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Growth and Yield Response of Barley and Chickpea to Water Stress Under Three Environments in Southeast Queensland. II* Root Growth and Soil Water Extraction Pattern

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Abstract

Root growth and water extraction of two barley cultivars, Corvette (early maturing), Triumph (late maturing) and one cultivar of chickpea (Amethyst at Redland Bay and Borwen at Hermitage) were compared under three environments: April sowing and July sowing at Redland Bay and June sowing at Hermitage Research Station, south-east Queensland. This work was designed to explain differences in dry matter production in terms of root growth and water uptake during the crop growth, which relied only on stored soil moisture.

In the April sowing where all crops grew well during the early stages of growth, decline in soil water with time for the whole profile was similar among all crops. In the winter sowings (June, July), total water use was less in chickpea than in barley, particularly during early stages when chickpea growth was poor. Water extraction patterns of two barley cultivars were similar in all experiments, though the late-maturing Triumph extracted slightly more water than early maturing Corvette towards maturity.

Water extraction front velocities of the three crops were similar in each experiment. At Redland Bay, the water extraction front velocities varied from 1·4 to 1·6 cm day^{-1} in the April sowing and 2·3 to 2·4 cm day^{-1} in the July sowing, while they varied from 2·0 to 2·3 cm day^{-1} at Hermitage. However, descent of the water extraction front commenced later in chickpea than in barley when sown in winter months, and this resulted in lower total water use in chickpea, particularly at Hermitage.

In both sowings at Redland Bay total root length increased rapidly to about 60 days after sowing in barley, whereas the increase was slower in chickpea. Root length density was high in the upper soil layers, and this was associated with high extractable soil water. In deeper layers both root length density and extractable soil water decreased. For a given root length density chickpea extracted more water than barley.

These results indicate that the differences in root growth and water extraction by the two barley crops were rather small and were unlikely to be the reason for the differences in total dry matter production. Chickpea on the other hand appeared to be susceptible to low temperatures during early stages of growth, and this caused poor growth of both shoots and roots.

Keywords: barley, chickpea, root length density, water extraction pattern, water extraction front velocity, extractable soil water, temperature.

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Introduction

Both root depth and root length density determine the amount of soil water that can be supplied to tops. A low root length density may limit water uptake. Crops frequently fail to extract all available water in the lower half of the root zone, because of low root density at deeper layers (Barraclough and Weir 1988; Robertson *et al.* 1993*a*). These differences in root length density at different depths may be associated with the speed at which roots elongate to depth, or may be related to proliferation rate at each soil layer. Robertson *et al.* (1993*a*, 1993*b*) found in sorghum that at deep layers where roots arrive during the later stages of growth, root length did not increase rapidly, and this limited water uptake from these layers. They also found that root length stopped increasing at about flowering. It is therefore likely that late-flowering cultivars have deeper root systems and higher root length density at depth, which allow them to extract more water than early-flowering cultivars. In the experiments reported in our previous paper (Thomas and Fukai 1995*a*), the difference in heading time between early-maturing Corvette and late-maturing Triumph barley varied greatly (8–42 days), depending on growing conditions. This differential heading date may have affected the pattern of root development and water extraction, particularly from deeper layers. Corvette also produced higher biomass than Triumph under water limiting conditions, and hence may have required more water.

Profiles of root length density vary substantially among species, so that the water extraction may also be different (Klepper and Rickman 1990). In our previous paper (Thomas and Fukai 1995*a*), chickpea was found to grow much more slowly and produce lower yield than in barley when these crops were sown in winter and stress developed in spring. However, when they were sown in autumn with favourable conditions during early stages of growth, the chickpea crop was established rapidly and rather high dry matter growth rates were maintained throughout crop growth. These species differences in dry matter production under water limiting conditions in the different experiments may have been associated with differences in root growth, and hence water uptake. In this paper, water extraction pattern and root length growth are examined in detail to investigate whether the dry matter growth and yield responses of different species and cultivars to soil water deficit are related to the water extraction pattern.

Materials and Methods

Environmental conditions and crop management were described in the first paper (Thomas and Fukai 1995*a*). Two cultivars of barley, Corvette (early maturing) and Triumph (late maturing), and chickpea cultivar Amethyst at Redland Bay and Borwen at Hermitage, were compared for their root growth and ability to extract soil water under a rainout shelter in three environments in South-east Queensland. In experiment 1, crops were sown in April at Redland Bay, where the plants experienced favourable growing conditions during early stages of growth, followed by low temperature towards maturity. In experiment 2, crops were sown in July at Redland Bay, where they experienced high solar radiation but matured rapidly as temperature increased in spring. Experiment 3 was conducted at Hermitage Research Station, in the Darling Downs where winter temperature was much lower than at Redland Bay.

Soil Water Content

Two 2-m long aluminium access tubes, with their lower ends sealed, were installed in each plot of the rainout shelter area, in all experiments. A neutron moisture meter (type

CPN 503 DR) was used to measure soil water content from 30 cm down to 170 cm at 20 cm intervals. Readings were made every 4–7 days. Soil water content at the surface (0–20 cm) was determined gravimetrically.

Pattern of Soil Water Extraction

A simple model to estimate the change with time in soil water content at different depths was proposed by Monteith (1986). When the root front arrives at a particular depth and starts to extract water, the soil water content begins to decline rapidly, often exponentially. Passioura (1983) suggested that the relationship between soil water content and time could be described as:

$$\Theta = \Theta_a \exp(-klt),$$

where Θ = soil water content, l = root length density, k = a constant with the dimensions of a diffusion coefficient, t = time, Θ_a is defined as the maximum amount of water that roots are capable of extracting from surrounding soil. In experiment 3 the soil water content was constant before the commencement of exponential decline. However, in experiments 1 and 2, it was noted that soil water content actually declined linearly with time before it declined exponentially. Therefore the equations which were fitted to the curves were as follows:

$$\Theta = \Theta_0 + bt, \text{ when } t \leq t_c \text{ and}$$

$$\Theta = \Theta_l + [(\Theta + bt_c) - \Theta_l] * \exp[-a * (t - t_c)], \text{ when } t > t_c,$$

where Θ = soil moisture content after crop establishment (%),
Θ_o = extrapolated soil moisture content at the time of sowing (%),
Θ_l = lower limit of soil moisture (%),
t = time after sowing (days),
b = the slope of the linear equation,
t_c = time after sowing when the root starts extracting water,
a = constant (=kl).

