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Evaluation of historic Australian wheat varieties reveals increased grain yield and changes in senescence patterns but limited adaptation to tillage systems

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ABSTRACT

Cropped area under no-till (NT) is increasing worldwide, but the extent to which breeding for yield is selecting for adaptation to NT is unclear. In addition, the consequences of selection for yield and that of tillage system on senescence patterns are not known. This study compared yield and senescence patterns of fourteen Australian wheat varieties released between 1958 and 2011, under no-till with stubble retention, and under conventional tillage (CT) without stubble. Grain yield increased at a rate of 21 kg ha^{-1} $year^{-1}$ irrespective of tillage system, which implied that selection for yield did not improve wheat adaptation to no-till. Selection for yield changed the pattern of canopy senescence, whereby modern varieties had lower peak normalised difference vegetative index (NDVI), higher NDVI at maturity, a faster rate of senescence, and greener leaves, compared with older counterparts.

1. Introduction

Advances in Australian wheat (*Triticum aestivum* L.) breeding and agronomy have steadily increased grain yield (Fischer, 2009; Richards et al., 2014). Between the 1900s and 2000s, yield increased at the rate of 9 kg ha^{-1} $year^{-1}$ in the driest years and 13 kg ha^{-1} $year^{-1}$ in the most favourable years (Richards et al., 2014). Varieties adapted to winter rainfall environments, and released between 1958 to 2007, showed yield improvement in the range of 18 – 25 kg ha^{-1} $year^{-1}$ (Sadras and Lawson, 2011; Sadras and Lawson, 2013). These rates are commensurate with expectations from low-yielding environments (Sadras et al., 2016a).

The cropped area under no-till (NT) and stubble retention have increased more recently (Kirkegaard et al., 2014). The main drivers of the adoption of NT are soil conservation and reduced costs (Llewellyn et al., 2012; Scott et al., 2013). Despite the conservation benefits, NT can reduce yield compared with conventional tillage (CT) (Pittelkow et al., 2015). Varieties that are specifically adapted to NT may help to improve yield (Trethowan et al., 2005; Joshi et al., 2007). However, varieties specifically bred for NT are scarce and the extent to which breeding is selecting for adaptation to NT is unclear. Often, the lack of significant variety × tillage system interaction limits the scope to breed for adaptation to NT (Trethowan et al., 2009) but the possibility to breed and adapt wheat to NT exists (Trethowan et al., 2012).

Delayed onset of senescence (stay-green) is a stress adaptation mechanism (Jordan et al., 2012) but it can limit yield if induced prematurely (Gregersen et al., 2013). Some traits that contribute to a stay-green phenotype include, (i) traits that conserve water and reduce stress during grain filling, such as early maturity and reduced canopy size, and (ii) traits that enhance water uptake, such as a deep rooting system (Sadras and Richards, 2014). Successes in stay-green have been observed in sorghum breeding, where this phenotype has been deployed to improve yield and reduce lodging (Jordan et al., 2012). While breeding for yield has altered the nitrogen economy of wheat in diverse environments (Sadras et al., 2016a), its effects on senescence patterns are unknown.

A combination of the traits that contribute to stay-green and adaptation to NT may shift water availability from pre- to post-flowering phase. In that case, delayed senescence would extend

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Abbreviations: CT, conventional tillage; NT, no till; GY, grain yield; GN, grain number; KW, kernel weight; PHT, plant height; BM, biomass; HI, harvest index; %NC, grain nitrogen content; $SPAD_{SE}$, leaf greenness at stem elongation; $SPAD_{FL}$, leaf greenness at flowering; $SPAD_{GF}$, leaf greenness at grain filling; NDVI, normalised difference vegetative index; minNDVI, minimum NDVI; maxNDVI, maximum NDVI; EC90, onset of senescence; EC50, time until loss of 50% of the maximum NDVI; SR, senescence rate.

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the duration of the photosynthetic apparatus to improve grain yield (Wu et al., 2012; Gregersen et al., 2013; Christopher et al., 2016). However, yield improvement from extended maturation may trade-off for reduced grain N concentration (Richards, 2000). To minimise this compromise, a fast rate of senescence is desired to promote the efficiency of nutrient cycling to the grain (Wu et al., 2012; Xie et al., 2016). On the other hand, accelerated senescence shortens the duration of grain filling which can lead to reduced kernel weight if there is not an enhanced remobilisation of resources gained from the longer period of photosynthesis (Brevis et al., 2010). Sink strength, both grain number and size, and N status, influence onset and progression of senescence (Borrell and Hammer, 2000; Borrell et al., 2001; Martre et al., 2006; Bogard et al., 2011). No-till and stubble retention can alter the dynamics of N in soil and plant (Berry et al., 2002), but the possible consequences on senescence patterns are not known.

The present study examines some historic Australian wheat varieties to: (i) identify time-trends in variety adaptation to conventional tillage and no-till, and (ii) investigate the effects of selection for yield, and of tillage systems, on senescence dynamics. We hypothesised that selection for yield improved the adaptation of Australian wheat to no-till.

2. Materials and methods

2.1. Site

The experiment was conducted at Roseworthy (34°53′S, 138°724′E), which has a Mediterranean-type climate and is 63 m above sea level. The site has 463 mm annual rainfall (315 mm during the growing season between April and October) and the growing season has 22.5 °C mean maximum temperature and 10.0 °C mean minimum temperature, which represents averages for the recent 60 years (Bureau of Meteorology, 2015). Weather data, including rainfall, evaporation, temperature, solar radiation and relative humidity were obtained from the Roseworthy Agriculture College station, which is located 500 m from the experiment site. Evaporation data were used to calculate reference evapotranspiration (ETo) while the maximum and minimum relative humidity data was used to calculate vapour pressure deficit at the time of daily maximum temperature.

