Field Crops Research 183 (2015) 14–22

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Physiological basis of yield variation in response to row spacing and plant density of mungbean grown in subtropical environments

Rao C.N. Rachaputi[a,*], Yashvir Chauhan[b], Col Douglas[b], William Martin[b], Stephen Krosch[b], Peter Agius[b], Kristopher King[b]

[a] Queensland Alliance for Agriculture and Food Innovation (QAAFI), The University of Queensland, Australia
[b] Department of Agriculture and Fisheries, Queensland (DAF), Australia

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 10 July 2015
Accepted 11 July 2015
Available online 28 July 2015

Keywords:
Mungbean
Row configurations
Water-use efficiency
Radiation-use efficiency
Harvest index

ABSTRACT

In this study, we investigated the extent and physiological bases of yield variation due to row spacing and plant density configuration in the mungbean [*Vigna radiata* (L.) Wilczek] variety "Crystal" grown in different subtropical environments. Field trials were conducted in six production environments; one rain-fed and one irrigated trial each at Biloela and Emerald, and one rain-fed trial each at Hermitage and Kingaroy sites in Queensland, Australia. In each trial, six combinations of spatial arrangement of plants, achieved through two inter-row spacings of 1 m or 0.9 m (wide row), 0.5 m or 0.3 m (narrow row), with three plant densities, 20, 30 and 40 plants/m^2, were compared. The narrow row spacing resulted in 22% higher shoot dry matter and 14% more yield compared to the wide rows. The yield advantage of narrow rows ranged from 10% to 36% in the two irrigated and three rain-fed trials. However, yield loss of up to 10% was also recorded from narrow rows at Emerald where the crop suffered severe drought. Neither the effects of plant density, nor the interaction between plant density and row spacing, however, were significant in any trial. The yield advantage of narrow rows was related to 22% more intercepted radiation. In addition, simulations by the Agricultural Production Systems Simulator model, using site-specific agronomy, soil and weather information, suggested that narrow rows had proportionately greater use of soil water through transpiration, compared to evaporation resulting in higher yield per mm of soil water. The long-term simulation of yield probabilities over 123 years for the two row configurations showed that the mungbean crop planted in narrow rows could produce up to 30% higher grain yield compared to wide rows in 95% of the seasons.

1. Introduction

Mungbean [*Vigna radiata* (L.) Wilczek] is an economically and nutritionally important food and feed legume crop. The crop meets its own nitrogen requirements by fixing atmospheric nitrogen, and is therefore valued as a rotation crop both in subsistence and mechanized agriculture.

Mungbean production and consumption are mainly concentrated in Asia (Weinberger, 2003). The demand for mungbean is increasing and is outstripping production resulting in a significant gap to be filled (Nair et al., 2013).

The Australian mungbean production has increased from 36,000 tonnes to 70,000 tonnes per annum in the recent years, and there is a potential for further increase. The average regional yield of mungbean has, however, remained stable at 1.1 t/ha although yield variation between seasons and farms varied between <0.5 and 2 t/ha for a range of reasons, including suboptimal agronomic practices and abiotic and biotic constraints.

Australian mungbean production is concentrated in central and southern Queensland and northern New South Wales between 16° and 32°S and 148° and 151°E. This region, known as the northern grains region, is characterised by summer dominant rainfall varying between 500 and 800 mm, with a coefficient of variation of 30% (Webb et al., 1997).

Developing new varieties or practices for a given production environment depends on understanding the eco-physiological basis of adaptation. A number of studies investigating the genotype × environment × management interaction in mungbean productivity have been attempted in semi-arid tropical (Muchow and Charles-Edwards 1982; Muchow, 1985; Tesfaye et al., 2006) and subtropical (Imrie and Butler, 1982) (Lawn, 1982a,b,c, 1983) environments. These studies concluded that rainfall variability

* Corresponding author.
E-mail address: rao.rachaputi@uq.edu.au (R.C.N. Rachaputi).

http://dx.doi.org/10.1016/j.fcr.2015.07.013

was a major yield limiting factor for mungbean, and equidistant planting resulted in higher productivity compared to row planting with the yield advantage from equidistant planting being greater in favourable rainfall environments. However, the conventional row spacing and plant density practices for commercial mungbean varieties grown in Queensland range between 0.30 and 1 m with 20–30 plants/m^2, mainly to suit mechanized cultivation of row crops in the cropping systems.

Yield improvement through optimising row spacing and seeding rates for a given environment has been demonstrated in various legume crops including mungbean (Lawn, 1983), soybean (Board et al., 1992; Borad and Harville, 1996; Cox and Cherney, 2011), and cowpea (Ismail and Hall, 2000), as well as maize (Bullock et al., 1988; Andrade et al., 2002). Narrow row spacing resulted in increased intercepted radiation in grain legumes (Lawn, 1983) and in maize (Andrade et al., 2002); increased water use efficiency (Barbieri et al., 2012); reduced competition from weeds (Knezevic et al., 2009; Fahad et al., 2014); and improved whole farm profitability (De Bruin and Palle, 2008). However, the response to narrow row spacing varied depending on the evaporative demand and the soil nutrient status of production environments (Barbieri et al., 2000, 2012).

There is little information on the effects of the spatial arrangement of plants on the performance of the new commercial mungbean variety Crystal, which is predominantly grown in the sub-tropical environment of north-eastern Australia. Since the adoption of Crystal has increased substantially in recent years, its suboptimal agronomy could affect individual farmer profitability, and also national production targets.

Since water use and radiation intercepted by plants underpin the carbon gain through photosynthesis, and consequently productivity, the effects of the spatial arrangement of plants can be analysed in terms of soil water uptake, radiation capture, efficiency with which these resources are converted into dry matter, and grain yield (Passioura, 1977). However, measurement of traits linked with the resource-use efficiency in field trials is laborious and expensive, particularly in multi-location trials. Integrating site and crop-specific data with validated crop growth models should assist in overcoming some of these limitations.

Earlier studies have shown that the Agricultural Production Systems sIMulator (APSIM) can accurately simulate soil water balance parameters in dryland environments (Verburg and Bond, 2003), potential evaporation (Jayeoba et al., 2006), complex physiological traits (Hammer et al., 2010) and the water supply and demand ratio of dryland crops (Lobell et al., 2013). The APSIM mungbean crop model has been recently validated and applied to simulate yield and dry matter production of mungbean in diverse production environments (Chauhan and Rachaputi, 2014).

This paper investigates the effects of row spacing and plant density on the productivity enhancement of Crystal, in both water-limited and irrigated conditions. The paper also attempts to use the validated APSIM model configured to site-specific agronomy, soil and climate data, to provide some insights into the physiological bases of differences in yield and dry matter observed in response to row spacing across different environments.

2. Materials and methods

Field experiments were conducted between 2009 and 2010 at the Department of Agriculture and Fisheries (DAF) research facilities located at Emerald (ERS; 23.3°S, 148.1°E), Biloela (BRS; 24.4°S, 150.5°E), Kingaroy (KRS; 26.5°S, 151.9°E) and Hermitage (HRS; 28.2°S, 152.1°E) in Queensland, Australia. These locations represented typical mungbean production environments in cereal–legume based cropping systems. The experimental details including soil properties, sowing and harvesting dates, and in-crop rainfall for each test site are presented in Table 1.