Using an iterative optimization procedure (Hammer *et al.* 1982), the equations were fitted to the change in soil water content with time at each depth for each replication for all crops, and t_c was estimated. Soil water contents at the upper limit Θ_u (i.e. soil water content at the first reading) and at the lower limit were also estimated for each soil depth. An example of the data set and fitted lines is shown in Fig. 1.

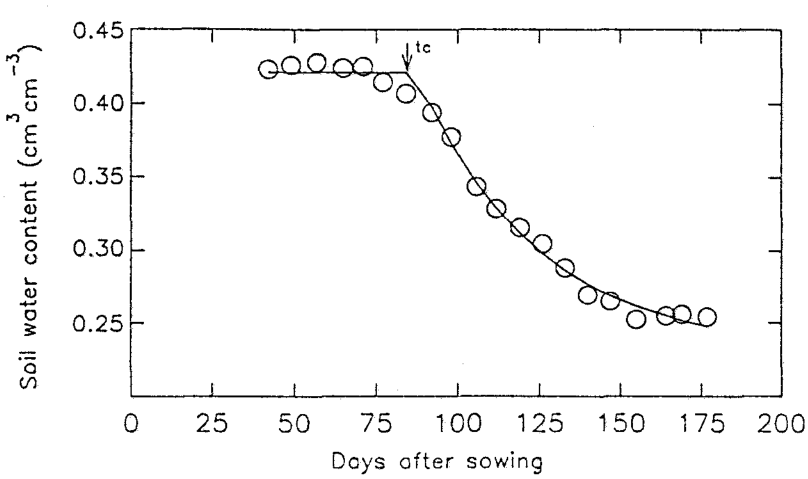

Fig. 1. An example of change in soil water content at a particular layer, and fitted curve. t_c indicates the time when roots start extracting water.

Root Length

Root samples were taken 21, 51, 62, 113, 153 (chickpea only), and 157 (Triumph only) days after sowing (das) in experiment 1 and 37, 65, 85, 98, 108 (chickpea only), and 111 (Triumph only) das in experiment 2, whereas only once at 102 das in experiment 3. Steel tubes, with internal diameter of 0·042 m in experiments 1 and 2 and 0·035 m in experiment 3, were used to take soil cores down to 2·0 m. The soil cores were cut into 20 cm sections and soaked in water for 48 h before being washed with a pneumatic root washer (type GVF 13000). The root length of each sample was read with a digital scanner calibrated with known lengths of cotton thread.

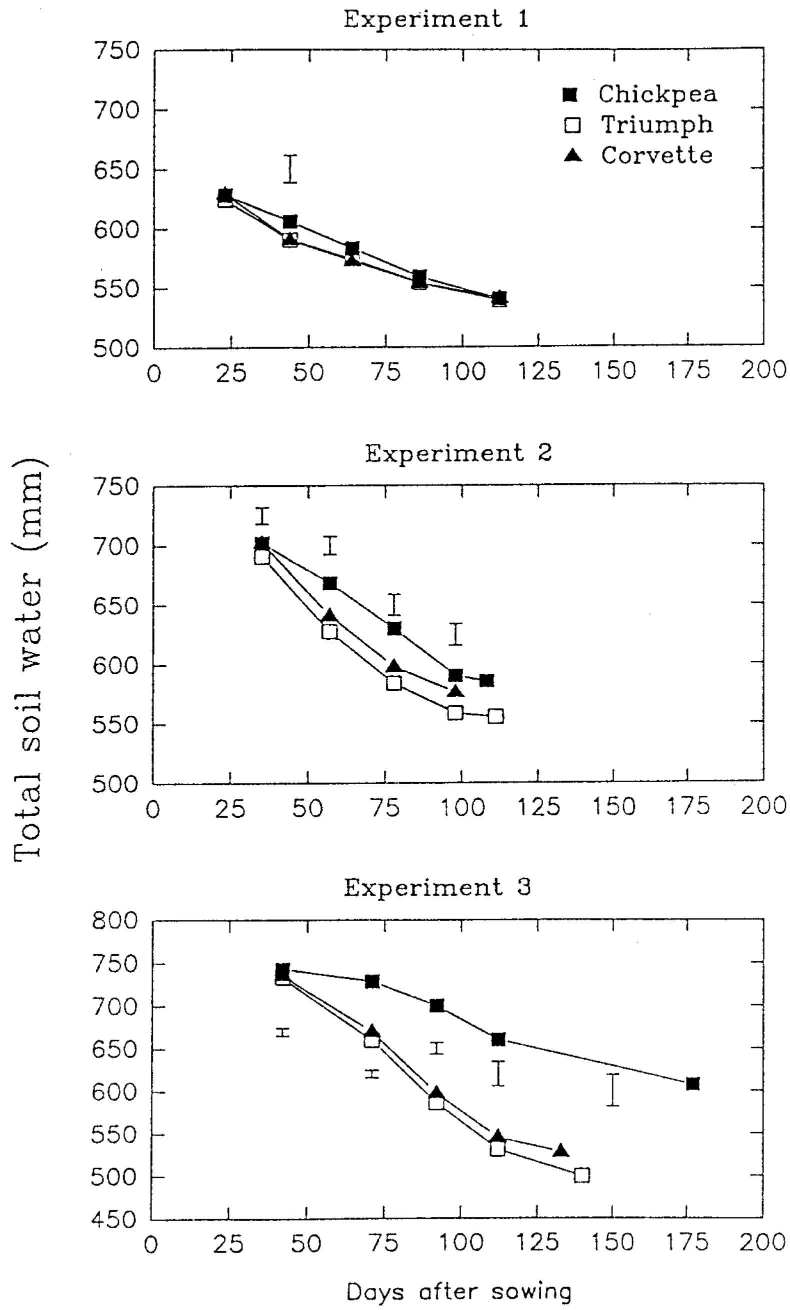

Fig. 2. Change in total soil water content with time of chickpea and Corvette and Triumph barley in experiments 1, 2 and 3. Vertical bars indicate l.s.d. (5%).

