Elsevier Editorial System(tm) for European Journal of Agronomy

Manuscript Draft

Manuscript Number:

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

Article Type: Research Paper

Keywords: evapotranspiration, transpiration; soil evaporation; dry matter production; grain yield; land equivalent ratio (LER); radiation-use efficiency; water-use efficiency; irrigation

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Manuscript Region of Origin:

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

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Short title: Wheat–chickpea mixed cropping

Abstract

There is a renewed interest in boosting farm productivity in the semi-arid Mediterranean agricultural zones of Australia through increased capture and use of solar radiation and soil-water by simultaneous growing of two or more species of plants in mixtures. The present study assessed the performance of wheat and chickpea, mixed at half their sole crop populations for their capacity to capture and use solar radiation and soil-water in the drought season of 1994 and close-to-normal rainfall season of 1995 in South Australia. 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 the low yielding capacity of chickpea and its inability 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 of chickpea-m by 44% over that of chickpea-s, while wheat-m fell to 65% that of wheat-s. Every millimetre of irrigation water increased yield by 10.0, 3.8 and 12.5 kg/ha 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. Using the land equivalent ratio (LER) to assess productivity in terms of grain yields for wheat–chickpea intercropping produced values of between 1.01 in 1994 and 1.02 in 1995; an LER of 1.10 was obtained with supplementary irrigation in 1995. Mixed cropping did not improve either radiation-use efficiency or water-use efficiency when compared to wheat-s.

It is concluded that there was no advantage of mixed cropping when based on total biomass or grain yield produced by the crops.

Keywords: evapotranspiration, transpiration; soil evaporation; dry matter production; grain yield; land equivalent ratio (LER); radiation use efficiency; water-use efficiency; irrigation

1. Introduction

Mixed cropping has been largely confined to non-mechanised farming systems in less advanced farming systems. Increasing attention being paid in recent years in advanced mechanised agricultural systems, where it's potential benefits for environmental and land management are being explored. In the southern Mediterranean regions of Australia, simultaneous growing of seasonal grain crops with pastures is recognised as an effective management strategy for hydrological control to minimise water logging and deep drainage (Egan and Ransom, 1996; Latta et al., 2001; Humphries et al., 2004). In the temperate cropping districts of Canterbury, New Zealand, mixed cropping of arable crops and pasture legumes is practised primarily to improve soil structure and fertility (Hayes and Francis, 1990). Even in these mechanised farming systems, however, the long term objective is to sustain high yields of grain crops and pastures.

An ideal mixed cropping system would meet long term management objectives while providing increased yields. Increased yields of crops in mixtures often accrue from their capacity of the crops to increase capture and use of biophysical resources relative to that which would be achieved by growing the component 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 not large enough to reduce the total yield of the mixture relative to those of either sole crop (Reddy and Wiley, 1981; Yunusa, 1989; Yunusa et al., 1995; Walker and Ogindo, 2003). 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). Ali (1993) associated increased yields for millet-groundnut mixtures with its greater light interception relative to that by the sole crops. 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 leading to increased growth. Enhanced canopy cover is also critical to crop water-use and water-use efficiency in the rainfall especially in the Mediterranean environments with winter rainfall. In these environments, early canopy cover promotes partitioning of evapotranspiration (ET) through transpiration rather than soil evaporation thereby increasing amount of yield per unit ET (Eberbach and Pala, 2005; Gregory et al., 2000; Yunusa te al. 1992).

In rainfall-limited environments, productivity of mixed cropping, as for any cropping system, would depend on availability of soil-water. Singh and Singh (1983) found that every extra millimetre of water supply through irrigation increased yields of wheat-chickpea mixtures by between 7 and 10 kg/ha. They also obtained lowest water –use efficiency (WUE) of 4.8 kg ha^{-1} mm^{-1} from sole crop of chickpea and the highest value of 12.0 kg ha^{-1} mm^{-1} from the chickpea –wheat intercrop. Much of the yield differences were associated with canopy development. To optimise productivity, an ideal mixed cropping will be one that limits competition for solar radiation and soil-water to optimise performance of the component species. This can be achieved by using crop species of widely different phenology and/or morphology to maximise capture of, and minimize competition for, solar radiation and soil-water (Trenbath, 1974). Crops such as wheat and chickpea, based on the known differences in their canopy development, could be appropriate for the low rainfall winter cropping districts 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 two resources were used to produce biomass and grains, and (3) determine the productivity of mixed crop relative to those of the sole crops.

