Associations between yield, intercepted radiation and radiation use efficiency in chickpea

Lachlan Lake and Victor O. Sadras

South Australian Research and Development Institute, Hartley Grove, Urrbrae, SA5064, lachlan.lake@sa.gov.au

Abstract

Relationships between yield, biomass, radiation interception (PAR_{int}) and radiation use efficiency (RUE) have been studied in many crops for use in growth analysis and modelling. Research in chickpea is limited with variation caused by environment and phenological stage not adequately described. This study aimed to characterise the variation in chickpea PAR_{int} and RUE with phenological stage, line, environment and their interactions, and the impact of this variation on yield. Six desi and one kabuli chickpea lines previously identified as varying for yield, competitive ability, crop growth rate, and phenology were compared in four environments resulting from a combination of two sowing dates and dry and irrigated water regimes. Yield varied from 0.7 to 3.7 t ha^{-1}. Line, environment, phenological stage, and the interactions line x environment and environment x stage affected both RUE and PAR_{int}; line x stage interaction also affected RUE. High PAR_{int} and RUE were associated with high yield but the interaction between environment and phenological stage dictated this relationship; higher PAR_{int} and RUE were observed in irrigated environments. Some environment x phenological stage combinations resulted in no significant associations, particularly before flowering in dry environments. These results emphasise the importance of understanding the effects of G x E on capture and efficiency in the use of radiation and have implications for growth analysis, modelling and breeding.

Keywords

adaptation, abiotic stress, seed number, ceptometer.

Introduction

Stress adaptation research in chickpea has identified a linear relationship between crop growth rate within the critical period and yield, particularly under water stress (Lake and Sadras 2016). The main determinants of crop growth rate are the ability of the crop to intercept photosynthetically active radiation (PAR_{int}) and radiation use efficiency (RUE) (Li et al. 2008; Giunta et al. 2009). Chickpea was domesticated as a spring sown crop and grows slowly during winter in comparison with both cereals and other pulses such as field pea meaning PAR_{int} is consequently naturally relatively low (Sadras and Dreccer 2015; Mwanamwenge et al. 1997). Further, water stress reduces both PAR_{int} and RUE (Singh and Rama 1989). Improving chickpea PAR_{int} and RUE are likely to increase yield and reliability (Li et al. 2010).

Research of PAR_{int} and RUE in chickpea includes a study on the effect of different leaf types, the effect of irrigation and the effects of increased carbon dioxide (Li et al. 2008; Kang et al. 2008; Saha et al. 2015). Singh and Sri Rama (1989) established that RUE was reduced by water deficit while Tesfaye et al. (2006) showed that RUE was more sensitive to early stage rather than late stage reproductive water deficit. Soltani et al. (2006) investigated biomass accumulation and partitioning in chickpea and assumed that RUE was constant over the crop cycle under non stressed conditions; however, changes in RUE with ontogeny was demonstrated in several crops (Lecoeur and Ney 2003; Albrizio and Steduto 2005).

For growth analysis, modelling and breeding for enhanced yield and reliability, it is necessary to understand how radiation capture and radiation use efficiency vary in response to stress and non-stress environments, phenological stage (before and after flowering), genotypes and all associated interactions. This study aimed to characterise the variation in chickpea PAR_{int} and RUE with phenological stage, line, environment and their interactions, and the impact of this variation on yield.

Methods

Plant material, crop husbandry and experimental design

A factorial experiment was established combining seven lines replicated three times in four growing conditions at Roseworthy South Australia in 2015. We compared six Desi (‘PBA HatTrick’, ‘Genesis 836’, ‘PBA Pistol’, ‘PBA Striker’, ‘PBA Boundary’, ‘CICA 1229’) and one Kabuli (‘PBA Monarch’) chickpea lines showing variation in yield and components, competitive ability, crop growth rate, and phenology when previously evaluated in environments varying for water stress. The four environments we used were a combination of two sowing dates and dry and irrigated water regimes. The first sowing date was 9 June (Early) and the second (Late) was 7 July. Within the early sown crops the water regimes were either sprinkler irrigated or rainout shelter canopy and for the late crops, sprinkler irrigated and rainfed. Rainfed and rainout shelter environments are hereon referred to as "dry". Plots were 6 rows, spaced 25 cm apart and 5 m long with 50 cm between plots. Single buffer plots were sown at each end of the bays.

Phenology, biomass, yield and yield components

Phenology was scored weekly to establish time to 50% of plants reaching: flowering, pod emergence, end of flowering and maturity. We used a thermal time scale, growing degree days (GDD), to express phenology, calculated from daily mean temperature and base temperature of 0°C. Biomass samples were collected six times over the growing season beginning 617 GDD after sowing until maturity. Samples were collected from two 0.5-m lineal cuts from central rows of plots, leaving at least 0.5 m between samples. We then fitted polynomials to characterise growth of biomass over time, and used the models to estimate biomass at any given time in the season. Yield was measured in two 1-m lineal samples taken from inner rows near the centre of plots.

Radiation interception and use efficiency

To measure PAR_{int} we used an Accupar LP-80 Ceptometer (Decagon Devices, WA, USA). Three measurements of PAR were taken randomly within the central part of the plot on clear cloudless days between 1100 and 1400 h ACST. PAR was measured above the canopy (PARa) and at the soil surface (PARb), holding the Ceptometer horizontal at right angles to the rows. Measurements were taken every 10 to 20 days across the season. Polynomials were fitted to quantify the progression of fractional PAR_{int} over time. We calculated PAR_{int} as the product between daily solar PAR obtained from the Roseworthy weather station and the fraction of PAR intercepted by the crop. RUE was calculated as the ratio of biomass production and PAR_{int} over three periods: the growing season, emergence to flowering and flowering to maturity.

