Can the development of drought tolerant ideotype sustain Australian chickpea yield?

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Abstract

Terminal drought is a major problem in many areas where chickpea is grown on stored soil moisture. This is exacerbated by the lack of a targeted breeding approach focusing on key traits contributing to yield formation under water-limited conditions. There is no study to develop a chickpea ideotype and test it against commercial varieties under various management systems across the Australian grain belt. This study proposed a chickpea ideotype that can be grown in water deficit areas and compared its performance with commercial chickpea genotypes across the Australian grain belt. Important traits for ideotype construction and breeding were identified and tested against selected commercial varieties *in silico* in the Australian grain belt using the APSIM crop model. The key phenological, morphological and physiological traits were determined in the field at the University of Sydney's IA Watson Grains Research Centre near Narrabri for ideotype targeting. Five commercial chickpea genotypes (Sonali, PBA Hatrick, Kyabra, Tyson and Amethyst) were selected for evaluation against the chickpea ideotype. The constructed chickpea ideotype showed 76% resemblance to Sonali which performed well under water limited conditions. Simulated yield ranged from 760 to 3902 kg/ha across the Australian grain belt, with consistently higher yield in the ideotype compared with the commercial cultivars. The growing environments were grouped into three major clusters using the soil water deficit method with varying water stress levels. It is evident that grain filling is the most critical stage where soil moisture deficit caused chickpea yield losses up to 16.5% in the present study. By incorporating key target traits and targeting the right environment, chickpea yields can be sustained in the Australian grain belt or in an area having similar agro-ecological characteristics.

Keywords Chickpea · Ideotype · Crop modelling · Soil water deficit · Environmental characterisation · Critical period

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Introduction

Plant breeders use genetic variation to select for yield in conventional plant breeding (Donald 1968). This variation is caused by mutation, recombination of genes during reproduction and lateral gene transfer. Plant breeders used this variation and knowledge of gene, environment and management interactions to develop high-yielding crop cultivars. Further, yield increases came through conservation of soil moisture, control of pests and diseases and use of appropriate nutrient management or fertiliser recommendation (Johnson 1984). Breeding programmes traditionally select the highest yielding genotypes in any given environment and cross these to generate high-yielding progenies for advancement (Allard and Allard 1999). The challenge with this approach is that very little is known about the physiological, morphological and biochemical drivers of yield in different genotypes in different environments. Furthermore, the heritability of yield is generally low (Ludlow and Muchow 1990) because the expression of

this polygenic trait is significantly highly influenced by the environment including drought, thus reducing the repeatability of results in given environment (Johnson and Geadelmann 1989).

Under drought, secondary traits linked to yield which exhibit higher heritability than yield could be selected (Blum 1988; Ludlow and Muchow 1990). This ideotype approach is an alternative strategy to empirical breeding (Peng et al. 1994) and allows the breeder to predict the ideal genotype in the target environment. An ideotype is a biological plant model which behaves in a known manner when exposed to a distinct environment (Donald 1968). Donald's concept was to consolidate several important traits that may manifest in different genotypes into one ideal genotype that would perform better than the individual parents. Definition of the plant type (Rasmusson 1987) provides plant breeders with clear cut objectives based on defined traits (Rasmusson 1991) that provide a blue print for pyramiding traits (Mock and Pearce 1975). Thus, ideotype breeding is more analytical than traditional empirical selection and breeding.

One of the most important steps in ideotype breeding is the identification of the target population of environments (Mock and Pearce 1975; Trethowan 2014). The target ideotype should perform optimally in the target environments. Some of the key factors to consider in the target environment include temperature, soil moisture and soil fertility (Mock and Pearce 1975). Each ideotype is normally designed for a certain target environment and could possibly be grown in areas which lie in the same environmental type or mega-environment. The next step is identification of the physiological and morphological traits that contribute to yield either directly or indirectly. These traits should show genetic diversity to be incorporated into an ideotype breeding programme (Rasmusson 1987). Ideally, the target traits should be easy to measure and highly heritable; however, this should not preclude traits that are laborious to measure if they are important and correlated with yield (Rasmusson 1987). Trait relationships must also be carefully considered because pleiotrophy, trait compensation and inferior donor germplasm may influence the target ideotype thus reducing breeding progress (Rasmusson 1991). The identified traits can then be pyramided in one genotype (Mock and Pearce 1975).

