

Water-use efficiency and the effect of water deficits on crop growth and yield of Kabuli chickpea (*Cicer arietinum* L.) in a cool-temperate subhumid climate

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SUMMARY

The present study was conducted from 1998 to 2000, to evaluate seasonal water use and soil-water extraction by Kabuli chickpea (*Cicer arietinum* L.). The response of three cultivars to eight irrigation treatments in 1998/99 and four irrigation treatments in 1999/2000 at different growth stages was studied on a Wakanui silt loam soil in Canterbury, New Zealand. Evapotranspiration was measured with a neutron moisture meter and water use efficiency (WUE) was examined at crop maturity. Water use was about 426 mm for the fully irrigated treatment and at least 175 mm for the non-irrigated plants. There was a significant correlation ($P < 0.001$) between water use and biomass yield ($R^2 = 0.80$) and water use and seed yield ($R^2 = 0.75$). There were also highly significant ($P < 0.001$) interacting effects of irrigation, sowing date and cultivar on WUE and the trend was similar to that for seed yield. The estimated WUE ranged from 22–29 kg DM/ha per mm and 10–13 kg seed yield/ha per mm water use.

The three chickpea cultivars were capable of drawing water from depths greater than 60 cm. However, most of the water use (0.49–0.93 mm/10 cm soil layer per day) came from the top 0–30 cm, where most of the active roots were concentrated. The study has shown that using actual evapotranspiration and water-use efficiency, the biomass yield and seed yield of Kabuli chickpeas can be accurately predicted in Canterbury. Soil water shortage has been identified as a major constraint to increasing chickpea production. Drought was quantified using the concept of maximum potential soil moisture deficit ($D_{p_{max}}$) calculated from climate data. Drought responses of yield, phenology, radiation use efficiency and yield components were determined, and were highly correlated with $D_{p_{max}}$. The maximum potential soil moisture deficit increased from about 62 mm (irrigated throughout) to about 358 mm (dryland plots). Chickpea yield, intercepted radiation and the number of pods per plant decreased linearly as the $D_{p_{max}}$ increased. Penman's irrigation model accurately described the response of yield to drought. The limiting deficit for this type of soil was *c.* 165 and 84 mm for the November and December sowings in 1998/99 and 170 mm in 1999/2000. Beyond these limiting deficits, yield declined linearly with maximum potential soil moisture deficits of up to 358 mm. There was little evidence to support the idea of a moisture sensitive period in these Kabuli chickpea cultivars. Yield was increased by irrigating at any stage of crop development, provided that the water was needed as determined by the potential soil moisture deficit and sowing early in the season.

INTRODUCTION

Most previous studies of chickpea (*Cicer arietinum* L.) water use have been undertaken in the Equatorial tropics and in Mediterranean semi-arid regions

(Brown *et al.* 1989; Dalal *et al.* 1997; Prasad *et al.* 1999). This is the first major study conducted in Canterbury, a subhumid temperate environment (43°38S, 172°30E). Low productivity in chickpea is accompanied by low evapotranspirational water-use efficiency (WUE), which is brought about by a combination of decreased biomass (leaf area index) and, for many environmental stresses, changes in WUE (Zhang *et al.* 2000). To achieve maximum growth and yield in chickpea requires an understanding of

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the detailed pattern of water use in relation to crop phenology and assimilate partitioning into the seeds.

The amount of soil water available for crop use depends on rooting volume and the amount of available water held in the soil for plant growth. Studies on chickpea water use are location specific. However, a crop uses between 100 and 450 mm of water to produce grain yields of 900–3000 kg/ha (Dalal *et al.* 1997; Prasad *et al.* 1999). The physiological basis of yield determination of chickpea can be considered by expressing yield (Y) in terms of the following components, when other factors are non-limiting:

$$Y = Et \times WUE \quad (1)$$

where Et is the amount of water transpired (evapotranspiration) and WUE is defined as the quantity of yield (biomass and seed yield) produced per unit of water transpired and Y increases with increasing WUE for a constant Et . Thus, WUE is particularly important in those circumstances where growth ceases as a result of depletion of a finite and limiting water source.

The detrimental effects of drought can be modified to some extent through management options such as irrigation (Soltani *et al.* 1999) and by sowing early in the season (Singh *et al.* 1997). However, in the literature there are differing views on the effect of irrigation timing coinciding with moisture-sensitive periods in chickpea. Some authors (Jadhav *et al.* 1997) suggest that chickpea are more sensitive to drought during flowering. However, others (Ravi *et al.* 1998; Reddy & Ahlawat 1998) suggested seed filling was the critical time for irrigation. In contrast, Ramakrishna & Reddy (1993) demonstrated a seed yield reduction of more than 50% in chickpea when they were irrigated due to excess vegetative growth, which leads to lodging. Nevertheless, the identification of genuine moisture-sensitive periods could have clear benefits for irrigation management. Yield responses to water deficit can be quantified by using maximum potential soil moisture deficit (Dp_{max}) as a measure of stress (French & Legg 1979). Responses to the Dp_{max} are given in terms of reductions in yield below the more stable fully irrigated yield. This also enables a calculation of limiting deficit beyond which yield is reduced, and the reduction in yield per unit of potential deficit when the limiting deficit is exceeded.

Therefore, the main objective of the present experiment was to examine the response of yield shown in Eqn 1 under different irrigation regimes and thus determine the physiological basis of yield variation. Secondary objectives were to investigate the water extraction pattern, the influence of drought and to determine whether moisture-sensitive periods exist for this crop.

MATERIALS AND METHODS

The experimental design, site and husbandry methods are fully described in the companion papers (Anwar *et al.* 2003a, b). However, sampling and measurement details specific to this paper will be described. Briefly, two experiments were carried out at Lincoln University, New Zealand, with a split-split plot randomized complete block design with eight irrigation levels during the 1998/99 season and four irrigation levels during 1999/2000 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.

Soil moisture content was measured weekly using the Time Domain Reflectometry (TDR) Trase system 1 Model 6050X1 for the top 0–30 cm of the soil profile. Moisture in the remaining soil depth was measured with a Neutron probe (NMM) model 3300 at 10 cm intervals to a depth of 100 cm in all 96 plots in 1998/99 and to 110 cm in all 48 plots in 1999/2000. Water use was assumed to be equivalent to the evapotranspiration (Et) between sowing and physiological maturity, which was calculated using the soil water balance approach:

$$Et = (P + I) - SWC - Ro - D \quad (2)$$

where Et = evapotranspiration, P = rainfall (mm), I = irrigation (mm), SWC = change in soil water content from time 1 to time 2 at 0–100 cm in 1998/99 and 0–110 cm depth in 1999/2000, Ro = runoff (mm) and D = drainage (mm).

In this experiment Ro was assumed to be zero, as the experimental site was level, and irrigation was applied by T-tape at a rate that was well below soil infiltration capacity. Drainage was also assumed to be zero below 100–110 cm soil depth, as the volumetric water content of the soil did not exceed field capacity at any time.

The water-use efficiency (WUE) was calculated as the total dry matter (TDM) production and final seed yield of the treatment divided by the total quantity of water used over that period and analysed using a model in which dry matter production is related linearly to the ratio of transpiration (E_{tr}) and the daytime vapour pressure deficit (Bierhuizen & Slatyer 1965):

$$\begin{aligned} \text{Transpiration efficiency} &= C/E_{tr} \\ &= k/(e^* - e) \end{aligned} \quad (3)$$

where C is the daily growth rate, k is an empirical constant with the dimensions of pressure and $(e^* - e)$ is the daytime vapour pressure deficit. Tanner & Sinclair (1983) used theoretical arguments and published values of C , E_{tr} and $(e^* - e)$ for several crops to estimate values of k . They concluded that k is a stable

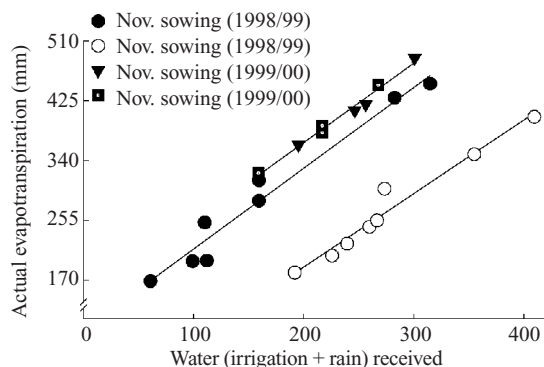


Fig. 1. Actual water use of Kabuli chickpea as a linear function of water received in Canterbury, New Zealand during 1998/99 and 1999/2000 seasons. $Y_{\text{Nov}(1998/99)} = 100.1 + 1.15 X$, $R^2 = 0.96$. $Y_{\text{Dec}(1998/99)} = -19.4 + 1.04 X$, $R^2 = 0.96$. $Y_{(1999/2000)} = 140.4 + 1.13 X$, $R^2 = 0.98$.

parameter, which characterizes the transpiration efficiency of a crop.

Daily daytime vapour pressure deficit data were collected from the records of the Broadfield Meteorological Station at Lincoln University.

Effective rooting depth (ERD) was derived from the neutron probe data. On a given date, ERD was defined as the depth at which soil water content was not significantly different from the measurement made on the previous date, during a period of transpiration and in the absence of water supply (Silim & Saxena 1993). Total soil water content was calculated by summing the water content of each slice in the soil profile. The topsoil layer was 30 cm while all other layers were 10 cm thick. Water extraction patterns of all treatments were checked to assess the maximum depth from which water was extracted. Cumulative water use per soil layer was calculated by partitioning the drainage to the next soil layer. Regressions of the cumulative water use over time for each soil layer were taken. The mean slopes of the regressions of each treatment (equivalent to water use per day) were then analysed by ANOVA, and the LSD at the 5% level of significance was calculated for each layer down to 100 cm in 1998/99 and to 110 cm in 1999/2000.

A simple index of potential soil water deficit (D_p) was calculated as the accumulated difference between the Penman evapotranspiration and irrigation and rainfall amounts for each treatment, as described by Jamieson *et al.* (1995). The maximum potential soil moisture deficits ($D_{p_{\text{max}}}$) for any treatment was taken as the maximum value of D_p attained during growth. This index gives a measurement of the maximum water stress experienced by the crop (Penman 1971; French & Legg 1979).

