The effect of irrigation and sowing date on crop yield and yield components of Kabuli chickpea (*Cicer arietinum* L.) in a cool-temperate subhumid climate

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SUMMARY

The canopy development, radiation absorption and its utilization for biomass production in response to irrigation at different growth stages of three Kabuli chickpea (*Cicer arietinum* L.) cultivars was studied on a Wakanui silt loam soil in Canterbury, New Zealand (43°38S, 172°30E). The study also aimed at quantifying the yield potential of the crop under varying irrigation regimes and sowing dates. Green area duration (GAD), intercepted radiation (F_i), radiation use efficiency (U) and total intercepted PAR were significantly ($P < 0.001$) increased by irrigation. Total dry matter (TDM) yield was more strongly correlated ($R^2 = 0.69–0.83$) with GAD than seed yield ($R^2 = 0.60–0.69$). Accumulation of TDM was highly related to intercepted PAR. Fully irrigated November-sown crops had a final U of 1.46 g DM/MJ PAR. The unirrigated crop had a U of only 0.92 g DM/MJ PAR. The U tended to decrease with delayed sowing.

Averaged over the 2 years, irrigation increased seed yield by 74–124% and trends were similar for TDM yield. Seed yield was doubled in November-sown chickpeas (4.6 t/ha) and cv. Sanford produced 14 and 16% more seed than cvs Dwelley and B-90 respectively. Full irrigation from emergence to physiological maturity always gave the highest seed yield (> 4.7 t/ha), and there was no indication of a critical period of sensitivity to water stress. Based on results collected in the first growing season a simple model relating seed yield to radiation interception, U and HI was made. Results from the second growing season were then used as a simple verification to test the accuracy of predictions. The results suggest that these varieties have the potential to yield more than 4.5 t/ha of seed in Canterbury.

INTRODUCTION

Variable seed yields are a deterrent to growing chickpea (*Cicer arietinum* L.) as they are mostly grown on residual soil moisture and often experience water stress during their growth in major chickpea growing countries (Singh *et al.* 1997). Irrigation has been shown to significantly increase chickpea seed yield (Zhang *et al.* 2000). Determining the physiological basis of yield variation may help determine

best management practices to maximize yield, which may help to identify other areas as potential production sites. The Canterbury Plains is one of the most important agricultural regions in New Zealand and there has been a resurgence of interest in using irrigation and rainfall water more efficiently for the production of crops. Although chickpeas have never been grown commercially, there is a high potential for seed yield (Anwar *et al.* 1999). Therefore, their potential production in response to irrigation, sowing date and cultivar was evaluated.

Crop growth can be considered as the product of incoming solar radiation, the fraction of that radiation which is intercepted (F_i) by the crop, as determined by the green area index (GAI). The F_i by a crop

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is a function of its GAI and the extinction or attenuation coefficient ($-k$), which is governed by a number of factors such as leaf size, shape, elevation of the sun and the proportion of direct and diffused solar radiation (Monteith & Elston 1983). In Canterbury, reported $-k$ values in grain legumes are 0.36–0.48 in field beans (*Vicia faba* L.) (Husain *et al.* 1988), 0.26 for lentils (*Lens culinaris* L.) (McKenzie & Hill 1991), and 0.74 in pinto beans (*Phaseolus vulgaris* L.) (Dapaah *et al.* 2000). However, no data are available for Kabuli chickpea. Different crop species have different leaf sizes, growth patterns and photosynthetic functions. This gives a wide range of differences not only of their radiation use efficiency (U) but also different levels of GAIs at which radiant energy interception or GAI approaches maximum (Hippes *et al.* 1983). Under non-limiting water supply, U is a key determinant of crop yield. Values of U have not been determined for these recently developed Kabuli chickpea cultivars. Since chickpea leaflet size is much smaller ($<1\text{ cm}^2$) than in most other crops (Singh 1997), it was of interest to know the basic response to solar radiation in a subhumid temperate environment.

The present investigation was designed to study the influence of irrigation at different growth stages and sowing dates on: (1) changes in green area development, radiation absorption and its utilization; (2) to determine the optimum sowing date for these cultivars; and (3) to measure harvest index and yield components and how they significantly influence Kabuli chickpea seed yield.

MATERIALS AND METHODS

The experimental design, site and husbandry methods are fully described in the companion paper (Anwar *et al.* 2003). Briefly, two experiments were carried out at Lincoln University, New Zealand. The first was a split-split plot randomized complete block design with eight irrigation levels (nil, full (emergence to maturity, e-m), full & half (emergence to flower, e-f), full & half (flower to pod, f-p), and full & half (pod to maturity, p-m)) in the 1998/99 season. In 1999/2000 there were four irrigation levels (nil, full (e-m), full (f-p), and full (p-m)) as main plots. Subplots were two sowing dates (3 November and 7 December in 1998/99 and 18 October and 22 November in 1999/2000). Three high yielding Kabuli chickpea cultivars (Sanford, Dwelley and B-90) were sub-subplots.

