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Genetic gains in NSW wheat cultivars from 1901 to 2014 as revealed from synchronous flowering during the optimum period

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ABSTRACT

Quantifying historic increases in water-limited potential yield (PY_w) achieved through breeding provides insight into associated changes in physiology and can assist with future cultivar improvement. We compared PY_w of bread wheat cultivars popular in southern New South Wales released between 1901 and 2014. In both 2015 and 2016, cultivars were sown at multiple sowing dates to allow comparisons to be made at a consistent optimal flowering date (early October), and thus control for the large differences in life cycle duration. Seasonal conditions were close to average in 2015 and extremely favorable in 2016. In both, grain yield increased across the historic period studied at 26 kg/ha per annum, regardless of whether a common sowing date or flowering date was used. Yield gain was not linear, and there was a period of rapid yield increase during the middle of the 20th century, that culminated with the release of semi-dwarf cultivars. Yield gain was relatively slower from the 1980s until the present day, possibly due to selection for grain quality traits (grain size) at the expense of grain number. Historic yield increases were not associated with earlier flowering, but with an interplay between greater grain number/m^2 and greater grain weight which was the result of increased partitioning of assimilates to spikes, and greater number of grains per unit spike weight (fruiting efficiency). Greater partitioning to the spike in modern cultivars was associated with reduced dry matter (DM) production prior to flowering. Modern cultivars have a less stable flowering time across sowing dates, and shorter life cycle, but improved partitioning in modern cultivars appeared decoupled from shorter developmental phases prior to flowering. The performance of the novel vernalisation sensitive cultivar Longsword showed that future yield gain may be achieved through the combination of early sowing and slow development, increased DM production and superior partitioning to grain.

1. Introduction

Despite regular drought and generally low yields in comparison to countries such as China, the UK and USA, Australian farm yield (FY) for wheat has increased on average from 0.5 t/ha to 2 t/ha over the 20th century (Hochman et al., 2017). FY is determined through field, farm, district, regional or national averages whereas potential yield (PY) is defined as the measured yield of the best cultivar grown with optimal agronomy and without manageable biotic and abiotic stresses (Fischer, 2015). Water-limited potential yield (PY_w) is the same as PY but yield is limited by the amount of seasonal available water (Fischer, 2015). Increases in PY_w achieved through wheat breeding are an important component of the production increases observed in Australia and around the world that have enabled wheat production to keep pace with global demand (Fischer et al., 2014). Today, further increases in wheat yield are necessary in order for Australian growers to cover increasing costs of production and remain competitive in a global market. Hochman et al. (2017) demonstrated that whilst national PY_w (as estimated by simulation) has decreased since 1990 due to declining rainfall and increasing temperatures, FY has been stable due to Australian wheat farmers closing the yield gap (where yield gap = PY-FY as per Fischer, 2015). This reduction in yield gap is likely due to adoption of advanced technologies both in agronomic management such as those described by Kirkegaard et al. (2014) and genetic yield improvements made by breeding.

One method to accurately estimate the genetic component of

Abbreviations: DR, double ridge; DM, dry matter; FY, farm-yield; FD, flowering date; HI, harvest index; NSW, New South Wales; PAR, photosynthetically active radiation; PY, potential yield; RUE, radiation use efficiency; SD, sowing date; TS, terminal spikelet; TOS, time of sowing; PY_w, water-limited potential yield

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increases in PY_w and FY is to grow a number of historic and modern cultivars side by side under typical rain fed conditions, with otherwise optimal agronomy and no pests or diseases (Fischer, 2009). This method allows quantification of yield improvement under current agronomy and climate, insight into associated changes in physiology and can assist with future improvement (Sadras and Lawson, 2011). Such studies have documented chronological changes in local cultivars in Western Australia (WA) (Perry and D'Antuono, 1989; Siddique et al., 1989a; Siddique et al., 1989b) and South Australia (SA) (Black et al., 2008; Saunders, 2008; Sadras and Lawson, 2011; Kitonyo et al., 2017). However, no published studies have considered cultivars adapted to the important grain producing region in the southern half of New South Wales (NSW). The studies from WA and SA demonstrated that Australian breeders have increased PY_w by breeding cultivars which flower earlier, have reduced plant height, increased harvest index (HI) and grain number per m^2 (grain/m^2) (Fischer et al., 2014). Fischer et al. (2014) predicted similar findings in other parts of eastern Australia, though publications are scarce.