All data were analysed with a standard analysis of variance using GENSTAT for Windows 3.2 (Laws

Table 1. The mean effects of irrigation, sowing date and cultivar on water use (WU) during the pre- and post-anthesis phases of growth and on maximum potential soil moisture deficits ($D_{p_{\text{max}}}$) at physiological maturity of Kabuli chickpea in New Zealand during 1998/99 season

Irrigation treatments†	Pre-anthesis WU (mm)	Post-anthesis WU (mm)	$D_{p_{\text{max}}}$ (mm)
Nil	71	104	311
Full (e-m)	255	171	102
Full (e-f)	231	158	136
Half (e-f)	130	176	226
Full (f-p)	77	188	232
Half (f-p)	75	153	274
Full (p-m)	63	163	265
Half (p-m)	75	134	285
Mean	122	156	229
S.E. (D.F. = 7)	6.1	12.8	0.1
<i>P</i>	0.001	0.05	0.001
Sowing date			
November 3	144	142	269
December 7	100	169	189
S.E. (D.F. = 8)	3.6	5.76	0.1
<i>P</i>	0.001	0.05	0.001
Cultivar			
Sanford	123	154	229
Dwellely	120	158	229
B-90	123	156	229
S.E. (D.F. = 32)	1.9	2.3	0.1
<i>P</i>	ns	ns	ns
CV (%)	8.9	8.5	0.2

† Irrigation treatments: 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; ns = nonsignificant.

Agricultural Trust, Rothamsted Experimental Station).

RESULTS

Seasonal evapotranspiration

Full details of the climate during the two seasons can be found in Anwar *et al.* (2003a). The actual evapotranspiration of Kabuli chickpea was a linear function of total water received (irrigation plus rain) in both years (Fig. 1). Irrigation applied at different phenological stages significantly affected the pre- and post-anthesis phases and total crop water use, which depend on the amount of water applied and the time of irrigation (Tables 1 and 2). In the 1998/99 season, the mean post-anthesis water use (averaged over all irrigation treatments) was about 28% higher relative to pre-anthesis water use (Table 1). However, under

Table 2. The effects of irrigation, sowing date and cultivar on total water use, water use efficiency for dry matter (WUE·DM² kg/ha per mm of water use) and on maximum potential soil moisture deficits (Dp_{max}) at physiological maturity of Kabuli chickpea during 1999/2000

Irrigation†	Total water use (mm)	WUE DM	Dp _{max} (mm)
Nil	342	19.8	326
Full (e-m)	466	23.4	170
Full (f-p)	400	21.9	267
Full (p-m)	400	22.7	272
Mean	402	21.9	258
S.E. (D.F. = 6)	4.2	0.52	0.1
P	0.001	0.05	0.001
Sowing date (SD)			
October 18	420	20.9	249
November 22	385	22.9	268
S.E. (D.F. = 16)	3.2	0.78	0.1
P	0.001	ns	0.001
Cultivar (Cv)			
Sanford	401	22.3	259
B-90	403	21.6	258
S.E. (D.F. = 16)	2.2	0.78	0.1
P	ns	ns	ns
CV (%)	2.7	17.4	0.1

† Irrigation treatments as in Table 1.

full irrigation from emergence to maturity (e-m) and emergence to flowering (e-f), the pre-anthesis water use was about 46-49% more than the post-anthesis water use. Total crop water use varied from 157-426 mm and was significantly affected by the irrigation by sowing date interaction (Fig. 2). The evapotranspiration from e-m was significantly higher ($P < 0.001$) for the fully irrigated treatments and was about 90% greater than in rainfed and late irrigated crops. Kabuli chickpea under full and half irrigation used c. 226 and 209 mm of water, respectively, when irrigation was applied late (pod fill to physiological maturity; p-m). November-sown Kabuli chickpea used 169-450 mm water, which was about 4-23% more than the December-sown fully irrigated (e-m and e-f) crops. However, in rainfed and p-m irrigated plots the December-sown crop used more water (about 7-29%) relative to the November sown crop (Fig. 2).

In 1999/2000, post-anthesis water use depended on the significant interactions ($P < 0.01$) of sowing date by cultivar and irrigation by sowing date on post-anthesis water use (Table 3). Generally, irrigated crops (e-m) sown in October used more water at post-anthesis than the same crops sown in November. Averaged over irrigation treatment, the mean post-anthesis water use (250 mm) was 64% greater than pre-anthesis water use. The total crop water use varied 342-466 mm, and was significantly ($P < 0.001$) affected by both irrigation and sowing date (Table 2).

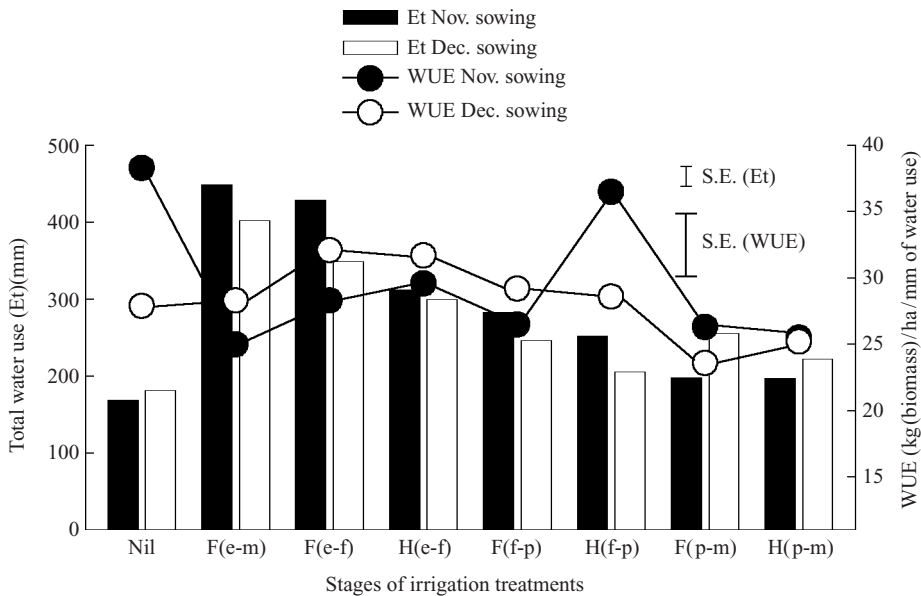


Fig. 2. The irrigation by sowing date interaction for total water use and water-use efficiency (WUE) of Kabuli chickpea in New Zealand, during 1998/99 season. Nil: rainfed; F: full irrigation to replace water lost from evapotranspiration; H: irrigated with half the amount of full; e-m: emergence to maturity; e-f: emergence to flowering; f-p: flower to podding; p-m: pod to maturity.

Table 3. The sowing date by cultivar interaction for pre and post-anthesis water use (WU) and irrigation by sowing date interaction for post-anthesis WU (mm) of chickpea during 1999/2000

Sowing date	Cultivars				Irrigation treatments*	Sowing date	
	Pre-anthesis WU		Post-anthesis WU			Post-anthesis WU	
	Sanford	B-90	Sanford	B-90		18 Oct	22 Nov
18 Oct	160	173	259	248	Nil	207	206
22 Nov	142	134	243	250	Full (e-m)	295	258
					Full (f-p)	261	250
					Full (p-m)	253	272
S.E. (D.F. = 16)	6.5		3.8			6.6	

* Irrigation treatments as in Table 1.

The evapotranspiration from e-m was significantly higher ($P < 0.001$) for the fully irrigated treatments and was about 17–36% greater than in the nil and late irrigated crops. October-sown chickpea used 420 mm of water, which was only 9% more than the November-sown crops.

Accumulated water use in relation to yield

There were strong linear relationships between final biomass (TDM) and total water use in both sowing dates in 1998/99 with an R^2 of 0.84 and 0.92 respectively (Fig. 3a). November and December-sown chickpea crops produced 2.31 and 3.28 g/m² TDM respectively for each mm of water used. Parallel linear relationships ($R^2 = 0.80$, $P < 0.001$) were also observed in the 1999/2000 season (Fig. 3c). In addition, chickpea seed yield in the November sowing (1998/99) was linearly correlated with total water use ($R^2 = 0.75$, $P < 0.01$) but the seed yield from December-sown chickpea crop showed a poor correlation with total water use (Fig. 3b). However, in 1999/2000 for all treatments, both October- and November-sown chickpea showed a highly significant ($R^2 = 0.78$, $P < 0.001$) linear relationship between seed yield and total water use (Fig. 3d).

Water use efficiency

In 1998/99, the mean water use efficiency (WUE) for all treatments was 28.9 kg DM/ha per mm of water use and 12.7 kg seed/ha per mm of water use. There was no significant difference in WUE between the different irrigation regimes but WUE for DM production depended on the interaction between irrigation level and sowing date (Fig. 2). Crops that received late or no irrigation in the November sowing had the highest WUE (c. 38.3 kg DM/ha per mm

of water use). The analyses with the transpiration efficiency model showed a stable relationship between DM production and water use (Fig. 4). The mean value of k (Eqn 3) was 0.041 and irrigation had no effect on k but there were statistically significant differences among sowing dates (1998–99) (Fig. 4). There were also highly significant effects of both sowing date ($P < 0.001$) and cultivar ($P < 0.01$) and their interaction ($P < 0.01$) on WUE for seed production (Table 4). The November sowing produced 16.5 kg seed/ha per mm of water used. This was about 80% higher than the December-sown chickpea crop. In the December sowing cv. Sanford had the highest WUE, which was 27% and 71% higher than in cvs Dwelley and B-90. In 1999/2000, there was also a highly significant ($P < 0.001$) interaction between irrigation, sowing date and cultivar on the WUE for seed (Table 4). At both sowing dates, both cultivars made more efficient use of the applied water (Full (e-m) and rainfall) in the production of seed and this was reflected in a greater WUE. The relationship between WUE and irrigation supply (Table 4) shows that per unit of water supplied, the WUE for seed was at similar rates in both cultivars, though the rate was greater in cv. Sanford than in cv. B-90. Cultivar Sanford had the greatest WUE in fully irrigated (e-m) plots but least in the nil irrigated plots. In the November sowing cv. Sanford had a higher WUE for seed in nil irrigated plots than cv. B-90.

