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Radiation- and water-use associated with growth and yields of wheat and chickpea in sole and mixed crops

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Abstract

A renewed interest in mixed cropping for its potential to boost yields through increased capture and use of solar radiation and soil-water by the component species. This led to the present study, in which we assessed the performance of wheat and chickpea, grown as sole crops or mixed at half their sole crop populations for their capacity to capture and use solar radiation and soil-water. Trials were conducted in the drought season of 1994 and with or without supplementary irrigation in an average rainfall season of 1995. For the rainfed crops in both years, there was no advantage of mixed crops over wheat grown as a sole crop (wheat-s) either in terms of green area index (GAI), fraction of photosynthetically active radiation intercepted by the canopy (i_{PAR}), dry matter (DM) or grain yield produced. The lack of a yield advantage of mixed cropping was associated with poor canopy development and low yielding capacity of chickpea; it was unable to compensate for its reduced population density in the mixture. Grain yield for chickpea in the mixed crop (chickpea-m) averaged just 29% that of its sole crop (chickpea-s), whereas wheat grown in mixture (wheat-m) produced 72% the yield for wheat-s. Supplementary irrigation from early spring onwards in 1995 increased yield for chickpea-m by 44% over that of chickpea-s, while yield for wheat-m fell to 65% that for wheat-s. Every millimetre of irrigation water increased yield by 10.0, 3.8 and 12.5 kg ha^{-1} for wheat-s, mixed crop and chickpea-s, respectively. Mixed cropping did not affect the time taken by either wheat or chickpea to attain maximum growth rate, flowering or maturity. The land equivalent ratio (LER) based on grain yields for wheat–chickpea intercropping were 1.01 in 1994, 1.02 without irrigation in 1995, and 1.10 with irrigation in 1995. Neither radiation-use-efficiency nor water-use-efficiency was improved by mixed cropping compared with wheat-s. The poor performance of the mixed crop was ascribed to its poor canopy development early in the season, especially by the chickpea that resulted in low i_{PAR} and transpiration. It is concluded that there was no advantage of growing wheat and chickpea in mixed crops in southern cereal belts of Australia if total biomass or grain yield is the primary purpose.

Keywords: Evapotranspiration; Transpiration; Soil evaporation; Dry matter production; Grain yield; Land equivalent ratio (LER); Radiation-use-efficiency; Water-use-efficiency; Irrigation

1. Introduction

Yield advantage of crops in mixtures often accrues from capacity of the component species to increase capture and use of biophysical resources relative to that achievable by growing the crops separately. Competition for these natural resources by the co-existing species could, however, reduce the yields of component crops. Often reductions in the yields of individual species are, however, not large enough to reduce the total yield of the mixture relative to those of either sole crops (Yunusa, 1989; Ogindo and Walker, 2005). Competitiveness of a given species for solar radiation, and subsequently its yield, depends on its leaf area index (LAI) and height relative to those of its companion crop(s) (Fukai, 1993; Midmore, 1993). Productivity of mixed crops can be optimised by using crop species of widely different phenology and/or morphology to maximise capture of, and minimise competition for, solar radiation and soil-water (Trenbath, 1974).

Crops such as wheat and chickpea with widely different habits and canopy development patterns could form productive mixtures in the low rainfall winter cropping districts of southern Australia. Growing these two species in mixtures is not common

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with most published studies confined to warm summer growing seasons and mainly under irrigation (Singh and Singh, 1983; Ali, 1993). Singh and Singh (1983) found that every extra millimetre of water supplied through irrigation increased yields of wheat–chickpea mixtures by between 7 and 10 kg ha^{-1}. Much of the yield differences were associated with canopy development. Ali (1993) associated increased yields for millet–groundnut mixtures with greater light interception relative to that achieved by the sole crops of either species. He further reported that increased yields from mixed cropping in which wheat and chickpea were sown in two alternate rows were due to enhanced light interception that promoted growth. Enhanced canopy cover is also critical to crop water-use or evapotranspiration and its partitioning between transpiration and soil evaporation, and subsequent water-use-efficiency (Gregory et al., 2000; Yunusa et al., 1993b). It is, however, uncertain whether a mixture of wheat and chickpea would enhance canopy development and water-use in the winter-rainfall cereal belts of southern Australia.

In the current study, we assessed growth and yield of wheat and chickpea sown in pure and mixed stands on the basis of their acquisition and use of radiation and soil-water in the South Australia. Our objectives were to (1) quantify amount of solar radiation and soil-water use by the crops during the season, (2) analyse the efficiency with which the above two resources were used to produce biomass and grains, and (3) determine the productivity of mixed crop relative to those of their sole crops.