In both experiments the final plant population, total dry matter (TDM) production, seed yield and harvest index were measured from a 2.0 m^2 harvest area from the central four rows of each subplot when the crop reached physiological maturity. The number of pods/plant and seeds/pod were measured from five randomly selected plants from the final 2.0 m^2 sample. The mean seed weight was estimated from five subsamples of the seed lot from the harvest area.

Green area index and the amount of radiation transmitted through the canopy (T_i) were measured using a LICOR LAI 2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, Nebraska, USA). Green area duration was calculated as the time integral of GAI (Hunt 1978). In both years, GAI and T_i were measured every 10 days from 28 days after sowing (DAS) until near harvest maturity. The proportion of radiation intercepted (F_i) by the canopy was calculated as (Gallagher & Biscoe 1978):

$$F_i = 1.0 - T_i \quad (1)$$

The amount of photosynthetically active radiation (PAR) intercepted S_a was calculated as (Szeicz 1974):

$$S_a = F_i \times S_i \quad (2)$$

where S_i is the total incident PAR.

The extinction coefficient ($-k$) of the canopy was calculated (from Eqn 3) using the linear regression of GAI as a function of logarithm (Ln) of T_i .

$$-k = -\text{Ln}(1 - F_i)/\text{GAI} \quad (3)$$

Therefore, the amount of solar radiation intercepted (F_i) can be expressed (Goudriaan & Monteith 1990) as follows:

$$F_i = 1 - e^{-k \text{ GAI}} \quad (4)$$

According to Gallagher & Biscoe (1978), crop growth or seed yield (Y) can be analysed using the following equation:

$$Y = S_a \times U \times \text{HI} \quad (5)$$

where S_a is the intercepted solar radiation, U is the radiation use efficiency and HI is harvest index. Yields were calculated using Eqn 5 with variables determined from the first growing season. As a simple verification, yields from the second growing season were compared with predicted yields as determined by the model.

Data from both years were analysed using analysis of variance procedures with the statistical program Genstat 5 (Genstat 5 Committee of the Statistics Department, Rothamsted Experimental Station, Hertfordshire, UK).

RESULTS

Green area duration

There were highly significant ($P < 0.001$) responses to irrigation, sowing date and cultivar on green area duration (GAD) in 1998/99 (Table 1) and a significant ($P < 0.05$) irrigation by sowing date interaction on GAD in 1999/2000 (Fig. 1). In 1998/99 and 1999/2000, the fully irrigated (emergence-maturity (e-m)) crops had 337 and 468 days GAD. This was 128 and 36% higher than the GAD of the unirrigated crop. The GAD in the December 1998/99 and October

Table 1. The effects of irrigation, sowing date and cultivar on green area duration (GAD) of Kabuli chickpeas in New Zealand, 1998/99

Parameter	GAD (days)
Irrigation*	
Nil	148
Full (e-m)	337
Full (e-f)	278
Half (e-f)	254
Full (f-p)	232
Half (f-p)	241
Full (p-m)	203
Half (p-m)	195
S.E. (D.F. = 7)	18.15
Sowing date	
November 3	218
December 7	254
S.E. (D.F. = 8)	13.90
Cultivar	
Sanford	229
Dwelley	230
B-90	249
S.E. (D.F. = 32)	9.90

* Irrigation: Nil=rainfed; full=full irrigation to replace water lost from evapotranspiration; half=irrigated with half the amount of full; e-m=emergence to maturity; e-f=emergence to flower; f-p=flower to pod; p-m=pod to maturity.

Fig. 1. The effects of irrigation and sowing date on green area duration of Kabuli chickpea in 1999/2000 season (averaged over cultivars). Nil: rainfed, Full: full irrigation to replace water lost from evapotranspiration, e-m: emergence to maturity, f-p: flower to pod and p-m: pod to maturity.

1999/2000 sowing was about 17 and 13% longer than the GAD of any of the other sowings. Cultivar B-90 had a significantly ($P < 0.001$) longer GAD than the cvs Sanford and Dwelley in 1998/99. The sowing date by irrigation interaction (Fig. 1) showed that in the October and November sowing, irrigation (e-m)

Fig. 2. The relationship between green area duration of Kabuli chickpea with (a) total dry matter and (b) seed yield in New Zealand (averaged over cultivars).

produced a much longer GAD than no irrigation or late irrigation (pod-maturity (p-m)). Total dry matter (TDM) production in both seasons was linearly and significantly related with GAD from e-m (Fig. 2a). The significant regression accounted for 83 and 69% of the variation in TDM yield in 1998/99 and in 1999/2000, respectively. Seed yield was also linearly related with GAD from e-m (Fig. 2b) ($R^2 = 0.69$ in 1998/99 and $R^2 = 0.60$ in 1999/2000).