Results

The ANOVA revealed significant effects of line, environment, stage and interactions between line and environment, and environment and stage on both PAR_{int} and RUE. The interaction between line and phenological stage also affected RUE. Across environments, lines and growth stages, variation in RUE was ~ 5 fold (0.55 – 2.44 g MJ^{-1}) while variation in PAR_{int} was ~ 12 fold (50 – 606 MJ^{-1}) (Figure 1). Canopy growth and PAR_{int} were higher in irrigated environments but RUE varied depending on phenological stage. Averaged across lines and environments, RUE dropped from 1.45 g MJ^{-1} before flowering to 0.96 g MJ^{-1} after flowering. Seasonal RUE averaged 1.14 g MJ^{-1} and dropped from 1.3 g MJ^{-1} in irrigated crops to 0.98 g MJ^{-1} in dry crops. In comparison with irrigated crops, RUE was 0.22 g MJ^{-1} higher in the dry environments before flowering ($P = 0.0268$), but was 0.44 g MJ^{-1} lower after flowering ($P < 0.0001$) when dry crops became increasingly stressed. PAR_{int} after flowering was also reduced by water stress with mean PAR_{int} for irrigated crops being 183 MJ^{-1} more than in their dry counterparts (Figure 1).

Across all crops, yield was positively related to PAR_{int} for all three phenological stages; environment was the main driver of this relationship (Figure 1). The relationships between yield and both PAR_{int} and RUE were stronger in irrigated crops, and also stronger for the seasonal or after flowering stages. Yield was only related to seasonal PAR_{int} and PAR_{int} after flowering in the irrigated crops; in the dry environments there was no relationship between yield and PAR_{int}. Yield was positively associated with seasonal RUE and RUE after flowering when all crops were combined. When crops were separated by water regime, yield was associated with RUE for all stages in irrigated crops; however, in the dry environments, yield was only associated with seasonal RUE.

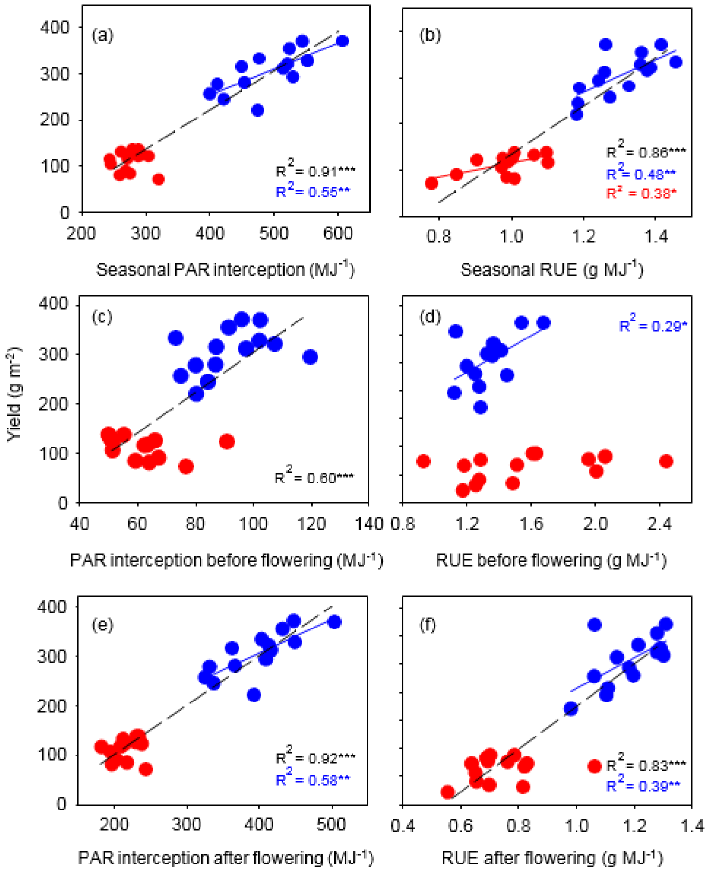

Figure 1. Relationship between yield and: (a) Total PAR$_{int}$, (b) seasonal RUE, (c) PAR$_{int}$ before flowering, (d) RUE before flowering, (e) PAR$_{int}$ after flowering and (f) RUE after flowering. Linear regression was fitted across environments and for dry and irrigated environments separately; only significant relationships are presented. Lines are Model II (Reduced Major Axis) regression accounting for error in both variables. Red represents dry environments while blue represents irrigated environments. Black lines are for regression across environments. Significance is denoted as * for P < 0.0001, ** for P < 0.01 and * for P < 0.05. Note, the difference in the x-scale among panels, reflecting the difference in range of PAR$_{int}$ and RUE during the different intervals.**

Conclusions

Research in chickpea looking at PAR$_{int}$ and RUE has shown that increased radiation interception is likely to provide the largest improvement in biomass and yield in unstressed crops, while research under water deficit concluded that increases in both traits would result in yield benefits (Singh and Rama 1989; Tesfaye et al. 2006; Li et al. 2008). Our results show that interactions between yield, RUE and PAR$_{int}$ in different environments are complex and have highlighted the critical importance of understanding the G x E interactions. Across lines and environments, we found significant variation for PAR$_{int}$ and RUE with interactions between line, environment and stage. These results have implications for growth analysis, modelling and for adaptation breeding selection strategies.

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