2. Materials and methods

2.1. Site

Field experiments were conducted during the winter cropping season (June–November) in 1994 and 1995 on the research farms of the University of Adelaide, Roseworthy Campus (34°32′S, 138°41′E), about 50 km north of Adelaide in South Australia. The region has a Mediterranean-type climate with a winter growing season (May–August) that is generally cool and wet. This is followed with a dry and warm spring period (September–October) when grain filling occurs. The soil at the site was alkaline in which pH measured in water increased from around 8.0 near the surface to 9.5 at 1.8 m depth. The soil is commonly referred to as a red-brown earth and belongs to the Natrixeralf of the American classification system (Soil Survey Staff, 2003). It has a duplex profile consisting of a sandy loam of between 0.6 and 0.8 m depths overlying a B-horizon of calcrete layers that contains considerable amounts of boron. Below the B-horizon is a heavy clay layer with low permeability. There is gradual rise in the bulk density with depth from 1.3 Mg m^{-3} in the top layers to 1.6 Mg m^{-3} at 1.8 m depth. Additional information on soil type and climate at Roseworthy were given by Yunusa et al. (2004).

2.2. Plot layout and crop management

Prior to sowing, existing stubble was slashed and then raked into the soil, which was then disked and rolled. The block was then treated with pre-seeding herbicides (glyphospate and trifluralin), and subsequent control of weeds was achieved by hand weeding. Super phosphate fertiliser was applied to supply 20 kg ha^{-1} of phosphorus (P). Nitrogen (N) fertiliser in the form of ammonium sulphate was applied at 50 kg N ha^{-1} at sowing. In both years, wheat (*Triticum aestivum*, cultivar Excalibur) and chickpea (*Cicer arietinum*, cultivar Semsen) were sown either in sole or in mixed plots of 2.4 m × 15 m. Sole wheat was planted in 0.20 m rows and sole chickpea in 0.40 m rows using a six row-seeder. The plots were planted to produce 155 plants m^{-2} for sole wheat and 40 plants m^{-2} for sole chickpea. Chickpea seeds were inoculated with appropriate commercial rhizobium before planting. Due to poor opening rains in 1994 planting was delayed until 19 July, while in 1995 planting was undertaken on 14 June. The intercrops were formed by sowing alternating two rows each of wheat and chickpea at rates that produced half their sole crop densities. This produced four rows each of wheat and chickpea per plot. All plant measurements were made in the inner two rows for each of the crops. Each of the three treatments (sole wheat, sole chickpea and mixed crops) was replicated four times in both years. In 1995 an additional three replicates were set up and were irrigated to further explore the role of soil-water supply in the productivity of mixed crops. Irrigation was applied with sprayer on a tractor-drawn water-tanker to these replicates between 9 September (tillering) and physiological maturity of wheat at 125 days after sowing (DAS) in late October. The first irrigation of 20 mm was followed with four sessions each of 37 mm at 10-day intervals making a total of 131 mm. Soil-water and growth variables were not measured in these three replicates, only DM and grain yield were measured at the end of the season.

2.3. Measurements

2.3.1. Growth and grain yield

Flowering in wheat was recorded when half the number of plants in a plot had at least one dehisced anther. Flowering in chickpea was taken to occur when half the number of plants in plot had at least one open flower with a visible corolla. Dry matter (DM) produced above ground by the crop was measured only at the end of the season in 1994, but six times in 1995 at 41, 73, 86, 95, 115 and 126 days after seeding. These dates in 1995 coincided with early tillering, jointing, late booting, flowering and grain filling of the wheat. On each occassion two quadrats (0.5 m × 0.8 m) samples were taken at random from each plot. The samples were dried at 70 °C for 72 h and then weighed. Grain yield was determined from the final quadrat samples taken at the end of the season. In 1995, logistic curves were fitted to DM data so that growth of the crops in the various treatments could be quantitatively defined. The general form of the curve used was:

$$y = \frac{C}{1 + \exp[-B/D(X - M)]} \qquad (1)$$

in which y was the response variable, M the days after sowing required for the crop to reach their maximum growth rate, C the maximum dry matter produced (kg ha^{-1}), B the parameter that estimates the slope of the curve, and D was the duration of growth.

2.3.2. Green area index (GAI)

This was determined only in the non-irrigated crops in 1995. The GAI was taken as the ratio of the areas of green surfaces (leaves and stems) produced by crops to that of the land area, and was determined from sub-samples of six plants of wheat and three plants of chickpea taken from the quadrat samples used for the DM. The areas of the green parts were measured with a planimeter (Patten Electroplate Electronic, model EP711, SA Australia). There were no green materials present at sampling on 126 DAS.