Radiation interception and extinction coefficient (-k)

There was significantly ($P < 0.001$) more radiation interception (F_i) by fully irrigated (e-m) plants (Fig. 3a-c). Peak F_i was $> 90\%$ in both years and it generally coincided with peak GAI. In irrigated plots in 1998/99 and all plots in 1999/2000 the F_i did not decline rapidly. In 1998/99, F_i varied significantly ($P < 0.001$) between sowing dates and December-sown plants intercepted 98% F_i 10 days before that of early November sowing (Fig. 3a,b). The crop canopies of the unirrigated and late irrigated (p-m)

Fig. 3. Effect of irrigation and sowing date on the proportion of intercepted radiation up to maximum green leaf index of Kabuli chickpea in 1998/99, (a) November sowing, (b) December sowing and (c) 1999/2000 season (mean across cultivars and sowing dates for 1999/2000). Irrigation treatments as in Fig. 1.

plants intercepted 86%, at most, of incident radiation in 1998/99. Plants in the irrigated (e-m and e-f) plots intercepted 98%. In 1999/2000, F_i did not vary between sowing dates. However, fully irrigated plants always intercepted more incident radiation than late and nil irrigated plants from 30 DAS to physiological maturity (Fig. 3c). Interception of radiation generally followed similar patterns in each cultivar. The F_i was strongly influenced by GAI, which displayed a typical exponential function (Fig. 4a, c). A GAI of 3.0–3.4 was required to intercept between 90–95% of incident radiation. The mean extinction coefficient ($-k$) of Kabuli chickpea in Canterbury was 0.84 (averaged over years, cultivar and sowing dates) (Fig. 4).

Intercepted PAR

Irrigation at any growth stage significantly ($P < 0.001$) increased intercepted PAR compared with rain-fed plants by 33% from 736 to 978 MJ/m² and 32% from 857 to 1128 MJ/m² in 1998/99 and 1999/2000, respectively. In both years, early sown plants also intercepted more PAR. Significant irrigation by sowing date (in 1998/99) and sowing date by cultivar (in both years) interactions indicated that the intercepted PAR response to irrigation depended on sowing date (Tables 2 and 3). In all irrigation treatments November-sown plants intercepted more PAR than December-sown plants. All three cultivars intercepted more PAR when they were sown early.

Total dry matter, seed yield and harvest index response to irrigation

The mean total dry matter (TDM) production at final harvest was very similar in both years and it increased significantly with irrigation. In both years, full irrigation (e-m) gave a significantly higher TDM production than nil and late irrigation (p-m) (Fig. 6). Averaged over the 2 years, fully irrigated crops pro-

duced 70% more TDM than nil and late irrigation. Late irrigation at flowering to pod-set (f-p) and p-m had no effect on TDM production (mean, 803 g/m²). In 1998/99, the effect of irrigation on TDM depended on sowing date. In 1999/2000, full irrigation (105 mm in October and 109 mm in November) significantly ($P < 0.001$) increased TDM production by 63% to 1030 g/m² (Table 4). Total dry matter at final harvest, over the two seasons, among sowing dates and cultivar ranged from c. 460–1330 g/m². The 1999/2000 crops produced about 4% more TDM than the 1989/99 crops.

In 1998/99, seed yield (averaged over the two sowing dates and cultivars) ranged from c. 280–490 g/m² and was influenced both by sowing date and cultivar as both these factors interacted significantly with irrigation ($P < 0.01$) (Fig. 5a, b). Irrigation increased seed yield by 74–90% and trends were similar to those for TDM yield. Seed yield was doubled in November-sown chickpea and cv. Sanford produced 14 and 16% more seed than cvs Dwelley and B-90 respectively (Fig. 5b). Generally, irrigated chickpea sown in November yielded over 100% more seed than the same cultivars sown in December. However, with late irrigation or no irrigation, the yield advantage of the early sown crop was less, about 34%. Irrigation also increased seed yield in 1999/2000 and there was a significant ($P < 0.01$) three-way interaction between irrigation, sowing date and cultivar (Fig. 5c). Full irrigation (105 mm, e-m) gave the highest seed yield compared with no irrigation or late irrigation. Generally cv. Sanford responded more to irrigation than cv. B-90. However, in unirrigated plots cv. B-90 out-yielded cv. Sanford in the October sowing while in the November sowing, cv. Sanford out-yielded cv. B-90.