Results

Total Soil Water Content

Changes in total soil water over 0–180 cm depth for the three experiments are shown in Fig. 2. In experiment 1, chickpea plots had slightly higher soil water content than barley plots on the second measurement occasion, but the difference was not significant. Soil water content in the two barley cultivars was very similar at any time until maturity of Corvette (112 das).

In experiment 2, the initial soil water content was higher than in experiment 1, and all crops used water more rapidly than in experiment 1. Chickpea extracted soil water more slowly than barley at the beginning of the stress period, but it extracted more water in the 77–97 das period. Slightly more water remained unused in the chickpea plots than in the barley plots. The water extraction pattern of the two barley cultivars were similar, though at maturity water content in the Triumph plots was slightly less than the Corvette plots.

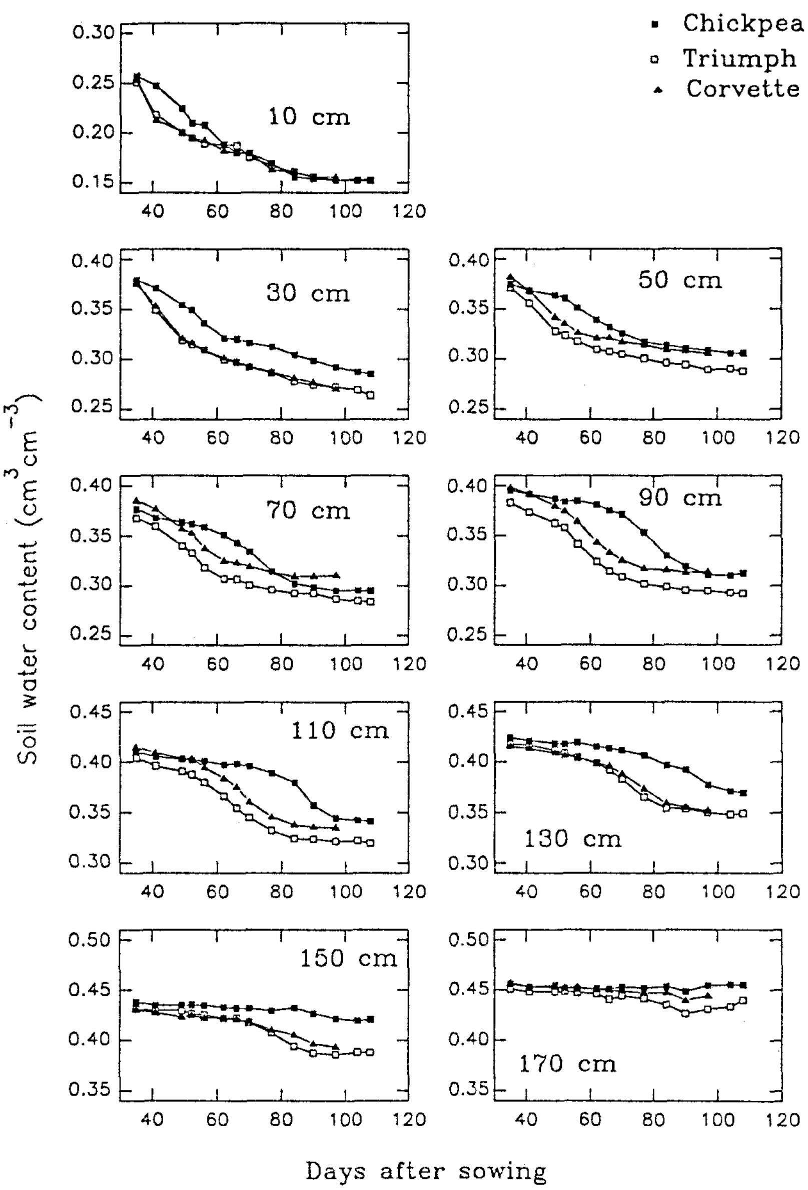

Fig. 3. Change in soil water content with time at various depths in chickpea and Corvette and Triumph barley in experiment 2.

In experiment 3 chickpea extracted water much more slowly than barley, and at maturity the soil in the chickpea plots contained about 100 mm more water than the barley plots, despite the fact that growth duration of chickpea was longer than for barley. The difference in water extraction pattern between the barley cultivars was similar to that found in experiment 2.

Water Extraction at Different Depths

The general pattern of water extraction for each soil depth was similar in all experiments and only the results obtained in experiment 2 are shown in Fig. 3. Soil water was extracted rapidly from the top three layers immediately after the stress period commenced. The soil water content at depths of 70, 90, 110 and 130 cm showed that there was a gradual linear decline, followed by an exponential decline, while soil water contents at 170 cm were nearly constant with time. Water extraction occurred earlier in upper layers, whereas in lower layers water extraction occurred later and to a lesser extent. Water extraction by chickpea occurred later than in barley at all depths.