The soil at the site is red-brown earth and classified as sodic, supracalcic, red chromosol with a firm sandy loam surface in the A horizon (Isbell, 2002). Soil tests before sowing at 0–20 cm depth returned a pH of 6.6 in $CaCl_2$, EC of 244 μS cm^{-1}, total N of 0.07% (by weight) measured by the Kjedahl method, and organic carbon of 1.41% (by weight) measured by the Walkley-Black chromic acid wet oxidation method. At 20–40 cm depth, the soil had a pH of 6.7, 252 μS cm^{-1} EC, 0.05% total N by weight and 1.21% organic carbon by weight.

The experimental site had a history of commercial production, with rotation of cereals, canola and crop legumes. Direct drill sowing equipment is typically used and stubble is typically reduced by grazing livestock.

2.2. Treatments and experimental design

We established a factorial experiment combining 14 varieties and two tillage systems over three seasons. The historic varieties used were previously studied (Sadras and Lawson, 2011, 2013; Sadras et al., 2012; Aziz et al., 2016) and comprised, Heron released in 1958, Gamenya in 1960, Halbard in 1969, Condor in 1973, Warigal in 1978, Spear in 1984, Machete in 1985, Janz in 1989, Frame in 1994, Krichauff in 1997, Yitpi in 1999, Wyalkatchem in 2001, Gladius in 2007; here we added Justica CL Plus to extend the series to 2011. The experiment was designed as a split-plot design with three replicates. Tillage system was assigned to the main plots, and varieties were allocated to the sub plots. Plots were 7 m long and 1.2 m wide, with six rows per plot and at inter-row spacing of 20 cm. Average plant density was 182 plants m^{-2} and crops were sown into the same plots every season.

2.3. Tillage systems and crop management

The two tillage systems were prepared according to Zhou et al. (2016). Briefly, CT plots were cultivated before sowing and all stubble was removed to mimic typical cultural practices prior to the historical introduction of NT. Using a spring-tined cultivator with a 10 cm wide tooth point, five passes were made in the CT plots to 5 cm depth, the usual cultivation depth for loamy soils in Australia. NT plots were sown using a direct-drill seeder fitted with knife-points and press-wheels, with minimal soil disturbance. In 2013, wheat crops were sown into surface applied stubble mulch at the rate of 2.5 t ha^{-1}. In 2014 and 2015, crops were sown into standing stubble, which was retained at full height after harvesting the previous crop. In all plots, basal di-ammonium phosphate fertilizer was applied at 80 kg ha^{-1}. Varieties were sown into the same plots every season at 95 kg seed ha^{-1}. The direct-drill seeder was used for seeding in the thoroughly tilled CT plots. Weeds were controlled with 1.5 L ha^{-1} of Glyphosate® (360 g L^{-1} glyphosate) and 85 mL ha^{-1} of Goal® (240 g L^{-1} oxyfluorfen, 108 g L^{-1} *N*-methyl pyrrdidone and 606 g L^{-1} liquid hydrocarbons) before sowing and 1.5 L ha^{-1} of glyphosate and 2.5 L ha^{-1} Boxer Gold® (800 g L^{-1} prosulfocarb and 120 g L^{-1} S-metolachlor) after sowing. Crops were protected with fungicides and trace element foliar sprays to correct for micro-nutrient deficiencies.

2.4. Measurements

Phenology was recorded regularly during crop growth, using the Zadoks scale (Zadoks et al., 1974). In three randomly selected 1-m row lengths per plot, plants were counted at 14 days after sowing (DAS) and 26 DAS to establish seedling emergence and survival, respectively. Shoot dry matter was sampled every two weeks after sowing and was oven dried at 60 °C for 72 h and weighed. Plant height at maturity was measured using a ruler.

At maturity, the number of heads and tillers were recorded by counting 1 m row length at three random locations of each plot. Four random 25 cm sections of central rows were hand-harvested to measure shoot biomass. Excluding the outer rows, the whole plot was harvested for grain using a plot harvester and expressed as t ha^{-1}. A subsample of the harvested grain was used for the determination of 1000 kernel weight and nitrogen content. In 2014, sheep (*Ovis aries* L.) inadvertently grazed the experiment just prior to grain harvest, which prevented yield collection.

In 2013, grain was dried at 60 °C for 48 h and then ground through a 0.5 mm size sieve to measure N content by semi-micro Kjeldahl method (Kjeltec 8200 Auto Distillation Unit, Foss, Hillerød, Denmark) (Dai et al., 2013). In 2015, after drying the grain at 60 °C to 11% moisture content, grain protein content (%) was determined by near infra-red spectroscopy, using FOSS Infratec® 1241 grain analyser. The NIR grain analyser was calibrated to wheat grain and two standards were analysed to check for accuracy before analysing the samples. Equivalent percent nitrogen content was obtained by dividing the percent protein content by 5.7 (Herridge, 2013).

Dynamics of senescence was assessed at leaf and canopy heights. Greenness of the uppermost fully expanded leaf was measured every two weeks from tillering to maturity, five times in 2014 and seven times in 2015. Five randomly selected plants per plot were sampled with a chlorophyll meter (SPAD – 502, Konica Minolta, Japan). In 2015, normalised difference vegetative index