Patterns of dry matter production, allocation and water use in perennial wheat

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Abstract
Perennial crops offer the prospect of flexible, diversified and stabilized farming systems, by contributing grain and grazing while protecting environmental services. Recently, perennial wheat derivatives developed between bread wheat (Triticum aestivum L. [6n]) and perennial grass (e.g. Thinopyrum intermedium [6n]) have been reported to survive, regrow and contribute grain in the field at Cowra NSW, for up to four years. This PhD project examined the performance of four perennial wheat derivatives, relative to annual wheat and perennial grass, under controlled and field conditions, over three years. Three experiments addressed patterns of dry matter production and partitioning over growth cycles, how they changed under source or sink limitation, and patterns of root growth and water extraction under prolonged water deficit. Perennials developed greater dry matter in successive cycles, especially root dry matter, relative to annually replanted bread wheat, with perennial wheat derivatives intermediate between annual wheat and perennial grass. Perennials showed greater root growth and water extraction capacity at depth in prolonged drought, in controlled conditions and in the field. Perennial wheats differed in the extent of these parameters, but the most promising derivative approached or exceeded the perennial grass. These results added to previous reports, showing how perennial wheat could regrow in subsequent years, with increased root growth allowing greater access to soil water, especially at depth, in controlled conditions and the field. These results confirm the proof of concept for perennial wheat, and that research on perennial wheat should continue.

Key words
Perenniality, dry matter allocation, regrowth

Introduction
Environment sustainability may be threatened in agricultural systems due to annual cropping, so perennial grain crops have been proposed to provide forage and grain in a more stable mixed-farming system, with greater flexibility and increased integration of livestock (Glover et al., 2010). This is especially important in Australia with variable rainfall and poor soils, in which water passing below the root zone of annual crops may contribute to water table rise and soil salinization. Recently, survival and yield of perennial wheat derivatives have been reported from field sites at Cowra and Woodstock (Hayes et al., 2012; Larkin et al., 2014), but data on dry matter and soil water were not reported. Consequently, this PhD study examined the patterns of dry matter production and partitioning over regrowth cycles under well-watered conditions. Subsequent experiments were done to examine how these patterns changed with source or sink limitation, and under prolonged water deficit, in order to further quantify the proof of concept for perennial grains.

Materials and methods
Together with one annual wheat (Triticum aestivum L., cv Wedgetail) and one tall wheatgrass (Thinopyrum intermedium, CPI-148055), four contrasting perennial wheat derivatives (OK7211542, CPI-147235a, CPI-147280b, 11955) were chosen from the 150 perennial wheat derivatives reported in field experiments by Hayes et al. (2012). In Experiment 1, large soil columns (360 PVC tubes, 150-cm long and 10-cm diameter), were sown in May 2011, thinned to a single plant, with the six genotypes replicated three times, to allow destructive sampling over three years. Annual wheat was re-sown in May 2012 and May 2013. Columns were watered fortnightly, fertilised monthly and weeded as needed. Partitioning of dry matter to root and shoot was measured through six sampling times. Samples were taken according to genotype phenology, at flowering (Oct-Nov 2011, physiological maturity (Nov-Dec 2011), at the end of dry season regrowth (April 2012 and 2013), and at end of the wheat growing season (Nov-Dec 2012 and 2013). At the end of each season, all of the remaining plants were cut to 8-10 cm from the soil surface. Root and shoot samples were
dried in a dehydrator at 70°C and weighed. Further details of the experiments are provided by Aktar (2015).

In Experiment 2, the effect of source or sink limitation on root and shoot dry matter partitioning in third-year regrowth was examined in soil columns using four treatments as main plots, the same six genotypes as subplots, and three replicates. The four treatments were: 1) Control - as in Experiment 1; 2) Source - shade cloth was used to reduce incoming photosynthetically-active radiation (PAR) by ~70% after spike emergence; 3) Sink - spikelets were carefully removed from one side of each spike after spike emergence; 4) Both source and sink limitation – shade cloth and spikelet removal were both applied after spike emergence.

In Experiment 3, third-year regrowth was examined under prolonged water deficit in soil columns and the field. In soil columns, the experiment comprised two water regimes as main plots, the same six genotypes as subplots, and three replicates. Plants at maximum tillering were transferred to a rain shelter, and water was withheld from deficit columns until physiological maturity. To minimise water loss from the soil surface, a layer of 5-8 mm crushed fine gravel was applied to the soil surface. At harvest, each soil column was opened, the soil core was divided into 10cm depth increments, and gravimetric water contents were measured. For validation purposes, soil cores to 150 cm depth were also taken in March 2014 and 2015 from field experiments at Cowra, which were described in Larkin et al. (2014).

**Results and discussion**

**Experiment 1**
In the first year, average above-ground dry matter increased from 25 g/plant at flowering to 40 g/plant at maturity (Fig. 1). In the second year, average above-ground dry matter regrowth was only 15 g/plant in the dry season, but increased to 50 g/plant at the end of the wheat growing season. In the third year, average above-ground dry matter regrowth was only 8 g/plant but increased in the third wheat growing season to 110 g/plant. Below-ground dry matter increased each year, but was not recorded at harvest 5.