2.0 Material and Methods

2.1 Site

Field experiments were conducted during winter cropping season (June to November) in 1994 and 1995on the experimental 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 climate with a winter growing season (May–August) that is generally cool and wet. This is followed with a dry and warm main 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 to 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. Further details of soil type and climate at Roseworthy were given by Yunusa et al. (2004).

2.2 Plot layout and crop management

Prior to sowing, the 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), 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 by 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. 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 2 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. Chickpea seeds were inoculated with appropriate commercial rhizobium before planting. All plant measurements were made in the inner two rows for each of the crops. Each of the three treatments (sole, 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. Irrigation was applied to these replicates between 9 September (tillering) and physiological maturity at 125 days after sowing (DAS) in late October. The first irrigation of 20 mm was followed with four sessions each of 37 mm applied 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 (DAS). These dates in 1995 coincided with early tillering, jointing, late booting, flowering and grain filling of the wheat. In both years, two quadrats (0.5 x 0.8 m) samples were taken at random from each plot. The samples were dried at 70ºC for 72 hours 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 so that growth of the crops in the various treatments could be quantitatively defined. The general form of the curve is:

$$y = C/(1 + EXP[-B/D(X-M)]) \qquad (1)$$

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

2.3.2 Green area index (GAI)

This 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})

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 hours 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. (1993b). 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 whether 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 non-irrigated plots using a neutron moisture meter (Campbell Pacific Nuclear model 503, Ca, USA) 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 along the tubes 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 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 an earlier 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. (1993a). E_c was obtained as follows (1994):

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

in which E_p was potential evapotranspiration (mm) according to Penman-Monteith's equation (Monteith and Unsworth, 1990), *K*, radiation extinction coefficient (dimensionless) for which we used a value of 0.30; GAI, green area index (dimensionless), defined above; SW, stored soil-water (mm) in the top 0.2 m profile. Once the faction of available soil water (FAW), calculated as given by Yunusa et al. (1992), fell to 0.35, E_c became dependent on soil-water. The FAW of 0.35 was found to be restricted on a red brown earth (Siddique and Sedgley, 1985; Yunusa et al 1994). Soil evaporation (E_s) was obtained as the difference between ET and T. Water-use efficiency (WUE) was obtained as the ratio of either DM or grain yields produced 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. This was calculated as given by Mead and Willey (1980):

$$LER = GY_{wm}/G_{ws} + GY_{cm}/GY_{cs} \quad (3)$$

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 blocks in 1995 were compared against the corresponding non-irrigated plots using standard errors of means.

3.0 Results

3.1 Weather

Mean temperatures and rainfall data for 1994 and 1995 and the long term averages are presented in Figure 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. The season of 1995 was close to normal in terms of rainfall during much of the season and, except during the winter, was particularly wet between June and July; the terminal growing period (September-October) was drier than normal in this year. Rainfall during growing season was 104 mm in 1994 and 272 mm in 1995 compared to the normal values of 292 mm.

3.2 Summary of yield data in 1994

The dry season in 1994 severely inhibited growth and yields for crops both in sole and mixed plots (Table 1). There was no advantage from mixing the crops in terms of maximum GAI and i_{PAR}, both of which were larger for wheat grown in sole crops (wheat-s) than for either of the other cropping systems. Mixed crop, however, had larger GAI than chickpea grown sole (chickpea-s). Both final DM at harvest and grain yield were similar for mixed crops and wheat-s, both of which were more productive than chickpea-s. The LER for the the mixed crop departed very little from unity, being 0.97 based on DM and 1.01

based on grain yield.

3.3 Extraction of soil-water in 1995

Changes in the soil's volumetric water content (θ) during the season are presented in Fig. 2. Water content was similar for the 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 to 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 and 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 Growth and yield variables in 1995

Anthesis occurred in wheat at 97 days after sowing (DAS) in both sole and mixed crops, while chickpea attained flowering on 101 DAS. There was no difference in the GAI (Fig. 3a) between wheat-s and the mixed crop throughout the growing season; both of these crops had larger canopies than chickpea-s until flowering. 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. Difference in i_{PAR} between the cops (Fig. 3b) reflected those in GAI in the first 90 days, after which it was similar for the three crops. Amount of energy captured during the season by the crops were similar for wheat-s and the mixed crop, which were at least 18% higher than for chickpea-s (Table 2).