Crop modelling has recently become an important enabling tool in the field of plant breeding (Hammer et al. 2006; Tardieu 2003). A crop ideotype from a modelling perspective is a set of defined crop parameters that drive growth and development in defined environmental conditions (Rotter et al. 2015). High-quality long-term data is an imperative for model calibration and the generation of accurate simulation results (Rotter et al. 2015). These ideotype models can also be refined to capture variability in the climate (Rotter et al. 2015).

Models have been a powerful tool in ideotype design and testing in silico (Semenov and Stratonovitch 2013). Data on

multiple sites over many years can be produced without running actual field trials, which reduces the cost of plant breeding. Chapman et al. (2002) emphasised that models provide a thorough understanding of the temporal and spatial environmental effects on crops, especially when experimentation is not possible.

Several crop ideotypes have been developed including rice (Khush 1995) and wheat (Semenov and Stratonovitch 2013). One software tool used in crop modelling is the Agricultural Production Systems sIMulator (APSIM) which simulates cropping systems using climate, soil, management and crop genetic coefficients to predict the economic yield of a crop species (Keating et al. 2003). The APSIM model uses the supply and demand concept of important plant growth resources to create a crop phenotype (Hammer et al. 2001).

There has been no attempt to develop and model the performance of a drought tolerant chickpea ideotype from a defined chickpea germplasm gene pool and compare the ideotype performance with drought tolerant and susceptible chickpea genotypes in the Australian grain belt which comprises regions across the southern, western and eastern Australia (specific towns are indicated in Fig. 3). Our hypothesis is: Can an ideotype with the desired traits for the target environment potentially yield better than commercial varieties in those environments?

This study aims to (i) develop one chickpea ideotype for testing in diverse environments, (ii) characterise the chickpea growing environments based on soil moisture deficits at various growth stages across the Australian grain belt, (iii) identify the critical stages where drought occurs to better match phenology to environment, and (iv) assess the performance of selected chickpea cultivars and a target ideotype across the Australian grain belt.

Materials and methods

The study is comprised of two distinct parts that are linked through analysis. The first part comprises of a field experiment which was designed to collect data and afterwards use the data to develop a chickpea ideotype. The second part comprised of simulation of the ideotype together with released varieties to assess its performance in comparison with the other varieties using APSIM.

Field experiments

Data from an experiment conducted at the University of Sydney's IA Watson Grains Research Centre at Narrabri (latitude 30.275616° S and longitude 149.803547° E) in 2014 and 2015 were used to develop the chickpea ideotype and parameterise and validate the APSIM-chickpea model (version 7.8). This site has a summer dominant rainfall

(December to February) pattern, and in winter, the rainfall is not sufficient for a successful crop. Hence, crops grown during winter, including chickpea, tend to experience terminal drought (Zaman-Allah et al. 2011). On average, the long-term annual rainfall is 662 mm distributed throughout the year with a peak in December and January. The long-term mean annual maximum and minimum temperatures are 26.5 °C and 11.7 °C, respectively, with the coldest month being July. The soil at the site is characterised by deep grey Vertosols, montmorillonitic in nature which shrink and swell with changes in soil moisture over the crop growing season (Isbell 2002).

The experiment comprised 30 entries (25 desi and 5 kabuli types) and for the purpose of the present study, five desi genotypes were chosen; Amethyst, Kyabra, PBA Hatrick, Tyson and Sonali. These genotypes were selected because of their differential response to drought based on yield ranking in well-watered and water-stressed conditions as well as stress tolerance index; Sonali has a high yield and is drought tolerant with a field stress tolerance index of 1.27 (Table 1) calculated according to (Fernandez 1992). Tyson is reported to be drought tolerant (Sarma et al. 2011) but showed moderate tolerance in this experiment with a stress tolerance index of 0.95. Tyson has also been used as a parent in breeding programmes to develop new varieties (Lake et al. 2016). Amethyst had a stress tolerance index of 0.84 and was classified as drought susceptible based on the field evaluation at Narrabri. PBA Hatrick, widely cultivated by farmers in northern NSW and Kyabra were classified as intermediate with stress tolerance indices of 1.02 and 0.87, respectively.