The annual wheat, Wedgetail, had consistent above- and below-ground dry matter in all wet seasons, when grain damage from birds was considered. The perennial grass, CPI-148055, was lower in above- and below-ground dry matter until dry season regrowth in the second year. By the second wet season, however, its above- and below-ground dry matter increased, and by the end of the third year, had doubled in above-ground dry matter and increased sixfold in below-ground dry matter, compared to annual wheat.

The perennial wheat derivatives accumulated more above-ground dry matter than annual wheat even in the first wet season. In subsequent wet seasons, the difference increased further. Highest above-ground (1 to 2 fold) and below-ground (2 to 5 fold) dry matter relative to annual wheat occurred in the third year.

The perennial grass CPI-148055 showed lower above- and below-ground dry matter compared to perennial wheat derivatives in the first year, but by the second year, more dry matter was partitioned below ground, so by the end of the second wet season, it showed the highest below-ground dry matter of all. In the third year, above-ground dry matter of CPI-148055 was comparable with the higher-producing perennial wheat derivatives CPI-147235a and 11955, but exceeded them in below-ground dry matter. These patterns for above-ground dry matter in soil columns were generally consistent with patterns of grain yield contribution in the field at Cowra (Larkin et al., 2014).

**Experiment 2**
In the resown annual wheat, Wedgetail, treatment effects on above- and below-ground dry matter were not statistically significant, after grain damage from birds was considered (Fig. 2). In the perennial wheat derivative, CPI-147235a, above-ground dry matter was significantly reduced by source- or sink-limitation, and was reduced further by their combination, though root dry matter was not affected. In the perennial grass CPI-148055, source limitation reduced above- and below-ground dry matter, and sink limitation increased below-ground dry matter. No explanation is available for why the combination of source- and sink-limitation increased above-ground dry matter in CPI-148055 only.

Nevertheless, this experiment showed the perennial grass CPI-148055 invested more dry matter below ground, especially when the source-sink balance was changed by removal of half the spikelets. This
result was consistent with earlier reports that dry matter allocation patterns were different in perennials compared to annuals, and that perennial persistence will require a greater investment below ground for continued survival, regrowth and yield (Garnier, 1992). Experiment 2 is to be repeated with a wider array of germplasm and additional measurements, in order to further understand how source and sink priority may differ among annual wheat, perennial wheat and perennial grass, and among perennial wheat derivatives.

Figure 1. Above and below ground dry matter of four perennial wheat derivatives and one perennial grass and one annual wheat over six harvests throughout three years. In first year of plant age two harvest, harvest 1 (First wet season a) at flowering in October – November 2011, harvest 2 at maturity in November - December 2011 (First wet season harvest b); in second year of plant age, harvest 3 (First dry season harvest) at the end of April 2012 and harvest 4 at maturity in November - December 2012 (Second wet season harvest) and in third year of plant age, harvest 5 (Second dry season harvest) at the end of April 2013 and harvest 6 at maturity in November – December 2013 (Third wet season harvest). Sowing was done in May 2011 for all genotypes, only exception is resown annual wheat, Wedgetail, in May 2012 and May 2013.

Figure 2. Above- and below-ground dry matter of one perennial wheat derivative CPI-148235a and one perennial grass CPI-148055 in the third wheat growing season 2013, compared with annual wheat Wedgetail in the same season, in Experiment 2, under control, source limitation, sink limitation, or both source and sink limitation.
Experiment 3
At the end of the drying cycle (at 71 days after watering was withheld) annual wheat lost 7.3 % of column weight, while perennial wheat and perennial wheat grass lost 10.4 % and 9.2 %, respectively. The perennial wheat derivative CPI-147235a and the perennial grass CPI-148055 had more roots in the deepest soil layer and were able to withdraw water throughout the soil profile. In contrast, roots were absent in annual wheat in the 100-150cm soil layer, so was unable to withdraw water from deep in the soil profile. This was consistent with reported root depths of annual crops and perennial grasses (Gutierrez et al., 2010; Lilley and Fukai, 1994; Zhou et al., 2013). Likewise, in the field, the perennial grass depleted soil water content to 9.1 %, while the perennial wheat derivative CPI-147235a depleted it to 11.3 %, and wheat to only 12.7 % (SE = 1.3). There was evidence that depth of water extraction was limited to about 120 cm in wheat, while the perennials were able to use soil water from 150 cm depth, at the Cowra field site.

Conclusions
Over the 3 year period, perennial wheat derivatives invested in a greater root biomass compared to annual wheat, and their root systems were able to regenerate over growing seasons, which was similar in response to the perennial grass. More dry matter was partitioned below ground in the perennials, but especially in the perennial grass, and more so under sink limitation. This ability to persist and increase root biomass was associated with increased soil water extraction during the extended dry down treatment and the field, providing an environmental advantage as a result of perennial characteristics.

These results show that perennial wheat can regrow in subsequent years, with increased root growth allowing greater access to soil water, especially at depth, in controlled conditions and the field, which provides further proof of concept for perennial wheat. Research in perennial wheat should continue, in order to provide further options for farmers in future farming systems. For example, Larkin et al. (2014) have recently outlined a breeding strategy for perennial wheat, which would involve selection within segregating populations derived by intercrossing compatible Triticum aestivum L. [6n]/Thinopyrum elongatum [2n] derivatives. Growth analysis of perennial wheat derivatives should also continue, to relate dry matter production and allocation to grain and forage yield and water use in the field.

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References