Water extraction pattern

Different irrigation regimes, sowing dates and cultivars did not affect the final depth of water extraction, or the extent to which each soil layer had been depleted by maturity (Fig. 5). It is also apparent that the chickpea crop was able to extract soil water to depths of 80 cm. Beyond 80 cm there was very little or no depletion of soil water content over time. Soil water

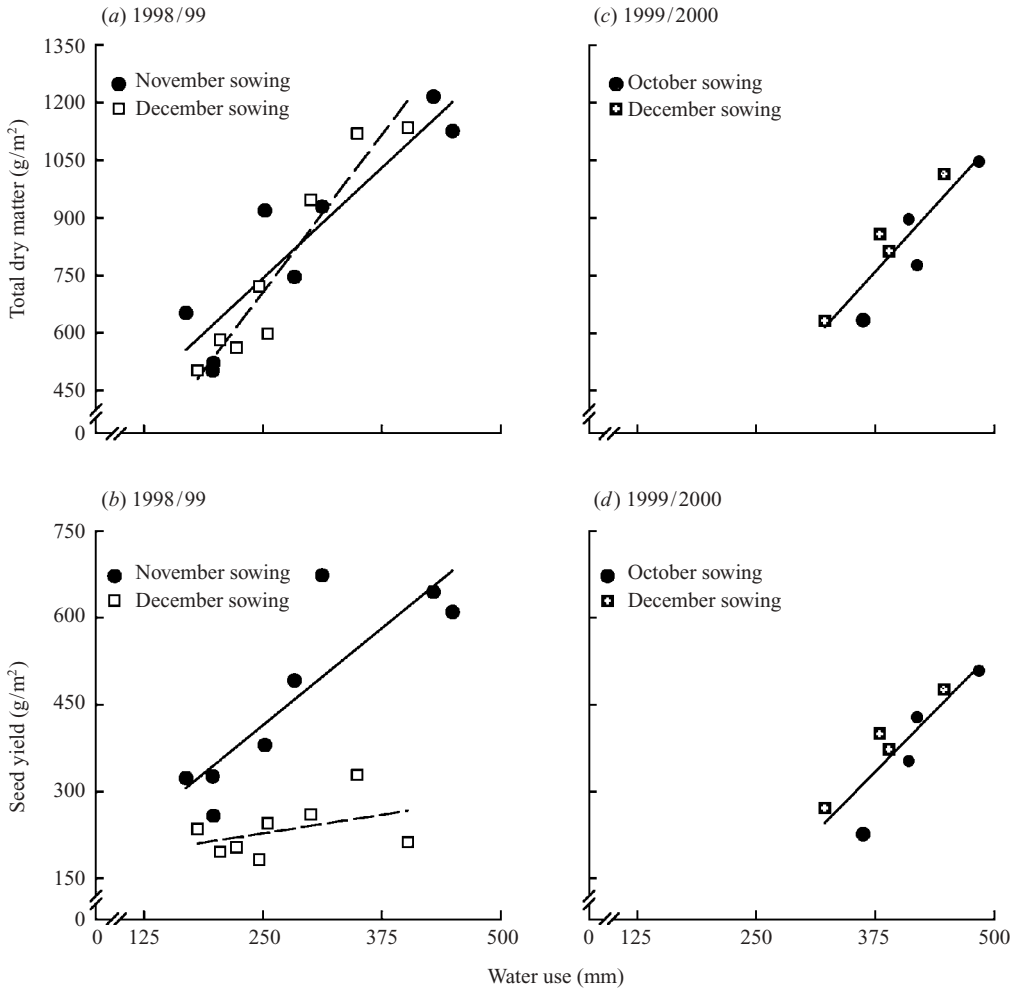


Fig. 3. Relationship between seasonal actual water use and total dry matter (a, c); seed yield (b, d) for Kabuli chickpeas in Canterbury, New Zealand during 1998/99 and 1999/2000 seasons. The slope of the lines is the water use efficiency. (a) $Y_{\text{November}}(\text{dry matter}) = 166.7 + 2.31 X$, $R^2 = 0.84$. $Y_{\text{December}}(\text{dry matter}) = -115.3 + 3.28 X$, $R^2 = 0.92$. (b) $Y_{\text{November}}(\text{seed yield}) = 80.4 + 1.34 X$, $R^2 = 0.75$. $Y_{\text{December}}(\text{seed yield}) = 163.1 + 0.26 X$, $R^2 = 0.17$. (c) $Y(\text{dry matter}) = -262.2 + 2.72 X$, $R^2 = 0.80$. (d) $Y(\text{seed yield}) = 292.0 + 1.67 X$, $R^2 = 0.78$.

extraction over time did, however, differ between sowing dates and seasons at different phenological stages. In 1998/99, chickpea plots sown in November had an initial water content (maximum at the time of emergence) of about 24 mm per 10 cm soil layer down to 30 cm soil depth, and about 29–31 mm per 10 cm soil layer down to 100 cm deep (Fig. 5a, b). Correspondingly, in December-sown plots, the maximum water content was about 16 mm per 10 cm soil layer to 30 cm soil depth and about 25–31 mm per 10 cm soil layer down to 100 cm. The final soil water contents (nearing harvest) over time were highly variable among irrigation treatments and at different depths down to 80 cm deep.

In both the October and November sowings in 1999/2000, the initial water content (Max) was c. 29 and 24 mm per 10 cm soil layer to 30 cm soil depth and about 32–35 mm per 10 cm soil layer down to 110 cm (Fig. 5c, d). In the October sowing the minimum or final soil water content (Min) in the top 0–30 cm of the soil profile was 7 mm per 10 cm soil layer down to 30 cm, at 90% physiological maturity and 15 mm per 10 cm soil layer down to 70 cm. Because of rainfall in the week after 90% physiological maturity (132 days after emergence) the soil water content of the top 0–30 cm was 16 mm per 10 cm soil layer. In the November sowing, Min in the top 0–30 cm soil profile was 6.5 mm per 10 cm soil layer

Table 4. The three-way interaction of irrigation, sowing date and cultivar during 1999/2000 and sowing date by cultivar interaction during 1998/99 in water-use efficiency (WUE) for seed yield of Kabuli chickpea in New Zealand

Irrigation treatments*	WUE (kg seed/ha per mm of water use)						
	Sowing date (1999/2000)				Sowing date (1998/1999)		
	18 Oct	22 Nov	18 Oct	22 Nov	Cultivar	3 Nov	7 Dec
	Sanford	B-90	Sanford	B-90			
Nil	5.8	7.8	10.3	7.7	Sanford	16.9	11.5
Full (e-m)	11.4	10.7	11.7	10.8	Dwellely	15.5	9.0
Full (f-p)	11.3	10.1	11.3	11.4	B-90	16.9	6.7
Full (p-m)	9.5	8.5	10.6	9.9			
S.E. (D.F.)	0.75 (16)						1.21 (32)

* Irrigation treatments as in Table 1.

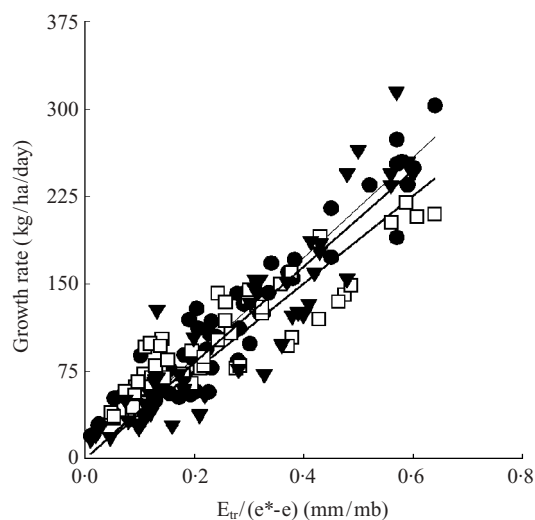


Fig. 4. Relationship between mean daily growth rate and the mean ratio of transpiration to vapour pressure deficit ($E_{tr}/(e^* - e)$) between successive harvests. Slopes of the regression lines, which were forced through the origin, give values for k of 0.041 mb ($R^2=0.85$) for November sowing (1998/99; ●), 0.038 mb ($R^2=0.69$) for December sowing (1998/99; □) and 0.043 mb ($R^2=0.91$) for the season 1999/2000 (▼).

and soil water depletion below 30 cm depth was similar to the October sowing. Rapid depletion of soil water in the 0–30 cm soil profile layer indicated the presence of more roots ($Max_{(roots)}$) and gradual depletion, even down to 80 cm, suggests an estimated effective rooting depth (ERD) of c. 80 cm.

Daily water use

The daily water use of chickpea at different depths (Figs 6 and 7) shows that there were significant

differences between the rate of daily water use down to 40 cm soil depth and these depended on the irrigation by sowing date interaction. In 1998/99, fully irrigated November-sown chickpeas used 0.93 mm of water per 10 cm soil layer per day, in the 0–30 cm soil profile. The rainfed crop used about 0.57 mm of water per 10 cm soil layer per day, which was about 11–20% more than the December-sown crops (Fig. 6). Below the 30 cm soil profile daily water use progressively declined but the fully irrigated chickpea crops always used more water. In general, at all depths (down to 80 cm), November-sown chickpeas used more water daily relative to the December-sown crops. From fully irrigated (109 mm irrigation, during 1999/2000 season) plots, the October-sown chickpea used 0.88 mm of water per 10 cm soil layer per day, in the 0–30 cm soil profile. The water use declined to 0.66 mm of water per 10 cm soil layer per day in the nil irrigation plots. Accordingly, daily water use declined from 0.82 mm of water per 10 cm soil layer per day in the November-sown fully irrigated (109 mm) chickpeas to 0.53 mm of water per 10 cm soil layer per day in the unirrigated plots. At the 40 cm depth October-sown plants irrigated from flowering to podset (61 mm) had the highest rate of water extraction at 0.27 mm of water per day. Below 80 cm soil depth there was hardly any water use in all the treatments.

