review. *Australian Journal of Experimental Agriculture*. 40(7): 1033-1046.

**Larkin, P.J. & Newell, M.T.** 2014. Perennial wheat breeding: Current germplasm and a way forward for breeding and global cooperation. In: C. Batello, L. Wade, S. Cox, N. Pogna, A. Bozzini, J. Choptiany (eds), *Proceedings of the FAO Expert Workshop on Perennial Crops for Food Security*, 28-30 August 2013, Rome, Italy, p 39-53.

**Li, G.D., Lodge, G.M., Moore, G.A., Craig, A.D., Dear, B.S., Boschma, S.P., Albertson, T.O., Miller, S.M., Harden, S., Hayes, R.C., Hughes, S.J., Snowball, R., Smith, A.B. & Cullis, B.R.** 2008. Evaluation of perennial pasture legumes and herbs to identify species with high herbage production and persistence in mixed farming zones in southern Australia. *Australian Journal of Experimental Agriculture*. 48: 449-466.

**Llewellyn, R., Robertson, M., Hayes, R., Ferris, D., Revell, C. & Descheemaeker, K.** 2013. A strategic approach to developing the role of perennial forages for crop-livestock farmers. In *Proceedings of the 22nd International Grasslands Congress*. 15-19 September 2013, Sydney.

**Love, G.** 2004. *Impacts of climate variability on regional Australia*, Australian Beureau of Agricultural and Resource Economics.

**Lumaret, R.** 1988. Cytology, genetics and evolution in the Genus *Dactylis*. *Critical Reviews in Plant Sciences*. **7**: 55-91.

**Malinowski, D.P., Zuo, H., Kramp, B.A., Muir, J.P. & Pinchak, W.E.** 2005. Obligatory summer-dormant cool-season perennial grasses for semiarid environments of the Southern Great Plains. *Agronomy Journal*. 97: 147-154.

**Martinek, P., Vinterova, M., Buresova, I. & Vyhnanek, T.** 2008. Agronomic and quality characteristics of triticale (X *Triticosecale* Wittmack) with HMW glutenin subunits 5+10. *Journal of Cereal Science*. 47(1): 68-78.

**McMullen, K.G. & Virgona, J.M.** 2009. Dry matter production and grain yield from grazed wheat in southern New South Wales. *Animal production Science*. 49: 769-776.

**Mergoum, M., Pfeiffer, W.H., Pena, R.J., Ammar, K. & Rajaram, S.** 2004. *Triticale crop improvement: the CIMMYT programme. Triticale improvement and production*. FAO plant production and protection paper 179. M. Mergoum and H. Gomez-Macpherson. Rome, Italy, Food and Agriculture Organization of the United Nations.

**Mills, A., Moot, D.J. & McKenzie, B.A.** 2006. Cocksfoot pasture production in relation to environmental variables. In *Proceedings of the New Zealand Grassland Association*. 68: 89-94.

**Moore, A.D.** 2009. Opportunities and trade-offs in dual-purpose cereals across the southern Australian mixed-farming zone: a modelling study. *Animal Production Science*. 49(10): 759-768.

**Motzo, R., Bassu, S. & Giunta, F.** 2011. Variation for kernel number and related traits in triticale (x *Triticosecale* Wittmack). *Crop and Pasture Science*. 62: 823-829.

**Neal-Smith, C.A.** 1955. *Report on herbage plant exploration in the Mediterranean region*. Rome, F.A.O.

**Newell, M., Hayes, R. & Larkin, P.** 2013. Perennial cereals: A novel source of feed for grazing livestock. *22nd International Grasslands Congress*. Sydney, Australia, In press.

**Nichols, P.G.H., Loi, A., Nutt, B.J., Evans, P.M., Craig, A.D., Pengelly, B.C., Dear, B.S., Lloyd, D.L., Revell, C.K., Nair, R.M., Ewing, M.A., Howieson, J.G., Auricht, G.A., Howie, J.H., Sandral, G.A., Carr, S.J., de Koning, C.T., Hackney, B.F., Crocker, G.J., Snowball, R., Hughes, S.J., Hall, E.J., Foster, K.J., Skinner, P.W., Barbetti, M.J. & You, M.P.** 2007. New annual and short-lived perennial pasture legumes for Australian agriculture - 15 years of revolution. *Field Crops Research*. 104(1-3): 10-23.

**Nichols, P.G.H., Revell, C.K., Humphries, A.W., Howie, J.H., Hall, E.J., Sandral, G.A., Ghamkhar, K. & Harris, C.A.** 2012. Temperate pasture legumes in Australia—their history, current use, and future prospects. *Crop and Pasture Science*. 63(9): 691-725.

**Norton, M.R. & Koetz, E.A.** 2013. Cover cropping and establishment of lucerne-based pastures in a semi-arid zone, mixed farming system of uniform rainfall distribution. *Grass and Forage Science*. 68: 1-14.

**Norton, M.R., Lelièvre, F. & Volaire, F.** 2006a. Summer dormancy in *Dactylis glomerata* L.: the influence of season of sowing and a simulated mid-summer storm on two contrasting cultivars. *Australian Journal of Agricultural Research*. 57(5): 565-575.

