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Research paper

Modelling phenological and agronomic adaptation options for narrow-leafed lupins in the southern grainbelt of Western Australia

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ABSTRACT

Australian modern narrow-leafed lupin (*Lupinus angustifolius* L.) cultivars tend to flower early and are vernalisation-unresponsive (VU). Cultivars have generally been selected for the warmer climates zones and sandy soils of the northern grain belt of Western Australia (NWA), where lupins are predominantly grown. In areas where climates are cooler and growing seasons are longer and wetter, such as the southern grain belt of Western Australia (SWA), it is probable that lupin would have a higher yield potential. Given that VU cultivars would have a longer vegetative phase (i.e. late flowering) we hypothesise that they may be more productive than those that are early flowering. Here we used a modelling approach to: 1) test the hypothesis that cool-climate SWA would have higher lupin yield than warm-climate NWA; 2) explore lupin phenological adaptation and yield potential in SWA over a range of proposed VU cultivars; and 3) further evaluate the combined effects of cultivar phenology, sowing time and seasonal type on lupin yields.

Simulations from the Agricultural Production Systems Simulator (APSIM) showed that, on average, lupin yield in SWA was higher than that in NWA, with 23% greater yield for the early-flowering cultivar Mandelup. Proposed cultivars flowering 22 days (late-flowering) and 15 days (medium flowering) later than Mandelup would have their phenology better adapted in the high and medium rainfall zones of SWA, producing 16 and 7% more grain in the two rainfall zones, respectively. The proposed late-flowering cultivar sown before the end of April achieved higher yields for all seasons in the high rainfall zone and for above average and average rainfall seasons in the medium rainfall zone. In more water-limited situations early sowing was preferable with no obvious difference in yield among cultivars. Despite this, the early-flowering cultivar yielded more when sown in late April. The results indicate that lupin production would benefit from breeding VU varieties with a long vegetative phase for the SWA that should be sown in mid to late April.

1. Introduction

Narrow-leafed lupin (*Lupinus angustifolius* L., hereafter referred to as lupin) is an important grain legume crop of high nutritive value for human and animal consumption (Petterson et al., 1997; Li et al., 2011). Lupins are an important component of a unique farming system of Western Australia (WA), where 80% of Australia's lupins are produced (White et al., 2008; Berger et al., 2012a, 2013). The majority of lupins produced in WA are currently grown in the northern grainbelt (NWA) (Palta et al., 2012) characterized by a warm Mediterranean climate and sandy soils. There is no need for vernalisation-inductive vegetative phase temperatures in these environments. However, there is an urgent need for lupins to adapt to new areas such as the southern grainbelt of WA (SWA) (Howieson et al., 2008; Palta et al., 2008). SWA has a cooler, wetter climate during crop growing season with very weakly vernalisation-inductive temperatures. Therefore it is hypothesized that lupins grown in SWA would have a longer growing season and higher yield potential than lupins grown in NWA. A quantitative understanding such of potential is of importance to determine whether lupins should be developed for higher rainfall zones. Since yield potential can be assessed using crop models (Van Wart et al., 2013); the first aim of this study was to test the hypothesis that SWA would have higher lupin yield potential than NWA.

Lupin yields have doubled since the 1970's through a combination of breeding for higher yield potential, better disease resistance and improved agronomic management (Buirchell, 2008; Berger et al., 2012b). The Australian lupin breeding program has targeted the warm, short growing season of NWA (Gool, 2009; Berger et al., 2012a). As a result, modern cultivars are generally vernalisation-unresponsive (VU) and early-flowering (Berger et al., 2012b). Neither the existing early-flowering VU cultivars nor late-flowering vernalisation-responsive (VR) lupin varieties are well adopted to the cooler, wetter SWA. This is

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because the former lacks the ability to take full advantage of the longer growing season and the vernalisation requirements of the latter cannot be met consistently due to the occasional warm seasons with low levels of vernalisation induction. Adaptive capability of a lupin crop is compromised by the fact that phenology and vernalisation response are confounded, and cannot be evaluated easily at this point in time.

It is expected that late-flowering VU cultivars are better adapted to the environment of SWA. We hypothesized that such cultivars would have higher yield potential than the current early-flowering VU cultivars. The vegetative stage of phenological development must match the pattern of water supply in the SWA so that its life cycle (time between sowing and harvest) is completed before lethal water deficits develop in late spring. Modelling the performance of VU cultivars with different lengths of vegetative phases (time between sowing and flowering) can guide breeders in their selection of appropriate crop phenology. The second aim of this research was to characterize general patterns of flowering time and grain yield over a range of long-vegetative VU cultivars to determine lupin phenological adaptation and yield potential in SWA.

With early-flowering cultivars, farmers usually delay sowing to allow for lupins flower at optimum time. With late-flowering VU cultivars, farmers can sow early. Early sowing (dry sowing) has been proved to be vital to maximising crop yield (Sharma and Anderson, 2004; Turner, 2011) and is recommended as an appropriate strategy to manage yield risk by increasing grain yields with a minimal increase of production risks (Fletcher et al., 2015). Given the strong interaction between phenology, rainfall and sowing options, crop yield of a certain cultivar could be improved by matching phenology to optimal sowing time and rainfall. The third aim of this study was to further evaluate the phenological adaptation of possible lupin cultivars under different sowing times and variable rainfall in SWA.