Pure seed of Crystal, obtained from the Australian mungbean breeding program, was used at all test sites. The six spatial arrangements tested included factorial combinations of two inter-row spacing and three plant density treatments. The two inter-row spacing treatments were 1 m (at ERS, BRS and HRS) and 0.9 m (at KRS), termed as ‘wide row’ spacing and 0.5 m (at ERS, BRS and HRS) and 0.3 m (at KRS), termed as ‘narrow row’ spacing. The three plant densities, 20, 30 and 40 plants /m^2, were used at all sites. The inter-row spacing of 1 m at ERS, BRS and HRS and 0.9 m at KRS, represented the conventional practice followed for row crops, including mungbean in the respective locations. The three plant densities, 20, 30 and 40 plants/m^2, cover the range of seed rate used by farmers.

At each site, rain-fed and irrigated trials were established in the same block with a 12 m buffer crop between the trials. This set up enabled crops to share similar soil and weather conditions excluding the supplementary irrigations given to the irrigated trials. Each trial was laid out in a randomised block design with the six spatial configuration treatments allocated randomly to plots in each of the three replications. Each plot consisted of three 12 m long, and 1.8 m (at KRS) or 2 m (at other sites) wide seed beds. The crop data were collected from the middle bed, with the outer two beds acting as guard plots. Prior to sowing, seeds were pre-treated with a peat slurry of *Bradyrhizobium* spp. inoculant (group I) specific to mungbean, and a starter dose of zinc, at the rate of 30 kg/ha was applied as part of a standard practice. The three plant densities were achieved by initially sowing excess seeds for each density using a planter and thinning the extra plants 2–3 weeks later. In all trials except at ERS, the soil profile at sowing was fully charged from the preceding rainfall. At ERS, a pre-sowing irrigation of about 25 mm was applied to enable sowing. Adequate rainfall at KRS and HRS did not warrant any irrigation, but the irrigated trials at BRS and ERS sites received supplementary irrigation mostly during the reproductive phase (Table 1). As irrigated trials could not be established at KRS and HRS sites, data from rain-fed trials was used for analysis. Appropriate plant protection practices were implemented to protect the trials from pests and diseases. At KRS, some powdery mildew incidence was unavoidable due to cooler temperatures and rainfall towards the end of the season.

2.1. Measured variables

2.1.1. Fractional intercepted radiation

The solar radiation intercepted by the canopy was recorded at KRS, HRS and BRS sites. The measurements were made on clear days between 11:30 and 13:30 h at 59, 79 and 104 days after sowing (DAS) at KRS, 64 DAS at HRS, and 51 DAS at BRS using a Ceptometer (AccuPAR model LP-80, Decagon Devices, USA). Solar radiation above and below the canopy at the ground level was simultaneously recorded at three random spots in each plot. The fractional intercepted radiation (*f*) on a given day was calculated as the ratio of the radiation measured below the canopy at the ground level to the incident radiation measured above the canopy.

2.1.2. Shoot biomass

The crops reached the peak biomass stage (end of the seed filling phase and before the start of leaf senescence) on different dates at the test sites, depending on the date of sowing and seasonal weather conditions. The peak biomass sampling in irrigated and rain-fed trials was done on 6 April 2010, 58 days after sowing (DAS) at Biloela, 7 April 2010 (70 DAS) at Kingaroy, 20 April 2009, (60 DAS) at Emerald, and 19 March 2010, (108 DAS) at Hermitage. Plants were hand-harvested at the ground level from a 2 m^2 area from each plot, and plant count recorded. The harvested plants were

Table 1
Soil type, plant-available water holding capacity (PAWC) of the soil, sowing and harvest dates, in-crop rain, evapo-transpiration and irrigation details of the mungbean trials conducted at Biloela (BRS), Emerald (ERS), Kingaroy (KRS) and Hermitage (HRS) sites during the 2009–10 growing seasons.

	Soil type	PAWC (mm)	Sowing date	Harvest date	In-crop rain (mm)	Evapo-transpiration (mm)	Irrigation date (amount) (mm)
Biloela (BRS)	Black Vertosol	145	08/02/10	28/04/10	340	202	19/3/10 (50)
Emerald (ERS)	Black Vertosol	145	20/02/09	18/05/09	92	159	2/4/09 (100)
Hermitage (HRS)	Brown Vertosol	162	23/12/09	23/04/10	379	258	Nil
Kingaroy (KRS)	Red Ferrosol	119	19/01/10	26/05/10	321	201	Nil

dried in a fan-forced oven at 80 °C for 48 h before recording shoot (leaves + stems + pods) dry weight.

2.1.3. Grain yield

The trials were harvested when 90% of plants had around 80% mature pods as indicated by the dark colour pod wall. Plants from another 2 m^2 ground area were hand-harvested from each plot to determine harvestable yield. The plants were counted, air-dried in a ventilated glass house, and the grain was harvested using a mechanical thresher. The remaining plot area was measured, and plants were desiccated in the field by applying a foliar spray of Glyphosate® at 2 L/ha before machine-harvesting. The grain samples collected from the harvester were cleaned to remove any extraneous matter and dried to 10% moisture content before weighing. As there was only a minimal difference between the hand-harvested and the machine-harvested yield, the data from machine-harvested yield was used for analysis since it was derived from a larger plot area.

2.2. APSIM crop model-simulated variables

The APSIM model (Robertson et al., 2002) with a modified extinction coefficient parameter (Chauhan and Rachaputi, 2014) was used to simulate a number of crop growth variables including fractional intercepted radiation (f) and simulated evapotranspiration (ETa) on a daily basis.

The APSIM user interface (Version 7.4) was configured to the site-specific soil properties including nitrogen, genetic parameters associated with Crystal, crop management (date of sowing, row spacing, plant density, irrigation dates and amounts for irrigated trials). The information on soil properties for the trial sites was obtained from the APSIM soil database (www.apsim.info) and the daily weather parameters (maximum and minimum temperature, solar radiation, and rain) were collected from automatic weather stations installed on the trial sites.

2.2.1. Radiation interception and radiation-use efficiency

The cumulative intercepted radiation from emergence to crop desiccation was computed as described below:

$$\mathrm{Sum(IR)} = \sum_{T1}^{Tn} (\mathrm{In}R \times f) \tag{1}$$

where Sum (IR) was the cumulative intercepted radiation (MJ/m^2) from the day of emergence ($T1$) to crop desiccation date (Tn), In R was the incident radiation on a given day, and f was the fractional intercepted radiation simulated by the APSIM model on a daily basis from $T1$ to Tn.

The radiation-use efficiency (RUE) was calculated as below:

$$\mathrm{RUE}\left(\mathrm{g/MJ}\right) = \frac{DM}{\mathrm{Sum\,(IR)}} \tag{2}$$

where Sum (IR) was the cumulative intercepted radiation over the crop growing period (calculated as per Eq. (1)), and DM was the shoot (stems + leaves + pods) dry matter/m^2 at the peak biomass stage.

2.2.2. Evapotranspiration, transpiration, soil evaporation

For each of the six production environments, the cumulative water loss due to transpiration (T) and soil evaporation (Es) was simulated for narrow and wide row spacing treatments using the APSIM model (Keating et al., 2003). Loss of water through drainage was considered negligible. The actual evapotranspiration (ETa) value was simulated by adding T and Es. However, these values were un-replicated.

The ETa-use efficiency for yield (ETa_y) was calculated as the ratio of the mean yield (Y) to the simulated cumulative ETa from the emergence to desiccation date as described below.

$$\mathrm{ETa\_}y\left(\mathrm{kg/mm/ha}\right) = \frac{Y}{\mathrm{ETa}} \tag{3}$$

2.2.3. Growing degree days (GDD)

GDD was calculated on a daily basis by APSIM using the base temperature of 7.5 °C for mungbean (Ellis et al., 1994; Robertson et al., 2002).