2.3.3. Fraction of radiation intercepted by the canopy (i_{PAR})

This was also measured only in the non-irrigated crops in 1995. A ceptometer (Decagon Devices Inc., USA) was used to measure photosynthetically active radiation (PAR) (400–700 nm) incident above (P_a) and below (P_b) the crop canopy. Measurements were made between 1100 and 1300 h mostly at fortnightly intervals, and used along with measurements of incident radiation to determine radiation-use-efficiency (RUE) following the procedures described by Yunusa et al. (1993a). Briefly, fraction of PAR intercepted by the canopy was obtained as: $i_{PAR} = 1 - (P_a/P_b)$, and was used to scale sums of incident solar radiation measured at a nearby weather station between sampling intervals to obtain amount of PAR intercepted by the crops (MJ m^{-2}); the PAR was taken as half of the incident solar radiation (Monteith and Unsworth, 1990). Radiation-use-efficiency (RUE) was calculated by dividing DM or grain yield with PAR intercepted during the season.

2.3.4. Soil-water storage and evapotranspiration

Soil-water was measured in 1.25 m depth profile only in unirrigated plots in 1995 using a neutron moisture gauge (Campbell Pacific Nuclear model 503, CA, USA). The gauge was used to take neutron counts along steel access tubes (37.5 mm internal diameter and 1.5 m length) installed in the inter-row space near the middle of each plot. Neutron counts were made at depths of 0.2, 0.4, 0.6, 0.8, 1 and 1.25 m starting on 9 September (wheat tillering stage), and repeated at approximately fortnightly intervals, until just before harvest. The water in the top 0.2 m of the soil was determined by gravimetry using soil samples taken near the access tubes. Soil-water at the start of the season and prior to planting was obtained from neutron gauge measurements taken in an adjoining paddock which had similar soil type and cropping history as the paddock used for the current study. The neutron meter was calibrated for the site in a separate study (Yunusa et al., 2004).

Crop water use or evapotranspiration (ET) was obtained from the change in the soil-water stored plus rainfall, since both runoff and deep drainage were negligible on this soil (Yunusa et al., 2004). We partitioned ET into transpiration (E_c) and soil evaporation, by estimating the former in two stages following the procedure given by Yunusa et al. (1993b):

$$\begin{aligned} E_c &= E_p\,e^{K\mathrm{GAI}}, && \text{when FAW} \geq 0.35 \\ E_c &= \frac{0.014 + 2.25\mathrm{SW}}{E_p}, && \text{when FAW} < 0.35 \end{aligned} \qquad (2)$$

in which E_p was potential evapotranspiration (mm) according to Penman–Monteith's equation (Monteith and Unsworth, 1990), K the radiation extinction coefficient (dimensionless) for which we used a value of 0.30, GAI the green area index (dimensionless), and SW is the stored soil-water (mm) in the top 0.2 m profile. Once the fraction of available soil-water (FAW), calculated as given by Yunusa et al. (1992), fell to 0.35, E_c became dependent on soil-water. Soil evaporation (E_s) was obtained as the difference between ET and E_c. Water-use-efficiency (WUE) was obtained as the ratio of either DM or grain yields to ET during the season.

The land equivalent ratio (LER) defined as land needed to produce in pure stand the same amount of yields of the crops in the mixture (Fisher, 1977) was used to analyse efficiency of intercropping system as follows:

$$\mathrm{LER} = \frac{\mathrm{GY_{wm}}}{G_{\mathrm{ws}}} + \frac{\mathrm{GY_{cm}}}{\mathrm{GY_{cs}}} \qquad (3)$$

in which the subscripts 'w' and 'c' refer to wheat and chickpea, respectively, in either sole (s) or mixed (m) crops. LERs >1.0 indicated yield benefit from the mixed crop, while <1.0 indicated lack of advantage of the mixed crop on yield.

2.4. Data analysis

Analysis of variance was performed on all data using the General Linear Model in the Minitab Version 13.1 Software package. When analysis of variance indicated effects of treatment, means were compared using Tukey–Kramer tests to determine significant differences between means at $p = 0.05$. Data for the three irrigated plots in 1995 were compared against the corresponding unirrigated plots using standard errors of means.

