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Can partial reduction of shoot biomass during early vegetative phase of chickpea save subsoil water for reproductive and pod filling?

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ABSTRACT

The present study investigated if partial reduction of shoot dry matter during early vegetative growth phase of chickpea crop (cv. PBA Seamer) saves sub-soil water for reproductive growth and grain filling of the crop grown at 9 diverse environments. The environments were created by a combination of 3 sites (Emerald, Hermitage and Kingaroy), 3 planting windows (environments 1, 2, 3 at each site) with and without supplementary irrigation. The effects of environments on canopy management (partial reduction in shoot dry matter vs control) and irrigation treatments on the water uptake by roots, crop growth and yield performance and yield components were investigated. Crops in the planting windows (EN 1, 2, 3) experienced variable environments at each site. Days to 50% flowering and crop maturity reduced progressively from EN 1 to EN 3 at the three sites. The environment had significant effect on shoot biomass, yield and HI at the three sites ($P < 0.01$ or $P < 0.0001$). Environments had bigger effects on crop that partial reduction in shoot biomass (PRS). The PRS at early vegetative phase resulted in a 25% reduction in radiation intercepted but rapid compensatory growth that followed, resulted in minimal effect on shoot biomass and yield. The HI varied from 0.18 in EN 1 at Kingaroy to > 0.5 in EN 2 at Emerald. There was a trend for an increase in HI from EN 1 to EN 3 at all sites. The response to Irr, computed as the difference in peak shoot biomass and yield between the Irr and RF treatments, was the highest at Hermitage and the least at Emerald site. Vapour pressure deficit during reproductive phase accounted for the majority of variation in shoot biomass response to irrigation ($r^2 = 0.66$, $P < 0.001$) for total dry matter and ($r^2 = 0.46$, $P < 0.01$) for yield. The environments had a significant effect on radiation use efficiency and water use efficiency and the yield components including hundred seed weight.

1. Introduction

Approximately 90% of world's chickpea (*Cicer arietinum* L.) is grown as a cool season food legume crop between the latitudes 20° and 40° (Croser et al., 2003; Kumar and Abbo, 2001). The crop is generally grown on receding soil moisture conditions where terminal drought is one of the major constraints for the productivity of the crop (Krishnamurthy et al., 1999; Lake et al., 2016). Deep rooting trait has been proposed for improving genetic tolerance of chickpea to terminal drought (Zaman-Allah et al., 2011). While genotypic variability for deep rooting trait has been explored extensively, there have been limited studies on canopy management during early growth phase to limit crop water use to ensure water availability for reproduction and grain filling (Zaman-Allah et al., 2011).

Any reduction in the aboveground portion of plant affects photosynthetic capacity of the plant thus affecting source-sink relationship depending on the crop stage (Beadle, 1985). Siddique and Sedgley (1985) showed that removing less productive lateral basal branches had no effect of shoot biomass but increased harvest index of chickpea by 31% in Mediterranean type of environment. Slower canopy

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development in de-branched crop was associated with lower water use during pre-flowering phase (Siddique and Sedgley, 1985) with moderate yield improvement under terminal drought situation. Beuerlein et al. (1971) have reported similar increase in seed yield due to removal of branches in soybean plants, with increased seed yields attributed to greater light interception during flowering and higher seed per m^2 of leaf area.

Partial defoliation during flowering resulted in a reduction in leaf area and it had minimal influence in seed yield or HI in chickpea (Iqbal et al., 2012; Li et al., 2010), while 50% defoliation during pod development phase resulted in significant reduction of shoot dry matter and yield (Pandey, 1984). The effect of defoliation on the compensatory growth of chickpea (Collin et al., 2000), is dependent on the environment and the crop growth stage when the defoliation is imposed (Iqbal et al., 2012). Continuous defoliation by 25%, 50%, or 75% of chickpea starting from first flower until physiological maturity in subtropical environment, resulted in significant reduction in yield and resulted in inability of the crop to compensate for lost leaf area (Sheldrake et al., 1978). In contrast, some studies concluded that de-topping during pre-flowering phase could be a profitable practice for chickpea growers (Baloch and Zubair, 2010). Reducing foliage during early stages of chickpea crop growth could increase number of branches while restricting profuse vegetative growth. Nipping practice in chickpea could have twofold advantage. On one hand, nipping at early growth stage of chickpea could improve yield while on the other hand, this practice would provide an opportunity for resource poor farmers to obtain green fodder for their livestock.

Defoliation reduces the photosynthetic capacity of plants temporarily but the compensatory growth during recovery phase allocates more carbon to the aboveground biomass depending on the environment. Some studies reported that following defoliation, root growth is reduced while leaf regrowth is accelerated due to the increase in the reallocation of reserves from root to shoot (Ourry et al., 1988).

Various mechanisms have been proposed for compensatory growth, such as higher photosynthetic rate of regrown foliage, higher stomatal conductance and delayed senescence (Striker et al., 2008).

However, there is limited information on the effect of partial removal of shoot dry matter during early vegetative phase on the shoot dry matter, radiation and water-use efficiencies, harvest index, yield and seed quality of chickpea in diverse environments. The present study investigates if partial reduction of shoot dry matter during early vegetative growth phase saves sub-soil water for reproduction and grain filling of the crop, in diverse environments. The effect of canopy management on the water uptake by roots, crop growth and yield performance of chickpea is investigated under nine diverse environments in Queensland, Australia.

2. Materials and methods

2.1. Experimental sites

Field experiments were implanted in the 2017 winter season (Apr to Nov) at the Department of Agriculture and Fisheries (DAF) research facilities located at Emerald Agricultural College (23.3 °S, 148.1 °E), Hermitage (28.2 °S, 152.1 °E) and Kingaroy (26.6 °S, 151.9 °E) research stations in Queensland, Australia. These locations represented typical chickpea production environments in cereal-legume based cropping systems. At Emerald and Hermitage, soils were 150 cm deep brown (Hermitage) or black (Emerald) vertisols while at Kingaroy the soil was 100 cm deep red ferrosol. The details of sowing and harvesting dates, Max and Min T, radiation, in-crop rainfall, dates and amounts of irrigation applied in each environment at each site are presented in Tables 1 and 2.

2.2. Experimental design and crop management

Seed of cultivar “PBA Seamer”, obtained from the Australian chickpea-breeding programme, was used at all sites. A starter dose of a commercial formulation of zinc (N 11.0%, P 21.8%, S 4.0% and Zn 1.0%) at the rate of 30 kg/ha at Emerald and Hermitage and 50 kg/ha at Kingaroy was incorporated into the soil at the time of planting as part of a standard practice. The crop was planted on non-limiting (Table 2) conditions in three sowing windows at 50 cm row spacing (Rsp), at the three sites. Appropriate plant protection practices were implemented at the three sites.

At all the three trial sites the trial was laid out as a split-split plot design with three sowing dates (EN 1, 2, 3) as main plots, irrigation (Irr) and rainfed (RF) treatments as sub plots, and two canopy management treatments i.e. partial reduction of shoot dry matter mechanically (PRS) and control (CON) as sub-sub-plots, with three replications (Rep). A 10 m buffer with PBA Seamer was sown at 50 cm row spacing to separate the Irr and RF treatments. Each sub-plot was 12 m long and 4 m wide. A plant population of approximately 30 ± 4 plants/m^2 was maintained in all sites. At Hermitage, the irrigation was applied using a drip system operated by a pressure pump while at Emerald and Kingaroy an overhead sprinkler irrigation system was used. At Hermitage, two drip lines of 12 m length containing 120 drippers per plot were laid out. Each dripper in the drip line emitted 1.1 L of water per hr. Amount of water delivered for each irrigation was calculated as “pump time in hr × emitting rate/dripper/hr × number of drippers per plot”. At Emerald and Kingaroy, the irrigation amount was estimated by multiplying a pre-calibrated rate (mm/hr) for the overhead system, with the period of each irrigation. The canopy management treatments were applied at 42 days after sowing. The PRS treatment was implemented by slashing top 15 cm of shoot foliage using a hand held mower.