2.2.4. Long-term APSIM simulations

To assess the value of narrow row spacing as a means of improving average mungbean yield on a long-term basis, yield probability scenarios were developed for the test sites, using the APSIM model configured with the site-specific soil properties and historical climate data for the last 123 years. For each site, yield was simulated for the crop planted in the month of January in narrow and wide row spacing, and at two starting soil moistures. Planting in January represented the normal sowing window for mungbean in the regions where the test sites were located. For consistency, the sowing density of 30 plants/m^2 was used at all the sites, and row spacing was set to 1 m (wide row) or 0.5 m (narrow row) at BRS, ERS and HRS, and 0.9 m (wide row) or 0.30 m (narrow row) at KRS. In simulating the time of sowing, any day between 1st and 31st January was considered, with the sowing rules set to start the simulation when there was at least a total of 30 mm of rain over a 3-day period. When assessing the effects of starting moisture, it was set at 50% and 100% of the plant-available water holding capacity (PAWC) in 120 cm soil profile for each site. These starting water levels were reset at sowing in each season.

2.3. Statistical analysis

Analysis of variance (ANOVA) was conducted for the crop growth parameters using a blocking structure of (Env/Rep), where Env was the production environment, including one rain-fed and one irrigated trial at each of the BRS and ERS sites, and one rain-fed

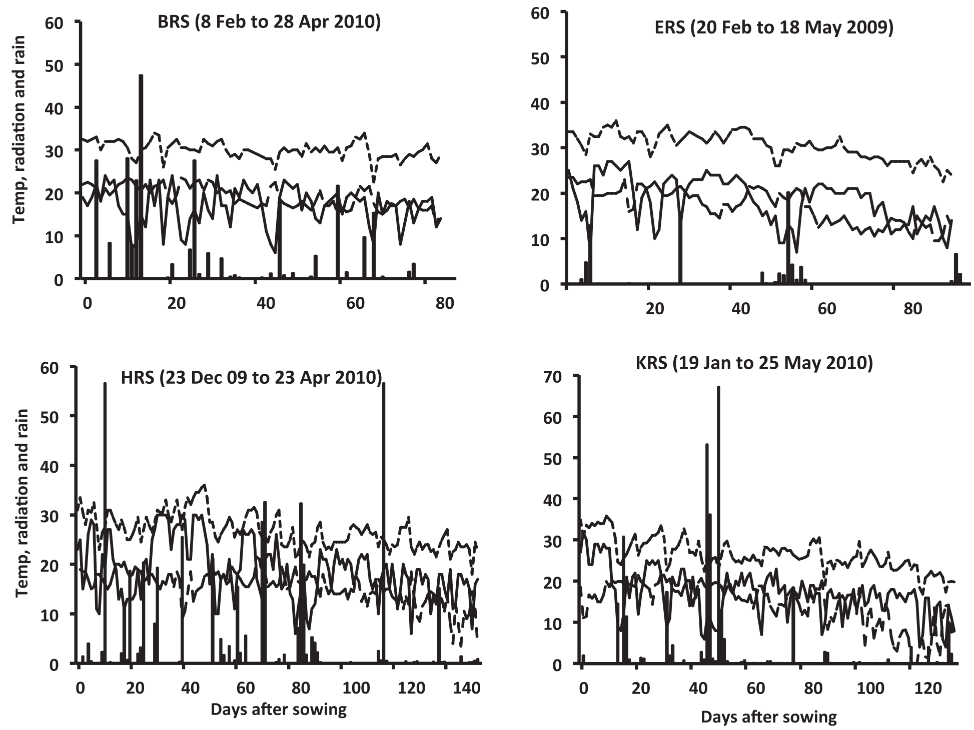

Fig. 1. Daily weather; ----- max temp (°C), — min temp (°C), (—) radiation (MJ/m^2), and rainfall events (mm) as vertical bars, during the crop growing period at the Biloela (BRS), Emerald (ERS), Kingaroy (KRS) and Hermitage (HRS) test sites. Dates of sowing and harvest of the trials are indicated in the figures.

trial at each of the HRS and KRS sites, and Rep was the replication. Thus, there were six production environments to allow comparison of treatment means.

As the ETa, *T*, Es, ETa$_{-Y}$ and RUE outputs simulated by the APSIM model for each treatment were un-replicated, the analysis of variance for these simulated parameters was conducted treating the six production environments as replications. GENSTAT (16.0 edition; http://www.genstat.co.uk) was used for the analysis. The relationships between the measured and APSIM-simulated intercepted radiation, shoot dry matter, and yield variables were analysed using a linear regression approach.

3. Results

3.1. Weather

The rainfall distribution varied considerably across the test sites. The HRS, KRS and BRS sites either received adequate rainfall, or experienced only short and mild dry spells during the season (Fig. 1). The ERS site experienced prolonged dry spells during the vegetative and reproductive phases. While maximum and minimum ambient air temperatures at ERS and BRS were around 30 and 20 °C respectively through the season, the KRS and HRS sites experienced a steady decline in temperature from 50 days after sowing.

3.2. Shoot dry matter, grain yield and harvest index

The Env effect on shoot dry matter and grain yield was significant ($P < 0.001$) (Table 2). The row spacing effects, and the interaction between Env and row spacing were significant for shoot dry matter and yield ($P < 0.001$). However, the plant density effects were not significant (Table 2), although there was a trend for 30 plants/m^2 to be optimum. As the effects of plant density or the interactions of plant density with row spacing or Env were not significant, only the main effects of row spacing at 30 plants/m^2 are presented in this paper.

In the rain-fed trials, the narrow rows on average produced 22% and 14% higher shoot dry matter and grain yield than wide rows respectively (Table 3). However, the narrow rows resulted in 10% lower yield in the rain-fed trial at ERS. Under irrigated conditions at the BRS and ERS sites, the yield advantage from narrow rows ranged from 13 to 27%. The harvest index was, however, stable (0.34 ± 0.01) across sites and treatments.

3.3. Fractional intercepted radiation

The fractional intercepted radiation (*f*) measured during the reproductive phase of the crop at the BRS, HRS and KRS sites is presented in Fig. 2. As the effects of irrigation and plant density on *f* were not significant, the data from irrigated and rain-fed trials at BRS was pooled for each row spacing treatment. It was clear that at all three sites, *f* was consistently higher in narrow rows suggesting greater interception of radiation by narrow rows.

3.4. Cumulative intercepted radiation and radiation use efficiency

The APSIM simulated *f* accounted for 83% of the variation in the observed *f* across sites and treatments (Fig. 3), suggesting that the model, in conjunction with the site-specific daily solar radiation data, could be used to simulate intercepted radiation for each row spacing on daily basis.

Plotting simulated changes in *f* during crop growth against thermal time (GDD) allowed comparison of the rate of canopy development of Crystal between sites and treatments without confounding effects from the site-specific ambient temperature, which could influence the rate of canopy development. The APSIM simulations showed that *f* was consistently higher in narrow rows throughout the crop growth at all sites (Fig. 4). Irrigation had little effect on *f* at BRS, whereas at ERS, irrigation resulted in an increase in *f* up to 0.8 in narrow rows (data not presented). At ERS, the rate

Table 2
Accumulated analysis of variance (ANOVA) for shoot dry matter (DM), grain yield (*Y*) and harvest index (HI) of Crystal grown in two row spacing configurations, three plant densities under rain-fed and irrigated environments (ENV) at Emerald, Biloela, and favourable rainfall environments at Kingaroy and Hermitage sites. In the ANOVA table, d.f is the degrees of freedom, ns = non-significant, ** and * indicate significance at 99% and 95% probabilities, respectively.