Soil water deficits

In the 1998/99 season, the maximum potential soil moisture deficits (D_{pmax}) varied between 102–311 mm (Table 1) with a mean D_{pmax} of 229 mm. The D_{pmax} for the non-irrigated plots increased steadily throughout the experiment and reached 358 mm in the November sowing, which was a 35% higher D_{pmax} than in the December sowing. In fully

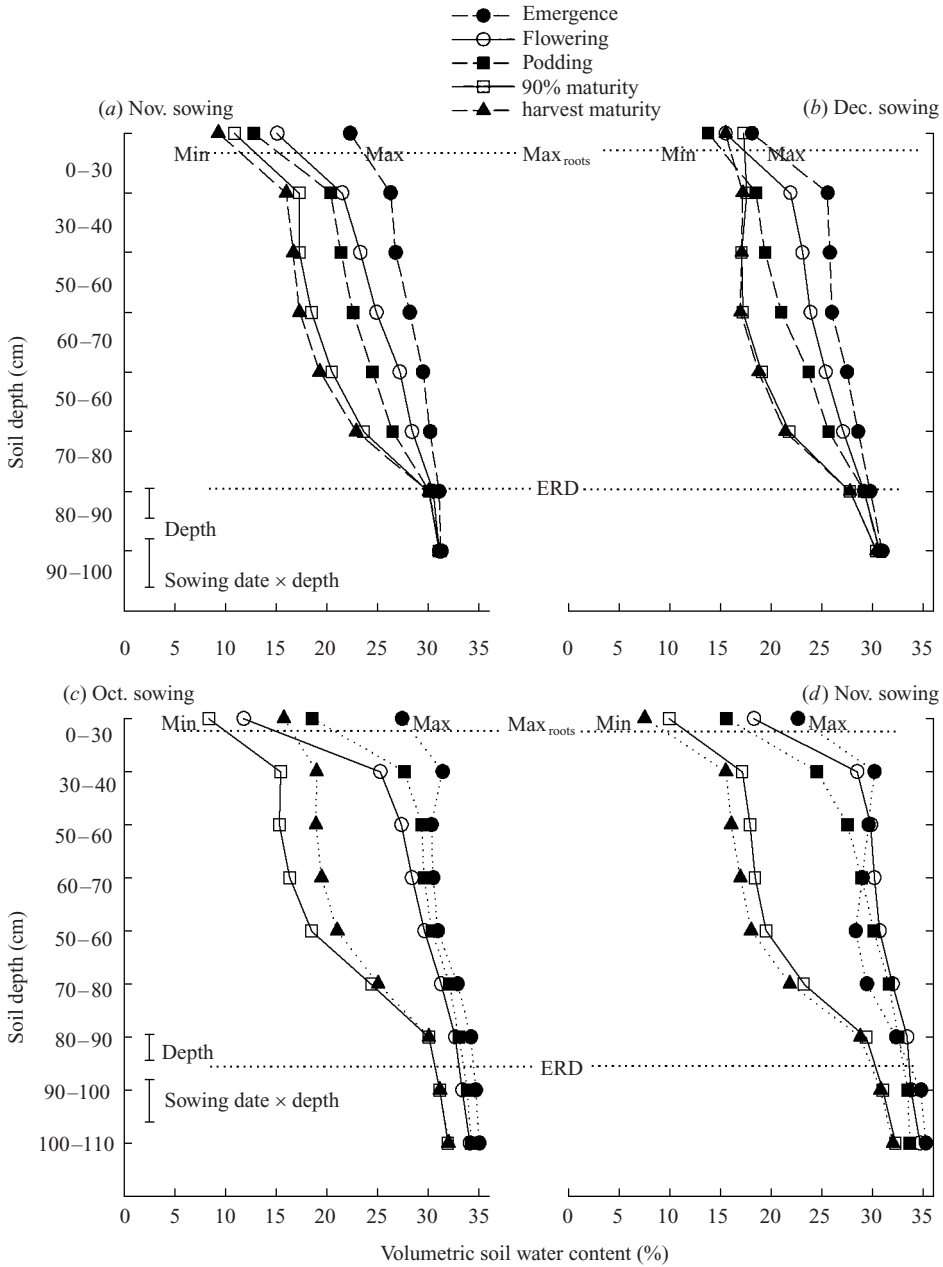


Fig. 5. Variation in volumetric soil water content with depth in Kabuli chickpea plots during 1998/99 (a, b) and 1999/2000 (c, d) seasons. Max: maximum soil water content near field capacity (day of emergence); Min: minimum soil water content at each depth nearing harvest. Horizontal dotted lines show the estimated effective rooting depth (ERD) and maximum ERD value (Max_{roots}). Each data point is the mean of two replicates. Bars indicate L.S.D. ($P < 0.01$).

irrigated plots the $D_{p_{max}}$ reached a maximum of 142 and 62 mm for the November and December sowings, respectively. In both sowings the late irrigation treatments attained similar $D_{p_{max}}$ values

(c. 257–340 mm for the November and 207–224 mm for the December sowing).

In 1999/2000, unirrigated chickpea plots recorded significantly ($P < 0.001$) higher $D_{p_{max}}$ values than the

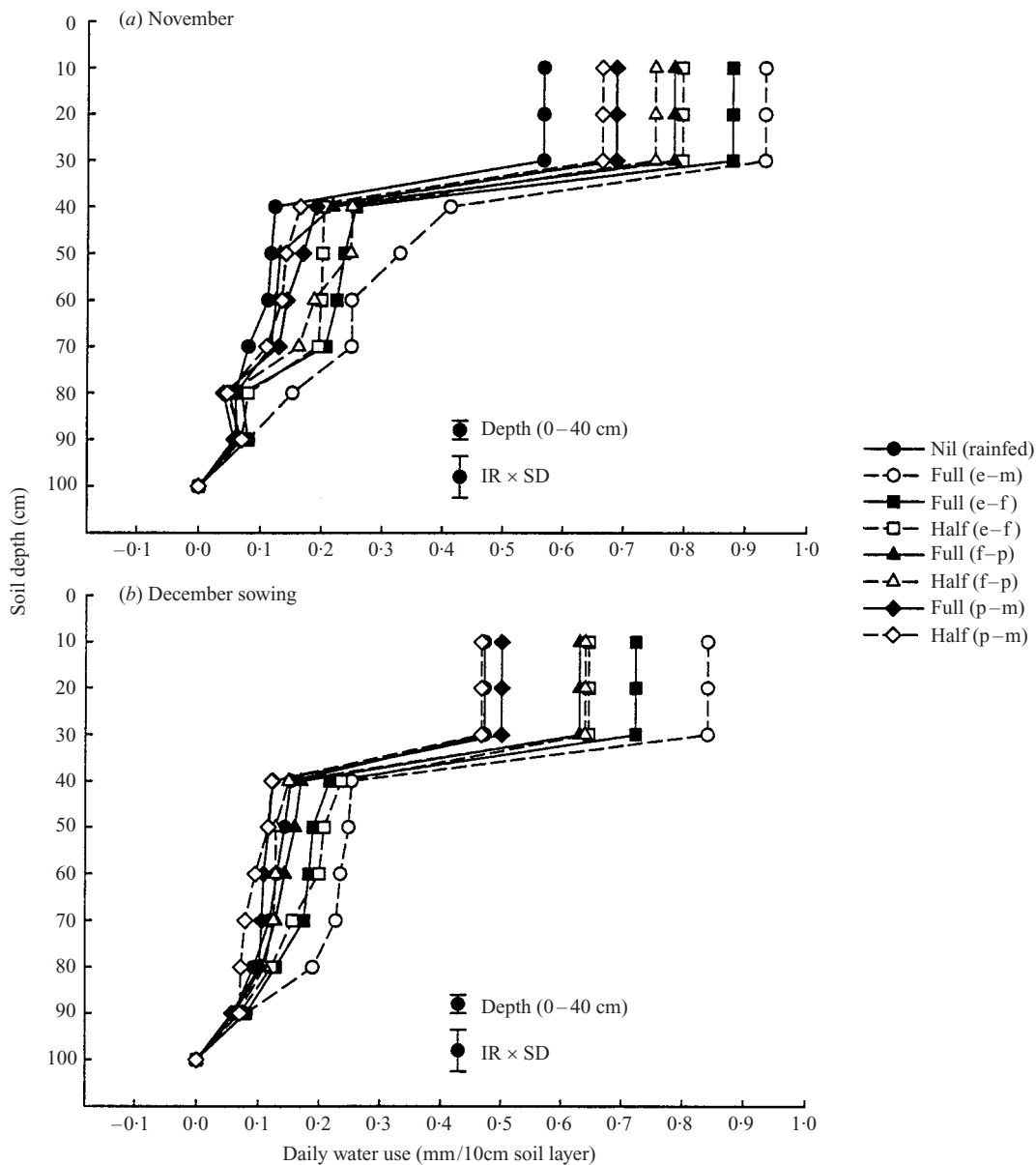


Fig. 6. Daily water use per depth of Kabuli chickpea under eight irrigation treatments (listed under Fig. 2) in the 1998/99 season. Bars indicate L.S.D. ($P < 0.01$) for main effect of irrigation (IR) and sowing date (SD).

full and late irrigated plots (Table 2). There were significant Dp_{max} differences between sowing dates. The November-sown plots recorded Dp_{max} values about 8% higher than the October-sown plots. The minimum Dp_{max} (170 mm) was recorded in fully irrigated (e-m) plots. The soil moisture deficits (Dp_{max}) for the rainfed treatment increased steadily throughout the experiment, and attained a maximum value of 315 and 337 mm in the October and November sowings,

respectively. In the October-sown, fully irrigated treatment, the Dp_{max} increased linearly to 72 days after sowing (DAS) and then decreased to 53 mm and again maintained a maximum of 163 mm (Dp_{max}). This was about 9% less than in the November sowing. In both sowings, the fully irrigated (flower to pod [f-p] and p-m) treatments attained a similar Dp_{max} (254-278 mm), although the timing of the maximum differed markedly.

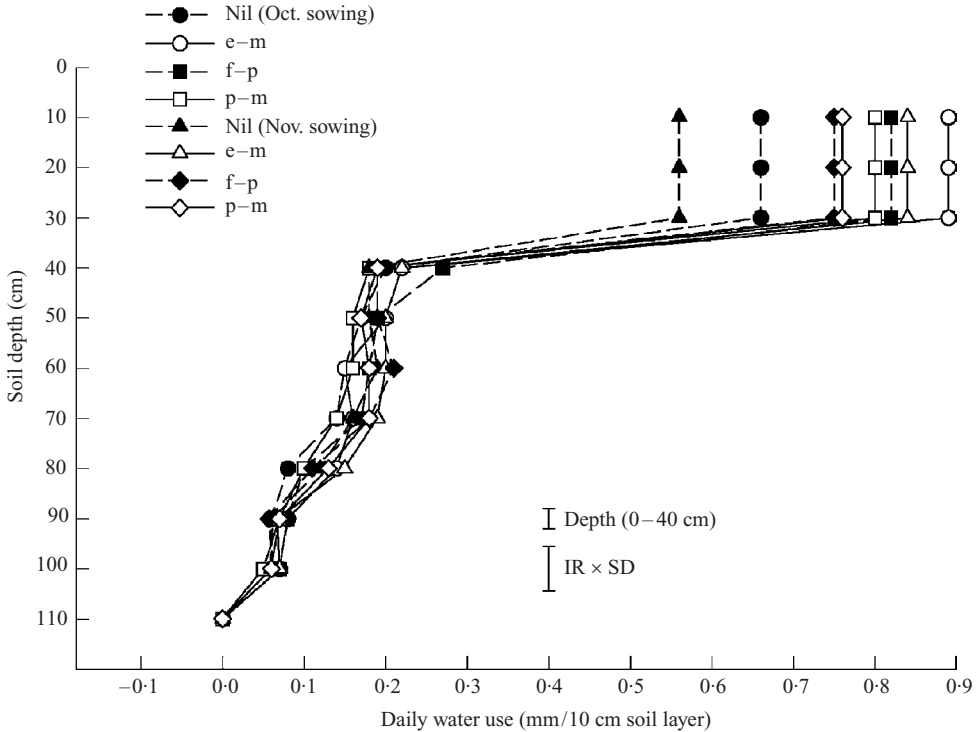


Fig. 7. Daily water use per depth of Kabuli chickpea under four irrigation treatments (listed under Fig. 2) in the 1999/2000 season. Bars indicate L.S.D. ($P < 0.05$) for main effect of irrigation (IR) and sowing date (SD).