Table 1

Site, environment, planting and harvesting date, crop duration (days), irrigation (mm) and days after sowing (DAS) when fractional intercepted radiation measurements were made (DASfRI) for chickpea crop grown at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) during the 2017 winter cropping season in Queensland, Australia.

Site	EN	Planting date	Photoperiod	Harvesting date	Days to 50% flowering	Crop duration (days)	Irrigation (mm)	DASfRI
EAC	EN 1	12/4/2017	12.61	15/9/2017	62	156	50	57, 72, 84
EAC	EN 2	16/5/2017	12.66	29/9/2017	61	136	50	45, 68, 84
EAC	EN 3	19/6/2017	12.77	29/10/2017	61	132	50	44, 70, 84
HRS	EN 1	29/5/2017	12.79	23/11/2017	96	178	134	95, 112, 132,165
HRS	EN 2	26/6/2017	12.87	29/11/2017	89	156	134	75, 95, 128
HRS	EN 3	25/7/2017	13.04	14/12/2017	81	142	134	63, 96
KRS	EN 1	17/5/2017	12.18	2/11/2017	92	169	70	70, 92, 112
KRS	EN 2	14/6/2017	12.32	2/11/2017	68	141	70	64, 77, 135
KRS	EN 3	13/7/2017	13.07	14/12/2017	70	154	70	62, 88, 113

EN 1, 2, and 3 represent planting windows 1–3, at each site, respectively.

Table 2

Average daily maximum temperature (MaxT), minimum temperature (MinT), incident solar radiation (Radn), vapour pressure deficit (VPD), cumulative incident radiation, rainfall and thermal time (TT) for pre-flowering and post-flowering stages of chickpea grown in three environments at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) in the 2017 winter cropping season.

		Average daily				Cumulative		
		MaxT (°C)	MinT (°C)	Radn (MJ/m^2)	VPD (kPa)	Radn (MJ/m^2)	Rain (mm)	TT (°Cd)
				EAC				
EN 1	Pre-flowering	27.1	13.0	15.2	2.4	929	20	942
	Post-flowering	27.2	10.4	16.7	2.4	1551	15	1347
EN 2	Pre-flowering	25.8	11.3	13.2	2.2	790	14	945
	Post-flowering	28.7	10.2	19.4	2.6	1156	5	940
EN 3	Pre-flowering	26.7	12.6	14.8	2.2	874	15	890
	Post-flowering	30.8	14.8	21.1	3.1	1436	165	900
				HRS				
EN 1	Pre-flowering	19.1	3.1	13.4	1.3	1241	60	1096
	Post-flowering	24.6	10.0	20.1	2.0	1764	119	1521
EN 2	Pre-flowering	20.8	2.8	16.7	1.5	1503	36	1000
	Post-flowering	25.4	13.0	20.0	2.2	1363	119	1039
EN 3	Pre-flowering	23.1	5.6	18.2	1.8	1531	54	1012
	Post-flowering	25.6	12.8	22.1	2.2	1327	107	918
				KRS				
EN 1	Pre-flowering	22.1	5.2	13.4	1.4	1235	69	1271
	Post-flowering	26.1	10.3	19.2	2.2	1458	184	999
EN 2	Pre-flowering	22.3	4.4	14.2	2.2	966	62	917
	Post-flowering	26.5	10.7	14.2	2.2	1400	184	968
EN 3	Pre-flowering	27.4	14.3	20.7	1.6	1254	23	877
	Post-flowering	27.4	14.3	20.7	2.5	1716	282	1261

2.3. *Measurements*

2.3.1. *Solar radiation interception*

Photosynthetically active solar radiation (PAR) above and below the canopy at the ground level were simultaneously recorded at three random spots in each plot at Hermitage, Emerald and Kingaroy sites on specified days during the growing season (Table 1). The measurements were made using a Ceptometer (AccuPAR model LP-80, Decagon Devices, USA) on clear days between 11:30 and 13:00 h. The fractional PAR intercepted (*f*) on a given day was calculated as the ratio of the radiation measured below the canopy at the ground level to the incident PAR measured above the canopy (Eq. (1)).

$$f = r/InR \qquad \text{(Eq. (1))}$$

Where, f = fractional PAR intercepted by the crop (MJ/m^2), InR = Incident PAR, r = PAR measured at the bottom of the crop canopy.

2.3.2. *Radiation use efficiency (RUE)*

The radiation use efficiency for total shoot dry matter (RUE$_{DM}$), was computed as the ratio of peak shoot dry matter (g/m^2) and cumulative PAR intercepted (RI) (MJ/m^2) by the crop (Sinclair et al., 1992), for each plot using Eq. (2). Peak shoot dry matter (PSB) was recorded prior to any leaf senescence when 50% of pods on a plant were mature. However, timing of the desiccation before final harvest varied between environments (Table 1).

$$\mathrm{RUE_{DM}},\ (\mathrm{g/MJ}) = \mathrm{PSB}\ \left(\mathrm{g/m^2}\right)/\mathrm{cumulative\ RI}\ \left(\mathrm{MJ/m^2}\right) \qquad \text{(Eq. (2))}$$

The radiation use efficiency for grain yield (RUE $_{yld}$) was computed using Eq. (3).

$$\mathrm{RUE_{yld}},\ (\mathrm{g/MJ}) = \mathrm{grain\ yield}\ \left(\mathrm{g/m^2}\right)/\mathrm{cumulative\ RI}\ \left(\mathrm{MJ/m^2}\right) \qquad \text{(Eq. (3))}$$

Where, cumulative RI (MJ/m^2) was the cumulative PAR intercepted by the canopy that was calculated as.

$$\mathrm{RI} = \sum \mathrm{f} \times \sum_{(e)}^{(PSB)} InR \qquad \text{(Eq. (4))}$$

Where, *f* was the fractional radiation intercepted at the PSB and 'ΣInR' was the cumulative incident PAR from emergence (e) to PSB.

2.3.3. *Soil moisture content*

Soil moisture content was measured at 25 cm, 45 cm, 65 cm, 85 cm, 105 cm and 125 cm depths using a neutron moisture probe (503 dr Hydroprobe CPN International) at Emerald, and (CPN 503 Elite Hydroprobe, Instrotek Inc.) at Hermitage sites. Aluminium tubes of 150 cm length and 50 mm dia. were installed in centre rows of sub-subplots when the crop was 20 day old and capped to protect from rain and dust. Two access tubes, one between the plants in the row and the other in the middle of rows were installed in each sub-sub plot, to examine the effect of canopy management (PRS and CON) treatments on the capture of soil water. In addition, three extra access tubes were installed in the uncropped area in the edges of the experimental site for the calibration of neutron probe.

The neutron moisture probe (NMP) was calibrated by regressing the gravimetric soil water content measured at different depths at three or four times during the season against the neutron moisture probe readings. The NMP readings accounted for 84% and 78% of variation in soil moisture content at Emerald and Hermitage sites, respectively (Rachaputi et al., 2015). The soil moisture was recorded from 4-leaf stage at 4–5 day-intervals until crop desiccation. The NMP measurements were also made before and after each irrigation in irrigated treatment or rainfall event. The total water extracted at each phenophase was calculated as indicated in Eq. (5).

$$Wex = \sum_{d1}^{d6}((E1 - E2) + (E3 - E4) + \cdots.) \qquad \text{(Eq. (5))}$$

Where, *Wex* was the water extracted from 125 cm soil profile at a given phenophase, *d1 and d6* were the depths, E1 and E2 were plant available water content (PAWC) in the soil measured at event 1 and E3 and E4 were PAWC at event 2, and so on. The soil moisture content in the top 0–10 cm layer was simultaneously sampled gravimetrically; the data was converted into volumetric units, and added to the 25 cm depth reading made by the neutron moisture probe. Total volume of water extracted from 125 cm soil profile was calculated by summing the six depths. The total water extracted for each phenophase was calculated as the sum of water extracted at the events within a given phenophase.