Water-use did not differ significantly between the three cropping systems throughout the season. For all cropping systems, ET (Fig. 3c) was particularly rapid between 80 and 100 DAS, when it averaged 3.4 mm d^{-1} for mixed crop compared with 3.2 mm $^{-1}$ for wheat-s and only 2.6 mm $^{-1}$ for chickpea-s. Total ET during the season for the mixed crop was 94% that for wheat-s and 9% more than for chickpea-s (Table 2). There were no differences between the cropping systems in their partitioning of the seasonal ET. While almost half of ET was used for transpiration (E_c) in wheat-s and mixed crops, only 35% was used for this process in chickpea-s. Thus, the mixed crop lost 10 mm less water to evaporation (E_s) than wheat-s and 22 mm less than chickpea-s.

There was no difference between mixed crops and wheat-s in their DM accumulation during the season; either of these crops produced significantly more biomass than chickpea-s (Fig. 3d). Much of the differences in biomass production between the crops occurred between 70 and 95 DAS when daily rates for DM (kg/ha.day) accumulation was 127 for the mixed crop compared with 151 for wheat-s and 84 kg for chickpea-s. At harvest, DM was in the order wheat-s > mixed crops > chickpea-s. DM for wheat-m was 72% that for wheat-s, while for chickpea-m it was just 28%.

Fitting logistic curves to DM showed that growing wheat and chickpea in mixtures changed their growth characteristics, such as number of days taken to attain maximum growth rate was earlier by four days for wheat-m than wheat-s (Table 3). For chickpea, this point was attained seven 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 values for wheat-s and wheat-m. Total duration of growth for the three cropping systems was similar.

Data in Table 4 show that grain yield was similar for the mixed crop (2445 kg/ha) and wheat-s (3042 kg/ha), either of which produced at least 70% more grains than chickpea-s (242 kg/ha). Grain yields produced by wheat-m was 72% that of wheat-s, while chickpea-m had only 30% the yield of chickpea-s.

3.4 Responses of DM and grain yield to irrigation in 1995

Application of supplementary irrigation significantly increased the performance of all the three cropping systems (Table 4). This improvement was particularly pronounced for chickpea-m in which both DM and grain yield were increased 2.5-fold and 4.4-fold, respectively. Improvements due to irrigation in the performance of wheat were modest; DM for wheat-s increased by 23% and for wheat-m by 50%, while the increases in grain yield were 44% and 30%, respectively. In the mixed crop, irrigation increased the grain yield for chickpea-m by 44% more than for chickpea-s, while grain yield for wheat-m declined to 65% that for wheat-s. Additional water supply increased DM by 38% and grain yield by 20% for the mixed crop. It also increased the harvest index (grain yield/DM at harvest) for all crops, except for wheat-m and mixed crop where it declined by about 15%. Every millimetre of irrigation produced a gain in grain yield of 10 kg/ha for wheat-s, 3.8 kg/ha for the mixed crop and 12.5 kg/ha for chickpea-s. Irrespective of irrigation, productivity of the mixed crop was not substantially higher than that for wheat-s, with LER based DM being just 1.07 for the non-irrigated mixed crop and 0.99 for the irrigated mixed crop; corresponding LER based on grain yield were 1.03 and 1.10.

3.5 Efficiency of resource use in 1995

The RUE based on either DM (RUE_d) or grain yield (RUE_g) was similar for wheat-s and mixed crops and was at least twice those for chickpea-s (Table 5). The WUE for DM (WUE_d) was also similar for wheat-s and mixed crops, either of which produced at least 20 kg of DM per hectare 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 (WUE_g) which for chickpea-s was less than a third those for wheat-s and the mixed crop.

4. Discussion

Results presented here suggested that a mixed crop of wheat and chickpea had no advantage over wheat planted as a sole crop in terms of either biomass or grain yield that we observed. It is noteworthy that DM for wheat-s and the mixed crop was similar in both the dry year of 1994 and 1995, and even with supplementary irrigation in 1995 (Table 4). Of the three factors comprising soil N, soil-water and radiation that determine growth and yield in mixed cropping (Fukai, 1993), the first was in adequate supply in the current study. The 50 kg N/ha applied at planting was sufficient to meet the needs for the crops either in their sole or mixed plots in a similar environment of southern Australia (Ofori and Stern, 1986). Also, earlier experimental and simulation studies found that 30 kg N/ha 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.