3. Results

3.1. Weather

Mean temperatures and rainfall data for 1994 and 1995 and the long term averages are presented in Fig. 1. The start of the seasons in 1994 and 1995 were cooler than normal, but 1994 experienced particularly warm growing season in winter when mean temperatures in June and July were warmer than in the preceding and following months. Except for January 1994 was much drier than normal with monthly rainfall being mostly about a third of their long term averages during the growing season. Rainfall in 1995 was close to the average pattern during much of the season, but the winter was particularly wet in June and July; the terminal growing period (September–October) in spring was drier than normal. Rainfall during growing season was 104 mm in 1994 and 305 mm in 1995 compared with the normal value of 420 mm. Thus, the irrigated blocks had a total seasonal water supply of 436 mm, above seasonal rainfalls for the district in the early 1990s (Yunusa et al., 2004).

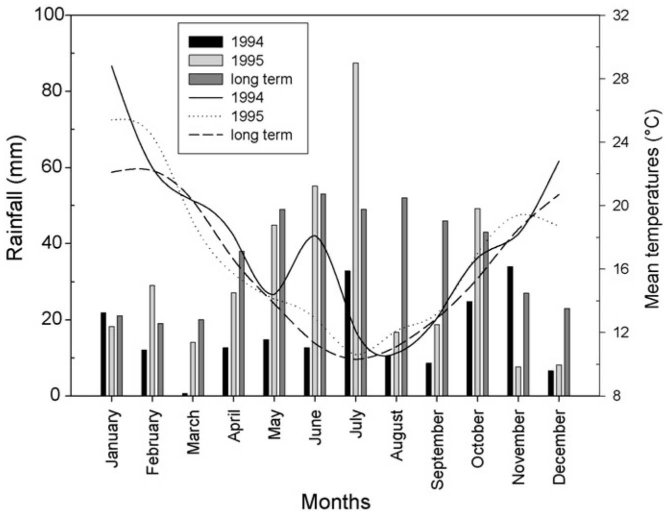

Fig. 1. Values for monthly rainfall (bars) and temperatures (lines) for 1994, 1995 and their long term averages at Roseworthy.

3.2. Growth and yields in 1994 and 1995

Wheat attained anthesis at 87 DAS while flowering for chickpea was at 92 DAS in both sole and mixed crops 1994. Mixed cropping failed to increase either DM or grain yields when compared with wheat-s in the three trials, but chickpea-s always had the least yield in 1994 (Table 1). Peak values for GAI produced by the crops during the season were in order wheat-s (1.5) > mixed crop (0.7) > chickpeas-s (0.4), the difference being significant; corresponding values for i_{PAR} were 0.31, 0.26 and 0.23, respectively.

In 1995 these stages were attained at 97 DAS for wheat and 101 DAS for chickpea in either sole or mixed crops and with or without irrigation. There were more frequent measurements of growth variables were made in 1995, but similar patterns as in 1994 were observed amongst the treatments with the magnitudes of GAI and i_{PAR} being wheat-s $\geq$ mixed crop > chickpeas-s, especially in the mid-season (Fig. 2). Decline in GAI towards the end of the season was slower for chickpea-s, which at 116 DAS had higher GAI than either of the other two crops. Accumulation of DM during the season also followed a similar pattern to canopy development. Between 70 and 95 DAS daily rates for DM (kg ha^{-1} day^{-1}) accumulation was 127 for the mixed crop compared with 151 for wheat-s and 84 kg for chickpea-s. The ET was not significantly affected by cropping system, but it was particularly rapid between 80 and 100 DAS, when it averaged 3.4 mm day^{-1} for mixed crop compared with 3.2 mm day^{-1} for wheat-s and only 2.6 mm day^{-1} for chickpea-s.

The final DM for the mixed crop and wheat-s was at least twice that for chickpea-s in 1995, while grain yield was similar for the mixed crop and wheat-s, both of which produced at least 70% more grains than chickpea-s (Table 1). DM and

Table 1
Summary of growth and yield variables for wheat and chickpea grown in sole or mixed crops, and the land equivalent ratios based on DM (LER$_d$) or grain yield (LER$_g$) without irrigation in 1994 and without or with irrigation in 1995 at Roseworthy

Variables	Cropping systems[a]		
	Wheat-s	Chickpea-s	Mixture
1994 season			
DM at harvest (kg ha^{-1})	3412a	1430b	2771a
Grain yield (kg ha^{-1})	1512a	552b	1368a
Harvest index	0.44a	0.37b	0.49a
LER$_d$	na	na	0.97
LER$_g$	na	na	1.01
1995 season unirrigated			
DM at harvest (kg ha^{-1})	6989a	2800b	6164a
Grain yield (kg ha^{-1})	3042a	802b	2445a
Harvest index	0.44a	0.29c	0.40b
LER$_d$	na	na	1.00
LER$_g$			1.02
1995 season irrigated			
DM at harvest (kg ha^{-1})	10618a	7007b	8532a
Grain yield (kg ha^{-1})	4366a	2446c	2938b
Harvest index	041a	0.35b	0.34b
LER$_d$	na	na	1.03
LER$_g$	na	na	1.10
Percentage change in values for irrigated relative to unirrigated crops in 1995			
DM at harvest (kg ha^{-1})	+51	+150	+38
Grain yield (kg ha^{-1})	+44	+204	+20
Harvest index	−7	+21	−15
LER$_d$			+3
LER$_g$			+9

na, not applicable.