2.3.4. Peak shoot biomass

The peak shoot biomass (PSB) was recorded when 50% pods on plants in plot were mature. Plants for PSB were hand-harvested at the ground level from one m^2 area in each plot, and plant count recorded. The harvested plants were dried in a fan-forced oven at 80 °C for 48 h before recording shoot (leaves + stems + pods + grains) dry weight.

2.3.5. Grain yield

The plot area (excluding the area harvested for peak shoot biomass) was measured and the final yield was assessed when 90% of plants in a plot had around 80% mature pods. Plants were desiccated by applying a foliar spray of Glyphosate® at 2 L/ha 5–7 days 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.

2.4. Statistical analysis

Analysis of variance (ANOVA) was conducted for each site for the PSB, yield and harvest index using a split-split design, using R software (R core Team, 2018). Analysis of water extraction was done for each phenophase separately for each site. Comparison among means were done using Tukey's test (Tukey, 1949). The association between the growth variables was analysed using regression approach. Graphs were developed using Sigma plot 10.0 (Systat Software, San Jose, CA) and R software.

3. Results

3.1. Weather

Details of planting and harvest dates (EN 1, 2, 3), crop duration (days), irrigation (mm) and days after sowing (DAS) at which fractional intercepted radiation (DASfRI) was measured at each site are presented in Table 1. It was apparent that crop duration and days to 50% flowering reduced progressively from EN 1 to EN 3 at the three sites i.e. Emerald, Hermitage and Kingaroy. Crops in the planting windows (EN 1, 2, 3) experienced highly variable environments across all sites.

In-crop weather during the pre-flowering and post-flowering phases of chickpea var. PBA Seamer grown in EN 1, 2 and 3 at the 3 sites are

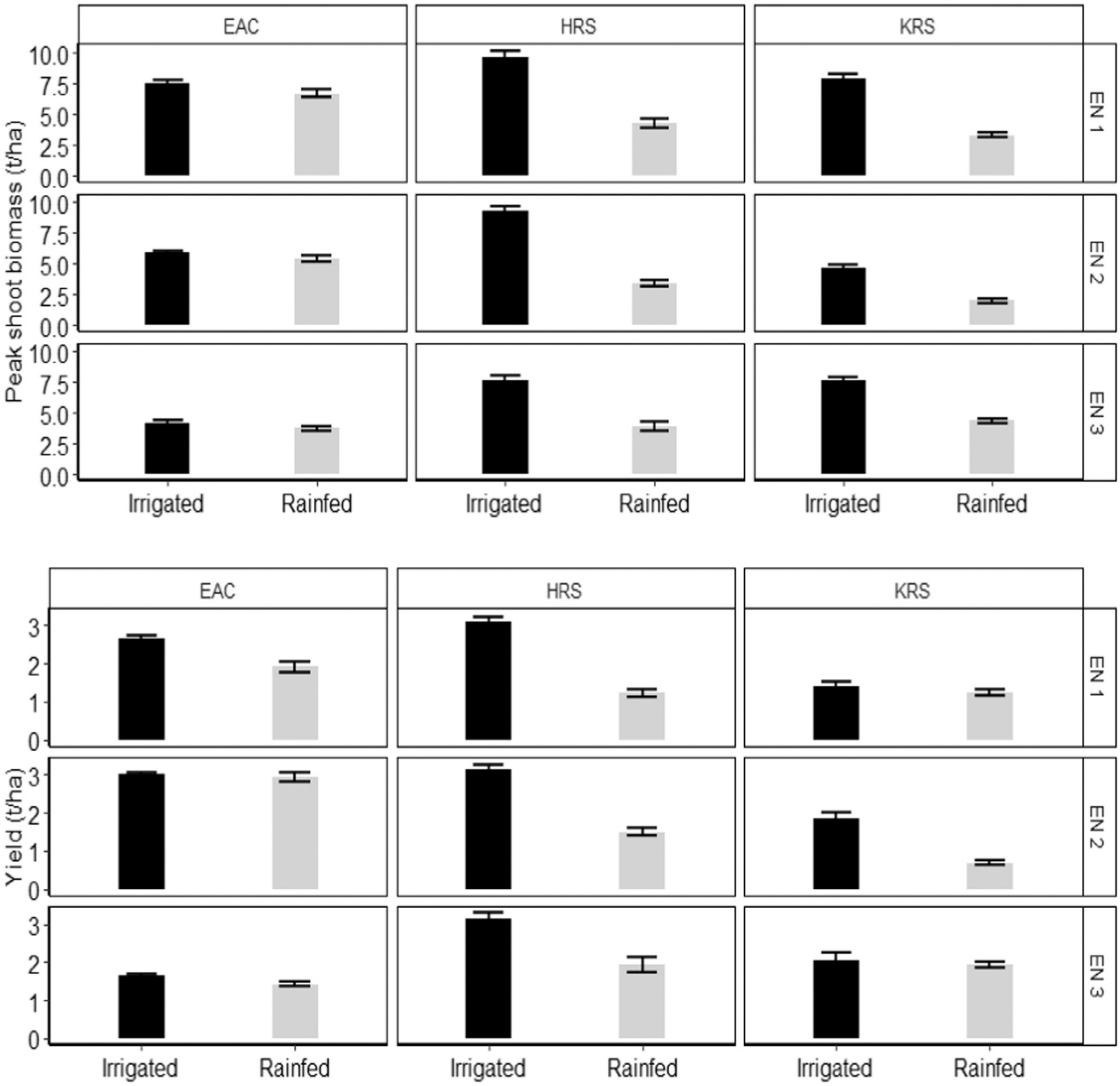

Fig. 1. Peak shoot biomass (t/ha) and yield (t/ha) response of chickpea (var. PBA Seamer) in diverse environments (3 ENs x 3 sites) under irrigated and rainfed conditions at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) sites in Queensland. Environment 1–3 represent mid-April (EN 1), mid-May (EN 2) and mid-June (EN 3) at Emerald, mid-May (EN 1), late-June (EN 2) and late-July (EN 3) at Hermitage and mid-May (EN 1), mid-June (EN 2) and mid-July (EN 3) at Kingaroy, respectively. The vertical lines above the bars indicate the standard error of the means.

presented in Table 2. At Emerald, MaxT and MinT ranged from 25.8 °C to 28.7 °C and 10.2–12.6 °C during pre-and post-flowering periods in EN 1 and EN 2, respectively. However, in the post flowering phase of EN 3 the MaxT and MinT raised to 30.8 and 14.8 °C. Mean daily radiation progressively increased from 15.2 in EN 1–21.1 MJ/m^2/day in EN 3. The cumulative radiation during post-flowering phase was consistently higher than that in the pre-flowering phase at all sites, except for EN 2 and EN 3 at Hermitage. There was also progressive increase in VPD in EN 1 to EN 3 at all sites. For instance, VPD during post flowering phase increased from 2.4 kPa in EN 1–3.1 kPa in EN 3 at Emerald, from 2.0 kPa to 2.2 at Hermitage and from 2.2 kPa to 2.5 kPa at Kingaroy sites.

The in-crop rain was highly variable across sites but generally post-flowering phase received more rain compared to pre-flowering phase at Hermitage and Kingaroy sites but in-crop rain was generally less at Emerald in EN 1 and EN 2 but there was 165 mm rain in EN 3.

The mean cumulative thermal time from sowing to maturity across three ENs, was 1885 ± 405°days at Emerald, 2195 ± 169°days at Hermitage and 2108 ± 199°days at Kingaroy.