The response to irrigation of harvest index (HI) in 1998/99 depended on sowing date (Table 2). The November sowing had an average HI of 0.58, which was about 80% higher than in the December sowing.

Fig. 4. Relationship between green area index and the proportion of intercepted radiation. (a) 1998/1999: $Y = 1 - e^{-0.85GAI}$ & (c) 1999/2000: $Y = 1 - e^{-0.84GAI}$. (b) 1998/1999: $\ln(1 - F_i)$, $Y = -0.005 - 0.85X$, $R^2 = 0.99$. (d) 1999/2000: $\ln(1 - F_i)$, $Y = -0.035 - 0.84X$, $R^2 = 0.99$. Slope = extinction coefficient ($-k$) for Kabuli chickpea in Canterbury. Dotted line indicates green area index at 95% radiation intercepted.

Only in the November sowing did chickpea crops irrigated half from emergence to flower (e–f) and while pods were filling (p–m) have a higher HI (0.72–0.74) than the fully irrigated and unirrigated control plots. Although the HI was stable among cultivars (0.56–0.59) in the November sowing, the HI decreased by about 15–47% when sowing was delayed to December (0.25–0.40) (data not shown). In 1999/2000, HI varied from 0.40–0.52 and was significantly affected by irrigation (Table 4). The HI was significantly ($P < 0.01$) higher (0.52) for crops irrigated during flower to podding (f–p). This was about 30% more than in the nil (0.40), 20% more than in the late and only 6% more than in the fully irrigated crops.

Yield components

In both growing seasons there were approximately 45 plants/m² (across all cultivars) by final harvest (data not shown). In 1998/99 the plant population in the December sowing was about 7% higher than in the November sowing. The significant ($P < 0.05$) sowing date by cultivar interaction (Table 5) shows that cv. B-90 had more plants in the December sowing. Irrigation significantly increased the number of pods per plant in both seasons. There was a highly significant ($P < 0.001$) cultivar by sowing date interaction (Table 5) in the 1998/99 season. November-sown cv. B-90 produced 100% more pods per plant than cv.

Table 2. *The effects of irrigation and sowing date on total absorbed PAR, radiation use efficiency (U), and harvest index (HI) of Kabuli chickpea in New Zealand, 1998/99*

	Total absorbed PAR (MJ/m ²)		U (g DM/MJ PAR)		HI	
			Sowing date			
	3 Nov	7 Dec	3 Nov	7 Dec	3 Nov	7 Dec
Irrigation*						
Nil	729	742	0.92	0.98	0.50	0.46
Full (e-m)	1037	918	1.46	1.23	0.58	0.18
Full (e-f)	944	868	1.27	1.01	0.53	0.30
Half (e-f)	906	818	1.51	0.97	0.74	0.28
Full (f-p)	851	803	1.40	1.20	0.68	0.25
Half (f-p)	875	786	1.22	1.08	0.41	0.33
Full (p-m)	839	796	1.31	1.12	0.50	0.40
Half (p-m)	828	786	1.35	1.13	0.72	0.39
S.E. (D.F. = 8)	9.6		0.028		0.072	

* Irrigation treatments as in Table 1.

Table 3. *The effects of sowing date and cultivar on total absorbed PAR of Kabuli chickpea in New Zealand, during 1998/99 and 1999/2000*

	Total absorbed PAR (MJ/m ²)			
	Sowing date 1998/99		Sowing date 1999/2000	
	3 Nov	7 Dec	18 Oct	22 Nov
Cultivar			Cultivar	
Sanford	883	812	Sanford	1013 963
Dwelley	878	813	B-90	1022 950
B-90	868	819		
S.E. (D.F. = 32)	12.7		S.E. (D.F. = 16) 13.2	

Dwelley at the same sowing date and about 90 % more than the December-sown crop. In 1999/2000, irrigation interacted with cultivar (Table 6). Fully irrigated (e-m), cv. B-90 produced 296 % more pods per plant than control plants. Across all treatments cv. B-90 produced the most pods per plant. Irrigation did not significantly affect the number of seeds per pod (data not shown) but in 1998/99, the response to irrigation of number of seeds per pod depended on both cultivar and sowing date (Table 5) and tended to increase with delayed sowing. However, November-sown cv. B-90 had 0.99 seeds per pod but only 0.86 in December. In general, over both experiments plants produced an average of one seed per pod.

In the 1998/99 season, the mean seed weight among cultivars changed significantly with sowing date ($P < 0.05$) (Table 5). The mean seed weight of cv.