Yield response to water deficit

The maximum TDM and seed yield achieved under different irrigation regimes could be related empirically to the $D_{p_{max}}$ experienced (Penman 1971; French & Legg 1979). Both TDM production and seed yield decreased linearly as $D_{p_{max}}$ increased above the limiting deficits of 142 and 62 mm in the November and December sowing respectively (Fig. 8). In the 1998/99 season, TDM differed significantly among the different estimated levels of $D_{p_{max}}$ ($P < 0.01$) and sowing dates ($P < 0.05$). As $D_{p_{max}}$ increased from 142 to 358 mm the TDM decreased from 1126 to 652 g/m² in the November-sown crops compared to 1135 to 503 g/m² TDM in the December with 62 to 264 mm $D_{p_{max}}$ (Fig. 8a). From the significant ($P < 0.01$; $R^2 \geq 0.79$) linear regression, the slope of the lines corresponds to a TDM reduction of 2.89 and 3.49 g/m² for every mm of $D_{p_{max}}$ above 142 and 62 mm in the November and December sowings, respectively. In the November sowing, seed yield also decreased linearly with increased $D_{p_{max}}$ (Fig. 8b). The regression was highly significant ($P < 0.01$) and accounted for 72% of the variation. Over the range of $D_{p_{max}}$ values experienced by the Kabuli chickpea crops (142–358 mm), for each additional

1 mm of deficit, about 1.69 g/m² of seed yield was lost. However, there was no consistent relationship ($R^2 = 0.14$) between seed yield and $D_{p_{max}}$ in the December-sown crops. Similarly in 1999/2000, both TDM and seed yield decreased significantly ($P < 0.001$; $R^2 \geq 0.86$) with increased $D_{p_{max}}$. The linear regression showed that in the October and November sowings, TDM decreased by 2.56 and 2.29 g/m² per mm $D_{p_{max}}$ ($R^2 = 0.86-0.93$; $P < 0.001$) respectively (Fig. 8c). Seed yield showed a similar pattern and yield decreased by 1.77 and 1.22 g/m² per mm $D_{p_{max}}$ ($R^2 = 0.88-0.91$; $P < 0.001$) for the October and November sowing respectively (Table 2 and Fig. 8d).

Solar interception response to water deficit

In both seasons, total intercepted photosynthetically active radiation (PAR) over the life of the crop decreased with increased $D_{p_{max}}$ (Fig. 9). The decrease was strongly linear ($R^2 \geq 0.82$; $P < 0.001$). However, the effect of stress was less severe in the December 1998/99 sown crops, as shown by the lower slope (0.79 MJ/m²). Over the 2 years, as the mean $D_{p_{max}}$ increased from 62 to 358 mm corresponding total PAR decreased from 1039 to 729 MJ/m². The

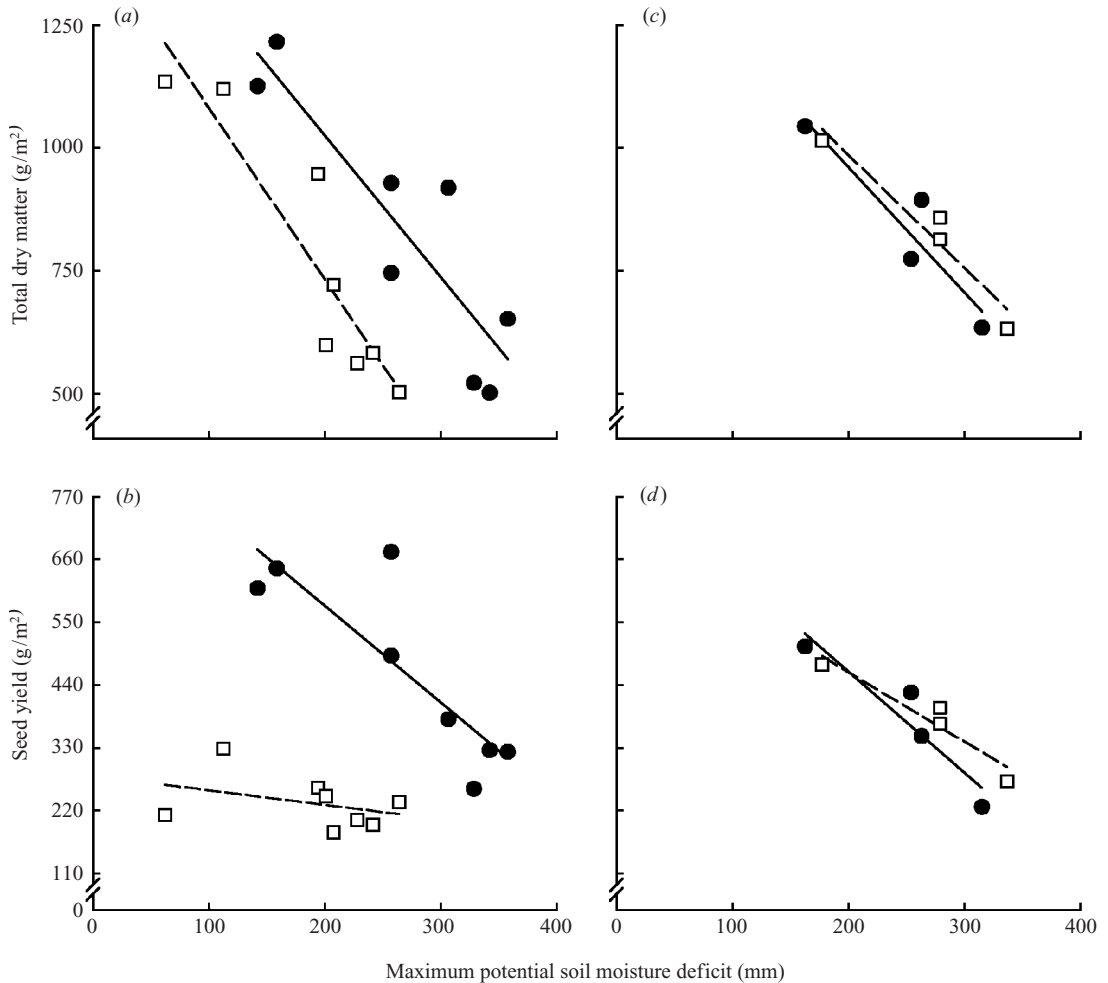


Fig. 8. The relationship between dry matter production, seed yield and maximum potential soil moisture deficit of Kabuli chickpeas during 1998/99 and 1999/2000 seasons. (a) Total dry matter, 1998/99: (●) November sowing, $Y=1602.9-2.89 X$, $R^2=0.79$. (□) December sowing, $Y=1431.2-3.49 X$, $R^2=0.84$. (b) Seed yield, 1998/99: (●) November sowing, $Y=918.4-1.69 X$, $R^2=0.72$. (□) December sowing, $Y=281.4-0.26 X$, $R^2=0.84$. (c) Total dry matter, 1999/2000: (●) October sowing, $Y=1471.9-2.56 X$, $R^2=0.86$. (□) November sowing, $Y=1443.6-2.29 X$, $R^2=0.93$. (d) Seed yield, 1999/2000: (●) October sowing, $Y=817.9-1.77 X$, $R^2=0.88$. (□) November sowing, $Y=706.4-1.22 X$, $R^2=0.91$.

relationship between radiation use efficiency (U) and Dp_{max} for the 2 years is presented in Fig. 9*b, d*. The U showed a marked decline from 1.29 to 0.66 g dry matter (DM)/MJ PAR over the range of Dp_{max} values experienced by the crop (62–358 mm). Neither sowing date nor season produced significantly different slopes and intercepts. This indicated a relatively constant decline in U for each additional 1 mm of Dp_{max} , about 0.002 g DM/MJ PAR was lost.

Pods per plant and limiting deficit

The number of pods per plant decreased as the water deficit increased in the November sowing in 1998/99

and in 1999/2000. The regression was highly significant ($P < 0.01$) and accounted for 87 and 78% of the variance at a given Dp_{max} (Fig. 10*a, c*). However, in the December 1998/99 sowing the relationship between pods per plant and Dp_{max} was weak and accounted for only 32% of the variance.