Agricultural system models, such as Agricultural Production Systems SIMulator (APSIM) (Holzworth et al., 2014) have proven to be an effective means of investigating the complex relationship between crop phenology, climate and management options (Hoogenboom, 2000; Deryng et al., 2011; Lobell et al., 2013). In a companion paper (Chen et al., 2016a), we demonstrated that APSIM was able to reflect the observed phenology and growth for both fully VR and VU cultivars, indicating the capacity of the model to simulate the full phenology range of current cultivars. Based upon this earlier work, the APSIM model was used to investigate lupin production potential, determine future lupin cultivar alternatives and establish the best agronomic options for SWA.

2. Materials and methods

Using a modelling approach, the analysis firstly investigated the lupin yield potential in SWA, which was done by comparing the simulated yields for an existing modern cultivar at SWA with those at NWA. The analysis then focused on evaluating lupin cultivar options for better adaptation of vegetative phenology to SWA environment, aiming for long season cultivars without vernalisation requirement. Finally the analysis evaluated the effects of sowing time on yield under variable rainfall to determine optimum agronomic practices for the identified lupin cultivars in the SWA.

2.1. APSIM-Lupin model and soil and climate data

APSIM is a modular modelling framework that simulates the dynamics of soil–plant–climate–management interactions within a single crop or cropping system, in particular where there is interest in the economic and ecological outcomes of management practices (Keating et al., 2003; Holzworth et al., 2014). The APSIM framework has a lupin module developed by Farr & et al. (2004), who described the routines to simulate lupin phenology, growth and yield. It has been well tested across Australia, especially WA (Farré et al., 2004; Chen et al., 2016a,b), and it is considered appropriate for the simulations conducted in this study. To configure APSIM (version 7.6) for simulating lupin development and growth, the lupin crop module (LUPIN) was linked with the soil water module (SOILWAT2), the soil nitrogen module (SOILN2), the surface residue module (SURFACEOM) and the management module (MANAGER).

Daily solar radiation, maximum and minimum temperature and rainfall during 1960–2014 required by the APSIM model were extracted from the SILO climate data archive (Jeffrey et al., 2001, www.longpaddock.qld.gov.au/silo/). A notable shift occurred in 1974 with weather patterns of WA (Smith et al., 2000). It is therefore not prudent to overwhelm the simulation with a disproportionately large number of pre- 1974 seasons. Thus simulations were carried out for the recent 55 years (1960–2014), which we think is long enough to characterize the seasonal climate of the study region.

A deep sand soil was used in all simulations with a rooting depth of 150 cm as used in Asseng et al. (2000). It is one of the soil types that lupin is predominantly grown on in WA, characterized as sandy at the surface, grading to loam or clay at depth (French and Buirchell, 2005). The plant available water holding capacity (PAWC) in the root-zone was 70 mm. A preliminary analysis found that adaptation was unaffected by soil PAWC. Further explorations of soil type were not considered necessary (data not shown).

2.2. Comparing lupin yield at selected sites of NWA and SWA

To compare lupin yield in SWA to that in NWA, six representative locations, i.e. Eneabba, Carnamah, Perenjori, Dinninup, Badgebup and Lake King were selected (Fig. 1, Table 1). A major consideration for the location selection is the contrasting rainfall environments. Eneabba, Carnamah and Perenjori are located in the high, medium and low rainfall zones in NWA, respectively; while Dinninup, Badgebup and Lake King are located in the high, medium and low rainfall zones in SWA, respectively. Annual average precipitation (1960–2014) varied from 311 to 499 mm at the three northern sites and 348–564 mm at the three southern ones (Table 1). Among the six sites, an estimated 68–81% of annual precipitation fell during the crop growing season (May–October). Mean temperature during the growing season ranged from 11.7 to 12.6 °C at the three southern sites and from 15.0 to 16.1 °C at the northern locations.

To compare the yield performance of lupin in NWA and SWA, an existing modern lupin cultivar, i.e. cultivar Mandelup that is early-flowering VU, was used for all simulation years (1960–2014) and six locations. For each year, sowing time was controlled by a sowing rule, i.e. lupin was sown if more than 15 mm of cumulative rainfall was received over a 5-day period within the traditional sowing window between 1 May and 10 June. If the sowing criteria was not met, lupin was sown on 10 June to ensure that it was sown every year. The simulated lupin crops were harvested at physiological maturity. The soil water profile was reset to the lower limit of plant-available water on 1 January each year, assuming maximum water use by the previous crop. At the same time, residues of previous crop were reset to 2000 kg ha^{-1} of wheat, with a C:N ratio of 70 based on Asseng et al. (1997). Initial soil nitrogen was reset to 50 kg N ha^{-1} at sowing. This rule was also employed in the following simulations.

2.3. Modelling the phenological adaptation of lupin to climate environment in SWA

To identify lupin cultivars that can better match phenology to climate conditions in SWA, where long-vegetative VU cultivars are expected to have better phenological adaptation, simulation experiments were performed. As there are no real cultivars that are late-flowering VU, six 'new' cultivars (Named as cv1, cv2, cv3, cv4, cv5 and cv6) were developed in the APSIM-Lupin model based on the existing modern cultivar Mandelup that had been parameterized in APSIM