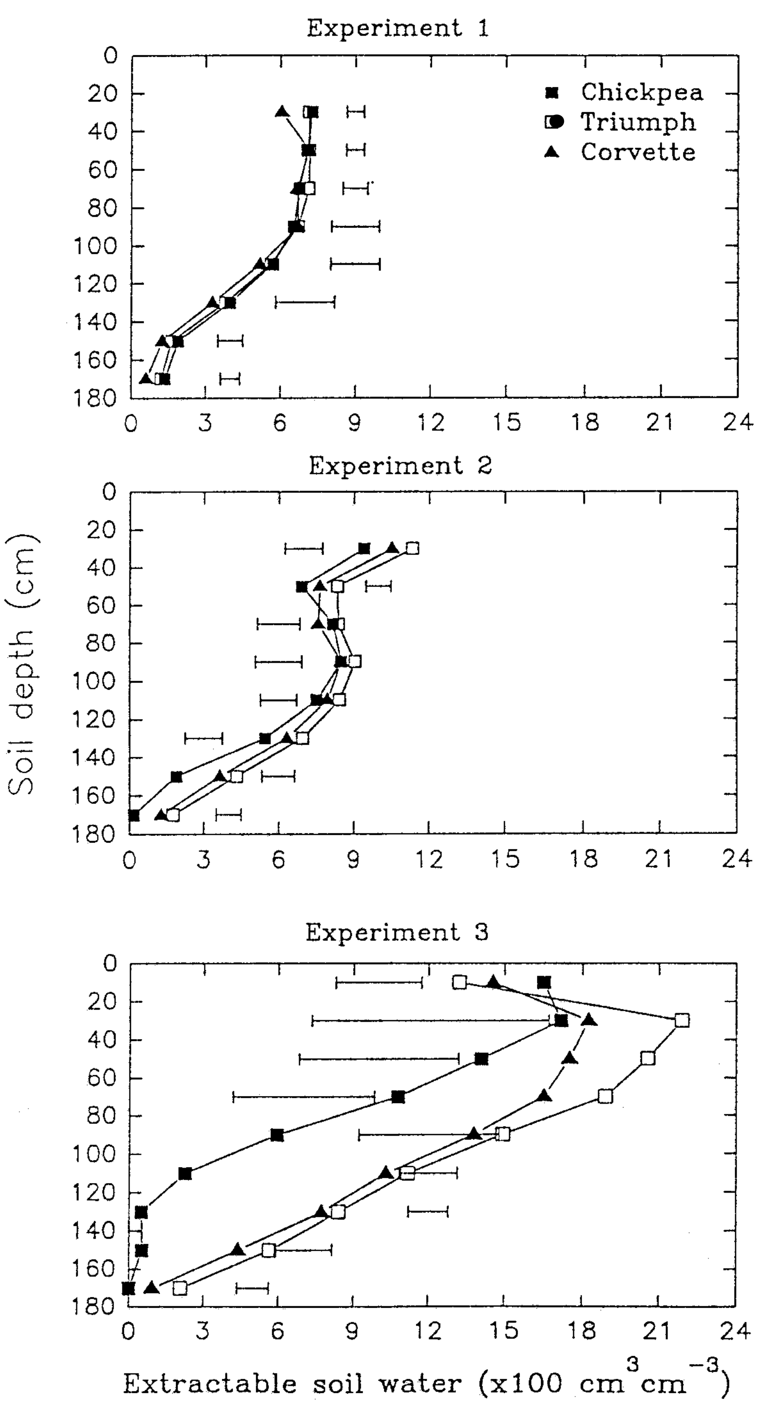

Fig. 4. Extractable soil water of chickpea and Corvette and Triumph barley in experiments 1, 2 and 3. Horizontal bars indicate l.s.d. 5%.

Profiles of extractable soil water, i.e. the difference between the upper limit (soil water content at the beginning) and lower limit (at maturity) in all experiments are shown in Fig. 4. In experiments 1 and 2 (Redland Bay), extractable soil water at different depths was similar to 100 cm depth, but decreased with a further increase in soil depth. In experiment 1, extractable water was similar among three crops at most depths. In experiment 2, chickpea extracted less water from the deeper layers compared with barley, whereas in the upper layers extractable water was not significantly different among crops. The maximum soil water extraction occurred at 20–40 cm, probably owing to soil evaporation from the soil surface. Extractable soil water in upper layers was greater in experiment 3 than in experiments 1 and 2, reflecting a higher water-holding capacity of the black earth soil at Hermitage. However, extractable soil water declined sharply with depth at this site. At soil depths below 60 cm, extractable soil water was much less with chickpea than with barley.

Water Extraction Front Velocity

The time of arrival of the extraction front (t_c) to a particular soil layer was estimated from exponential curves fitted to soil water measurements for each soil layer. The equations fitted well for all data sets with R^2 greater than $0\cdot9$ in most cases. The water extraction front descended linearly with time in each crop in each experiment (Fig. 5). Heading of Corvette and flowering of chickpea occurred at 66 and 73 days after sowing, respectively in experiment 1 (Thomas and Fukai 1995*a*), but this did not appear to have any effects on the descent of the water extraction front. The slope of the regression line is the water extraction front velocity, and the x-intercept is the lag time after which extraction front starts to descend. The values for these parameters are shown in Table 1. Water extraction front velocity was less in experiment 1 than in others, but it did not differ much between crops within each experiment. On the other hand, the lag period was affected by both environment and crop. In experiment 1 in which temperature was high immediately after sowing, crops established quickly and the lag period was short. Winter sowings (experiments 2 and 3) prolonged the lag period, and this was particularly obvious at Hermitage (experiment 3), where temperature in winter was lower than at Redland Bay (experiment 2). Chickpea had a longer lag period than barley, particularly when sown in winter, probably reflecting the crop's sensitivity to low temperature during establishment.