In 1998/99, both the November and December sowings showed a highly significant relationship when their TDM relative to the fully irrigated crops was plotted against Dp_{max} ($R^2=0.79$; $P < 0.01$ and $R^2=0.85$; $P < 0.001$ for the November and December sowing respectively) (Fig. 10*b*). This indicated a limiting deficit (cDp_{max}) of about 165 and 84 mm for the November and December sowings,

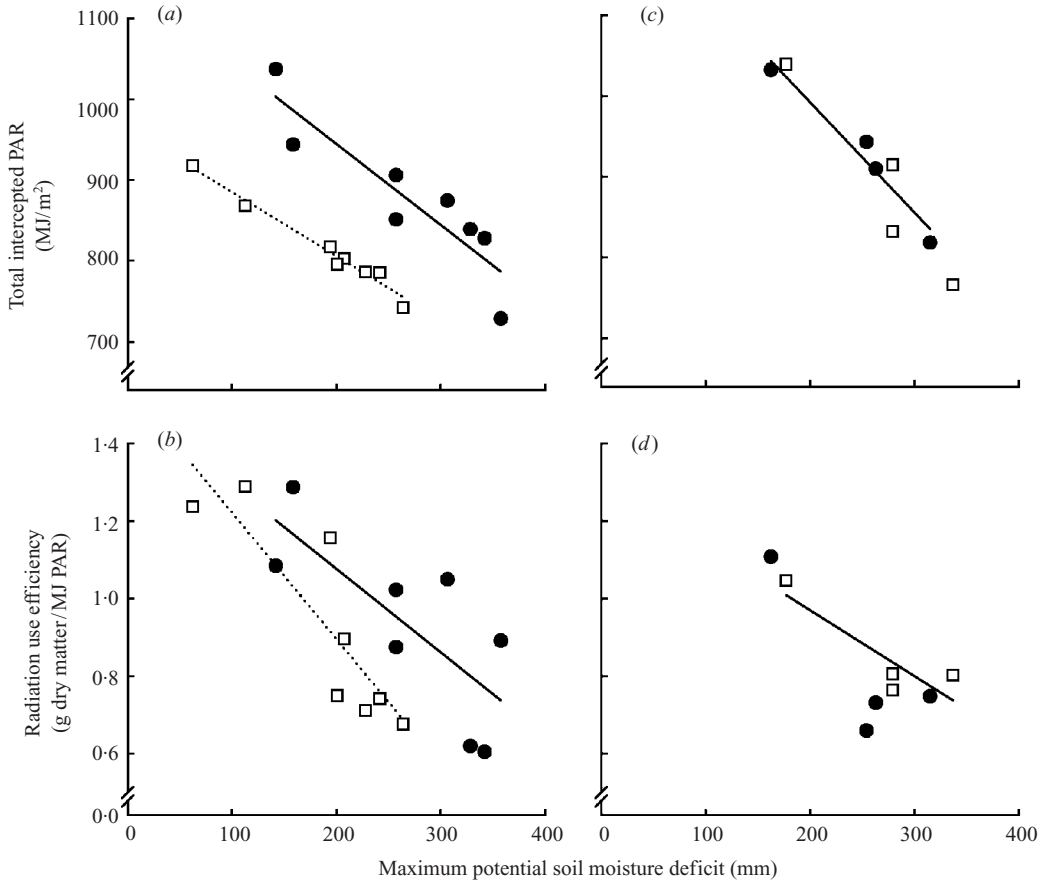


Fig. 9. The relationship between total intercepted PAR, radiation use efficiency and maximum potential soil moisture deficit of Kabuli chickpeas during 1998/99 and 1999/2000 seasons. (a) Total intercepted PAR, 1998/99: (●) November sowing, $Y = 1145.4 - 1.00 X$, $R^2 = 0.82$. (□) December sowing, $Y = 964.7 - 0.79 X$, $R^2 = 0.97$. (b) Radiation use efficiency, 1998/99: (●) November sowing, $Y = 1.51 - 0.002 X$, $R^2 = 0.57$. (□) December sowing, $Y = 1.54 - 0.003 X$, $R^2 = 0.75$. 1999/2000 season, (●) October sowing and (□) November sowing. (c) Total intercepted PAR: $Y = 1307.1 - 1.55 X$, $R^2 = 0.92$. (d) Radiation use efficiency: $Y = 1.35 - 0.002 X$, $R^2 = 0.61$.

respectively, for this soil. This assumes that the growth of fully irrigated crops was not restricted by water deficit. The slopes of the lines indicate that yield declined by about 0.26 and 0.31% for the November and December sowings, respectively, for each mm increase of $D_{p_{max}}$ above $cD_{p_{max}}$. For 1999/2000, the relationship between relative TDM production of rainfed or partially irrigated yield to that of a fully irrigated crop and $D_{p_{max}}$ is presented in Fig. 10d. Neither the October nor the November sowing gave significantly different slopes and intercepts, so the data were pooled. The regression was highly significant ($P < 0.001$) and accounted for 85% of the variance. This indicated an approximate $cD_{p_{max}}$ of 170 mm, assuming that the fully irrigated crop was not restricted by water deficit. The yield loss

as $D_{p_{max}}$ increased above each mm $cD_{p_{max}}$ was about 0.23%.

Prediction of yield

The relationship between yield and total actual evapotranspiration is usually linear and can be defined by a slope and an (extrapolated) intercept on the evapotranspiration axis (Fig. 3). Yield of this chickpea crop was related to the cumulative total evapotranspiration. Equation 1 was used to verify the prediction of DM increase and seed yield. As shown in Fig. 11, the relationship between the predicted and actual DM production and seed yield for all treatments over the 2 years was highly significant with an $R^2 = 0.98$, indicating the yield could

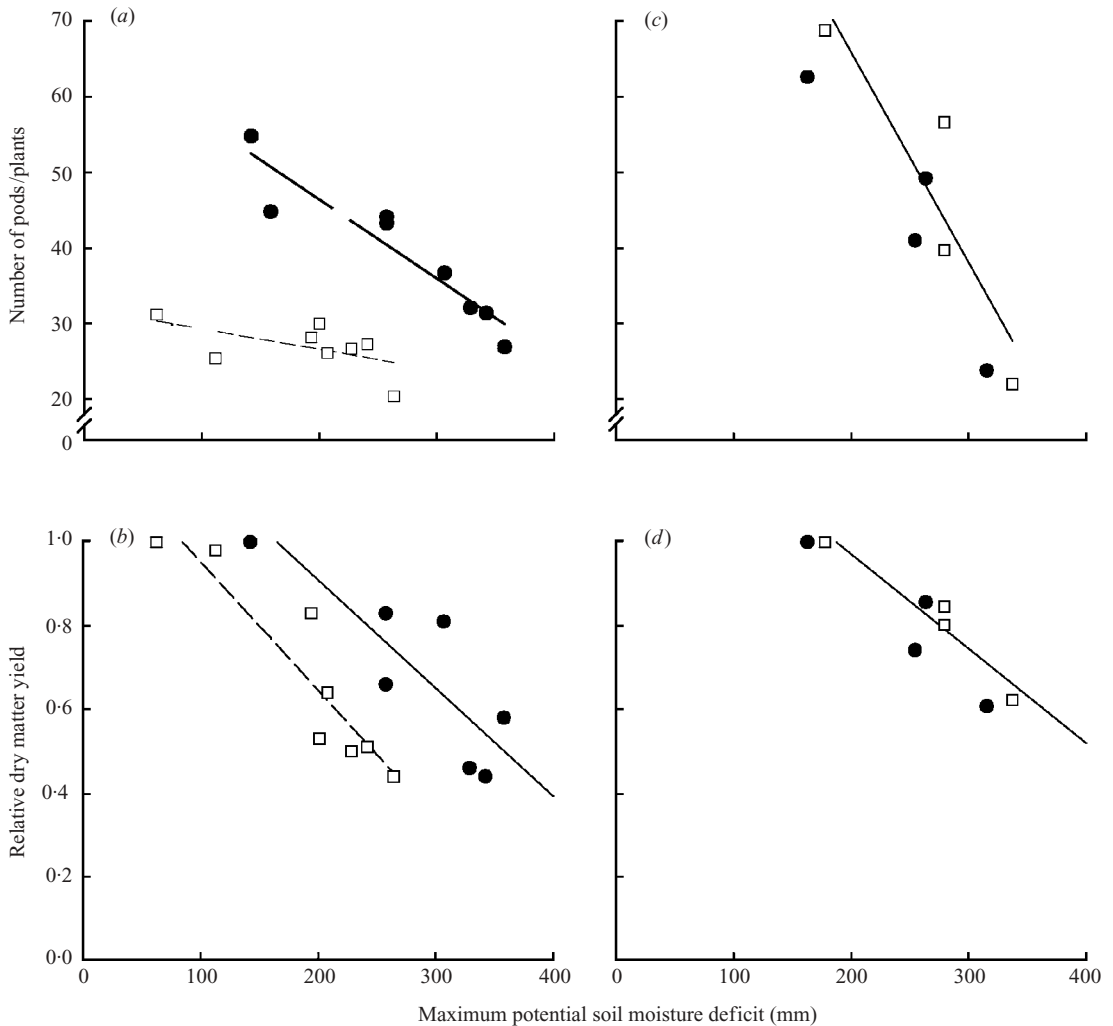


Fig. 10. The relationship between number of pods per plant, relative dry matter yield of unirrigated or partially irrigated yield to that of a fully irrigated crop and maximum potential soil moisture deficit of Kabuli chickpeas during 1998/99 and 1999/2000 seasons. (a) Number of pods/plant, 1998/99: (●) November sowing, $Y=67.3-0.10 X$, $R^2=0.87$. (□) December sowing, $Y=31.1-0.03 X$, $R^2=0.32$. (b) Relative dry matter yield, 1998/99: (●) November sowing, $Y=1.43-0.0026 X$, $R^2=0.79$. (□) December sowing, $Y=1.26-0.0031 X$, $R^2=0.85$. 1999/2000 season, (●) October sowing and (□) November sowing. (c) Number of pods/plant: $Y=109.4-0.25 X$, $R^2=0.78$. (d) Relative dry matter yield: $Y=1.39-0.0023 X$, $R^2=0.85$.

be predicted reasonably well from WUE and evapotranspiration.

DISCUSSION

Yield response in relation to water use

Growing conditions over the 2 years of the study differed, as shown by rainfall distribution, temperature, solar radiation and the Penman evapotranspiration (Anwar *et al.* 2003a). The total rainfall during the

growing seasons was approximately 200–260 mm and Kabuli chickpea yield was related to water use and sowing date in a similar way to that for lentils (McKenzie & Hill 1990) grown in the same environment and in chickpea (Silim & Saxena 1993; Prasad *et al.* 1999). Irrigation at any growth stage produced increased yield (both biomass and seed). However, the highest yields for all cultivars were achieved where drought stress was completely eliminated by irrigating throughout the growing season. This response may be a function of differing balances