Productivity of mixed crops in terms of biomass production is often associated with canopy development and intercepted radiation. Since the mixed crop in the present study did not have advantage in either GAI or i_{PAR} compared to wheat-s (Fig. 3), there were no differences between these two treatments in the amount of solar energy intercepted and/or the amount of water used. Consequently, DM produced by wheat was not affected by cropping system. Total energy absorbed by the three cropping systems during the season was reduced only for chickpea-s by as much as 37% (Table 2). Interception of radiation during the season by the mixed crop increased relative to that of chickpea-s only and not to that of wheat-s. This was contrary to experience of Tsubo et al. (2001) who obtained a 15% increase in incident radiation intercepted by maize–bean *(Phaseolus vulgaris*) mixtures relative to those of the sole crops of either of the component species.

An inability of the mixed crop to significantly modify solar energy interception also ensured similarity in its water use and that of wheat-s. There was therefore no difference in the DM and grain yields between these two cropping systems in the dry year of 1994 and in 1995. Performance of the mixed crop was largely determined by wheat that had a higher growth rate and productivity than chickpea (Table 3). Shading of chickpea by wheat in the mixture was minimised by the planting configuration of alternating two rows of each species. The relatively low yields of chickpea in either cropping system were therefore a consequence of its genetic characteristics, which limits its yield capacity to less than that for wheat even at the same level of input and management (Thomas and Fukai, 1995). Thus the legume failed to increase its relative yield in the mixture to compensate for its low plant density. For instance, both DM and grain yields of chickpea-m never exceeded 30% those of chickpea-s, except with irrigation when grain yield rose to 44%; whereas wheat-m produced 72% the yields of wheat-s. Given that both crops were sown at 50% their sole crop population, their yields in the mixture would nominally be expected to be half those of their sole crops. However, yield of wheat-s was 72% that of wheat-s resulting in yield-to-density ratio of 1.44 (i.e 72/50), while it was just 0.60 for chickpea-m. Chickpea has one of the lowest growth rate and small 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). Furthermore, there were only small differences in the phenology between wheat and chickpea so that both crops attained peak canopy development, flowering and maturity at about the same time.

Inherent limitation of chickpea also included its apparent shallow rooting as shown in the depths of extraction of soil-water (Fig. 2). This crop did not appear to have developed roots and extract water below 0.8 m, unlike wheat-s and mixed crop under which the top 1.0 m of the soil was drier for much of the pre-flowering period up to 103 DAS. Later extraction in the post-flowering period still left considerable amount of soil-water unused below 0.8 m depth under chickpea-s compared to either mixed crop or wheat-s at the end of the season. Poor canopy development also exposed much of the soil surface to solar radiation thereby promoting soil evaporation at the expense of transpiration. While wheat-s and mixed crop used almost half of ET for transpiration, E_c constituted just 35% for chickpea-s (Table 2). Much of the E_s would have occurred early in the season when frequent rainfall kept the exposed soil surface wet for most of this time as is common in Mediterranean environments (Eberbach and Pala, 2005; Gregory et al., 2000; Yunusa et al., 1992). A more rapid and larger canopy development by the cereal, therefore, enabled wheat-m to exploit soil-water at the expense of chickpea-m. This enabled wheat-m to produce 75% of its sole crop yield with half the density of wheat-s, while chickpea-m could produce only 30% that of its sole crop yield.

Supplementary supply of soil-water changed the yield dynamics of the mixed crop. Additional water supply benefited chickpea in both mixed and sole crops than it did wheat (Section 3.4). Furthermore, the ratio of grain yields for chickpea-m relative to that for chickpea-s of 2.3 was almost 50% greater than 1.5 for wheat-s:wheat-m (Table 4). Increases in yields per unit amount of water from irrigation are consistent with 7 –10 kg/ha found for wheat–chickpea mixed crops (Singh and Singh, 1983) and for wheat (Yunusa et al., 1993a). Relative to non-irrigated crops, yield of chickpea-m increased by 75% compared to only 29% for wheat-m. This improvement in chickpea yield could be associated with extended crop duration (Thomas and Fukai, 1995), observed in the delayed senescence of the non-irrigated chickpea during grain filling (Fig. 3a). Delayed senescence for chickpea-s, which had a larger GAI than either mixed crop or wheat-s at 122 DAS (Fig. 3), enabled the legume to make a good use of the extra water to improve its harvest index especially in the mixture. This increased the harvest index increased by 74% for chickpea-m, while companion wheat-m experienced a 14% decline. This suggested that relative yield of chickpea could improve appreciably in the mixture when soil-water supply is adequate and is reflected in the LER of 1.10, compared to 1.02 without irrigation. It also suggests that wheat could be vulnerable to competition from chickpea under conditions of adequate supply of soil-water. These yield responses to late season ET further demonstrated the significance of soil-water supply during grain filling in the Mediterranean environment of Australia (Passioura, 1977; Sedgley, 1991).