Root Length

A profile of root length density (cm of roots per cm^3 of soil) from the April and July sowing of each crop subjected to water stress conditions is presented in Fig. 6. In experiment 1, the root length density of chickpea increased at all depths from 21 to 62 das, 11 days before the commencement of flowering, in the 40–100 cm layers up to 113 das, and in the 60–140 cm layers to 153 das. For Triumph, root length density increased rapidly between 21 and 51 das in the top 80 cm, but there was no further increase after 51 das in any of the layers. Root length density declined sharply between 62 and 113 das (5 days after heading), and then decreased slightly up to 157 das in the top two layers. The pattern of change in root length density with time for Corvette was similar to Triumph, although there was an increase in root length density between 51 and 62 das (4 days before heading) in the top two layers. Between 62 and 113 das root length

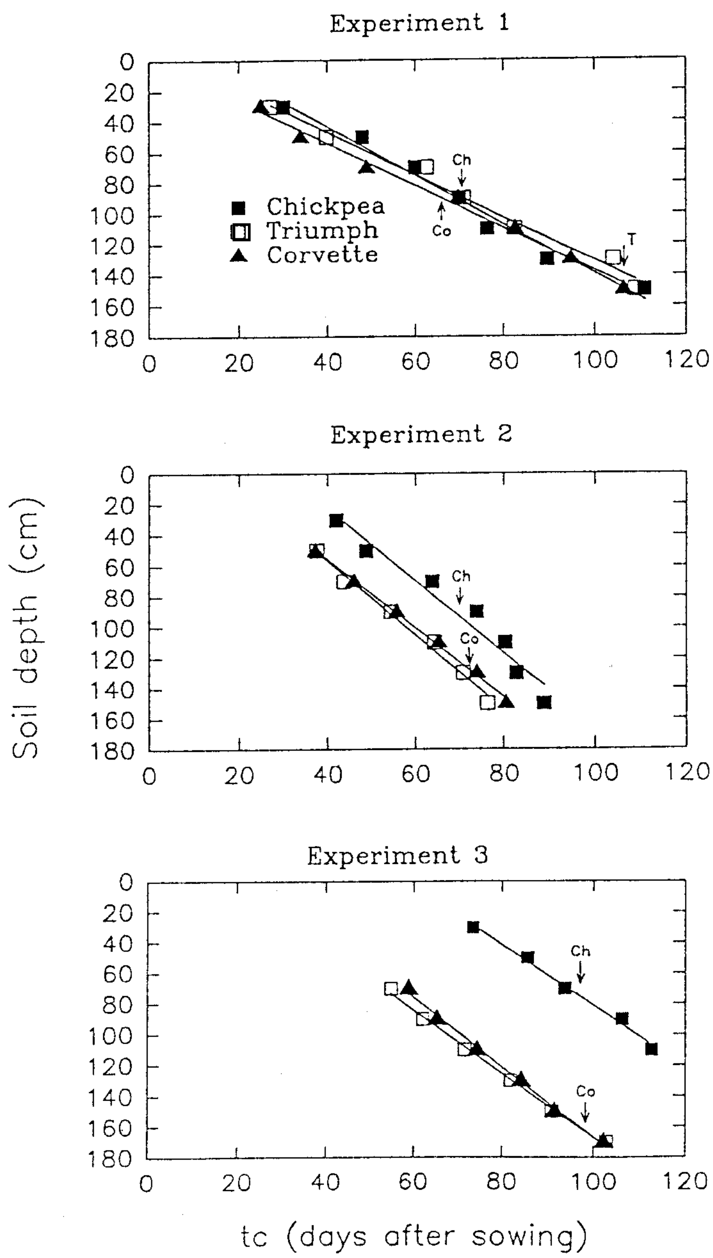

Fig. 5. The t_c values of chickpea and Corvette and Triumph barley at each soil layer in experiments 1, 2 and 3. Arrows indicate time of flowering of chickpea (Ch) or heading of Corvette (Co) and Triumph (T) barley.

Table 1. Water extraction front velocity and lag period before water extraction front starts to descend in chickpea, and Corvette and Triumph barley in three experiments

	Water extraction front velocity (cm day^{-1})	Lag period (days)
Experiment 1		
Chickpea	1·60	12·9
Corvette	1·39	1·1
Triumph	1·40	6·5
Experiment 2		
Chickpea	2·36	30·5
Corvette	2·26	15·4
Triumph	2·43	16·7
Experiment 3		
Chickpea	1·99	59·4
Corvette	2·28	26·8
Triumph	2·07	19·3

density increased at 80 and 120 cm of depth; however, only a small number of roots was found below 120 cm at 113 das. Maximum root depth increased with sampling occasions in all crops.