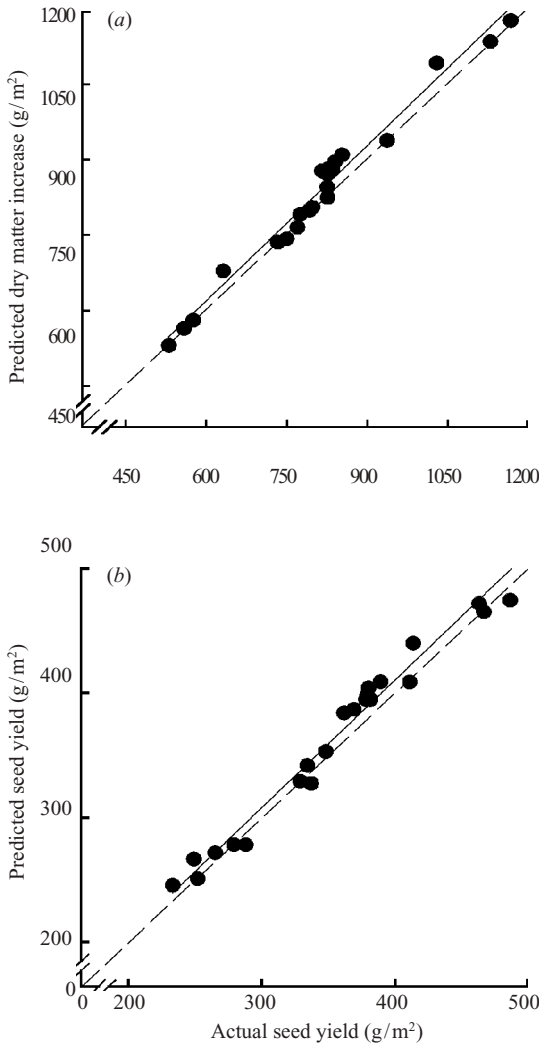


Fig. 11. The relationship between predicted and observed yield of Kabuli chickpeas in Canterbury, New Zealand, during the 1998/99 and 1999/2000 seasons. The solid line is the fitted regression line and the dashed line is the 1:1 fit. (a) Y (dry matter) = $-3.34 + 1.03 X$, $R^2 = 0.98$. (b) Y (seed yield) = $0.15 + 1.03 X$, $R^2 = 0.98$.

between canopy size and crop water demand (Lawlor 1995). Alternatively, both total biomass and seed yield production under rainfed conditions can be expected to be lower as a direct function of their shorter growth cycle, and lower total intercepted radiation receipt (Thomas & Fukai 1995). The major cause of yield reduction under rainfed and late irrigation conditions was low DM accumulation and the production of fewer pods per plant (Anwar *et al.* 2003b). Partitioning the DM of rainfed plants into

yield components demonstrated a significantly lower harvest index (40%, mean of 2 years) compared with the irrigated crops (48%, mean of 2 years) (Anwar *et al.* 2003b). The initial conclusions from yield and water use data from the present study are that Kabuli chickpeas use between 165 and 466 mm of water to produce a biomass yield of between 577 and 1130 g/m² and a seed yield of between 249 and 492 g/m². Within this range there is a close linear relation ($R^2 = 0.80$ to 0.92 for DM and $R^2 = 0.75$ to 0.78 for seed yield) between the amount of water use and yield (Fig. 3).

Seasonal evapotranspiration

Pre-, post-anthesis and total water use was significantly ($R^2 = 0.96$, $P < 0.001$) regulated by irrigation regimes and by rainfall (Fig. 1). Under full irrigation (e-m) and early irrigation (e-f), total water use was highest and ranged from 350–466 mm. This agrees with previous work in Canterbury where a fully irrigated lentil crop used 332 mm (McKenzie & Hill 1990). In India, Prasad *et al.* (1999) and in Northern Syria, Zhang *et al.* (2000) made similar observations in chickpea crops. Irrigation increased soil moisture content, stomatal opening, leaf area index and increased crop duration and these components caused higher transpiration. The present study also revealed significant differences in the pre-, post-anthesis and total water use among sowing dates, where early sown crops transpired more water (Tables 1 and 2). However, a combination of high summer temperatures and potential evapotranspiration during December–January (1998/99) was probably the main cause of greater post-anthesis water use in the 1998/99 December-sown crops (Table 1). This observation is common in low-rainfall, temperate environments where differences in water use have been reported for different grain legumes or agronomic treatments (McKenzie & Hill 1990).

Water-use efficiency

The dependence of water-use efficiency (WUE) on water supply has been demonstrated for various grain legumes including chickpea and changes in WUE may reflect changes in grain yield (Ali *et al.* 2000). The estimates of WUE for Kabuli chickpea in the present study (22–29 kg DM/ha per mm water use and 10–13 kg seed yield/ha per mm water use) were comparable to those reported for chickpea grown elsewhere (Herridge *et al.* 1995; Dalal *et al.* 1997). However, the WUE values in the present study appear higher than those reported by Zhang *et al.* (2000) for chickpeas grown in a Mediterranean environment (8.7 kg DM/ha per mm and 3.2 kg seed yield/ha per mm water use). Part of the higher WUE in the results

from the present study could be attributed to the different climate. At the site of the present experiments, during the growing season there was high solar radiation (16–24 MJ/m² per day), high mean daily minimum temperature (8–11 °C) and a long photoperiod (more than 15 h). In addition, the magnitude of the seed yield response in their experiments, about 848 kg/ha on a fine clay (calcixerollic) soil was about 77% less than the average response 3635 kg/ha reported here. Alternatively, by analysing with the transpiration model (Eqn 3 and Fig. 4), the mean value of $k=0.041 \pm 0.001$ mb was within the range for C₃ crops (0.040–0.065 mb) given by Tanner & Sinclair (1983). This means that dry matter production cannot be increased without using more water in transpiration (E_{tr}). The conditions required to achieve maximum yields are the same as for maximum water use. Consequently, the main prospect for improving WUE lies in improved management to increase E_{tr} as a fraction of evapotranspiration. However, there are limits to such improvements; the WUE can only approach transpiration efficiency as the upper limit (Tanner & Sinclair 1983). Growing crops in humid climates where vapour pressure deficit is small could also increase transpiration efficiency. Further, root weight could have an effect on WUE, but almost all reports of WUE are based on top dry matter only. This is an area where further work is required.

Water extraction pattern and water uptake rates

It was evident from the Neutron-probe measurements that none of the irrigation or rainwater was lost to drainage or to deep percolation from sowing to maturity. The differences in the pattern of variation in the volumetric soil water content with time depended on rainfall and irrigation and the amount of water remaining in the soil profiles usually increased with the number of irrigations. Thus, an increase in soil moisture content on successive dates was attributed to rainfall/irrigation and a decrease was attributed to root uptake. Generally, the surface horizons lost water more or less exponentially and the slope became more gradual with depth (Fig. 5). At some depths the initial gradual loss of water at a particular time (date) was followed by an accelerated rate of water loss. Dardanelli *et al.* (1997) has suggested that the depth of soil to which accelerated rate of soil drying was observed can be considered as the 'effective rooting depth'. In the present study the effective rooting depth (ERD) was approximately 0–90 cm. An increase in the frequency of irrigation presumably resulted in higher root proliferation, mostly in the upper layer (0–30 cm) (Silim *et al.* 1993). Thus, more water was used by the plants from the upper soil layer.

The daily rate of water uptake decreased with depth and depended on the irrigation by sowing date interaction (Figs 6 and 7). Leport *et al.* (1999) reported that a chickpea crop in Australia used 90% of the water from 0–80 cm soil depth. The mean daily water use of the three Kabuli chickpea cultivars ranged from 0.49–0.93 mm per 10 cm soil layer per day from 0–30 cm in the soil profile and decreased logarithmically from the immediate subsoil layer.

Response to drought

The present work showed that yield responses to Dp_{max} fit reasonably well to the Penman model (Penman 1962*a, b, c*; Penman 1970; French & Legg 1979). As expected, the Dp_{max} values were large for rainfed and late irrigated crops (Tables 1 and 2) and are similar to those experienced by Kabuli chickpea crops in Syria (Saxena *et al.* 1990). Chickpea seed yield is the ultimate consequence of the amount of DM accumulated during the growing season and its partitioning into seeds (Soltani *et al.* 1999). Water deficits decrease the photosynthesis process both on a per unit area of soil and per unit area of leaf (Lawlor 1995), subsequently DM and seed yield decreases (Dahan & Shibles 1995). This argument is supported by the observation of a significant measured decline in TDM production and seed yield in response to increased Dp_{max} .

In addition, the Penman model enabled the present authors to define the limiting soil moisture deficit (cDp_{max}) of about 165 and 84 mm for the November and December sowings in 1998/99 and 170 mm in 1999/2000 (Fig. 10*b, d*). This indicates that yield reduction is a linear response (averaged over 2 years by 0.26%) to Dp_{max} for Dp_{max} greater than cDp_{max} . In Canterbury, Stone *et al.* (1997) reported cDp_{max} of approximately 90 mm for sweetcorn. This limiting deficit allows for informed decisions about the yield benefit (if any) to be gained by irrigation at any stage throughout the life of the crop.

Evidence for moisture-sensitive periods

The concept of 'moisture-sensitive periods' is important in the context of scheduling irrigation. The available literature is somewhat conflicting, as the most critical period in chickpea is usually considered to be the flowering stage (Jadhav *et al.* 1997). Tomar *et al.* (1999) indicated that the grain filling stage may also be critical. Further, application of three irrigations at branching, pre-flowering and seed development stages, gave the highest yield (up to 119% greater than the unirrigated yield) (Yusuf *et al.* 1980; Nimje 1991). In the present experiments there was little evidence to support the existence of a moisture-sensitive period in Kabuli chickpea crops. This is because of two major problems: difficulty in quantifying

the degree of drought during the supposed 'sensitive periods' and lack of control over rainfall. However, in the present study sowing date had the dominant effect on grain yield as the irrigation by sowing date and the sowing date by cultivar interactions (Anwar *et al.* 2003*b*) indicated that the response to drought depended on the sowing date. Averaged over the 2 years there was a more than 100% increase in Kabuli chickpea seed yield as a result of full irrigation (e-m), compared with the rainfed crops.

Analyses by Hebblethwaite (1982), in faba beans, did not show any particular sensitive period in that crop. From the $D_{p_{max}}$ analysis, no additional yield increase will occur in response to extra water applied once the $D_{p_{max}}$ is less than 165 mm. Kabuli chickpea yield was reduced by water deficit at any stage of development, provided the deficits were greater than the limiting water deficit ($cD_{p_{max}}$). The maximum $D_{p_{max}}$ experienced by a crop during the growing season is the event that sets the upper limit to final yield. Therefore, there is no point in irrigating to maintain a low $D_{p_{max}}$ if a large deficit has already occurred. This applies equally at all stages of crop development because there was no evidence of any period of particular vulnerability to water deficit. This was clear from the simple linear relationship between $D_{p_{max}}$ and yield (Fig. 8).

Unequivocal evidence on the presence or absence of critical periods of sensitivity to water stress will come from growing chickpeas beneath rain shelters. However, the present findings can form the basis of irrigation management to maximize chickpea yield in a subhumid temperate environment where annual rainfall averages only 600 mm.