Source of variation	d.f.	DM	*Y*	HI
Env	5	**	**	ns
Residual	12		12	
Env × Rep × *Units* stratum				
Plant density	2	ns	ns	ns
Row spacing	1	**	**	ns
Env × plant density	10	ns	ns	ns
Env × row spacing	5	**	**	ns
Plant density × row spacing	2	ns	ns	ns
Env × plant density × row spacing	10	ns	ns	
Residual	60			
Total	107			

Table 3
Grain yield and shoot dry matter of Crystal grown under narrow and wide row spacing configurations under irrigated (IRR) and rainfed (RF) environments at Biloela (BRS) and Emerald (ERS), and favourable rainfall environments at Hermitage (HRS) and Kingaroy (KRS). In the table ** indicate significance at 99% probability.

	Grain yield (kg/ha)			Shoot dry matter (kg/ha)		
Environment	Narrow rows	Wide rows	Change over wide rows (%)	Narrow rows	Wide rows	Change over wide rows (%)
BRS_RF	1758	1293	36	4919	3662	34.3
BRS_IRR	1744	1372	27.1	5019	3949	27.1
ERS_RF	728	809	−10	2675	2683	−0.3
ERS_Irr	1022	906	12.8	2908	2435	19.4
HRS_RF	2125	1931	10	6688	5000	33.8
KRS_RF	1911	1581	20.9	5940	4927	20.6
Significance						
Env	**			**		
Row spacing	**			**		
Env x row spacing	**			**		

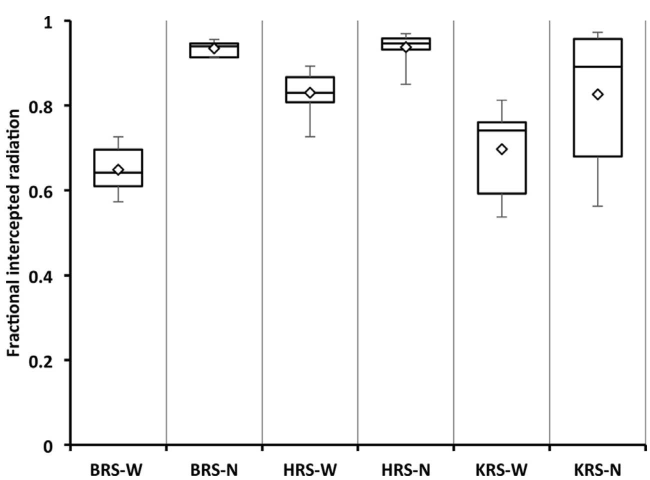

Fig. 2. Fractional intercepted radiation (*f*) measured in wide (W) narrow (N) row spacing treatments on 51 days after sowing (DAS) at Biloela (BRS), 64 DAS at Hermitage (HRS), and 59, 79 and 104 DAS at Kingaroy (KRS) sites. The data of irrigated and rain-fed treatments were pooled at BRS for each row spacing. The size of the box accounts for 60% of the variation in the *f* values measured in each treatment. The mean (diamond) and median (cross line in the box) values are indicated within the box. Whiskers represent maximum and minimum values of the data set.

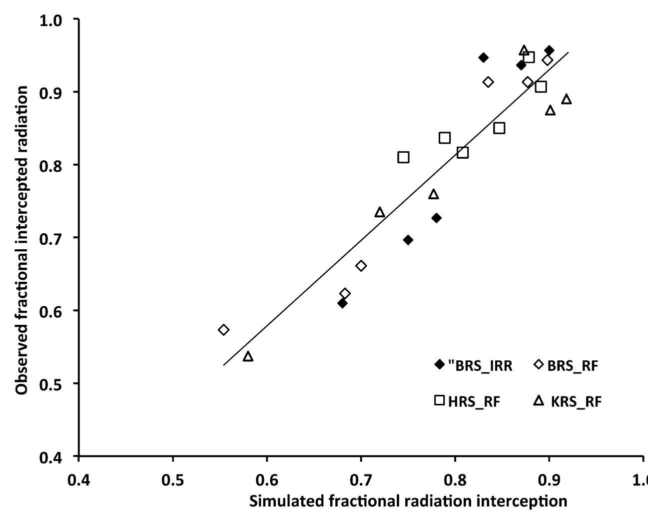

Fig. 3. Relationship between simulated and observed fractional intercepted radiation in irrigated (IRR) and rainfed (RF) trials at Biloela (BRS), and rain-fed trials at Hermitage (HRS), and Kingaroy (KRS) test sites. In the figure solid line is the fitted linear regression between the simulated and observed fractional intercepted radiation. For the regression the value in the paranthesis is the standard error of the associated coeffient and R^2 is the proportion of variation accounted for, and ** indicate significance at 99% probability. $y = 1.17\ (0.08)x - 0.124$, $R^2 = 0.83$**.

of canopy development was comparable to other sites until 600 °C GDD, but severe drought affected further development of canopy, resulting in *f* reaching to a maximum of only 0.6 in narrow rows, and 0.5 in wide rows, with no further change until 900 °C GDD (Fig. 4b). A rapid decline of *f* followed due to drought induced leaf senescence at ERS.

At BRS (Fig. 4a), HRS (Fig. 4c), and KRS (Fig. 4d), *f* reached >0.9 in narrow rows compared to <0.7 in wide rows by 900 °C GDD which corresponds to the active seed filling phase. However, canopy development was initially slow at BRS, with *f* reaching a maximum of 0.7 in wide rows by 900 °C GDD (Fig. 4a). A gradual reduction in the simulated *f* after 900 °C GDD at all sites was associated with leaf senescence in both row spacing treatments.

The mean simulated cumulative intercepted radiation across the eight trials was significantly higher (by 22%) in narrow rows compared to wide rows (Table 4). The simulated cumulative intercepted radiation accounted for 80% of the variation in total dry matter, and

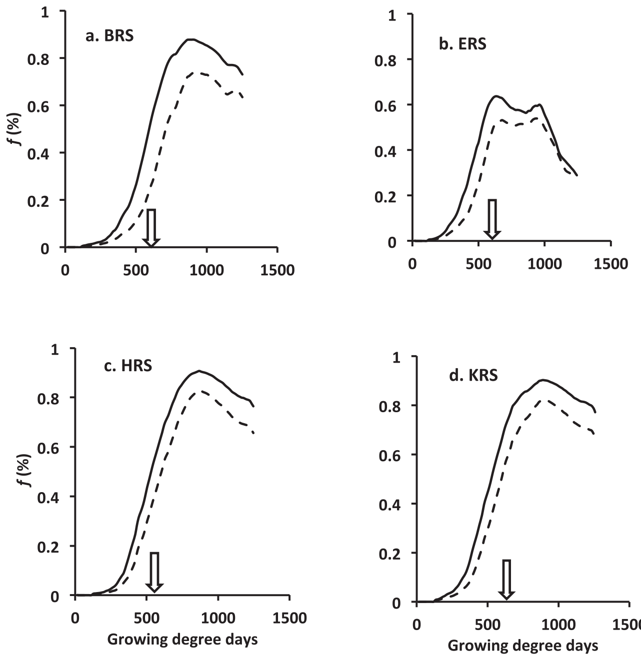

Fig. 4. APSIM-simulated fractional intercepted radiation (f) from sowing to maturity (expressed in thermal time) of Crystal grown under rain-fed conditions in narrow (—) and wide row (-----) spacing treatments at (a) Biloela (BRS), (b) Emerald (ERS), (c) Hermitage (HRS) and (d) Kingaroy (KRS) sites. The arrows pointing to x-axis indicate the thermal time to 50% flowering.