Chickpea ideotype development

The chickpea ideotype was designed following the suggestions of Rasmusson (1987), Martre et al. (2015) and Rotter et al. (2015). Field data obtained from the two seasons (2014 and 2015) in Narrabri was used to construct the chickpea ideotype. The data was subjected to analysis using Genstat® version 18 to output means, test genetic variation of traits at 95% confidence levels and generate least significant differences (LSD) at $P < 0.05$ using the linear-mixed models in the Residual Maximum Likelihood function (Patterson and Thompson 1971). Multiple linear regression analysis was subsequently used to identify traits that significantly explained

yield variation. The measured traits were also subjected to correlation analysis following the method described by Snedecor and Cochran (1987). Trait relationships with yield and individual inter-relationships were considered and traits optimised to a maximum (Marinho et al. 2014) or minimum depending on their correlation with yield (Fig. 1). The maximum and minimum values were chosen as relevant and the LSD was used to establish a range for the trait (Fig. 1). This was done using the trait ranges measured at Narrabri to give breeders some flexibility while targeting traits. The optimised values were generated and assigned to the ideotype and then subjected to analysis (Laurila et al. 2012) using Genstat® version 18. The degree of similarity between the five selected genotypes and the constructed ideotype was determined using a minimum spanning tree generated from a principal component analysis (Genstat®). This analysis allows the plant breeder to identify a variety to prioritise based on similarity to the ideotype.

Introduction, validation and calibration of the APSIM-chickpea

The APSIM is a dynamic (process-oriented) crop model package combining both management and biophysical modules through a central engine. It simulates the growth, development and yield of a given crop on a daily-basis as a function of climate data, soil profile data, agronomic management information and crop genetic coefficients. Biophysical, phenological and physiological processes, which can be simulated by the chickpea model are described in detail at <https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Plant.aspx>.

The APSIM-chickpea model was firstly validated in terms of flowering and grain yield against a 2-year field experimental dataset obtained at Narrabri, NSW. Statistical metrics used to measure goodness-of-fit between observed and modelled values included 1:1 line, r-square and root mean square error (RMSE). The chickpea model was also calibrated to derive genetic coefficients for the ideotype and PBA Hatrick based on field datasets using trial and error approach. Genetic coefficients for other genotypes are available in the chickpea model. Please refer to the “Field experiments” section for details of the field experiments.

Table 1 Drought tolerance/susceptibility levels of chickpea varieties based on stress tolerance index

Variety	Characteristics of genotype	Stress tolerance index	Source
Sonali	Drought tolerant	1.27	Field trials data in the current study
PBA Hatrick	Drought tolerant	1.02	Field trials data in the current study
Tyson	Drought tolerant/intermediate	0.95	(Sarma et al. 2011)
Kyabra	Intermediate tolerance	0.87	Field trials data in the current study
Amethyst	Drought susceptible	0.84	Field trials data in the current study

Fig. 1 Flow diagram for chickpea ideotype construction. LSD stands for least significant difference at $P < 0.05$. +ve means a positive correlation and –ve means a negative correlation

Environmental characterisation: the soil water deficit approach

APSIM-chickpea model was used to characterise the chickpea production environment in terms of soil moisture stress index and to evaluate the performance of the ideotype and existing genotypes based on grain yield.

To characterise production environment and evaluate the performance of genotypes including ideotype, 50 locations within the Australian grain belt based on the chickpea National Variety Trials (NVT) sites (<http://www.nvtonline.com.au/>) were selected. These locations are regularly used to conduct the national variety trials to help release new chickpea varieties based on their performance in different locations with varying climatic conditions (<http://www.nvtonline.com.au/>).

The soil water deficit was derived from the water supply (Ws)/water demand (Wd) ratio as explained by Chenu et al. (2013) and used to analyse soil moisture stress levels at each growth stage. This approach uses the amount of water accessible to the plant which is considered as the balance between supply and the water required by the plant for transpiration, to

estimate plant demand at any one growth stage. This was determined in the current study using an inbuilt function in the APSIM model for chickpea. The soil water deficit was then estimated for important phenophases of chickpea such as the juvenile, floral initiation, flowering, start of grain filling, end of grain filling and maturity stages. An index of 1 indicated no moisture stress (no drought) and 0 very low moisture (severe drought) as described by Kholová et al. (2013) with an index less than 0.7 considered a drought event (Lake et al. 2016).