3.2. Peak shoot dry matter, yield and HI

The Fig. 1 presents the mean effects of environments (EN 1, EN 2 and EN 3) and irrigation treatments (Irr and RF) on peak shoot biomass (PSB) of chickpea (PBA Seamer) at each of the three sites. Environmental effect was significant with PSB progressively declining from EN 1 to EN 3 in both irrigated (Irr) and rainfed (RF) treatments at Emerald and Hermitage sites but PSB was significantly reduced in EN 2 at Kingaroy in both RF and Irr treatments, due to severe dry spell for 2 months during early reproductive phase (Supplementary Fig. 1). Environments accounted for most variation in PSB at Emerald and Kingaroy ($P < 0.001$) and Hermitage ($P < 0.01$) (Table 3). At Emerald, Irr treatment had minimal effects on PSBs within each of the three ENs, although PSB declined steadily from 7.5 t/ha to 6.0 t/ha and 4.0 t/ha in EN 1, EN 2, and EN 3 respectively (Fig. 1; Table 3). At Hermitage, the PSB was the highest in EN 1 and EN 2 (~ 10 t/ha) in Irr treatment, however, PSB declined to 9 t/ha and 7.5 t/ha in EN 2 and EN 3, respectively. The RF treatment resulted in a significant reduction (up to 60%) in PSB compared to Irr treatment in all the three ENs at Hermitage. At Kingaroy, PSB declined significantly in RF treatments in EN 2 compared to EN 1 and EN 3 demonstrating significant effect of environment.

The grain yield was highly variable across ENs at the three sites (Fig. 1; Table 3). At Emerald, yields declined significantly ($P < 0.001$) in EN 3 compared to EN 1 but yields were the highest in EN 2 compared to EN 1 and EN 3, suggesting that EN 2 was most optimal for planting chickpea for this site. At Hermitage, yields of > 3 t/ha were maintained under Irr treatment in all the three environments. The Irr treatment in general resulted in higher grain yield compared to RF treatment in most ENs at all sites. However, at Hermitage and Kingaroy, yields in RF treatment were the lowest in EN 1 and EN 2 (1 t/ha) and highest > 2 t/ha in EN 3.

The HI varied from 0.18 in EN 1 at Kingaroy to > 0.5 in EN 2 at Emerald. There was a trend for an increase in HI from EN 1 to EN 3 at all sites. The mean HI increased from 0.32 (EN 1) to 0.41 (EN 3) at Emerald, 0.33 (EN 1) to 0.41 (EN 2) at Hermitage, and 0.18 (EN 1) to 0.27 (EN 3) at Kingaroy (data not presented). It is worth noting that despite high peak shoot biomass, HI was lowest in EN 1 at Kingaroy. However, further analysis of daily weather data at this site suggested that there was a 6 weeks of severe dry spell during early reproductive stage (mid-September to mid-October) followed by 131 mm of rain in 3 days period followed by bright sunshine close to maturity. This event severely affected reproductive development in EN 2 at Kingaroy. There was a negative relationship between cumulative incident radiation and HI across ENs (Fig. 2, $r^2 = 0.38$, $P < 0.001$).

3.3. Effects of environment, irrigation, canopy management

The environment had significant effect on PSB, yield and HI at all sites ($P < 0.01$ or $P < 0.001$) (Table 3). Irrigation (IR) also had significant effect on PSB and yield at all sites ($P < 0.001$) but HI was affected by IR only at Kingaroy site ($P < 0.001$). The canopy management

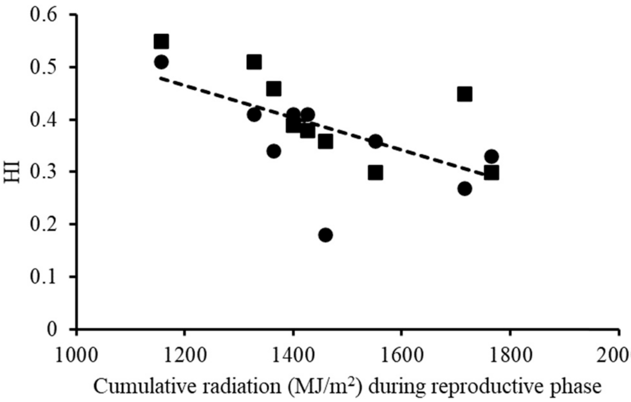

Fig. 2. Relationship between harvest index and cumulative incident solar radiation for var. PBA Seamer grown under irrigated (●) and rainfed (■) conditions with control and partial biomass reduction treatments in each of the 9 (3ENVs x 3 sites) diverse environments in Queensland. The regression coefficient was $y = -0.0003x + 0.8335$; $r^2 = 0.38$.

Table 3

Mean sum of squares of peak shoot biomass (PSB) (t/ha), yield (t/ha) and harvest index (HI) of chickpea sown in three environments, two water regimes (irrigated and rainfed) and two managements (control and slash) at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) in the 2017 winter cropping season.

		EAC			HRS			KRS		
	DF	PSB	Yield	HI	PSB	Yield	HI	PSB	Yield	HI
Replication	2	0.21	0.98*	0.008	11.66*	0.40	0.017	0.12	0.37	0.024*
Environment (EN)	2	58.86**	12.50***	0.253*	8.42*	0.88*	0.129*	49.09***	3.94**	0.065**
Error a	4	3.04	0.12	0.015	1.55	0.14	0.012	0.78	0.17	0.002
Irrigation (IR)	1	6.27**	2.18*	0.004	458.94**	44.78***	0.061	223.80***	4.33***	0.253**
EN * IR	2	0.32	0.73	0.013	7.3*	0.63	0.041	5.56*	2.08***	0.108**
Error b	6	0.38	0.21	0.005	1.76	0.31	0.012	0.86	0.11	0.008
Management (M)	1	0.00	0.62***	0.019	4.25	0.39	0.007	5.40*	0.01	0.035*
M * EN	2	0.18	0.03	0.002	3.64	1.82**	0.017	0.24	0.04	0.011
M * IR	1	1.14	0.10*	0.027	1.05	0.00	0.000	0.12	0.00	0.005
M * EN * IR	2	0.01	0.02	0.003	2.64	0.06	0.026*	2.04	0.32	0.001
Error c	12	0.84	0.02	0.009	1.17	0.16	0.006	0.89	0.16	0.006

* Indicate significance for mean squares of traits at $P < 0.05$, respectively.

** Indicate significance for mean squares of traits at $P < 0.01$, respectively.

*** Indicate significance for mean squares of traits at $P < 0.001$, respectively.

treatment significantly affected grain yield only at Emerald ($P < 0.001$) and PSB ($P < 0.01$) at Kingaroy, where there was a significant reduction in PSB in EN 2 compared to EN 1 or EN 3 (Table 3). The EN × IR interaction was significant for PSB, yield and HI at Kingaroy and significant for PSB at Hermitage (Table 3).

3.4. *Response to irrigation*

The response to Irr, computed as the difference in peak shoot biomass (PSB) and yield between the Irr and RF treatments, was the highest at Hermitage and the least at Emerald site (Fig. 3). At Hermitage, the yield response to irrigation was the highest (up to 2 t/ha) in EN 1 but steadily declined in EN 2 (1.5 t/ha) and EN 3 (1.25 t/ha). However, the yield response to irrigation amongst ENs varied from 0.25 to 0.75 t/ha at Emerald, while at Kingaroy, yield response was the highest in EN 2 (1–1.25 t/ha), but less than 0.5 t/ha in EN 1 and EN 3. Further analysis of the environmental factors underpinning the variable response to irrigation across ENs revealed that vapour pressure deficit (VPD) during reproductive phase accounted for the majority of variation in PSB response to irrigation ($r^2 = 0.66$, $P < 0.001$) for PSB (Fig. 4), and ($r^2 = 0.91$, $P < 0.001$) for yield at Hermitage and Emerald (Supplementary Fig. 2).