The overall yield response under the different values of $D_{p_{max}}$ was the net effect of variation of intercepted radiation, radiation use efficiency and number of pods per plant. Early sowing and frequent irrigation probably created a higher vapour pressure gradient between the crop canopy and the atmosphere as shown by Fiscus & Markhardt (1979). This might have caused a relatively larger water uptake than in the other schedules. On the other hand, the low green area index coupled with low stomatal conductance (Passioura *et al.* 1995; Turner 1997) was mainly responsible for low water use from the rainfed stressed plants. This was reflected in the highest WUE in the rainfed plots during 1998/99, which had the lowest seed and biomass yield. By extracting soil water to a greater extent, Kabuli chickpeas grown with full irrigation always produced higher biomass and seed yields compared with nil and late irrigation. Therefore, it appears that irrigation water (application based on maximum potential soil moisture deficit) could be used efficiently in this type of soil and environment; the apparent threshold for maintenance of favourable plant water status resulted in higher yields. The present study has shown that using actual evapotranspiration and water-use efficiency, the biomass yield and seed yield of Kabuli chickpeas can be accurately predicted. Therefore, yield variations could be associated with changes in any of these parameters.

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REFERENCES

- ALI, M., DAHAN, R., MISHRA, J. P., SAXENA, N. P., ALI, M. & KNIGHT, R. (2000). Towards the more efficient use of water and nutrients in food legume cropping. In *Linking Research and Marketing Opportunities for Pulses in the 21st Century: Proceedings of the Third International Food Legumes Research Conference* (Ed. R. Knight), pp. 355–368. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- ANWAR, M. R., MCKENZIE, B. A. & HILL, G. D. (2003*a*). Phenology and growth response to irrigation and sowing date of Kabuli chickpea (*Cicer arietinum* L.) in a cool-temperate subhumid climate. *Journal of Agricultural Science, Cambridge* **141**, 273–284.
- ANWAR, M. R., MCKENZIE, B. A. & HILL, G. D. (2003*b*). 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. *Journal of Agricultural Science, Cambridge* **141**, 259–271.
- BIERHUIZEN, J. F. & SLATYER, R. O. (1965). Effect of atmospheric concentration of water vapour and CO₂ in determining transpiration-photosynthesis relationships of cotton leaves. *Agricultural Meteorology* **2**, 259–270.
- BROWN, S. C., GREGORY, P. J., COOPER, P. J. M. & KEATINGE, J. D. (1989). Root and shoot growth and water use of chickpea (*Cicer arietinum* L.) grown in dryland conditions: effects of sowing date and genotype. *Journal of Agricultural Science, Cambridge* **113**, 41–49.
- DAHAN, R. & SHIBLES, R. M. (1995). Comparative responses of chickpea (*Cicer arietinum* L.) cultivars to water deficit. II. Leaf development, growth rates, water use and yields. In *Improving Production and Utilization of Grain Legumes: Proceedings 2nd European Conference on Grain Legumes* (Ed. C. Hedley), p. 118. Paris: AEP.
- DALAL, R. C., STRONG, W. M., DOUGHTON, J. A., WESTON, E. J., McNAMARA, G. T. & COOPER, J. E. (1997). Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage or legumes. 4. Nitrogen fixation, water use and yield of chickpea. *Australian Journal of Experimental Agriculture* **37**, 667–676.
- DARDANELLI, J. L., BACHMEIER, O. A., SERENO, R. & GIL, R. (1997). Rooting depth and soil water extraction patterns of different crops in a silty loam Haplustoll. *Field Crops Research* **54**, 29–38.

- FISCUS, E. L. & MARKHARDT, A. H. (1979). Relationships between root system water transport properties and plant size in *Phaseolus*. *Plant Physiology* **64**, 770–773.
- FRENCH, B. K. & LEGG, B. J. (1979). Rothamsted irrigation 1964–76. *Journal of Agricultural Science, Cambridge* **92**, 15–37.
- HEBBLETHWAITE, P. (1982). The effects of water stress on the growth, development and yield of *Vicia faba* L. In *Faba Bean Improvement* (Eds G. Hawtin & C. Webb), pp. 165–175. The Hague: Martinus Nijhoff.
- HERRIDGE, D. F., MARCELLOS, H., FELTON, W. L., TURNER, G. L. & PEOPLES, M. B. (1995). Chickpea increases soil-N fertility in cereal systems through nitrate sparing and N₂ fixation. *Soil Biology and Biochemistry* **27**, 545–551.
- JADHAV, J. D., SHEWALE, M. R., MOKASHI, D. D., GAIKWAD, C. B. & PATIL, J. D. (1997). Crop coefficients and actual evapo-transpiration of gram (*Cicer arietinum*) grown in lysimeter. *Indian Journal of Agricultural Sciences* **67**, 33–35.
- JAMIESON, P. D., MARTIN, R. J., FRANCIS, G. S. & WILSON, D. R. (1995). Drought effects on biomass production and radiation-use efficiency in barley. *Field Crops Research* **43**, 77–86.
- LAWLOR, D. W. (1995). The effects of water deficit on photosynthesis. In *Environment and Plant Metabolism: Flexibility and Acclimation* (Ed. N. Smirnov), pp. 129–160. Oxford: Bios Scientific Publishers.
- LEPORT, L., TURNER, N. C., FRENCH, R. J., BARR, M. D., DUDA, R., DAVIES, S. L., TENNANT, D. & SIDDIQUE, K. H. M. (1999). Physiological responses of chickpea genotypes to terminal drought in a Mediterranean-type environment. *European Journal of Agronomy* **11**, 279–291.
- McKENZIE, B. A. & HILL, G. D. (1990). Growth, yield and water use of lentils (*Lens culinaris*) in Canterbury, New Zealand. *Journal of Agricultural Science, Cambridge* **114**, 309–320.
- NIMJE, P. M. (1991). Irrigation and fertilizer requirement of chickpea (*Cicer arietinum*) genotypes in deep Vertisol. *Indian Journal of Agronomy* **36**, 111–114.
- PASSIOURA, J. B., CONDON, A. G. & RICHARDS, R. A. (1995). Water deficits, the development of leaf area and crop productivity. In *Environment and Plant Metabolism: Flexibility and Acclimation* (Ed. N. Smirnov), pp. 253–264. Oxford: Bios Scientific Publishers.
- PENMAN, H. L. (1962*a*). Woburn irrigation 1951–59. I. Purpose, design and weather. *Journal of Agricultural Science, Cambridge* **58**, 343–348.
- PENMAN, H. L. (1962*b*). Woburn irrigation, 1951–59. II. Results for grass. *Journal of Agricultural Science, Cambridge* **58**, 349–364.
- PENMAN, H. L. (1962*c*). Woburn irrigation, 1951–59. III. Results for rotation crops. *Journal of Agricultural Science, Cambridge* **58**, 365–379.
- PENMAN, H. L. (1970). Woburn irrigation, 1960–68. IV. Design and interpretation. *Journal of Agricultural Science, Cambridge* **75**, 69–73.
- PENMAN, H. L. (1971). Irrigation at Woburn – VII. Rothamsted Experimental Station. Report for 1970, Part 2, 147–170.
- PRASAD, S. N., SINGH, R. & RAO, D. H. (1999). Effect of pre-sowing irrigation and soil mulch on yield attributes, yield and water-use of chickpea (*Cicer arietinum*), linseed (*Linum usitatissimum*) and Indian mustard (*Brassica juncea*). *Indian Journal of Agricultural Sciences* **69**, 424–426.
- RAMAKRISHNA, A. & REDDY, S. L. N. (1993). Production potential and economic feasibility of different crop sequences in rice (*Oryza sativa*) fallows. *Indian Journal of Agricultural Sciences* **63**, 611–615.
- RAVI, N., SHARMA, H. M., SINGH, R. N. P. & NANDAN, R. (1998). Response of late-sown chickpea to irrigation and foliar nutrition in calcareous soil. *Journal of Applied Biology* **8**, 5–8.
- REDDY, N. R. N. & AHLAWAT, I. P. S. (1998). Response of chickpea (*Cicer arietinum*) genotypes to irrigation and fertilizers under late-sown conditions. *Indian Journal of Agronomy* **43**, 95–101.
- SAXENA, M. C., SILIM, S. N. & SINGH, K. B. (1990). Effect of supplementary irrigation during reproductive growth on winter and spring chickpea (*Cicer arietinum*) in a Mediterranean environment. *Journal of Agricultural Science, Cambridge* **114**, 285–293.
- SILIM, S. N. & SAXENA, M. C. (1993). Adaptation of spring-sown chickpea to the Mediterranean basin. I. Response to moisture supply. *Field Crops Research* **34**, 121–136.
- SILIM, S. N., SAXENA, M. C. & ERSKINE, W. (1993). Adaptation of lentil to the Mediterranean environment. II. Response to moisture supply. *Experimental Agriculture* **29**, 21–28.
- SINGH, K. B., MALHOTRA, R. S., SAXENA, M. C. & BEJIGA, G. (1997). Superiority of winter sowing over traditional spring sowing of chickpea in the Mediterranean region. *Agronomy Journal* **89**, 112–118.
- SOLTANI, A., GHASSEMI, G. K., KHOUIE, F. R. & MOGHADDAM, M. (1999). A simple model for chickpea growth and yield. *Field Crops Research* **62**, 213–224.
- STONE, P. J., WILSON, D. R. & GILLESPIE, R. N. (1997). Water deficit effects on growth, water use and yield of sweet corn. *Proceedings of the Agronomy Society of New Zealand* **27**, 45–50.
- TANNER, C. B. & SINCLAIR, T. R. (1983). Efficient water use in crop production: research or re-research. In *Limitations to Efficient Water Use in Crop Production* (Eds H. M. Taylor, W. R. Jordan & T. R. Sinclair), pp. 1–27. American Society of Agronomy Monograph.
- THOMAS, S. & FUKAI, S. (1995). Growth and yield response of barley and chickpea to water stress under three environments in southeast Queensland. I. Light interception, crop growth and grain yield. *Australian Journal of Agricultural Research* **46**, 17–33.
- TOMAR, R. K. S., SHARMA, P., YADAV, L. N. & SHARMA, P. (1999). Comparison of yield and economics of irrigated chickpea under improved and local management practices. *International Chickpea and Pigeonpea Newsletter No. 6*, 22–23.
- TURNER, N. C. (1997). Further progress in crop water relations. *Advances in Agronomy* **58**, 293–338.
- YUSUF, M., SINGH, N. P. & DASTANE, N. G. (1980). Yield and water-use efficiency in relation to water supply in chickpea. *Indian Journal of Agronomy* **25**, 235–238.
- ZHANG, H., PALA, M., OWEIS, T. & HARRIS, H. (2000). Water use and water-use efficiency of chickpea and lentil in a Mediterranean environment. *Australian Journal of Agricultural Research* **51**, 295–304.