[a] Means in the same rows followed by different letter(s) are statistically different at $p \leq 0.05$.

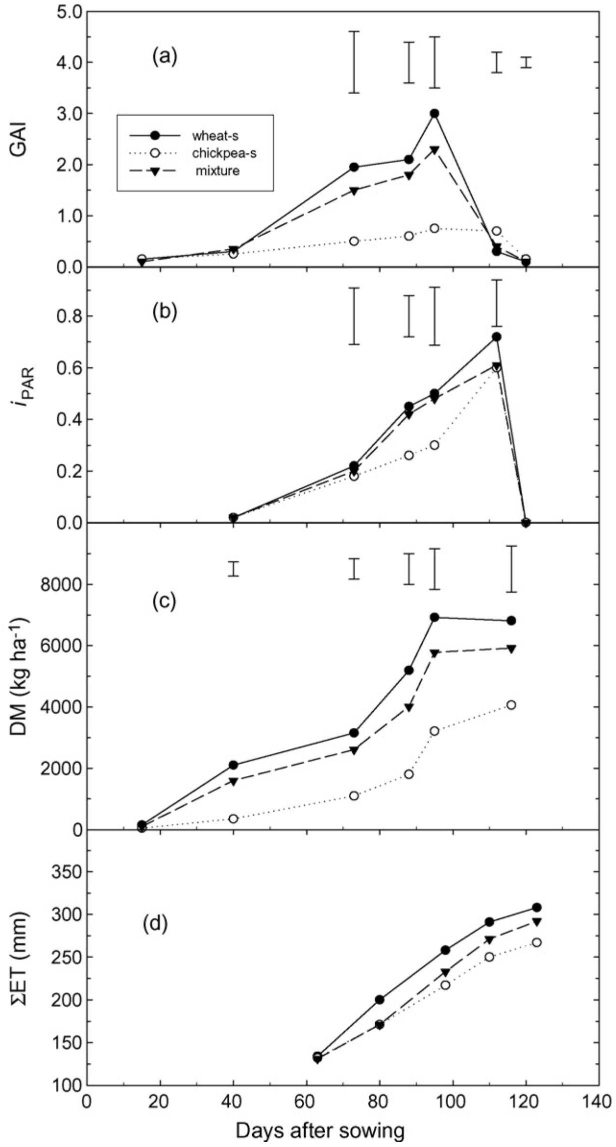

Fig. 2. Growth variables for sole crops of wheat (wheat-s) and chickpea (chickpea-s) and for the mixed crops at Roseworthy in 1995: (a) green area index (GAI), (b) fraction of PAR intercepted (i_{PAR}), (c) dry matter (DM) accumulation, and (d) cumulative evaptranspiration (ET). Bars are LSD at $p = 0.05$, there were no significant effects of cropping system on cumulative ET. Flowering was recorded at 97 DAS for wheat and at 101 DAS for chickpea.

grain yields were partitioned between the two crops at harvest (data not presented) and showed that grain yields for wheat-m was 72% that for wheat-s resulting in yield-to-density ratio of 1.44 (i.e. 72/50), while for chickpea-m it was just 30% that for chickpea-s producing a ratio of 0.60.

Application of supplementary irrigation significantly increased the performance of all three cropping systems in 1995, but differences in DM and grain yields between the three cropping systems were similar to those in the unirrigated plots. Increases in the performance of the mixed crop due to irrigation were modest, being less than 40%, compared with the sole crops in which DM and grain yield rose by 51 and 44%, respectively, for wheat-s and both by more than 140% for chickpea-s.