3.5. *Radiation interception and radiation use efficiency*

The reduction in fractional radiation interception (*f*) because of the canopy management treatments in all ENs, (excepting EN 3 at Hermitage) is presented in Fig. 5. It was clear that there was a reduction *f* (up to 25%) in PRS treatment initially, followed by rapid recovery. In most ENs, the differences between control and PRS treatments disappeared as the crops reached maturity. At Emerald, the crops in both control and partial reduction in shoot biomass (PRS) treatments were intercepting close to 100% by 1250 GDD with minimal difference between Irr and RF treatments. At Hermitage and Kingaroy, *f* reached > 80% in both canopy management treatments in Irr treatment only but in RF treatment *f* was 50–60%. There was a trend for reduction in *f* beyond 1250 GDD at both the sites although the reduction in *f* was more pronounced after 1250 GDD in EN 2 at Kingaroy, due to severe dry spell which caused leaf senescence. There was a significant positive relationship between cumulative PAR intercepted and peak shoot biomass (PSB) across diverse environments (Fig. 6). However, radiation use efficiency (g/MJ) was much lower at Kingaroy compared to Emerald and Hermitage sites. The RUEs for biomass was 0.74 g/MJ ($r^2 = 0.97$, $P < 0.001$) for Emerald and Hermitage and 0.54 g/MJ ($r^2 = 0.95$, $P < 0.001$) for Kingaroy and the RUE for yield was 0.28 g/MJ ($r^2 = 0.95$, $P < 0.01$) for Emerald and Hermitage and 0.15 g/MJ ($r^2 = 0.98$, $P < 0.001$) for Kingaroy.

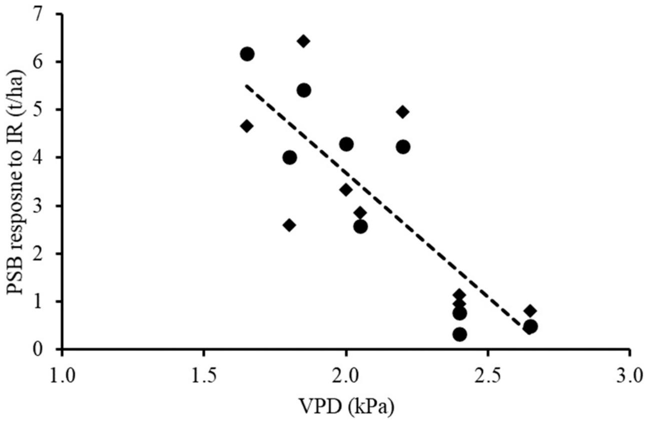

Fig. 4. Relationship between VPD during reproductive phase and the reponse of peak shoot biomass (PSB) to irrigation in chickpea var. PBA Seamer in each of the 9 environments (3 ENs x 3 sites) Symbols • and ◆ represent control and partial biomass reduction treatments. The regression coefficient was $y = -5.1683x + 14.024$; $r^2 = 0.66$ ($P < 0.01$).

3.6. *Water extraction patterns*

The effects of canopy management treatments on temporal patterns of water extraction by chickpea was measured under irrigated and rainfed treatments only in EN 2 and EN 1 at Emerald and Hermitage sites (Figs. 7 and 8). At Emerald, during the pre-flowering phase, the water extraction pattern was similar between the Irr and rainfed treatments as well as the canopy management treatments (Fig. 7). However, during the post-flowering phase, plants under irrigated treatment extracted more water up to 75 cm depth compared in rainfed treatment in both canopy management treatments. It was also clear that at Emerald, plants in control treatment extracted more water up to 110 cm rooting depth in

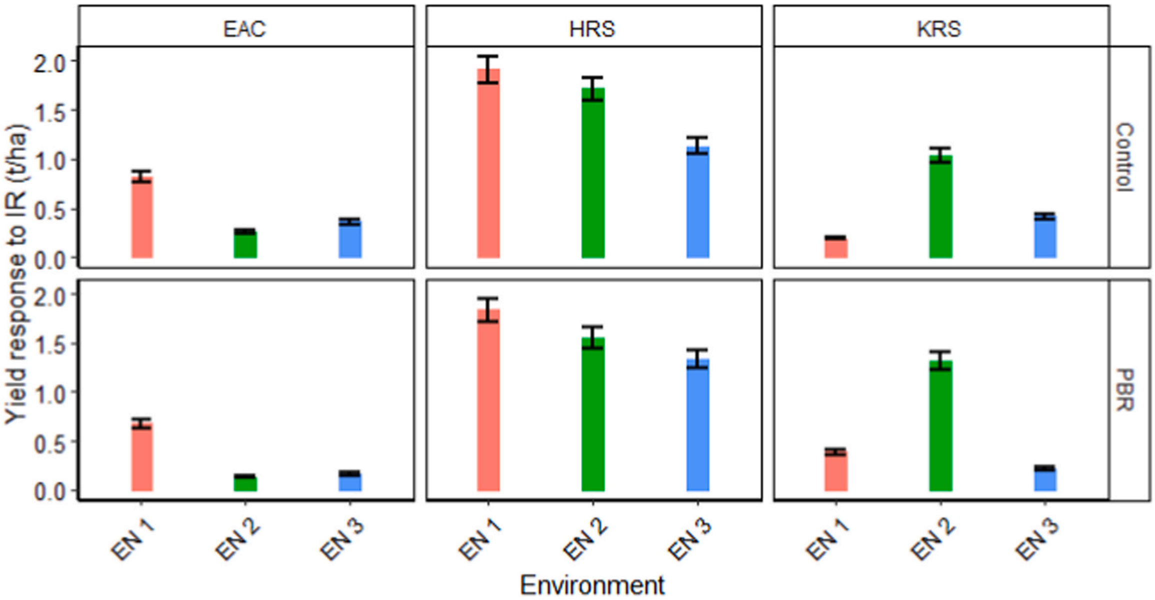

Fig. 3. Chickpea peak shoot biomass (PSB) and yield response to irrigation (IR) at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) for two managements (control and partial biomass reduction (PBR)) in the year 2017 winter cropping season. EN 1–3 represent environments 1–3, respectively.

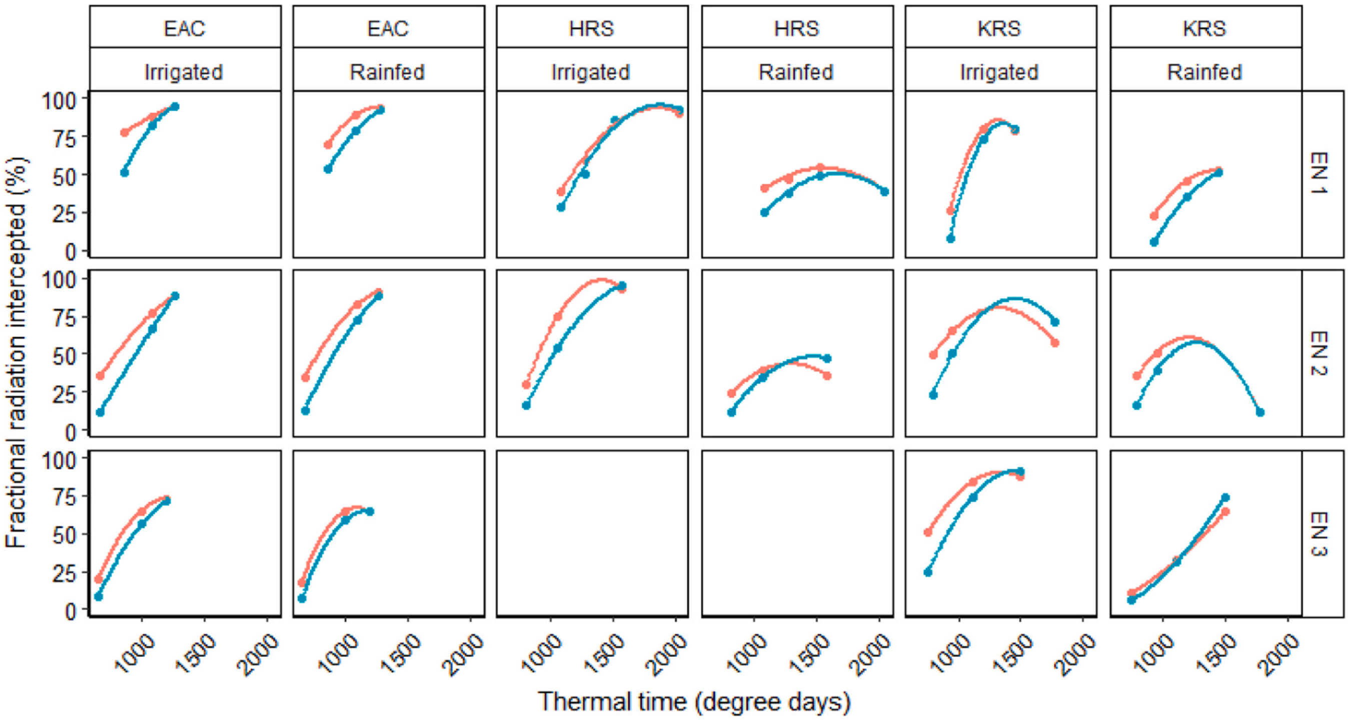

Fig. 5. Fractional radiation intercepted (%) for chickpea (var. PBA Seamer) under different environments (EN), irrigation and canopy management at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) in the 2017 winter cropping season. Red and cyan lines represent values from control and partial reduction in shoot biomass (PRS) treatments, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