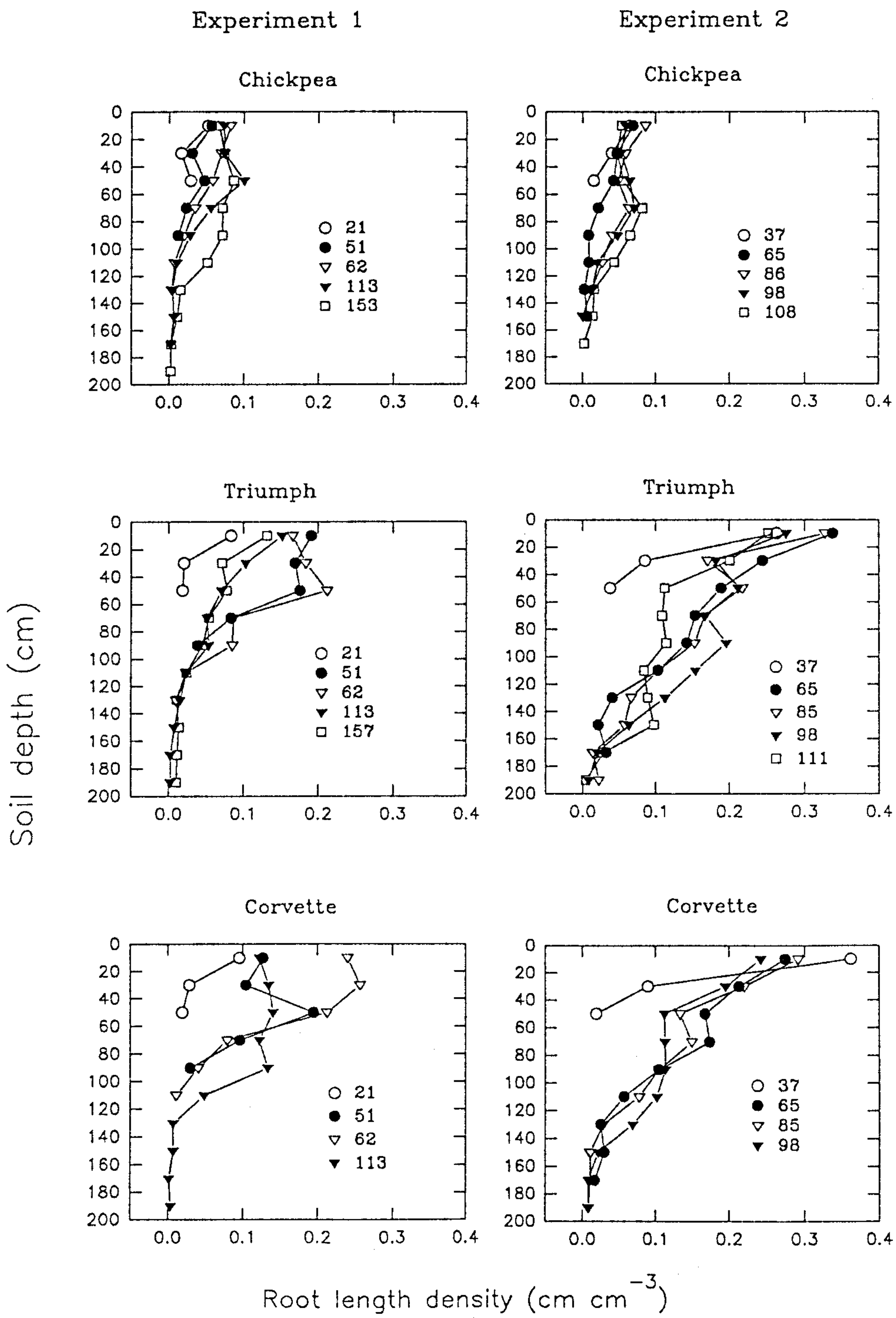

Fig. 6. Profiles of root length density of chickpea and Corvette and Triumph barley measured at several times in experiments 1 and 2.

In experiment 2, chickpea roots grew similarly to those of experiment 1, and root length density increased gradually with time in deeper layers. The root length density of chickpea was less than $0 \cdot 1$ cm cm^{-3} in all layers at any time. Root length density of Triumph was always high in the top layer. In the 40–140 cm layers, root length density was highest at 98 das, and declined between 98 and

Table 2. Root length density in each soil layer and total root length determined at 102 das in experiment 3 (Hermitage)

Numbers in rows followed by the same letter are not significantly different at $P < 5\%$

Depth (cm)	Root length density ($cm\ cm^{-3}$) Chickpea	Corvette	Triumph
0–20	0·349[a]	0·351[a]	0·526[a]
20–40	0·211[b]	0·392[a]	0·339[a]
40–60	0·193[b]	0·324[a]	0·388[a]
60–80	0·083[b]	0·332[ab]	0·541[a]
80–100	0·0[b]	0·268[a]	0·323[a]
100–120	0·0[b]	0·242[a]	0·287[a]
120–140	0·0[b]	0·109[a]	0·292[a]
Total length ($km\ m^{-2}$)	1·67[b]	4·04[a]	5·40[a]

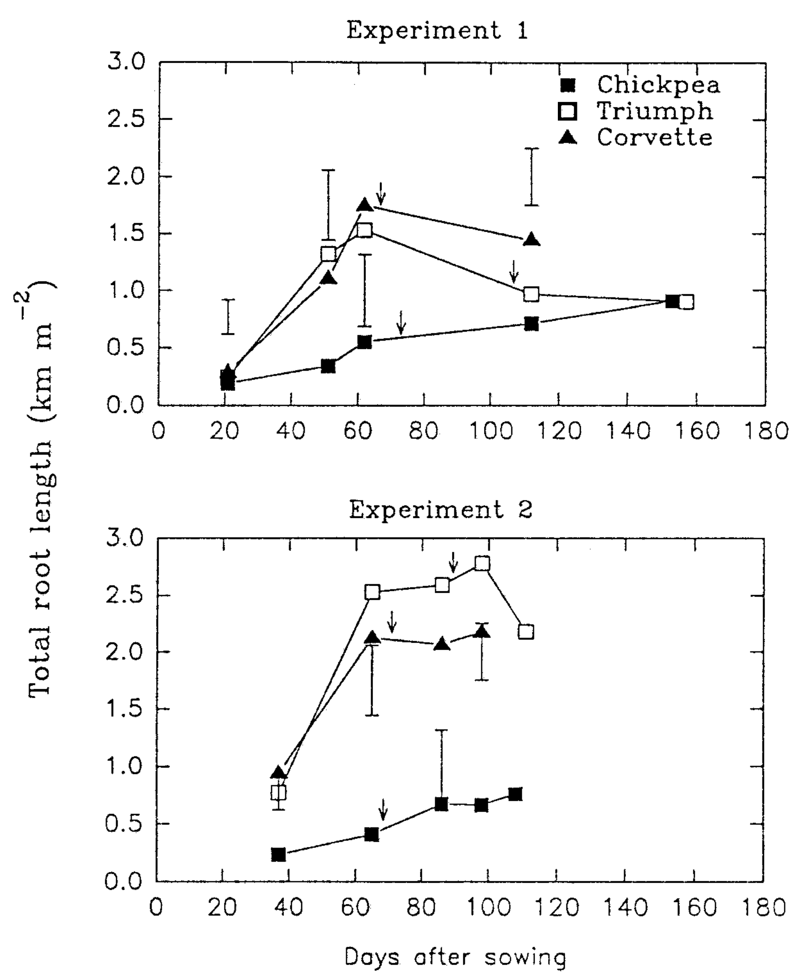

Fig. 7. Change in total root length with days after sowing of chickpea and Corvette and Triumph barley in experiments 1 and 2. Arrows indicate time of heading for Corvette and Triumph barley or time of flowering for chickpea. Vertical bars indicate l.s.d. 5%.