Table 4. *Effect of irrigation on total dry matter (TDM) at final harvest, harvest index (HI) and radiation use efficiency (U) of Kabuli chickpea in New Zealand during 1999/2000 season*

	TDM (g/m ²)	HI	U (g DM/MJ PAR)
Irrigation*			
Nil	633	0.40	0.78
Full (e-m)	1030	0.49	1.08
Full (f-p)	816	0.52	0.71
Full (p-m)	854	0.43	0.77
S.E. (D.F. = 6)	49.3	0.023	0.047

* Irrigation treatments as in Table 1.

Dwelley was higher in the November sowing than cv. B-90 in the December sowing. In 1999/2000 (data not shown) the trend was similar to 1998/99. However, there was a highly significant ($P < 0.001$) interaction between sowing date and irrigation for mean seed weight. Table 6 shows that the nil and late irrigation (p-m) treatments had the highest mean seed weights. In the November sowing, unirrigated chickpeas had a mean seed weight of 0.31 g, which was about 63 % higher than that of the late irrigated plants.

In 1998/99 simple correlation analysis (Table 7) between seed yield and yield components showed that pods/plant, seeds/pod and mean seed weight were positively correlated with seed yield ($r = 0.64$, 0.43 and 0.53 respectively, $P < 0.01$). However, in 1999/2000, only pods per plant was positively correlated ($r = 0.41$, $P < 0.01$) with seed yield (Table 7). In

Fig. 5. (a) The irrigation by sowing date, (b) sowing date by cultivar interaction during 1998/99 season, and (c) the three way interaction of irrigation, sowing date and cultivar during 1999/2000 season on seed yield of Kabuli chickpea in New Zealand. Irrigation treatments defined in Table 1.

both seasons, TDM production and HI were positively and significantly ($P < 0.01$) correlated with seed yield.

Radiation use efficiency

In both years, for all irrigation treatments, there was a highly significant linear relationship between accumulated TDM and accumulated intercepted PAR over the growing season (Fig. 6). The regression accounted for 97 and 98% of the variation for the November and December sowing, respectively, in 1998/99 (Fig. 6a,b). The slope of the line indicated radiation use efficiency (U) at 1.24 g DM/MJ PAR,

16% higher than in the December-sown crop (1.07). Similarly, in both the October and November sowing in 1999/2000 there was a linear relationship between intercepted PAR and accumulated TDM (Fig. 6c,d). The corresponding U was 1.04 g DM/MJ PAR in November but was only 0.95 g DM/MJ PAR in October-sown plants. The seed yield in both seasons was highly related with intercepted PAR (Fig. 4). The regression accounted for 65% of the variance and the slope indicated 0.57 g of seed was produced per MJ of intercepted PAR (Fig. 7a). The final U (TDM at harvest divided by total PAR) was significantly ($P < 0.001$) affected by irrigation level in both years (Tables 2 and 4) and there was significant ($P < 0.001$)

Table 5. *The effects of sowing date and cultivar on plants per m², pods per plant, seeds per pod and mean seed weight of Kabuli chickpea in New Zealand, during 1998/99 season*

	Plants/m ²		Pods/plant		Seeds/pod		Mean seed wt. (g)	
					Sowing date			
	3 Nov	7 Dec	3 Nov	7 Dec	3 Nov	7 Dec	3 Nov	7 Dec
Cultivar								
Sanford	48	47	33	27	1.01	1.06	0.33	0.24
Dwelley	46	49	28	24	0.99	1.01	0.37	0.23
B-90	46	53	56	30	0.99	0.86	0.21	0.12
S.E. (D.F. = 32)	4.3		12.2		0.031		0.038	

Table 6. *The effects of irrigation and cultivar on the number of pods per plant and of irrigation and sowing date on the mean seed weight of Kabuli chickpea during 1999/2000 season*

	Pods/plant (cultivars)		Mean seed wt. (g) (sowing dates)	
	Sanford	B-90	18 Oct	22 Nov
Irrigation*				
Nil	23	23	0.32	0.31
Full (e-m)	41	91	0.26	0.26
Full (f-p)	41	56	0.22	0.30
Full (p-m)	32	56	0.32	0.19
S.E. (D.F. = 16)	14.8		0.058	

* Irrigation treatments as in Table 1.

irrigation by sowing date interaction in 1998/99. The biggest effect of irrigation was on the November sowing (Table 2). Fully irrigated (e-m) November-sown crops had a final *U* of 1.46 g TDM for every MJ of PAR while with no irrigation this was reduced to 0.92. It also tended to fall with delayed sowing. In the 1999/2000 season, the fully irrigated (e-m) plants produced 1.08 g TDM for every MJ of PAR and only 0.78 g without irrigation. Equation 5 was used to verify the prediction of seed yield for Kabuli chickpeas. As shown in Fig. 7*b*, the relationship between predicted and actual seed yield for all treatments over the 2 years showed a highly significant relationship with an R^2 of 0.74.