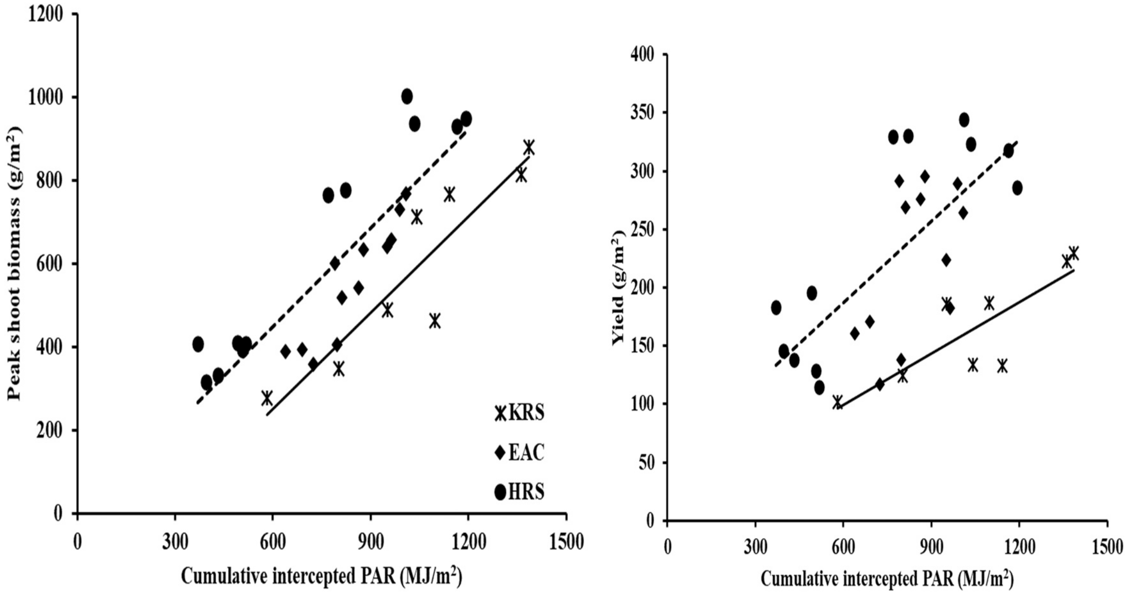

Fig. 6. Relationship between cumulative intercepted photosynthetically active radiation (PAR) (MJ/m^2), and peak shoot biomass (g/m^2) (a) and yield (g/m^2) (b) for chickpea (var. PBA Seamer A) grown at Emerald (EAC), Hermitage (HRS) and Kingaroy (KRS) in the 2017 winter cropping season. Data points in all sites are from the three environments (EN 1–3). For EAC (●) and HRS (◆) $y = 0.3951x - 24.717$, $r^2 = 0.73$), KRS (*) $y = 0.3546x - 209.81$, $r^2 = 0.83$) for peak biomass and $y = 0.2324x + 47.76$, $r^2 = 0.49$ for EAC and HRS, and $y = 0.1479x + 10.088$, $r^2 = 0.70$ for yield.

both irrigated and rainfed conditions compared to those in PBR treatment where active water extraction was limited to 50 cm depth only (Fig. 7). At Hermitage, there was rapid extraction of water to a depth of 60 cm in both irrigated and rainfed treatments, in pre-flowering phase, although plants in rainfed conditions extracted 80 mm more water from 60 cm depth compared with plants in irrigated treatment which extracted 40 mm from the same depth (Fig. 8). However, during the post-flowering phase, there was more water extraction up to 50 cm depth in PBR treatment compared to control, in both irrigated and rainfed conditions. There were no differences between irrigated and rainfed conditions below 50 cm depth in control treatment. However, in PBR treatment, more water was extracted in irrigated treatment up to 60 cm depth, after which, irrigated treatment extracted more water compared to rainfed treatment up to 125 cm depth.

The evapo-transpiration (ET) by chickpea crop under the two canopy management practices (control and PBR) and under irrigated and

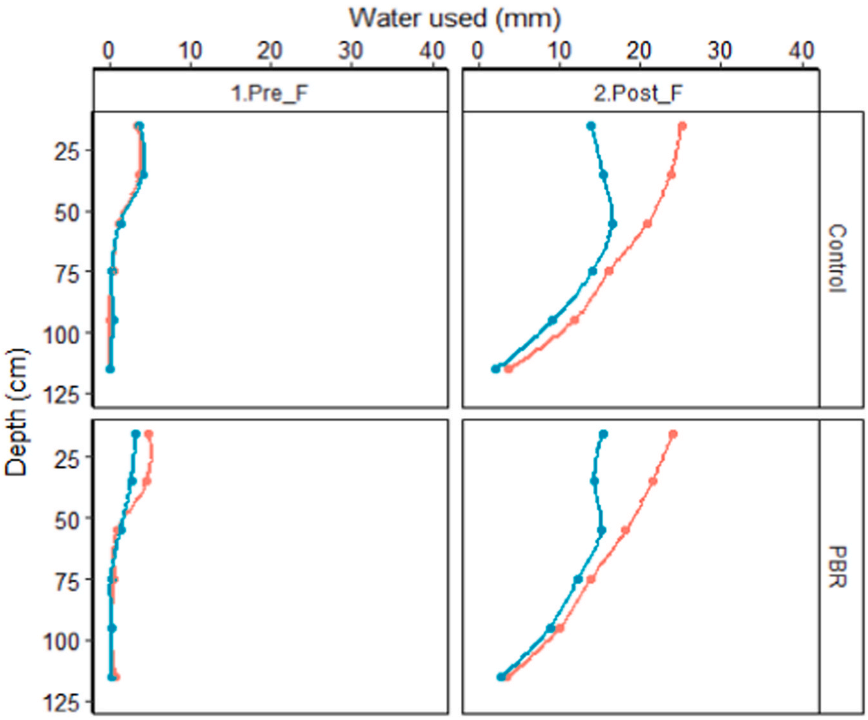

Fig. 7. Water extracted (mm) from different depths, by chickpea in control and partial biomass reduction (PBR) treatments for environment 2 (EN 2) at EAC in the 2017 winter cropping season. Pre_F and Post_F phases represent pre-flowering and post-flowering phases, respectively. Red and cyan lines represent values from irrigated and rainfed treatments, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