For the model to work properly, chickpea planting window, soil types and relevant location-specific climate data had to be identified. The critical chickpea planting window for each location was obtained from the chickpea sowing guides provided by each state (<http://www.pulseaus.com.au/growing-pulses/bmp/chickpea>) whereas the soils for each location, was identified using the SoilMapp iPad® application developed by Commonwealth Scientific and Industrial Research Organisation (CSIRO). This application searches the Australian Soil Resource Information System (ASRIS) map discovery database and obtains the relevant soils for each location. Once the soil type was identified for each location, it

was selected from the APSIM soils repository and used for analysis. The Scientific Information for Land Owners (SILO) climate database was used in the simulation analysis. SILO is a patched point dataset with a daily time step and includes approximately 4600 locations in Australia. More information on this database can be found in Jeffrey et al. (2001). Climate data for the period from 1905 to 2004 (100 years) was extracted and used for analysis.

APSIM was configured during the simulations so that sowing was conducted when cumulative rainfall in three consecutive days in the sowing window was greater than 15 mm and there was at least 200 mm of available soil water. The planting density for each genotype was set at 25 plants per m² with a 30-mm depth and an inter-row spacing of 300 mm. In APSIM, the initial surface residue in the no-till management system was set at 1000 kg/ha with a 0.6 fraction of standing residue remaining. No fertilisers were applied in both no-till and till systems in the simulations. In total, 60,000 simulations were performed denoting combinations of 6 genotypes (including the ideotype), 2 management systems (till and no-till), 100 years of climate data and 50 locations.

Simulation was done for the soil water deficit values for all the varieties tested, and then the averages were tabulated for each site and then subjected to average link cluster analysis using Euclidean distances generated in Genstat® Version 18. This allowed distinct stress environments in the Australian grain belt to be identified.

Results

Chickpea ideotype

A total of 21 parameters listed in Table 1 were identified through multiple linear regression on yield and they accounted for 91% of the total variation in yield at $P < 0.001$. These traits were considered in isolation and their inter-relationships were also considered. High yielding genotypes developed ground cover early in the season and also had high normalised difference vegetation index (NDVI) both at early and late podding stages. These genotypes also produced their first flower earlier in the season and finished flowering earlier. Genotypes that continued flowering and had a late date to last flower were associated with low NDVI at flowering and low-shoot harvest index, hence rendering low NDVI an undesirable trait. However, a longer flowering period was associated with longer leaves and higher yield. Plant height had no clear correlation with yield but shorter machine-harvestable plants were preferred because they were associated with early flowering, longer flower duration and high NDVI scores which all contributed positively to yield. Genotypes with high chlorophyll content at mid-podding and low chlorophyll content at late-podding produced higher yield. Leaf characteristics (number

of leaflets per leaf, single leaflet area and single leaf area) were not significantly correlated with yield. Average-sized leaves should be selected as opposed to small leaves because larger leaf area was associated with early flowering and shorter flowering duration which are desirable traits for increasing yield in water-limited environments. Average-shoot harvest index was selected because plants with high-shoot harvest index also had slower ground cover, lower chlorophyll content at mid-podding, lower NDVI, flowered earlier and were shorter. All these traits influence yield in opposite directions, hence the average was chosen. Similarly, plants with high-pod harvest index also had high NDVI. However, they had short narrow leaves, were taller, flowered later and had lower seed mass.

All five genotypes varied widely in their trait ranges and the chickpea ideotype was constructed using a high, moderate or a low trait value, depending on the objective. Percentage-early ground cover ranged from 13.2 to 25.9% with the selected ideotype at 23.2% (Table 2). Days to first flower, 50% flowering and days to last flower ranged from 68 to 93, 80 to 103 and 118 to 124, respectively, with the ideotype classified as 70, 82 and 119 days in the same trait order. Sonali was closest to the ideotype in days to flowering whereas the other genotypes flowered later. All genotypes stopped flowering around the same time regardless of when they started to flower. Flower duration ranged from 31 to 50 days with the ideotype classified at 48 days. NDVI at early podding ranged from 0.66 to 0.74 and at late podding 0.22–0.41. Both NDVI and chlorophyll measures at the podding stages of the five selected genotypes were comparable to the ideotype. Variation in number of leaflets was low compared to leaf area. Number of pods per plant ranged from 21 to 54 and pod biomass ranged from 6.4 to 31.6 g. Shoot biomass varied greatly (13.6–52.6 g); however, the range in shoot harvest index was relatively narrow (0.33–0.48). The ideotype values for shoot biomass and shoot harvest index were 17.7 and 0.39 g, respectively. Seed weight also varied greatly with an observed range of 139–392 g and the ideotype was classified as 148 g.