DISCUSSION

Dry matter production

Total dry matter of Kabuli chickpeas was significantly correlated with GAD ($R^2 = 0.83$, $P < 0.001$) in

1998/99 but only 69 % of the variation was accounted for in 1999/2000 (Fig. 2*a*). The difference in the positive relationship between TDM and GAD for chickpea growing under different levels of water availability showed that effects of water stress and growth habit were mainly on the size and duration of the canopy. Husain *et al.* (1988) reached a similar conclusion in work on field beans.

The greater GAD in fully irrigated plants, which led to increased total dry matter production, was mostly due to a greater GAI. This difference was probably the result of greater water stress in 1998/99. Water deficits and high temperature during both vegetative and reproductive growth phases hastened changes in GAI over time and decreased GAD (Patra *et al.* 1998). Also, as predicted by Monteith & Elston (1983), temperature was the main factor that controlled the duration and final size of the canopy of well-irrigated crops. However, GAD is not necessarily a cause of yield differences as it does not take into account the amount of solar radiation available for crop photosynthesis, the attenuation of irradiance within the canopy, or the efficiency of leaves in utilizing available radiation.

In Canterbury, where rainfall during the growing season is usually about 270 mm, Kabuli chickpea yield was related to irrigation and sowing date in a similar way to pea (White *et al.* 1982), field bean (Husain *et al.* 1988), lentil (McKenzie & Hill 1990) and pinto bean (Dapaah *et al.* 2000). The sowing date by irrigation and sowing date by cultivar interactions indicated that cultivar response to irrigation depended on the sowing date. This was probably because the reproductive phase in November-sown chickpeas was initiated during a more favourable thermal and moisture regime than in the December sowing. This gave a longer crop duration and larger plants. When irrigation was applied from e-m or only until flowering (only in 1998/99 season) it significantly increased TDM production (> 1000 g/m², averaged over the 2 years) by about 87 % over the unirrigated

Table 7. Correlation matrix for yield, yield components and harvest index (HI) of Kabuli chickpea grown in New Zealand, during 1998–2000

	Seed yield	Total DM	HI	Plants/m ²	Pods/plant	Seeds/pod
1998/99						
Total DM	0.50**					
HI	0.69**	−0.21*				
Plants/m ²	−0.05	0.16	−0.21*			
Pods/plant	0.64**	0.31**	0.42**	−0.06		
Seeds/pod	0.43**	0.27**	0.31**	−0.01	0.10	
Mean seed wt.	0.53**	0.10	0.53**	−0.24**	−0.10	0.32**
1999/2000						
Total DM	0.67**					
HI	0.60**	−0.17				
Plants/m ²	0.14	0.02	0.17			
Pods/plant	0.41**	0.61**	−0.04	0.08		
Seeds/pod	0.06	0.13	−0.03	−0.20	−0.05	
Mean seed wt.	−0.17	−0.07	−0.20	−0.13	−0.30*	0.17

* $P < 0.05$, ** $P < 0.01$.

control. In Australia, Thomas & Fukai (1995) also obtained a maximum TDM yield of 1150 g/m² from irrigated chickpea.

In both years, there was a substantial differential effect of irrigation on the proportion of intercepted radiation (F_i) (Fig. 3). This is similar to results for lentil and pinto bean in New Zealand (McKenzie & Hill 1991; Dapaah *et al.* 2000). The higher F_i in fully irrigated (e-m, f-p and p-m) plants was mainly due to their higher GAI and to the timing of canopy closure. This is a major factor in radiation interception, as a larger vegetative frame increases the capture of PAR. The critical GAI of 3.5 is similar to that reported by Muchow (1985) in soybean and Dapaah *et al.* (2000) in pinto bean. The mean extinction coefficient ($-k$) over the 2 years was 0.84 (Fig. 4), indicating a crop with near-horizontal leaves on the top of the canopy. The high $-k$ of the canopy accounted for the lower GAI required to intercept about 95% radiation, as a high $-k$ means lower leaves will receive less solar energy. In a chickpea crop in Australia, Thomas & Fukai (1995) reported a $-k$ value as high as 1.1.