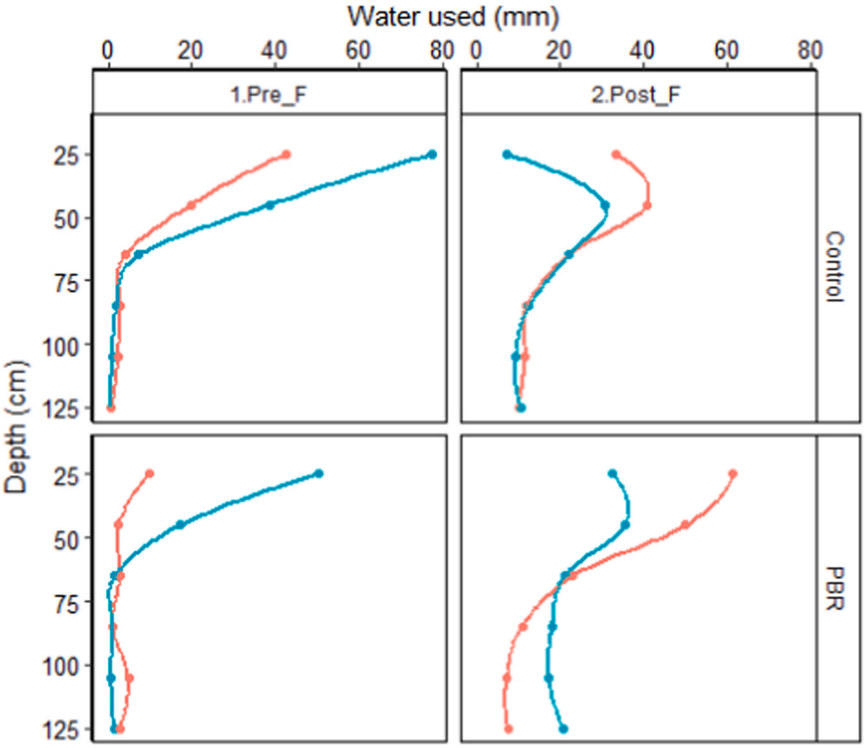

Fig. 8. Water extracted (mm) from different depths by chickpea grown under control and partial biomass reduction (PBR) treatments in environment 1 (EN 1) at HRS in the 2017 winter season. Pre_F and Post_F represent pre-flowering and post-flowering phases, respectively. Red and cyan lines represent values from irrigated and rainfed treatments, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rainfed conditions was measured at Emerald and Hermitage sites (Table 4). The total ET by the crop differed significantly between Emerald and Hermitage, but the differences between control and PBR treatments at a given site were less pronounced. For instance, at Emerald, PBR treatment extracted 3 mm and 17 mm less water under Irr, and rain fed conditions compared to control, respectively.

The water use efficiency (WUE) for peak shoot biomass and grain yield differed significantly between sites with the mean WUE values for PBS being higher at Emerald (22.6 kg/ha/mm) compared to (15.6 kg/ha/mm) at Hermitage (Table 4). The mean WUE for yields were 9.1 and 5.7 kg/ha/mm at Emerald and Hermitage, respectively.

Table 4
Site, environment (EN), irrigated vs rainfed treatment, canopy management (control vs partial biomass reduction (PBR)), evapotranspiration (ET) (mm), water use efficiency for peak shoot biomass (PSB) (kg/ha/mm) and yield (kg/ha/mm) for chickpea grown at Emerald (EAC) and Hermitage (HRS) in Queensland.

Site	EN	Irrigated	Canopy management	ET	WUE PSB	WUE yield
EAC	EN 1	Irrigated	Control	246	23.4	10.4
EAC	EN 1	Irrigated	PBR	243	24.7	9.5
EAC	EN 1	Rainfed	Control	257	21.1	8.3
EAC	EN 1	Rainfed	PBR	240	21.5	8.5
HRS	EN 2	Irrigated	Control	380	24.4	8.4
HRS	EN 2	Irrigated	PBR	424	20.2	7.2
HRS	EN 2	Rainfed	Control	436	9.1	3.7
HRS	EN 2	Rainfed	PBR	420	8.9	3.5

3.7. *Yield components*

The yield components were measured at Kingaroy and Hermitage sites, and at Hermitage they were measured only at EN 1 and EN 2 (Table 5). The irrigation had a significant effect on most of the yield components excepting for hundred seed weight (HSW) at both sites (Table 5). Sites had significant effect on all yield components. For instance, plant height (PHt) and plant height to first pod (PHt1P) were significantly higher at Kingaroy compared to Hermitage. However, there was a trend for progressive reduction in PHt from EN 1 to EN 3 under irrigated treatment at Kingaroy, but not at Hermitage. The number of primary branches (PBR) per plant were significantly less under RF and Irr treatments at Kingaroy compared to Hermitage. There was a trend for increased PBR under Irr treatment at Hermitage. However, the total pod number (TP) and total seed number (TSN) were generally higher with Irr treatment compared to RF at both sites, but Hermitage site tended to have higher TP and TSN than Kingaroy site. Interestingly, the number of seeds aborted (TSA) per plant were significantly higher at Kingaroy compared to Hermitage site and the TSA were significantly higher in Irr than the RF treatment at both the sites. The hundred seed weight (HSW) was significantly higher at Hermitage compared to Kingaroy and Irr treatment had only small effect on HSW at both sites.

4. Discussion

Because of the indeterminate growth habit of chickpea, the reproductive growth and development, and physiological maturity occur simultaneously in different parts of the plant along with vegetative growth (Saxena, 1984). A thorough understanding of the response of the crop growth and development to environmental factors is thus critical to interpret the crop's performance across environments. The most important environmental factors affecting chickpea growth and development are temperature (Siddique and Sedgley, 1985), photoperiod (Summerfield et al., 1991; Upadhyay et al., 1994; Ellis et al., 1994) and soil moisture (Saxena et al., 1990).

Terminal drought is one of the major constraints for chickpea productivity in semi-arid tropics (Krishnamurthy et al., 2010) and extensive root growth has been suggested as the desirable genotypic trait that could contribute to seed yield under terminal drought conditions (Kashiwagi et al., 2005; Subbarao et al., 1995; Turner et al., 2001). However, genotypic strategies that save water during early vegetative growth phase for use during reproductive and grain filling phase could be equally critical (Zaman-Allah et al., 2011). Many studies focussed on the genotypic traits contributing to yield under water deficit, but effects on temporal patterns of water use on crop phenological development have not been reported in chickpea (Lake et al., 2016). Our study quantified temporal variation in environmental variables and their effect on crop growth and development in nine diverse environments.

4.1. *Phenology*

We considered each sowing date as an "environment" which involved a combination of various environmental components, which is an approach that is more comprehensive. Intensive experiments using growth chambers with environmental control are needed to tease out effects of the individual variables.

Environments had significant effect on crop phenology by hastening the onset of 50% flowering at Hermitage and Kingaroy and maturity at the three sites (Table 1). Time to 50% flowering was hastened by 15 days and 22 days at Hermitage and Kingaroy, respectively while time to 50% flowering unaffected at Emerald. This could be due to indeterminate growth habit of chickpea influencing source-sink balance depending on the temperature and soil moisture availability resulting in significant effects on vegetative growth, crop maturity and yield (Lawlor et al., 2001; Li et al., 2010). Roberts et al. (1985) found that rate of progress towards flowering is a linear function of mean temperature with no interaction with photoperiod.

Our study showed that crop maturity was accelerated from EN 1 to EN 3 by 24 days, 36 days and 15 days, at Emerald, Hermitage and Kingaroy sites, respectively (Table 1). These changes in crop maturity could be due to combined increases in temperature, variations in soil moisture, VPD and radiation from EN 1 to EN 3. Kanchan and Bhatia (2014) observed similar effects of elevated temperature.

Table 5
Mean rainfed and irrigated chickpea plant height (PHt) (cm) from the ground level, plant height to the first pod (PHt1P) (cm), number of primary branches (PBR) per plant, total number of pods (TP) per plant, total number of seeds (TSN) per plant, number of seeds aborted (TSA) per plant and hundred seed weight (HSW) (g) at Kingaroy (KRS) and Hermitage (HRS) sites in the 2017 winter cropping season.