All five selected genotypes were compared to the ideotype based on their performance against the 21 parameters used for ideotype construction. This was conducted using a minimum spanning tree to identify the nearest neighbours or sequences along a defined gradient. Thus, a connection between all possible points was made without closed loops to form a chain of links (Gower and Ross 1969). Sonali was the closest to the ideotype with 76% resemblance. This resemblance was primarily based on phenology (days to first flower, days to 50% flowering, days to last flower and flower duration), leaf characteristics and number of pods per plant. The next closest resemblance to the ideotype was Tyson at 73.2% similarity. This resemblance was based on pod biomass, NDVI, plant height and chlorophyll content. Kyabra and PBA Hattrick

Table 2 Trait range, genotype and ideotype values

Parameter	Trait range	Amethyst	Kyabra	PBA Hattrick	Sonali	Tyson	Ideotype
Early ground cover (%)	13.2–25.9	15.7	22.2	18.9	15.1	16.2	23.2
Days to first flower	68–93	88	88	87	77	86	70
Days to 50% flowering	80–103	99	99	98	88	97	82
Days to last flower	118–124	120	122	121	118	120	119
Flower duration (days)	31–50	32	34	34	41	34	48
NDVI at early podding	0.66–0.74	0.70	0.71	0.72	0.69	0.70	0.72
NDVI at late podding	0.22–0.41	0.28	0.28	0.29	0.22	0.25	0.25
Plant height at late flowering (cm)	49–64	58	64	64	56	54	51
Plant height at late podding (cm)	54–69	62	68	69	60	56	55
Chlorophyll cont. at mid pod (SU)	65–74	69	74	71	65	66	72
Chlorophyll con. at late pod (SU)	49–68	52	54	56	49	52	51
No of leaflets per leaf	12–15	14	14	12	14	14	14
Single leaf area (cm ²)	4–21	6	7	6	8	5	7
Single leaflet area (cm ²)	0.3–1.6	0.4	0.5	0.5	0.6	0.3	0.5
Leaflet length (cm ²)	1.0–2.2	1.2	1.2	1.2	1.3	1.0	1.2
No of pods per plant	21–54	42	30	34	32	35	31
Pod biomass per plant (g)	6.4–31.6	12.4	10.5	10.0	10.5	8.5	8.8
Pod harvest index	0.75–0.82	0.81	0.81	0.80	0.79	0.81	0.80
Shoot biomass	13.6–52.6	25.0	24.8	21.6	18.1	16.2	17.7
Shoot harvest index	0.33–0.48	0.42	0.34	0.37	0.48	0.43	0.39
1000 seed weight (g)	139–392	151	224	206	192	139	148

SU, SPAD units; NDVI normalised difference vegetation index

were the most closely related pair of genotypes at 90.3% similarity, followed by Tyson and Amethyst at 83.7% similarity. Sonali and Tyson showed drought tolerance under field conditions (Narrabri) with stress tolerance indices of 1.27 and 0.95, respectively, compared to the drought susceptible cultivar Amethyst (0.84).

Validation of the APSIM-chickpea model

The predicted days to flowering compared to the observed days to flowering in the Narrabri field experiment returned a coefficient of determination of 0.6 and a root mean square error of 12 (Fig. 2a). When the 1:1 line was fitted, the simulated values were slightly underestimated. The coefficient of determination for simulated and observed yield was 0.7 with a root mean square error value of 823 (Fig. 2b); thus, the simulated yield was slightly overestimated.

Environmental characterisation and soil water deficit patterns

Cluster analysis performed on the soil water deficit output from APSIM grouped the environments into three major clusters and two ungrouped environments at 95% similarity value (Fig. 3). The first cluster was comprised of four sites only; Albany, Hamilton, Minlaton and Riverton. The second cluster

represented 33 locations making it the largest group and the third cluster comprised 10 locations. The two ungrouped locations were Bourke and Rudall.