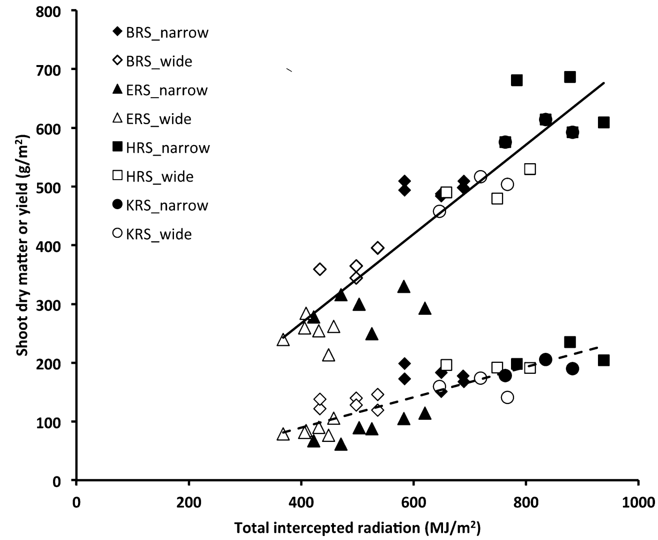

Fig. 5. Relationship between the simulated cumulative intercepted radiation from sowing to maturity and measured shoot dry matter (shoot and pods) and grain yield of Crystal grown under narrow and wide rows Biloela (BRS), Emerald (ERS), Hermitage (HRS) and Kingaroy (KRS) sites. The fitted linear regressions between the simulated intercepted radiation (x axis) and observed shoot dry matter and grain yield (y axis) are indicated by solid and dashed lines, respectively. The R^2 in the regression equation is the proportion of variation accounted for, and ** indicate significance at 99% probability. Shoot dry matter, $y = 0.760x - 36.7$, $R^2 = 0.80^{**}$; grain yield, $y = 0.258x - 13.80$, $R^2 = 0.72^{**}$.

Table 4
The environmental mean values of simulated evapo-transpiration (ETa), proportions of simulated transpiration (T) and soil evaporation (Es) in ETa, ETa-use efficiency for yield (ETa_y), cumulative intercepted radiation (IR), and radiation use efficiency (RUE) of Crystal grown in narrow and wide row spacing during the 2009–10 season at the six production environments, Biloela (BRS, irrigated and rain-fed), Emerald (ERS, irrigated and rain-fed), Hermitage (HRS, rain-fed) and Kingaroy (KRS, rain-fed). The analysis of variance was conducted using the six production environments as replications. In the table, ns and ** indicate non-significant and significance at 99% probability respectively.

	Environmental means		
Parameter	Narrow Rows	Wide Rows	Significance
Mean ETa (mm)	216	205	**
T/ETa (%)	56	51	**
Es/ETa (%)	44	49	**
ETa_y (kg/mm/ha)	7	6.3	**
IR (MJ)	735	603	**
RUE (g/MJ)	0.6	0.6	ns

72% of grain yield measured in the six production environments, resulting in an overall radiation use efficiency of 0.76 g/MJ for dry matter, and 0.26 g/MJ for grain yield (Fig. 5).

3.5. Long-term simulations

The long-term yield simulation analysis showed that planting Crystal at 100% starting PAWC would result in greater yield than planting at 50% PAWC in 95% of the seasons at all sites except at Kingaroy. The yield advantage from narrow row spacing was apparent throughout the yield range for the crop planted at 100% starting PAWC (Fig 6).

The yield response to narrow row spacing was not apparent for the crop planted at 50% PAWC below the environmental mean yield of 1000 kg/ha at Biloela and Emerald, and 1500 kg/ha at Hermitage (Fig. 6). There was no evidence of major yield loss from narrow rows, even when the environmental mean yield was lower than 750 kg/ha at the Biloela and Emerald sites.

At Kingaroy, where PAWC is generally low and crops rely on current rainfall, starting soil moisture, unlike other locations, did not seem to affect yields. Planting in narrow rows had higher yield probabilities when the environmental mean yield was above 1200 kg/ha.

4. Discussion

The observed increase in the productivity of mungbean in narrow rows in this study is in agreement with earlier studies in mungbean (Lawn, 1983) as well as other legumes, including soybean (Borad and Harville, 1996; Cox and Cherney, 2011) and cowpea (Ismail and Hall, 2000). In our study, the yield response to narrow rows was observed under irrigated and rain-fed conditions at the BRS site, whereas at the ERS site, the response to irrigation was observed only in narrow rows. At ERS, high evapotranspiration, coupled with the lack of rain, might have resulted in the rapid depletion of soil water in the rain-fed trial leading to severe water deficit in narrow rows.

Yield response to irrigation in narrow rows at the BRS site could be due to short cycles of intermittent stress, and availability of water to support the reproductive growth of the crop. Similar results were observed in chickpea (Vadez et al., 2014) and peanut (Ratnakumar et al., 2009), where high yield was related to combined intermittent stress and adequate water availability during the grain-filling period. Earlier studies showed that the response to irrigation in peanut (Nageswara Rao et al., 1988) and mungbean (Pannu and Singh, 1993; Thomas et al., 2004; Raza et al., 2012) was influenced by the timing and intensity of water deficits. It was also possible that the intermittent and mild water deficits in narrow rows could have contributed to an increase in instantaneous transpiration use efficiency at the leaf level (Sengupta et al., 2011).

Higher dry matter and yield in narrow rows were associated with greater intercepted radiation measured during the seed filling phase (Fig. 2), and simulated through most of the crop growing period (Fig. 4), which supported earlier studies in soybean (Ouyang et al., 2011) and maize (Andrade et al., 2002). A critical leaf area