		PHt		PHt1P		PBR		TP		TSN		TSA		HSW	
		RF	IR	RF	IR	RF	IR	RF	IR	RF	IR	RF	IR	RF	IR
KRS															
Environment	EN 1	51^{a}	95^{a}	24^{a}	31	2.0	2.2	31^{a}	59^{a}	33^{a}	57	3.9	11.2^{a}	19^{b}	17^{c}
	EN 2	38^{b}	83^{b}	22^{b}	33	1.7	2.3	16^{b}	39^{b}	16^{b}	43	2.6	4.1^{b}	17^{c}	18^{b}
	EN 3	48^{a}	70^{c}	22^{b}	31	2.0	2.5	32^{a}	43^{b}	41^{a}	50	2.8	4.7^{b}	21^{a}	21^{a}
Management	PBR	44	80	21^{b}	31	2.0	2.3	27	48	31	51	3.7	7.8	18^{b}	19^{a}
	Control	47	85	25^{a}	33	1.8	2.3	25	46	29	50	2.4	5.5	19^{a}	18^{b}
HRS															
Environment	EN 1	30	54	18	27^{b}	4.9^{a}	5.1	25	61	25	62	0.8	6.4^{b}	23	23^{b}
	EN 2	29	58	16	33^{a}	4.0^{b}	4.8	31	54	34	62	0.5	5.1^{b}	22	24^{a}
	EN 3		53		31^{ab}		4.3		61		71		9.6^{a}		21^{c}
Management	PBR	28^{b}	54	17	29	4.4	4.7	29	57	32	62	0.5	7.2	23	23
	Control	32^{a}	57	17	31	4.5	4.9	26	60	27	68	0.8	6.9	23	23

EN 1, 2, and 3 represent planting windows 1–3, at each site, respectively. PRB represents partial biomass reduction. Values with the same superscripted letter are not different at $P < 0.05$.

4.2. *Crop growth*

The peak shoot biomass was reduced from EN 1 to EN 3 by 44%, 21% and 4% at Emerald, Hermitage and Kingaroy sites, respectively. Despite the reduction in peak shoot biomass, the yield reduction occurred only at Emerald site (by 41%) but not at Hermitage and Kingaroy sites. Temperatures above 30 °C in EN 3 at Emerald might have affected reproductive processes (Devasirvatham et al., 2012; Summerfield et al., 1984) and high VPD (> 3 kPa) during the reproductive phase might have resulted in stomatal closure leading to reduced transpiration affecting water uptake by the crop under irrigated condition (Lobell et al., 2013; Sadras et al., 2015). Indeed, the negative relationship between biomass response to irrigation and VPD during reproductive phase of the crop (Fig. 4) supports this observation. Increasing temperatures of the growing environment (managed by sowing date) resulted in a progressive reduction in LAI (by 62%), PSB (by 32%) and seed yield (by 46%) (Salih et al., 2018). Temperatures above 15 °C caused flower and pod abortion in parts of the Indian subcontinent and Australia (Clarke, 2001; Srinivasan et al., 1998).

4.3. *Response to irrigation*

Environments had profound effect on chickpeas response to irrigation. For instance, at Emerald, where the temperature and VPD increased from EN 1 to EN 3, response to irrigation progressively reduced in both canopy management treatments. While at Hermitage, the response to irrigation was significantly higher in the three environments, compared to Emerald because of lower temperatures and VPD at Hermitage, although the response to irrigation reduced steadily from EN 1 to EN 3 (Fig. 3). At Kingaroy, minimal response to irrigation in EN 1 and EN 3 could be due to different reasons. Leaf senescence due to severe dry spell spanning EN 3 followed by 282 mm rain during the final stages of crop growth resulted in minimal response to irrigation.

4.4. *Canopy management*

The present study contributes to the current understanding on the physiological responses of chickpea to canopy management (partial biomass reduction and control) and elaborates how canopy management treatments influence crop growth and source-sink relations under diverse environmental conditions. As shown in Fig. 5, partial reduction in shoot biomass during early vegetative phase (by around 25%) may accelerate photosynthetic capacity of rest of the canopy resulting in rapid compensatory growth (Iqbal et al., 2012) and accelerate sink metabolism by remobilizing carbon and nitrogen reserves (Khan et al., 2007; Paul and Foyer, 2001). Canopy management practices like defoliation (Iqbal et al., 2012), nipping or cutting back (Baloch and Zubair, 2010) or removal of basal branches (Siddique and Sedgley, 1985) implemented during vegetative phase had either no effect or positive effect on yield. In the present study, there were minimal effects of canopy management practices on yield in all the environments, at the three sites.

4.5. *Water use efficiency*

Sites had significant effects on evapotranspiration (ET) and water use efficiency (WUE) (Table 4). At Emerald, the ET was lower and WUE for peak-shoot biomass (PSB) and grain yield was higher. While at Hermitage, ET was higher but WUE was lower for PSB and yield. The increase in the seasonal ET outweighed the increase in the crop yield, thus resulting in relatively lower water use efficiency at Hermitage. There were no significant effects of canopy management treatments on WUE at both sites (Table 4). The WUE for PSB and grain yield values reported in the current study (3.5–10.4 kg grain /ha/mm) are comparable to number of studies reported for chickpea (Angadi et al., 2008; Gan et al., 2009; Miller et al., 2001) (between 5 and 10 kg grain/ha/mm). The variation in WUE observed at the two sites in the current study could be due to environment × management interactions.

4.6. *Water extraction patterns*

Environment had profound effect on water extraction pattern. At Emerald, where the temperature and VPD were about 27 °C and 2.4 kPa respectively, during pre-flowering phase, there was little difference between treatments, in water extraction. However, at Hermitage, amount of water extracted in control treatment during pre-flowering period (80 mm) was significantly higher than partial shoot biomass reduction (PRS) treatment (50 mm) supporting the hypothesis that the canopy reduction during early vegetative phase reduces water use by the crop, thus saving water. However, there was greater water extraction during reproductive phase at both sites although extraction depth varied between sites and treatments. In the present study, water extraction was observed up to 110 cm depth in control compared to 75 cm in PBR treatment, at Emerald. However, at Hermitage, which had higher rainfall, water extraction during pre-flowering stage was from 60 cm depth in control compared to 125 cm in PBR treatment. However, most of the water used came from top 0–40 cm (Anwar et al., 2000). Higher water extraction in irrigated treatment at Hermitage resulted in higher yield as observed in earlier studies (Anwar et al., 2000; Oweis and Hachum, 2003).

4.7. *Yield components*

Several studies reported relationships between yield and yield components with an aim of identifying stable genetic trait(s) for use in the chickpea crop improvement programmes (Güler et al., 2001; Arshad et al., 2003). Some studies reported significant genotype × environment (G × E) interactions for yield components in chickpea (Arshad et al., 2003; Bakhsh et al., 2006), however, there is limited information about the environmental factors underpinning the observed G × E interaction in yield components. The current study investigated the effects of two canopy management treatments (control and partial biomass reduction) and two water treatments (supplementary irrigation and rainfed) in nine diverse environments (created by 3 different dates of sowing at 3 locations) on the yield components at Kingaroy and Hermitage sites (Table 5). Higher plant height, height to first pod, at Kingaroy could be associated with weather components (lower radiation and higher rainfall) during the growing seasons or soil N status (Namvar et al., 2011). High seed abortion at Kingaroy in both RF and Irr treatments, compared to Hermitage, could be due to leaf senescence caused due to 11–17% lower radiation due to persistent overcast followed by 34–47% higher rainfall during the active seed-filling phase. This situation may also have resulted in lower 100-seed weight at Kingaroy. Daily mean temperatures during post flowering period were above 15 °C in all environments, ruling out the possibility of low temperature being a cause for seed abortion (Croser et al., 2003).

5. Conclusions

Environments had significant effect on crop phenology by hastening the onset of 50% flowering at Hermitage, Kingaroy, and crop maturity at the three sites. The peak shoot biomass was reduced from EN 1 to EN 3 by 44%, 21% and 4% at Emerald, Hermitage and Kingaroy sites, respectively. The variation in rainfall and VPDs with in the environments had profound effect on chickpea's response to irrigation. Partial reduction in shoot biomass (PRS) treatment during early vegetative phase resulted in a 25% reduction in photosynthetically active radiation intercepted by the canopy but rapid compensatory growth following the PSB treatment led to closing of the gap between two canopy management treatments. Environment also had a profound effect on water extraction pattern during at pre-and post-flowering phases.

The study suggested that the effects of partial reduction in shoot biomass had minimal effects on crop growth and yield in all environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2020.106704.

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