In the first cluster, genotypes flowered and matured on average at 89 and 175 days, respectively (Fig. 4a). The second cluster flowered slightly earlier at 86 days after sowing and matured earlier at 159 days. The third cluster was the earliest flowering and maturing of the three clusters at 79 and 147 days, respectively. The ungrouped locations flowered at 70 days and matured at 128 days on average. Cluster 1 was the highest yielding (3645 kg/ha) followed by clusters 2 (2700 kg/ha) and 3 (1801 kg/ha) which can be referred to high, mid and low potential areas, respectively (Fig. 4b). The two ungrouped locations had a low mean yield of 928 kg/ha.

The first cluster had a 97% chance of yielding over 2500 kg/ha in every season and less than a 0.3% chance of yielding less than 1000 kg/ha (Fig. 5). Cluster 2 had a 60% chance exceeding 2500 kg/ha/year and an approximately 30% chance of yielding between 1000 and 2500 kg/ha. The third cluster had a 30% chance of yielding 2500 kg/ha or more with an equal chance of yielding 1000 kg/ha or below. The two ungrouped locations had a mean yield of 928 kg/ha. All the simulated genotypes produced similar yield patterns with little variation in the frequencies in all the clusters with the ideotype performing better in all comparisons (Fig. 5).

Fig. 2 **a** Days to 50% flowering and **b** grain yield for observed and simulated data. R^2 is the coefficient of determination and RMSE is the root mean square error

Stress timing and the critical period for yield penalty

There was adequate soil moisture on average at all locations during the juvenile stage (Fig. 6). However, a gradual decline in soil moisture occurred from the juvenile stage to flowering in all three clusters. The two ungrouped locations (Bourke and Rudall) experienced a sharp moisture decline immediately after the juvenile stage. Cluster 1 maintained soil moisture all the way to maturity with a gentle decline during the grain

filling period, levelling off at maturity. Clusters 2 and 3 experienced sharp moisture decline from flowering until the end of grain filling. While terminal drought was experienced in both clusters 2 and 3, the intensity of drought was greater in cluster 3. The two ungrouped locations experienced both intermittent and terminal drought.

Multiple linear regression of all growth stages was significant ($P < 0.001$) and accounted for 96.2% of the total variation in grain yield. The start of grain filling was the critical

Fig. 3 Dendrogram of environment characterisation based on soil moisture deficit. Arrows indicate the start of a new cluster or group

Fig. 4 **a** Mean days to 50% flowering (grey bars) and maturity (black bars) for each cluster and **b** mean grain yield in kg/ha for each cluster. Numbers on the X-axis represent the cluster numbers

point where drought most severely affected yield. However, stress later in grain-filling also limited yield but to a lesser extent. These results show that the whole grain filling period is very sensitive to any soil water deficit.

Discussion

The ideotype developed in this study targets terminal drought conditions and therefore considered several drought tolerance traits (Sedgley et al. 1990). Most of these traits can be incorporated into the same background, although trade-offs can be expected when many traits are combined in the same

background and this could negatively affect yield. Early ground cover enables the plant to cover bare ground quickly (Singh et al. 1993) Toker et al. 2007), thereby reducing evaporative water loss (Sekhon et al. 2010) and was therefore proposed as a key trait for consideration. Early flowering was equally important, especially under terminal drought as the plant can complete pod setting before the onset of water stress (Jain 1975; Singh et al. 1993; Toker et al. 2007). However, there is often a trade-off between early flowering and high yield potential under favourable climatic conditions. Short-statured machine-harvestable plants are desirable in water-limited environments, partly because they are less susceptible to lodging and partition resources more effectively.

Fig. 5 Mean performance (frequency %) of each genotype in the clusters identified in Fig. 5

Fig. 6 Soil water deficit in different growth stages over 100-year period $\times$ 50 locations $\times$ six varieties. JV juvenile stage, FI floral initiation, FL flowering, SGF start of grain filling, EGF end of grain filling, MT maturity stage

Small leaflet, which reduces water loss through evapotranspiration, is a desirable trait in water-limited conditions (Toker et al. (2007) Saxena (2003); Saxena and Johansen (1990). However, small leaves were also associated with late flowering and hence not desirable under water-limited conditions. In our case, medium-sized leaves were included in developing the ideotype to allow for earlier flowering as opposed to using small leaves which were associated with late flowering. High chlorophyll content at mid-podding was associated with higher yields under drought condition whereas high chlorophyll content at later stages of the growing period resulted in lower yields (Jain 1975; Nayyar et al. 2005). This is probably a function of slightly later development which exposed the plant to moisture stress during the late pod filling stage. High harvest index is an important determinant of yield under moisture-limited conditions (Siddique and Sedgley (1985); Jain (1975). In the current study, the harvest index of Sonali and Tyson were closer to the ideotype than the widely grown cultivar PBA Hattrick.