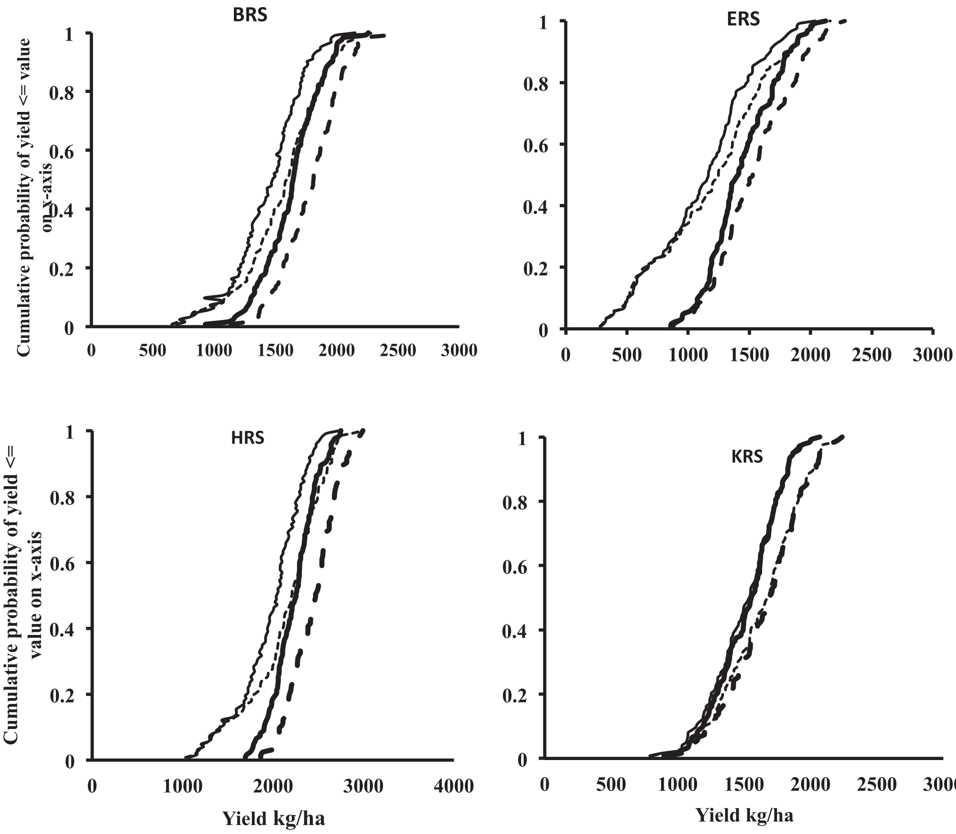

Fig. 6. Cumulative probability of simulated yield distribution of Crystal planted at 50% plant-available water holding capacity (PAWC) in narrow (50 cm) (- - -) and wide rows (1 m) (—) spacing or 100% PAWC in narrow (- - - -) and wide rows (**—**) at Biloela (BRS), Emerald (ERS), Hermitage (HRS) and Kingaroy (KRS) sites. The yields were simulated for rain-fed crop using site-specific soil properties and historical climate data over 123 years.

index (LAI) value of 3.5 to 4.0 for maximum light interception (Holshouser and Whittaker, 2002), and a critical threshold level of 600 g/m^2 total dry matter at the R5 stage, were identified as key factors for maximum yield of soybean (Board and Modali, 2005). In this study, narrow rows at BRS (irrigated), HRS and KRS sites were intercepting >90% of radiation during reproductive phase (Fig. 2), with 5–6 t dry matter/ha recorded at the seed filling phase (Table 3), suggesting that narrow rows were performing close to their physiological potential at the sites not affected by severe water deficits.

Harvest index (HI) of Crystal was relatively stable across the row spacing treatments and the production environments, except at ERS where HI was reduced due to drought. These results are in agreement with an earlier study which showed that variation in yield due to spatial arrangement in mungbean was largely explained by variation in biomass accumulation, rather than HI (Thomas et al., 2004).

While various crop models have been applied for assessing the effects of environment and crop management (Sinclair and Seligman, 1996; Robertson et al., 2002; Nelson et al., 2002; Chauhan and Rachaputi, 2014), the use of such models to predict complex traits associated with resource-use efficiency has been limited (Hammer et al., 2009, 2010).

The significant relationships between the measured crop growth attributes (DM and yield) and simulated intercepted radiation (Fig. 5), provide an opportunity to use APSIM to explore the role of other complex physiological mechanisms such as soil evaporation, crop transpiration, water and radiation-use efficiencies, in explaining the productivity differences between the row spacing treatments. Earlier studies have shown a close relationship between the above ground biomass and the amount of water transpired by crops (Passioura,1977; Dunin and Passioura, 2006). Varietal or agronomic management practices that increase the contribution of transpiration to total evapotranspiration resulted in increased water productivity of crops under water-limited conditions (Passioura and Angus, 2010). In the present study, APSIM was used to determine if the increased intercepted radiation, dry matter production and yield in narrow rows were associated with increased water uptake or greater use of soil water to support transpiration to support crop growth. The simulated cumulative evapotranspiration (ETa) was significantly higher ($P < 0.001$) in narrow row spacing (216 mm) compared to wide row spacing (205 mm) (Table 4). The estimated proportion of transpiration (T) in total ETa was also significantly higher ($P < 0.001$) in narrow rows, while the proportion of soil evaporation (Es) in total ETa was significantly higher ($P < 0.001$) in wide rows, suggesting more efficient use of soil water in narrow rows compared to wide rows. Significantly higher ($P < 0.05$) ETa_y in narrow rows (7.0 kg yield/mm/ha) compared to wide rows (6.3 kg yield/mm/ha) suggests higher water productivity in narrow rows (Table 4).

The simulated row spacing responses in soil water use in our study are consistent with earlier studies which reported higher yield, increased initial leaf area development and total crop water use with equidistant spacing, compared to 1 m row spacing for a range of grain legumes including mungbean (Lawn, 1983). The 6–8 kg/mm/ha ETa_y values reported in our study for Crystal are comparable to the values reported for 11 erect type grain legume species (4–8 kg/mm/ha) (Siddique et al., 2001), but higher than those reported for old mungbean varieties Berken and CES-ID-21 in humid tropics (2–5 kg/mm/ha) (Muchow, 1985; Pannu and Singh, 1993), and variety Berken in subtropics (Lawn, 1983). The differences in ETa_y values between the current and the earlier studies could be due to a range of reasons including seasonal differences in

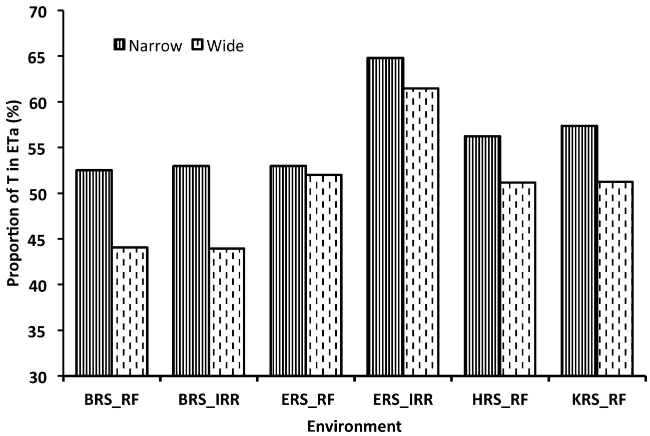

Fig. 7. The simulated proportion (%) of transpiration (*T*) in total evapo-transpiration (ETa) in narrow and wide row spacing treatments in the irrigated (IRR) and rainfed (RF) environments at Biloela (BRS) and Emerald (ERS), and favourable environments at Hermitage (HRS) and Kingaroy (KRS). The differences between row spacing treatments were significant at 99% probability (see Table 4).

evaporative demand, genotypic variation in leaf and root architecture which affect light interception and soil water uptake.

The higher ETa in narrow rows could be due to increased soil water uptake, greater root length density (Sharratt and McWilliams, 2005), and deeper root systems (Sadras et al., 1989), as well as soil evaporation. The higher proportion of *T* in ETa in narrow row spacing treatments across all the six production environments (Fig. 7) could be as a result of rapid canopy closure in narrow rows resulting in reduced evaporative losses, better availability of soil water to support crops transpiration (Andrade et al., 2002; Sharratt and McWilliams, 2005; Drouet and Kiniry, 2008).

Deeper roots (Pannu and Singh, 1993; Sadras et al., 1989) and higher transpiration-use efficiency at leaf level due to intermittent and mild water deficits (Sengupta et al., 2011) might also have contributed to increased water uptake and crop water use efficiency in narrow rows. Higher *T* in narrow rows could be a key driver underpinning the canopy growth and development and that in turn, could have led to higher dry matter production in narrow rows.

The simulated RUE for Crystal in this study (0.76 g/MJ, Fig. 5) was marginally less than the baseline RUE values (0.8–0.9 g/MJ) reported for mungbean in earlier studies (Muchow, 1985; Muchow et al., 1993). The lower RUE in this study could be attributed to limited biomass harvests used in the analysis and possible variable leaf nitrogen across treatments and sites (Sinclair, 1986).