Compared to the west of the country, high rainfall regions of south-eastern Australia experience cooler winters, relatively mild springs and typically have an optimal flowering period for wheat from late September to mid-October (Flohr et al., 2017). Significant yield progress has been made by breeders selecting cultivars that develop from autumn establishment to flower during the optimal flowering period (Richards et al., 2014). Cultivar rate of reproductive development is dependent on sensitivity to temperature (earliness *per se*), vernalisation (response to cold) and photoperiod (response to daylength) (Slafer et al., 2015b). Since the release of the cultivar Federation (1901), cultivars have varied in sensitivity to vernalisation and photoperiod, but generally sensitivity to both has decreased with time (Pugsley, 1983; Davidson et al., 1985; Richards, 1991; Eagles et al., 2009). Although faster development is advantageous in drought, the consequence of reduced sensitivity to vernalisation and photoperiod is that seasonal temperature variation can alter crop development rates such that flowering does not reliably occur within the optimal flowering period (Loss and Siddique, 1994). Vernalisation sensitivity has been linked to greater flowering date stability and extended sowing date opportunities (Penrose, 1997; Flohr et al., 2018). Depending on development rate (fast, mid, slow etc.), different sowing dates are required for crops to flower within the optimal flowering period to maximize yield (Kerr et al., 1992; Flohr et al., 2017). Therefore flowering date is a function of cultivar rate of development and time of sowing (TOS), in which sowing time can be controlled (to a degree) by breeders, agronomists and farmers.

Bodner et al. (2015) and Flohr et al. (2017) have stressed the importance of time of flowering on grain yield in drought prone environments. Thus it is logical that previous historic wheat experiments, which have generally been sown later than is optimal for all cultivars, have associated some of the yield increase observed to faster development and earlier flowering dates (Perry and D'Antuono, 1989; Siddique et al., 1989a; Siddique et al., 1989b; Richards, 1991). Studies have also hypothesized that breeding for earlier flowering has resulted in chronological decrease in duration of pre-flowering growth, through a shorter vegetative phase and improved partitioning of resources to the spike to increase grain/m^2 (Kirby et al., 1989; Siddique et al., 1989b; Siddique et al., 1990b). Most of these experiments have been planted on a single date, erring on the late side of the optimal sowing date, and consequently not all cultivars flowered within the optimal flowering period. Thus genetic yield gain observed from these studies may be confounded by the effects of sowing date, which although historically dependent on timing of opening rains, can now usually be manipulated by growers through management such that it can be optimal for cultivars with different development speeds (Anderson et al., 1996). Therefore the questions still remain; how much observed yield gain is due to earlier flowering, how much yield gain is due to reduced duration to flowering, and how much yield gain is due to inherently better partitioning of assimilates to grain?

To answer these questions we measured yield gain and associated change in the phenology and physiology of an historic cultivar set sown with multiple sowing dates, such that flowering of at least some sowings occurred concurrently and within the defined optimal flowering period, thereby controlling for the large genetic differences in duration of life cycle that is common across such sets. A secondary aim was to fill the gap in relation to quantifying the genetic yield gain and change in physiology of popular southern NSW bread wheat cultivars. Thirdly, to compare the growth and development patterns of a novel wheat ideotype (fast-winter) that may interact with management (earlier sowing) to offer significant future increases in PY_w.

2. Materials and methods

2.1. Site, treatments and agronomy

A field experiment using an historic set of milling quality spring wheat cultivars was conducted at the Temora Agriculture Innovation Centre (−34.4064°S, 147.5259°E), NSW in 2015 and 2016. Cultivars were selected based on historic popularity (Fitzsimmons, 1991; Brennan and Bialowas, 2001; GrainCorp, 2014) among growers in southern NSW since 1900. The last cultivar in the series (Condo) was chosen on the basis of being the highest yielding and hard white cultivar in southern NSW at the time of its release in 2014 (ACAS, 2007). Seed of historic lines was obtained from the Australian Winter Cereals Collection, and grown in rows at Black Mountain, Australian Capital Territory in 2013 to confirm type, purity and to bulk seed for field experiments. The fast-winter cultivar Longsword (Flohr et al., 2018; Hunt, 2017), recently released (2017) by Australian Grains Technology (AGT) was also included in the series to compare against modern and historic spring cultivars, but was not included in chronological regressions or means shown in the results.

All cultivars were sown at four TOS (Table 1) between mid-April to mid-May and had four replicates. Thirteen wheat cultivars were grown in 2015 and eleven in 2016 (Table 2). TOS is defined as the calendar date at which seeds become imbibed and begin the process of germination. For instance, this could be the date on which they are sown into a moist seed bed, or the date on which they received rainfall/irrigation after being sown into a dry seed bed. In 2016 the first two TOS were irrigated with 15 mm of water which was applied to all plots of that TOS using pressure compensating drip irrigation. This irrigation is assumed not to have contributed to crop transpiration and yield, as 2016 experienced an extremely wet winter and spring during which the soil profile filled below rooting depth. In 2015 the target plant density was 120 plants/m^2, and plots were 12 m × 1.8 m with 305 mm row spacing. In 2016 the target plant density was 140 plants/m^2, and plots were 10 m x 1.8 m with 305 mm row spacing. In all experiments, chemical fertilisers and pesticides were applied such that nutrients, weeds, pests or diseases did not limit yield.

Table 1
Sowing dates of the field experiments at Temora in 2015 and 2016.

Time of sowing	2015	2016
1	17 April	15 April
2	27 April	27 April
3	7 May	6 May
4	15 May	15 May