Table 2

Seasonal totals for evapotranspiration (ET) and its components of transpiration (E_c) and soil evaporation (E_s) and radiant energy intercepted, and water-use-efficiency and radiation-use-efficiency for the unirrigated wheat and chickpea and their mixtures at Roseworthy in 1995

Variables[a]	Cropping systems[b]		
	Wheat-s	Chickpea-s	Mixture
ET (mm)[c]	302	261	285
E_c (mm)	144	91	137
E_s (mm)	158	170	148
E_c/ET	47.7	34.9	48.1
PAR intercepted (MJ m^{-2})	375a	273b	331a
RUE_d (g MJ^{-1} m^{-2})	1.42a	0.87b	1.59a
RUE_g (g MJ^{-1} m^{-2})	0.73a	0.25b	0.66a
WUE_d (kg ha^{-1} mm^{-1})	20.4a	9.4b	20.8a
WUE_g (kg ha^{-1} mm^{-1})	8.6a	2.6b	10.3a
LER_d	na	na	1.00
LER_g	na	na	1.02

[a] Subscripts 'd' and 'g' denote efficiency based on either dry matter or grain yields.

[b] Means in the same rows followed by different letter(s) are statistically different at $p \leq 0.05$.

[c] There were no significant differences in ET between cropping systems; E_c (and indirectly E_s) was approximated with Eq. (2).

Chickpea-s was the only cropping system in which irrigation raised the harvest index (grain yield/DM at harvest), while this variable declined for wheat-s and mixed crop. Partitioning of DM and grain yields between the component species in the mixed crop (data not presented) found that irrigation increased these variables by 50 and 27% for wheat-m, while they were up to 2.5- and 4.4-fold for chickpea-m. On the whole, every millimetre of irrigation produced a gain in grain yield of 10 kg ha^{-1} for wheat-s, 3.8 kg ha^{-1} for the mixed crop and 12.5 kg ha^{-1} for chickpea-s.

For the unirrigated crops, the quantity of PAR captured by the crops during growth in 1995 was similar for wheat-s and the mixed crop, which were at least 21% higher than for chickpea-s (Table 2). Total ET for the mixed crop was 94% that for wheat-s, but was 9% more than for chickpea-s. Chickpea-s, however, partitioned only 35% of its ET through E_c compared with 48% for either wheat-s or the mixed crop.

Fitting logistic curves to DM showed that growing wheat and chickpea in mixtures changed their growth characteristics. For instance, number of days taken to attain maximum growth rate was earlier by 4 days for wheat-m than wheat-s (Table 3). For chickpea, this point was attained 7 days earlier in mixture than in sole crops, while for the mixed crop the duration was similar for the component wheat and chickpea. Peak DM produced by the crops was reduced by 22% for wheat-m and 75% for chickpea-m compared with those by either wheat-s or chickpea-s. This value for the mixed crops lies almost mid-way between those for wheat-s and wheat-m. Total duration of growth for the three cropping systems was similar (Table 3).

3.3. Extraction of soil-water in 1995

Changes in the soil's volumetric water content (θ) during the season are presented in Fig. 3. Water content was similar for the

Table 3
Mean values (±standard errors of means) for growth indices for the unirrigated wheat and chickpea in sole or the mixed crop in 1995

Indices	Cropping systems				
	Wheat-s	Wheat-m	Chickpea-s	Chickpea-m	Mixture
Days to maximum growth rate (*M*)	92 ± 1.9	88 ± 1.0	95 ± 1.6	88 ± 2.4	89 ± 1.4
Peak amount of DM produced (*C*)	7015 ± 183	5249 ± 272	3027 ± 130	771 ± 46	6211 ± 280
Growth duration (*D*, days)	126 ± 3.7	123 ± 6.7	128 ± 5.2	125 ± 8.6	126 ± 4.8

three cropping systems at early tillering (53 DAS), when the top 0.1 m of the profile was dry and had only 10% moisture content. Below the top layer, θ was largely uniform (∼30%) down to 1.0 m, but increased to 35% at 1.4 m depth for all treatments. At all later dates chickpea had the wettest profile while wheat had the driest; the differences in θ for these treatments were especially evident between 0.3 and 0.8 m depths, indicating this was the zone of vigorous activity by the wheat root. In this zone, the difference in θ between wheat-s and chickpea-s averaged 10% at 73 DAS, but grew to a maximum of 15% at 103 DAS shortly after anthesis. The zone of soil between 0.2 and 1.2 m depths was always wetter under chickpea-s, then mixture and then sole wheat; there were no changes in θ at 1.4 m depth for all cropping systems throughout the season. At the end of the season, chickpea had a wetter soil profile than the other two treatments.