The cumulative yield probabilities calculated from long-term simulations for the four test sites highlighted the crucial role of starting soil moisture in determining the riskiness of the season for mungbean. Sowing mungbean at full soil profile moisture (close to 100% PAWC) seemed essential to capitalise on the yield advantage from narrow rows. Sowing in narrow rows at partial (50% or less) PAWC could reduce the yield benefit, and even result in yield loss depending on the seasonal rainfall. However, the simulations showed that the frequency and magnitude of yield losses from narrow rows were small compared to long-term yield benefits.

The conclusions drawn from this study are limited to two-row spacing treatments with one variety. However, empirical findings observed in this study corroborated earlier empirical mungbean research in the Australian subtropics and the value added by this study is through the use of simulation modelling to make long-term extrapolations and provide a probabilistic assessment of the effects of row spacing in mungbean. This study provides some insights into the physiological basis for yield differences between row spacing treatments across the six production environments. It is necessary to compare more row spacing treatments using genotypes with different morph-physiological characters to gain a greater understanding of the genotype × environment × management interactions and optimise productivity of mungbean.

From a rotation benefit point of view narrow row spacing can result in higher dry matter per unit land area, and thus can potentially contribute more nitrogen (N) to a following cereal crop through increased root stubble (Kirkegaard et al., 2008). Recent studies revealed that N contribution, as well as atmospheric N-fixation was higher for Crystal planted in narrow rows (Seymour et al., 2014). Having a short duration legume break crop like mungbean could also result in indirect benefits such as more efficient use of water, reduced risk of deep drainage, maintenance of soil cover, and reduced erosion risk (Tanaka et al., 1997). However, break crops especially those planted in narrow rows, may affect residual water, particularly in situations where complete recharge of the soil water profile may not occur prior to, or during, the growth of the subsequent cereal crop (Norwood 2000). Being an ultra-short duration crop (less than 90 days), the adverse effect of mungbean on residual water is expected to be minimal as the short duration trait would leave some fallow period after harvest, allowing recharging of the soil profile.

5. Conclusion

Sowing mungbean in narrow row configurations in subtropical environments consistently produced higher dry matter than the crops planted in wide row spacing. The narrow rows resulted in up to 11% more grain yield per mm of water than the wide rows. The yield benefits of narrow row spacing were more apparent in the favourable environments; however, narrow rows resulted in no yield benefit, or even some yield loss, under a severe drought environment. Integrating in-crop measurements with the validated APSIM mungbean crop model, configured to site-specific soil and weather parameters, offered insights into physiological factors underpinning environment × management interactions for mungbean. The model simulations suggested that the increased dry matter production in narrow rows could be due to rapid canopy development, leading to increased cumulative intercepted radiation and increased soil water uptake, and more efficient use of soil water to meet crop water demand. The long-term cumulative yield probabilities simulated by APSIM suggested that the benefits of narrow row spacing are more pronounced for crops planted at the full soil profile moisture compared those planted at partial profile moisture. For the crops planted at partial soil profile moisture, the yield differences between the row spacing treatments depended on the seasonal rainfall, and were small in the environments in which yield was less than 750 kg/ha. Knowledge of soil water holding capacity and starting moisture, therefore are useful to realize the benefits of narrow row spacing.

Acknowledgements

This research was funded, in part, by contributions from the Australian Centre for International Agricultural Research (ACIAR), Grain Research and Development Corporation (GRDC) and the Department of Agriculture and Fisheries, Queensland. Authors gratefully acknowledge the input from Alison Kelly and Kerry Bell, principal and senior Biometricians respectively, at the Crop and Food Science, DAF, Queensland. Authors would also like to thank the two anonymous reviewers for their constructive comments.

References

Andrade, F.H., Calvino, P., Cirilo, A., Barbieri, P.A., 2002. Yield responses to narrow rows depend on increased radiation interception. Agron. J. 94, 975–980.

Barbieri, P.A., SaizRozas, H.R., Andrade, F.H., Echeverria, H.E., 2000. Row spacing effects at different levels of nitrogen availability in maize. Agron. J. 92, 283–288.

Barbieri, P.A., Echartem, L., Maggiora, A.D., Sadras, V.O., Echeverria, H., Andrade, F.H., 2012. Maize evapotranspiration and water-ese efficiency in response to row spacing. Agron. J. 104, 939–944.

Board, J.E., Kamal, M., Harville, B.G., 1992. Temporal importance of greater light interception to increased yield in narrow row soybean. Agron. J. 84, 575–579.

Borad, J.E., Harville, B.H., 1996. Growth dynamics during the vegetative period affects yield of narrow-row, late planted soybean. Agron. J. 88, 567–572.

Board, J.E., Modali, H., 2005. Dry matter accumulation predictors for optimal yield in soybean. Crop Sci. 45, 1790–1799.

Bullock, D.G., Nelson, R.L., Nyquist, W.E., 1988. A growth analysis of corn grown in conventional and equidistant plant spacing. Crop Sci. 28, 254–258.

Cox, W.J., Cherney, J.H., 2011. Growth and yield responses of soybean to row spacing and seeding rate. Agron. J. 103, 123–128.

Chauhan, Y.S., Rachaputi, R.C.N., 2014. Defining agro-ecological regions for field crops in variable target production environments: a case study on mungbean in the northern grains region of Australia. Agri. For. Meteorol. 194, 207–217.

De Bruin, J.L., Palle, P., 2008. Effect of row spacing and seeding rate on soybean yield. Agron. J. 100, 704–710.

Drouet, J.L., Kiniry, J.R., 2008. Does spatial arrangement of 3D plants affect light transmission and extinction coefficient within maize crops. Field Crops Res. 107, 62–69.

Dunin, F., Passioura, J., 2006. Prologue: amending agricultural water use to maintain production while affording environmental protection through control of outflow. Aust. J. Agric. Res. 57, 251–255.

Ellis, R.H., Lawn, R.J., Summerfield, R.J., Qi, A., Roberts, E.H., Chay, P.M., Brouwer, J.B., Rose, J.L., Yeates, S.J., Sandover, S., 1994. Towards reliable prediction of time to flowering in six annual crops. IV. Cultivated and wild mungbean. Exp. Agric. 30, 31–43.

Fahad, S., Hussain, S., Saud, S., Hassan, S., Muhammad, H., Shan, D., Chen, C., Wu, C., Xiong, D., Khan, S.B., Jan, A., Cui, K., Huang, J., 2014. Consequences of narrow crop row spacing and delayed *Echinochloa colona* and *Trianthema portulacastrum* emergence for weed growth and crop yield loss in maize. Weed Res. 54, 475–483.

Hammer, G.L., Dong, Z., McLean, G., Doherty, A., Messina, C., Schussler, J., Zinselmeier, C., Paszkiewicz, S., Cooper, M., 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the US corn belt? Crop Sci. 49, 299–312.

Hammer, G.L., Oosterom, E.V., McLean, G., Chapman, S.C., Broad, I., Harland, P., Muchow, R.C., 2010. Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. J. Exp. Bot. 61, 2185–2202.

Holshouser, D.L., Whittaker, J.P., 2002. Plant population and row-spacing effects on early soybean production systems in the Mid-Atlantic USA. Agron. J. 94, 603–611.

Imrie, B.C., Butler, K.L., 1982. An Analysis of variability and genotype × environment interaction in mungbean (*Vigna radiata*) in South-eastern Queensland. Aust. J. Agric. Res. 33, 523–530.