APSIM is a dynamic crop simulation model that takes into account management options in farming systems to simulate both biological and physical processes (Keating et al. 2003). It has been effectively parameterised for various crops including mungbean, peanut and chickpea (Robertson et al. 2002), wheat and soybean (Mohanty et al. 2012), pearl millet (Akponikpè et al. 2010), sorghum (Whish et al. 2005) and maize (Archontoulis et al. 2014). In the present study, the comparison between predicted and observed field data returned coefficients of determination of 0.6 and 0.7 for days to flowering and yield, respectively, across all genotypes. These data are comparable to Carberry (1996) and Robertson et al. (2002) who each reported a coefficient of determination of 0.7 for days to flowering and yield in chickpea, respectively.

Chauhan et al. (2008) identified six chickpea growing clusters in Australia and three in India. This diversity reflects the

importance of yield stability for both plant breeders and grain growers. However, this challenge can be tackled by exploiting genotype by environment by management interactions and matching crop phenology to the target environment. The majority of the locations had simulated yields greater than the break-even yield for chickpea of 1 t/ha reported by Whish et al. (2007) which makes chickpea a profitable venture for farmers. High yield in some locations coupled with the benefits of soil amelioration that chickpea provides should lead to wider adoption of chickpea in the Australian grain belt farming systems.

Kholová et al. (2013) used the soil moisture deficit approach to characterise sorghum growing environments. Lake et al. (2016) and Chenu et al. (2011) used the same approach to characterise chickpea and wheat growing environments, respectively. The present study grouped environments into three distinct clusters with two arid locations (Bourke, Rudall) ungrouped. This classification differs slightly from Lake et al. (2016) who reported four clusters. Nevertheless, the stress patterns are similar to the Lake study with the majority of locations classified as limited by terminal drought. However, in the current study, no environments recovered from terminal drought as reported by Lake et al. (2016). This classification identified the best locations to grow chickpeas across the Australian grain belt as well as the pattern of drought. This information will help grain growers match varieties to the environment to avoid periods of moisture stress.

Stress generally started at the reproductive phase, with early podding/start of grain filling being the most sensitive to drought. A similar finding was reported by (Nayyar et al. 2006; Thudi et al. 2014). To avoid heavy losses during the reproductive phase, early maturing genotypes which show plasticity can be targeted to escape drought at the reproductive phase. Furthermore, these genotypes can respond

to adequate soil moisture in better seasons to produce more yields.

Conclusions

This study developed a chickpea ideotype that can be targeted for breeding chickpea for water deficit areas. This ideotype also allows comparison with commercial chickpea varieties across the Australian grain belt. The study has shown that ideotype breeding can increase chickpea drought tolerance and hence sustain yields across the Australian grain belt and areas having similar agro-climates. It is an efficient way to evaluate chickpea genotype performance over a wide range of environments *in silico* rather than testing the genotypes in all the desired environments. The developed chickpea ideotype outperformed the other genotypes in a wide range of environments and was closely followed by Sonali which was identified as drought-tolerant genotype. Since Sonali had 76% similarity to the ideotype, it can be used as a target background for incorporating the ideotype traits into. Incorporating traits associated with drought tolerance into commercially grown genotypes can lead to faster adoption of drought-tolerant genotypes and resilient chickpea production systems.

The soil water deficit approach is a good way of characterising growing environments. In the present study, three main chickpea growing environments have been identified, namely high, mid and low potential chickpea environments. The same approach can be used to characterise the growing environments for any crops grown in the Australian grainbelt as well as other parts of the world where drought is a major problem. By characterising the growing environments, it is possible to match crop phenology with the environment and target specific drought environments which in turn ensure the crop has adequate moisture during the reproductive phase which is the most susceptible to drought. Sonali which was the drought-tolerant genotype in the present study flowered and matured earlier than the other genotypes and hence did not suffer moisture stress during flowering and podding stages. Similarly, the framework for developing chickpea ideotype can be used to develop ideotypes of other crops which are important strategies in adapting to adverse environments.

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