3.4. Efficiency of resource use in 1995

The RUE based on either DM ($\mathrm{RUE_d}$) or grain yield ($\mathrm{RUE_g}$) was similar for wheat-s and mixed crops and was at least twice those for chickpea-s (Table 2). The WUE for DM ($\mathrm{WUE_d}$) was also similar for wheat-s and mixed crops, either of which produced at least 20 kg DM ha^{-1} for every millimetre of ET compared to just 9.4 kg for chickpea-s. A similar trend was obtained for water-use-efficiency based on grain yield ($\mathrm{WUE_g}$) which for chickpea-s was less than a third that for wheat-s or the mixed crop. Irrespective of irrigation, productivity of the mixed crop was not substantially higher than that of wheat-s. The LER based DM being just 1.07 for the unirrigated mixed crop and 0.99 for the irrigated mixed crop; corresponding LER based on grain yield were 1.03 and 1.10.

4. Discussion

Of the three factors (soil N, soil-water and radiation) that determine growth and yield in mixed cropping, N was in adequate supply in the current study. The 50 kg N ha^{-1} applied at planting was sufficient to meet the needs of the crops either on their own or as a mixture in a similar environment of southern Australia (Ofori and Stern, 1986). Earlier experimental and simulation studies found that 30 kg N ha^{-1} was adequate for optimum yield of wheat in this environment (Yunusa et al., 2004). This leaves interception of solar energy and soil-water as major factors that might have limited productivity of the mixed crop in this study.

Biomass production of mixed crops is often associated with canopy development and intercepted radiation. Similarity in GAI and i_{PAR} between the mixed crop and wheat-s (Fig. 2) meant that neither seasonal interception of PAR, total ET nor DM for wheat-m was reduced by mixing with chickpea. Similarity in the GAI and i_{PAR} between the mixed crop and wheat-s, especially early in the season, ensured parity in their seasonal ET. A rapid canopy development for the mixed crop early in the season when the top layers of the soil were moist, would have enabled the crop to use this water that would otherwise be lost through E_{s}. This was almost certainly the case in the study of Ali (1993) in which the mixed crops closed their canopies and intercepted almost all of the incident radiation within 8 weeks of sowing; even chickpea-s in that study had an i_{PAR} as high as 0.95. A similar pattern of rapid canopy development was observed for the maize–bean (*Phaseolus vulgaris*) mixtures for which i_{PAR} was 15% higher than for either sole crops in South Africa (Tsubo et al., 2001). In the winter growing season by contrast, poor canopy development due to low winter temperatures imposes little restraint on E_{s} from the often moist soil (Gregory et al., 2000). These conditions could last for up to 80 days after sowing in cereals (Eberbach and Pala, 2005), i.e. much of the vegetative phase of the crop, and up to 50 days into the season even in pre-existing legume pastures (Yunusa et al., 1992). Thus, the generally poor canopy covers in the current study, in which i_{PAR} was below 0.5 for all the three crops during the vegetative phase (Fig. 2), is the norm and resulted in the high E_{c}/ET ratios in the current study (Table 2). A more rapid and larger canopy development by the cereal, therefore, enabled wheat-m to proportionally exploit more of the soil-water, at the expense of chickpea-m, allowing it to produce 75% the yield of wheat-s, but with half the population density (Section 3.2). While chickpea-m by contrast produced only 30% that of its sole crop yield.

Wheat and chickpea used in this study were apparently not ideal for maximising yields from their mixed crops. Chickpea was particularly slow in growth (Table 3), which coupled with its short stature, made it unable to effectively compete against wheat especially for soil-water. Chickpea is shown to have one of the slowest growth rates and smallest canopies amongst winter pulses in Australia, where its peak GAI is often about a quarter that of other pulses such as faba bean (*Vicia faba*) (Mwanamwenge et al., 1997). By the time chickpea-s in the current study attained peak GAI and i_{PAR} late in the season at 101 DAS, the soil profile under mixed crop was as dry as that under wheat-s (Fig. 3). It was therefore not able to take a full advantage of its relatively intact canopy at this time to