111 das. The profile of root length density for Corvette was similar between 65 and 98 das.

At Hermitage (experiment 3) root length densities of chickpea in 0–60 cm soil layers were much higher than those obtained at Redland Bay (experiments 1 and 2), but no roots were observed below 80 cm (Table 2). On the other hand, barley crops in this experiment produced higher root length densities throughout the soil profile compared to those at Redland Bay. Total root length (km of root per m^2 of ground area) for barley was higher than that of chickpea.

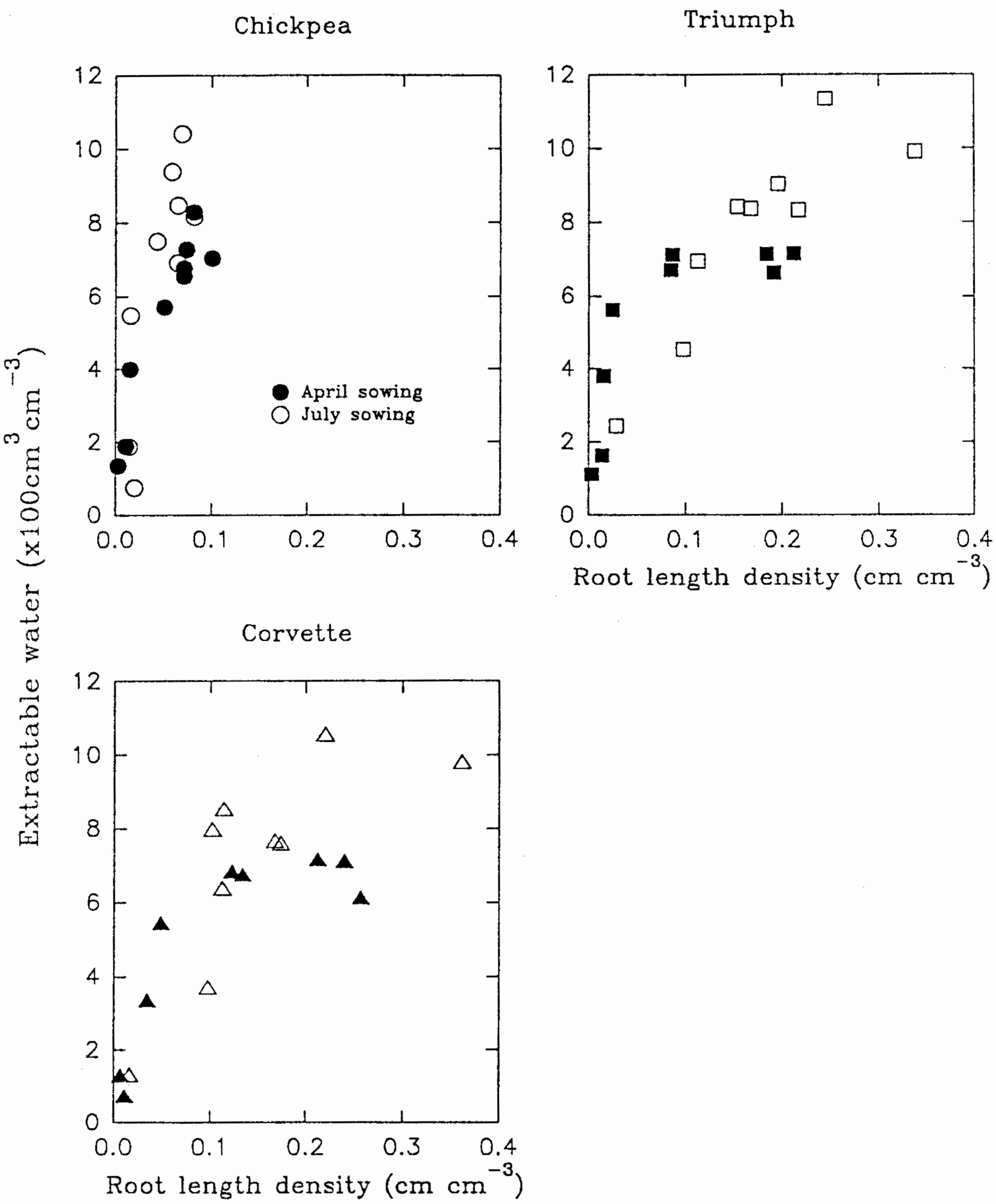

Fig. 8. The relationship between the maximum root length density of chickpea and Corvette and Triumph barley at each layer and extractable soil water of the layer in experiments 1 (April sowing solid symbols) and 2 (July sowing open symbols).

The change in total root length with time for experiments 1 and 2 is shown in Fig. 7. In experiment 1 (April sowing) Triumph and Corvette produced most of their roots between 21 and 62 das, with total root length declining after 62 das, well before heading date for Triumph. The total length of chickpea was small in early stages of growth, but it continued to increase through flowering up to maturity. Similar patterns of change were found in the July sowing (experiment 2). In all crops, and particularly in Triumph, the maximum total root length in the July sowing was higher than the April sowing.