In both years, irrigation at any growth stage increased total intercepted PAR. The highest intercepted PAR for all cultivars was observed when drought stress was completely eliminated by irrigating throughout the season (Table 2). This was probably because the large leaf canopy that developed in the irrigated crop closed early and senesced late, which led to a high interception of PAR. Early sowing had a dominant positive effect on total intercepted PAR, as the irrigation by sowing date and sowing date by cultivar interactions indicated that the response to irrigation depended on the sowing date. The amount of incident solar radiation was different

at all the sowing dates (Anwar *et al.* 2003). This, coupled with variation in canopy characteristics (GAI and GAD), perhaps resulted in differences in total intercepted PAR between irrigation treatments within a sowing date. In Syria, Saxena *et al.* (1990) recorded higher total intercepted PAR in an early-irrigated chickpea crop due to a longer growth period.

Irrigated plots produced more dry matter than unirrigated plots, and this eventually resulted in a higher radiation use efficiency (U) of about 38–40% (Tables 2 and 4). This is similar to the results of Thomas & Fukai (1995) in a well-watered chickpea crop. The U in 1998/99 was 1.24 g DM/MJ intercepted PAR in the November sowing, decreasing to 1.07 in the December sowing. Generally, U will increase from sowing as mean monthly temperatures increase (McKenzie & Hill 1991). This increase in U is usually due to increased photosynthetic rate and increased radiation receipts. Upon reaching a maximum, U will usually remain stable until senescence occurs at physiological maturity.

Seed yield

Seed yield was linearly correlated with GAD (Fig. 2b) but explained proportionately less, about 60–69%, of the variation in seed yield. Dapaah *et al.* (2000) reported that GAD explained a large proportion of the variation ($R^2 = 0.95$) in seed yield of pinto bean. In contrast, Ishag (1973) in field bean reported that there was no relationship between seed yield and GAD. Seed yield was also linearly related to total intercepted PAR ($R^2 = 0.65$) and the slope showed that c. 0.57 g seed/m² was produced from each MJ of absorbed PAR, similar to the results of Husain *et al.* (1988) in irrigated field bean.

Fig. 6. Accumulation of photosynthetically active radiation (PAR) in relation to dry matter production during crop growth up to maximum dry matter stage for Kabuli chickpea (mean across cultivars). (a) 3 Nov 1998/1999 sowing, $Y = 9.58 + 1.24X$, $R^2 = 0.97$. (b) 7 Dec 1998/1999 sowing, $Y = -23.06 + 1.07X$, $R^2 = 0.98$. (c) 18 Oct 1999/2000 sowing, $Y = -28.04 + 0.95X$, $R^2 = 0.85$. (d) 22 Nov 1999/2000 sowing, $Y = -37.45 + 1.04X$, $R^2 = 0.92$.

In 1998/99 more than 410 g/m² of seed was produced by sowing in November and applying full irrigation (197 and 231 mm) from e-m and until flowering. This was twice the yield of the December sowing. Cultivar Sanford produced 14 and 16% more seed than cv. Dwelley and cv. B-90, respectively. In Poland, Poniedzialek *et al.* (1999) also recorded a yield reduction in cv. Sanford when sowing was de-

layed from 17 April to 14 May. In 1999/2000 in the present study, seed yield was affected by the interaction of irrigation by sowing date by cultivar. Under full irrigation (105 and 109 mm), seed yield of both cultivars at both sowing dates ranged from 450 to 520 g/m². In the present work, the indeterminate chickpea responded to soil moisture and there was prolonged flowering and podding, which eventually

Fig. 7. (a) The relationship between intercepted photosynthetically active radiation (PAR) and seed yield and (b) relationship between predicted and observed seed yield of Kabuli chickpea in New Zealand during 1998–2000 seasons (mean across years, sowing date and cultivars).

increased grain yield (Malhotra *et al.* 1997). The highest yields for both cultivar and sowing date were achieved when drought stress was completely eliminated by irrigating throughout the growing season (Fig. 5). October-sown cv. Sanford was more susceptible to drought, which gave a very low unirrigated yield, compared with the November sowing.

These irrigation results have important implications for chickpea growers worldwide. Many reports have suggested that chickpeas respond the most when irrigated at flowering (Sharma *et al.* 1994; Maliwal *et al.* 1999) or at pod initiation (Reddy & Ahlawat 1998). The present results, however, show clearly that water stress at any stage can reduce seed yield, and that no stage is any more sensitive to water stress than another. Additionally, the reduction in yield is due to physiological factors, primarily reduced absorbed PAR and reduced U .