Ismail, A.M., Hall, A.E., 2000. Semidwarf and standard-height cowpea responses to row spacing in different environments. Crop Sci 40, 1618–1623.

Jayeoba, O.J., Tabo, R., Owonubi, J.J., Chude, V.O., Oluwasemire, K.O., 2006. Evaluation of APSIM to simulate soil water balance of a long term Sorghum based cropping system in Sudano-Sahelian zone of Nigeria. Savannah J. Agric. 1, 33–38.

Keating, B.A., Carberry, P.S., Hammer, G.L., et al., 2003. An overview of APSIM, a model designed for farming systems simulation. Euro. J. Agron. 18, 267–288.

Kirkegaard, J., Christen, O., Krupinsky, J., Layzel, D., 2008. Break crop benefits in temperate wheat production. Field Crops Res. 107, 185–195.

Knezevic, S.Z., Evans, S.P., Mainz, M., 2009. Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). Weed Technol. 17, 666–673.

Lawn, R.J., 1982a. Response of four grain legumes to water stress in south-eastern Queensland. I. Physiological response mechanisms. Aust. J. Agric. Res. 33, 481–496.

Lawn, R.J., 1982b. Response of four grain legumes to water stress in south-eastern Queensland. II. Plant growth and soil water extraction patterns. Aust. J. Agric. Res. 33, 497–509.

Lawn, R.J., 1982c. Response of four grain legumes to water stress in south-eastern Queensland. III. Dry matter production, yield and water use efficiency. Aust. J. Agric. Res. 33, 511–521.

Lawn, R.J., 1983. Agronomic studies on *Vigna* spp. south-eastern Queensland. III. Response to sowing arrangement. Aust. J. Agric. Res. 34, 505–515.

Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. Nat. Climate Change, http://dx.doi.org/10.1038/nclimate1832

Muchow, R.C., 1985. Phenology, seed yield and water use of grain legumes grown under different soil water regimes in a semi-arid tropical environment. Field Crops Res. 11, 81–97.

Muchow, R.C., Charles-Edwards, D.A., 1982. An analysis of the growth of mungbean at a range of plant densities in tropical Australia. I. Dry matter production. Aust. J. Agric. Res. 33, 41–51.

Muchow, R.C., Robertson, M.J., Pengelly, B.C., 1993. Accumulation and partitioning of biomass and nitrogen by soybean, mungbean and cowpea under contrasting environmental conditions. Field Crops Res. 32, 13–36.

Nageswara Rao, R.C., Williams, J.H., Sivakumar, M.V.K., Wadia, K.D.R., 1988. Effect of water deficit at different growth phases of peanut. II. Response to drought during pre-flowering phase. Agron. J. 80, 431–438.

Nair, R.M., Yang, R.Y., Easdown, W.J., 2013. Biofortification of mungbean (*Vigna radiata*) as a whole food to enhance human health. J. Sci. Food Agric. 93, 1805–1813.

Nelson, R.A., Holzworth, D.P., Hammer, G.L., Hayman, P.T., 2002. Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. Agric. Syst. 74, 393–414.

Norwood, C.A., 2000. Dryland winter wheat as affected by previous crops. Agron. J. 92, 121–127.

Ouyang, Z., Chen, Y.H., Zhou, X.B., 2011. Row spacing effect on leaf area development light interception, crop growth and grain yield of soybean crop in Northern China. Afr. J. Agric. Res. 6, 1430–1437.

Pannu, R.K., Singh, D.P., 1993. Effect of irrigation on water use, water-use efficiency, growth and yield of mungbean. Field Crops Res. 31, 87–100.

Passioura, J.B., 1977. Grain yield, harvest index, and water use of wheat. J. Aust. Inst. Agric. Sci. 43, 117–121.

Passioura, J.B., Angus, J.F., 2010. Improving productivity of crops in water-limited environments. Adv. Agron. 106, 37–67.

Raza, M.H., Sadozai, G.U., Baloch, M.S., Khan, E.A., Din, I., Wasim, K., 2012. Effect of irrigation levels on growth and yield of mungbean. Pak. J. Nutr. 11, 974–977.

Ratnakumar, P., Vadez, V., Nigam, S.N., Krishnamurthy, L., 2009. Assessment of transpiration efficiency in peanut (*Arachis hypogaea* L.) under drought using a lysimetric system. Plant Biol. 11, 124–130.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2002. Simulation of growth and development of diverse legume species in APSIM. Crop Pasture Sci. 53, 429–446.

Sadras, V.O., Hall, A.J., Trapani, N., Vilella, F., 1989. Dynamics of rooting and root-length: leaf area relationships as affected by plant population in sunflower crops. Field Crops Res. 22, 45–57.

Sengupta, D., Kannan, M., Reddy, A.R., 2011. A root proteomics-based insight reveals dynamic regulation of root proteins under progressive drought stress and recovery in *Vigna radiata* (L.) Wilczek. Planta 233, 1111–1127.

Seymour, N., Rachaputi, R., Cox, H., 2014. Impacts of genotype and row spacing on N-fixation in chickpea and mungbean. In: Proceedings of the 17th Australian Nitrogen Fixation Conference, 28 Sept–2 Oct. 2014, Uni Adelaide, South Australia.

Sharratt, B.S., McWilliams, D.A., 2005. Microclimatic and rooting characteristics of narrow-row versus conventional-row corn. Agron. J. 97, 1129–1135.

Siddique, K.H.M., Regan, K.L., Tennant, D., Thompson, B.D., 2001. Water use and water use efficiency of cool season grain legumes in low rainfall Mediterranean-type environments. Euro. J. Agron. 15, 267–280.

Sinclair, T.R., 1986. Water and nitrogen limitations in soybean grain production I. Model development. Field Crops Res. 15, 125–141.

Sinclair, T.R., Seligman, N.G., 1996. Crop modelling: from infancy to maturity. Agron. J. 88, 698–703.

Tanaka, D.L., Bauer, A., Black, A.L., 1997. Annual legume cover crops in spring wheat fallow systems. J. Prod. Agric. 10, 251–255.

Tesfaye, K., Walker, S., Tsubo, M., 2006. Radiation interception and radiation use efficiency of three grain legumes under water deficit conditions in a semi-arid environment. Eur. J. Agron. 25, 60–70.

Thomas, Robertson, M.J., Fukai, S., Peoples, M.B., 2004. The effect of timing and severity of water deficit on growth, development, yield accumulation and nitrogen fixation of mungbean. Field Crops Res. 86, 67–80.

Vadez, Vincent, Kholova, J., Medina, Susan, Kakkera, A., Anderberg, H., 2014. Transpiration efficiency: new insights into an old story. J. Exp. Bot. 65, 6141–6153.

Verburg, K., Bond, W.J., 2003. Use of APSIM to simulate water balances of dryland farming systems in south eastern Australia. In: Tech Rep. 50/03. CSIRO Land and Water, Canberra, Australia.

Webb, A.A., Grundy, M.J., Powell, B., Littleboy, M., 1997. The Australian subtropical cereal belt: soils, climate and agriculture. In: Clarke, A.L., Wylie, P.B. (Eds.), Sustainable Crop Production in the Sub-tropics QI 97035. Queensland Department of Primary Industries, Brisbane, pp. 8–26.

Weinberger, K., 2003. Impact analysis on mungbean research in South and Southeast Asia. In: Final Report GTZ Eigenmassnahme No. 99.9117.5. AVRDC, Shanhua,Taiwan.