**Norton, M.R., Lelièvre, F. & Volaire, F.** 2012. Summer dormancy in *Phalaris aquatica* L., the influence of season of sowing and summer moisture regime on two contrasting cultivars. *Journal of Agronomy and Crop Science*. 198(1): 1-13.

**Norton, M.R., Volaire, F. & Lelièvre, F.** 2006b. Summer dormancy in *Festuca arundinacea* Schreb.; the influence of season of sowing and a simulated mid-summer storm on two contrasting cultivars. *Australian Journal of Agricultural Research*. 57(12): 1267-1277.

**Oram, R.N.** 1990. *Register of Australian herbage plant cultivars*, third edition. Canberra, CSIRO Division of Plant Industries.

**Oram, R.N., Ferreira, V., Culvenor, R.A., Hopkins, A.A. & Stewart, A.** 2009. The first century of *Phalaris aquatica* L. cultivation and genetic improvement: a review. *Crop and Pasture Science*. 60(1): 1-15.

**Peoples, M.B., Brockwell, J., Hunt, J.R., Swan, A.D., Watson, L., Hayes, R.C., Li, G.D., Hackney, B., Nuttall, J.G., Davies, S.L. & Fillery, I.R.P.** 2012. Factors affecting the potential contributions of $N_2$ fixation by legumes in Australian pasture systems. *Crop and Pasture Science*. 63(9): 759-786.

**Picasso, V.D., Brummer, E.C., Liebman, M., Dixon, P.M. & Wilsey, B.J.** 2008. Crop species diversity affects productivity and weed suppression in perennial polycultures under two management strategies. *Crop Science*. 48(1): 331-342.

**Picasso, V.D., Brummer, E.C., Liebman, M., Dixon, P.M. & Wilsey, B.J.** 2011. Diverse perennial crop mixtures sustain higher productivity over time based on ecological complementarity. *Renewable Agriculture and Food Systems*. 26(4): 317-327.

**Ridley, A.M. & Simpson, R.J.** 1994. Seasonal development of roots under perennial and annual grass pastures. *Australian Journal of Agricultural Research*. 45(5): 1077-1087.

**Russelle, M.P., Entz, M.H. & Franzluebbers, A.J.** 2007. Reconsidering integrated crop-livestock systems in North America. *Agronomy Journal*. 99(325-334).

**Salehi, M. & Arzani, A.** 2013. Grain quality traits in triticale influenced by field salinity stress. *Australian Journal of Crop Science*. 7(5): 580-587.

**Salmanowicz, B.P. & Dylewicz, M.** 2007. Identification and characterisation of high-molecular-weight glutenin genes in Polish titicale cultivars by PCR-based DNA markers. *Journal of Applied Genetics*. 48(4): 347-357.

**Scott, J.F., Lodge, G.M. & McCormick, L.H.** 2000. Economics of increasing the persistence of sown pastures: costs, stocking rate and cash flow. *Australian Journal of Experimental Agriculture*. 40(2): 313-323.

**Stork, P.R. & Jerie, P.H.** 2003. Initial studies of the growth, nitrogen sequestering, and de-watering potential of perennial grass selections for use as nitrogen catch crops in orchards. *Australian Journal of Agricultural Research*. 54(1): 27-37.

**Tian, L.H., Bell, L.W., Shen, Y.Y. & Whish, J.P.M.** 2012. Dual-purpose use of winter wheat in western China: cutting time and nitrogen application effects on phenology, forage production, and grain yield. *Crop and Pasture Science*. 63(6): 520-528.

**Tracey, B.F. & Sanderson, M.A.** 2004. Productivity and stability relationships in mowed pasture communities of varying species composition. *Crop Science*. 44: 2180-2186.

**USDA.** 2013. *World Agricultural Production*. (Available at www.fas.usda.gov/wap/current/default.asp).

**Virgona, J.M. & Dear, B.S.** 1996. Comparative performance of Caucasion clover (*Trifolium ambiguum* cv. Monaro) after 11 years under low-input conditions in south-eastern Australia. *New Zealand Journal of Agricultural Research*. 39: 245-253.

**Virgona, J.M., Gummer, F.A.J. & Angus, J.F.** 2006. Effects of grazing on wheat growth, yield, development, water use, and nitrogen use. *Australian Journal of Agricultural Research*. 57(12): 1307-1319.

**Volaire, F.** 1995. Growth, carbohydrate reserves and drought survival strategies of contrasting *Dactylis glomerata* populations in a Mediterranean environment. *Journal of Applied Ecology*. 32: 56-66.

**Volaire, F. & Conejero, G.** 2001. Drought survival and dehydration tolerance in *Dactylis glomerata* and *Poa bulbosa*. *Australian Journal of Plant Physiology*. 28: 743-754.

**Volaire, F. & Norton, M.** 2006. Summer dormancy in temperate grasses. *Annals of Botany*. 98: 927-933.

**White, J. & Edwards, J.** 2008. *Wheat growth and development*. Orange, NSW Department of Primary Industries.

**Wilkins, R.J.** 2008. Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. *Philosophical Transactions of the Royal Society of British*. 363 (517-525).