Harvest index

The HI values were highly variable in 1998/99 but were relatively stable in 1999/2000 (mean 0.46). The large HI value of 0.74 might have been an artefact caused by the time of harvest, where leaf material that was lost prior to final harvest, while the plants were drying, was not recovered. However, these results compare well with HI values observed elsewhere (Saxena *et al.* 1990; Leport *et al.* 1999). Date of sowing regulates the amounts of solar energy received (radiation and degree days), rainfall and the amount of stored soil water (Singh *et al.* 1997). Table 2 shows

the negative effect of full irrigation on HI in the December sowing with a high population compared with November sowing. Sowing in November allows the crop to mature before it experiences significant water stress and, with a higher seed yield, resulted in an increased HI in all the cultivars. Harvest index responses to irrigation treatments were similar among the cultivars. Irrigation tended to increase HI during 1999/2000 (Table 4). During this season, the soil profile for the October and November sowings had stored enough water (Anwar *et al.* 2000) and this, combined with a uniform rainfall distribution, supported normal growth and the irrigation eliminated any water stress. Consequently, this pattern of water availability provided the longest reproductive phase with a larger photosynthetic green surface and reproductive storage capacity to give a higher allocation of dry matter to seed. Concurrently, at both the sowing dates the HI was stable and it was significantly higher under irrigation (f–p). Thomas & Fukai (1995) recorded a maximum HI of 0.43 in a well-watered chickpea trial over stressed plants (0.19).

Yield components

In the present study, fully irrigated chickpea always produced the most pods/plant, and this depended on the sowing date by cultivar interaction. Overall, the increase in pods/plant was probably due to the greater availability of reproductive sinks and the greater radiation use efficiency in the fully irrigated plants.

The high number of pods/plant may be related to the lower density in the November-sown chickpea (Table 5). The number of seeds/pod tended to be stable at about 1, similar to the value reported by Verghis *et al.* (1999). However, there is often significant variation in the number of seeds/pod as some seeds fail to develop after pod set (Goldsworthy 1984). As expected, cultivar had the most significant effect on the number of seeds/pod. The response to sowing date and irrigation level was inconsistent. In Syria, Keatinge & Cooper (1983) found a significant increase in the proportion of empty pods in spring-sown chickpea grown on dry sites compared with winter-sown plants on the same sites. In the present work, cv. B-90 produced only 0.86 seeds/pod when sowing was delayed to December in 1998/99. This was probably due to increased competition for assimilate from the high vegetative growth in the December sowing. This may result in a reduction in seed number per pod caused by an increase in the number of seeds that fail to fill, commonly called seed abortion (Dracup & Kirby 1996). In 1999/2000, cv. B-90 produced 1.13 seeds per pod with full irrigation (e-m) when sown in October and from full irrigation (f-p) in the November sowing. The irrigation probably allowed the plants to fulfil their full genetic potential.

Mean seed weight depended on sowing date and cultivar, as both factors interacted significantly (Tables 5 and 6) with irrigation levels. The 19 and 57% reduction in mean seed weight with full irrigation (e-m) compared with no irrigation in both years is similar to the results of Saxena *et al.* (1990). High dry matter production from the fully irrigated chickpea plants probably increased vegetative demand for assimilates. This increased respiratory demand, which eventually gave lighter seeds. Palta & Plaut (1999) reported a similar trend in lupin (*Lupinus angustifolius*). However, the decrease in mean seed weight in the present study was compensated for by a marked increase in the number of pods/plant. This gave a higher seed yield under full irrigation. Yield compensation due to plasticity of yield components is a common feature in grain legumes (Dapaah *et al.* 2000). Partitioning the correlation coefficients of yield

components into negative and positive effects further helps to understand the associations involved (Williams *et al.* 1980). The results (Table 7) show that the positive yield response to irrigation of chickpeas was due to the significant positive correlation of TDM, HI and pods/plant with seed yield and was stable during both years. These results suggest either that the processes that limit vegetative growth under drought also reduce seed development, or that decreases in vegetative growth under soil water deficit directly limit plant reproductive development. The present study confirms recent observations that chickpea seed yield is a function of vegetative growth, HI and the number of pods/plant (Jettner *et al.* 1999). Chickpea seed yield potential depends on inherent plant characters such as reproductive characteristics, biomass production and assimilate partitioning. The realization of that yield potential depends on the interaction of these characters with environmental factors such as water supply (Singh 1991). The results of the present experiment suggest that when water is in short supply the seed yield of Kabuli chickpea can be substantially increased by fully irrigating at any stage of crop development up to the pod stage. The overall yield response under the different irrigation levels was the net effect of variations of intercepted radiation, *U* and HI.

Using these variables, the seed yield of Kabuli chickpea can be accurately predicted (Fig. 7*b*) in Canterbury's subhumid temperate environment. Any reduction in intercepted radiation due to water stress during the vegetative stage can be compensated for by irrigation during subsequent growth stages that increase the *U* and the HI. These findings can form the basis of irrigation management to maximize yields of Kabuli chickpea, and provide basic data for the development of a fully mechanistic computer simulation model of chickpea growth and development similar to that developed for lentils by McKenzie *et al.* (1994).

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