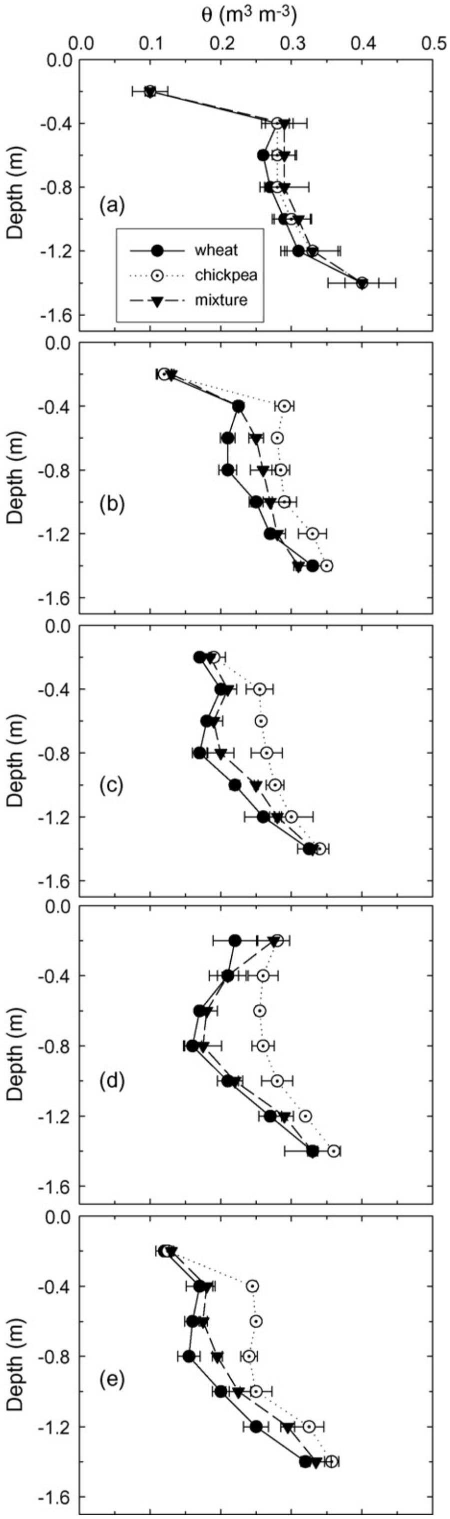

Fig. 3. Distribution of volumetric soil moisture content (θ) (±standard errors of means) in the 1.4 m soil profile under wheat-s, chicpea-s and in mixed crops at Roseworthy in 1995: (a) 53, (b) 73, (c) 91, (d) 103 and (e) 116 days after sowing.

enhance ET and grain yield, because the profile was almost dry. Hence, supplementary irrigation in spring benefited chickpea in both mixed and sole crops than it did wheat. Increases in yields per unit amount of water from irrigation are consistent with 7–10 kg ha^{-1} found for wheat–chickpea mixed crops (Singh and Singh, 1983) and for wheat (Yunusa et al., 1993b). This improvement in the yield and harvest index for chickpea could be associated with extended crop duration (Thomas and Fukai, 1995), observed in the delayed senescence of the unirrigated chickpea during grain filling (Fig. 2). An increase in the harvest index by 74% for chickpea-m, compared to a 14% decline for wheat-m, was reflected in the LER of 1.10 for the irrigated mixed crop compared to 1.02 without irrigation. With adequate supply of soil-water, therefore, chickpea could compete with wheat and be productive in mixed cropping with this cereal. These yield responses to irrigation late in the season are consistent with the concept of conserving soil-water for grain filling in semi-arid Mediterranean environments of Australia (Rickert et al., 1987). The decline in the harvest index for wheat-s and mixed crop with irrigation (Table 1) indicated that these crops still experienced a degree of water shortage during grain filling.

There was no advantage of mixed cropping over wheat-s in terms of overall productivity. The low LERs presented here (Table 1) were not surprising and showed that mixed cropping increased productivity based on grain yield by only 2%, while there was no advantage when based on biomass production. These LER values were much lower than a range of 1.12–1.21 reported by Ali (1993) for a similar mixed cropping of wheat–chickpea in which the two crops were grown in two alternating rows. The component crops in this earlier study, however, captured larger proportions of incident solar radiation than achieved here. Our LER values were also generally a range values of between 1.18 and 1.39 often reported for mixed cropping involving tropical and subtropical cereals (Reddy and Willey, 1981; Yunusa, 1989). We recognise, however, that mixed cropping may be practised for other purposes than just an increase in the productivity of the current crops. Other common objectives for mixed cropping include improvements in soil N reserves and conservation of soil health. The latter is the main motivation for the renewed interest for this cropping system in the southern cropping regions of Australia, where it is employed for hydrological control to minimise water logging and deep drainage (Egan and Ransom, 1996), and of the Canterbury region of New Zealand for improving soil structure and fertility (Haynes and Francis, 1990).

5. Conclusions

We did not find wheat and chickpea to be an ideal combination for mixed cropping under the three seasonal water supply conditions experienced during the course of this study. Hence, growing these two crops in mixtures is unlikely to provide any yield advantage in the Mediterranean-type environment of southern Australia. This was principally because of the similarity in the phenology of the species, sluggish growth of chickpea and, most importantly, the cool temperatures and low rainfall during much of the growing season. Planting the component crops at different times may shift peak demands for soil-water by one of the component species to minimise inter-specific competition, but may not be viable due to the well-defined rainy season and technical and management difficulties this would entail.

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