The relationship between root length density and extractable water at the corresponding depth in experiments 1 (April) and 2 (July) is shown in Fig. 8. The root length density was taken as the maximum value for each layer from five sampling times for each experiment. Extractable soil water content increased with an increase in root length density both in chickpea and barley. The relationship appears linear in chickpea but not in barley, where there is little increase in extractable water for root length densities greater than about $0 \cdot 15$ cm cm^{-3}. Chickpea extracted a larger amount of water with the same root length density, compared with barley.

Discussion

The difference in the pattern of change in soil water content with time between barley and chickpea depended on growing conditions. In experiment 1 in which temperature was high at the beginning and the crops grew well during the early stages, water extraction was similar between the species. However, in winter sown crops, particularly in experiment 3 where winter temperature was low, chickpea used water more slowly, and there was unused water at maturity, despite the plants being water stressed, and the yield was greatly affected (Thomas and Fukai 1995*a*). The pattern of water use in the two barley cultivars was almost the same despite the difference in phenology and biomass production during the early stages of growth. The only difference, which was small and not significant, occurred towards maturity of Corvette when Triumph tended to extract more water. In experiments 2 and 3, in which water use was determined to the maturity of Triumph, maturity difference was only 7 days (Hermitage) and 13 days (Redland Bay) between the two cultivars. Thus using the water extraction front velocity of $2 \cdot 2$ cm day^{-1} and the extractable water content of 8% for Redland Bay and 20% for Hermitage, the difference in total extractable water content would be expected to be 2–3 cm, which was close to that observed.

At Redland Bay the water extraction front velocity in the July sowing (experiment 2) was higher than in the April sowing (experiment 1). According to the study by Siddique and Sedgley (1987) in the Western Australian cereal belt, the rate of increase of rooting depth in chickpea increased from $0 \cdot 7$ cm day^{-1} for a 11 May sowing to $1 \cdot 0$ cm day^{-1} for a July 20 sowing, assuming that root growth stopped at the end of the flowering period. Thus the trend with sowing time was the same as in this study and late sowings stimulated root elongation, though the rate was about half of the extraction front velocity in south-east Queensland. Monteith (1986) estimated the extraction front velocity of barley to be about 2 cm day^{-1} for an experiment in Rothamstead reported by Day *et al.* (1978). The mean air temperature in the period 30–110 das and 41–89 das in experiments 1 and 2, respectively was similar (i.e. $16 \cdot 3$°C and $16 \cdot 8$°C), and hence temperature difference did not explain differences in water extraction front velocity. In addition, lower temperature at Hermitage (experiment 3) did not result in reduced extraction front velocity. It is possible that the extraction front velocity may have been affected by the demand of the crop for water supply, as suggested by Meinke *et al.* (1993). Unlike their study, however, the difference in extraction front velocity in different soils (i.e. between experiment 2 and experiment 3) was not associated with the difference in the lag period.

The lag period which estimates the time required for the water extraction front to start to descend differed greatly among the three experiments, and this appeared to be related to air temperature. For example, the lag periods for barley (mean of two cultivars) were 3·8, 16·1 and 23·1 days, and corresponding temperatures were about 22, 14 and 11°C, for experiments 1, 2 and 3, respectively. Thus higher temperatures at seedling establishment which promoted early shoot growth (Thomas and Fukai 1995*a*) also assisted early development of the root system and early commencement of descent of the water extraction front. Compared with barley, chickpea took a much longer time for commencement of descent of the water extraction front, and this was associated with its slow shoot growth at establishment, particularly when it was sown in winter. Because of this delayed commencement of descent of extraction front in chickpea in experiments 2 and 3, the depth of soil water extraction of chickpea was shallower than in barley. In experiment 1 chickpea grew better during the early stages and the difference in the depth of extraction was smaller. The long duration of the lag period and greatly reduced depth of soil water extraction in chickpea at Hermitage resulted in reduced water use and low grain yield in experiment 3 (Thomas and Fukai 1995*a*).

The total root length of chickpea was less than in barley at any measurement occasion in experiment 2, from 51 to 111 das in experiment 1 and at 102 das in experiment 3. The total water use of chickpea up to 111 das in experiment 1 was similar to barley, which may indicate that the chickpea root was more efficient in extracting soil water, as shown in Fig. 8. Hamblin and Tennant (1987) also found that water uptake per unit root length in lupin was greater than in wheat. They explained that the axial resistance of the root was three times higher in the cereal crop than in the legume crop.

In barley, roots were mostly formed up to 65 das, and thereafter there was no major increase in root length. Lugg *et al.* (1988) found that the maximum root length of barley occurred around anthesis. This was the case in Corvette in experiments 1 and 2, and Triumph in experiment 2 in this study. However, root length density did increase at lower layers during grain filling in Corvette, indicating that root growth can occur during grain filling provided there is adequate water in the layer and sufficient assimilate being provided by the shoot. Maximum root depth and water extraction front of Corvette also increased after anthesis. The results of Triumph, on the other hand, suggest that root growth can cease much earlier than anthesis. It is possible that more rapid water extraction by the barley crop and consequential drier soil prevented new root development and promoted senescence, compared with chickpea, which used water more slowly and where the total root length increased until maturity.

The pattern of change in total root length with time in chickpea in the present experiments is similar to that observed by Brown *et al.* (1989). From visual observations of chickpea, the root diameter was much bigger and the roots hardier than those of barley. Therefore chickpea roots may not have decayed as quickly as those of barley, and this may also have contributed to the difference in total root length towards the crop's maturity.

This work has shown the susceptibility of chickpea to low temperature which caused poor root growth in winter, and the similarities in root growth and water extraction pattern of the two barley cultivars which had some differences in phenological development and biomass production. Thus the varieties appeared to differ in the efficacy of utilizing extracted water to produce biomass. This is examined in the following paper (Thomas and Fukai 1995*b*), together with species difference in water use efficiency.

Acknowledgments

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