The mixed crop, when compared with wheat-s, did not improve interception of solar radiation and ET by the crop nor the efficiency of converting these resources to yields (Table 5). Values for RUE (g DM MJ^{-1}) were all within the range found in this environment for wheat of between 1.52 and 2.40 (O'Connell et al., 2004; Yunusa et al., 1993b) and for chickpea of between 0.49 and1.15 (Thomas and Fukai, 1995); the low end values were generally associated with water stress (Hughes et al., 1987; Thomas and Fukai, 1995). Also, WUE (kg DM/ha/mm) were consistent with 8.0–12.0 for wheat (Yunusa et al., 1993a) and 6.8–9.5 for chickpea (Siddique and Sedgley, 1986). The low LERs presented here were, therefore, not entirely surprising. They showed that mixed cropping increased productivity based on grain yields by only a 2%, while there was no advantage when based on biomass production. These LER values were much lower than those found with mixing tropical and subtropical cereals and legumes for which values of between 1.18 and 1.39 are often reported (Reddy and Willey, 1980; Yunusa, 1989).

5. Conclusions

Mixing wheat and chickpea in the Mediterranean environment of southern Australia was not beneficial to yield when compared to growing wheat as a sole crop. The crops species used in our mixtures produced low LER mainly because they had similar phenology by which both attained flowering within a few days of each other, and also due to slow growth of the legume. Similarity in phenology ensured that both species made maximum demand for resources, especially on soil-water, in mid-season (between 70 and 110 DAS). This severely penalised the slow growing chickpea in the mixture and reduced its grain yield to just 30% that of its sole crop, whereas wheat-m produced 70% of its sole crop yield. There is limited opportunity to shift peak demands for soil-water by one of the component species to minimise inter-specific competition, except by planting them on widely different days. This strategy may however not be viable due to the rainfall being confined to just a few months of the year. Furthermore, it may also present management challenges. We recognise, however, that mixed cropping may be practised for other purposes than for just an increase in the productivity of the current crops. In Australia, these include improvements in soil N reserves over the long term and protection of soil surface especially early in the season.

Acknowledgements

The advice and support given by Dr Phil Tow were gratefully acknowledged. We thank the farm staff at Roseworthy along with Mr David Mathew, Mr Paul Harris and Ms Anne Mowday for their untiring assistance during the course of this program. The Islamic Republic of Iran is acknowledged for providing the opportunity for Dr Mohammad Reza Jahansooz to undertake his PhD studies in Australia.

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Table

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) at Roseworthy in 1994

Variables	Cropping systems [a]		
	Wheat-s	Chickpea-s	Mixture
Maximum GAI	1.5a	0.4c	0.7b
Maximum i_{PAR}	0.31a	0.23b	0.26ab
DM at harvest (kg/ha)	3412a	1430b	2771a
Grain yield (kg/ha)	1512a	552b	1368a
Harvest index	0.44a	0.37b	0.49a
LER_d	na	na	0.97
LER_g	na	na	1.01

[a] Means in the same rows followed by different letter(s) are statistically different at $p \leq 0.05$; na, not applicable.

Table 2. Seasonal totals for evapotranspiration (ET) and its components of transpiration (E_c) and soil evaporation (E_s), and radiant energy intercepted for the non-irrigated wheat and chickpea and their mixtures at Roseworthy in 1995

Variables	Cropping systems[a]		
	Wheat-s	Chickpea-s	Mixture
ET (mm)	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

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

Table 3. mean values (± standard errors of means) for growth indices for the non-irrigated 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	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

Table 4. Growth and grain yield variables for wheat and chickpea in sole and mixed crops grown with (+irrig) or without (0-irrig) irrigation at Roseworthy in 1995

Variables	Irrigation	Cropping systems[a]				
		Wheat-s	Wheat-m	Chickpea-s	Chickpeas-m	Mixture
DM at harvest ((kg/ha)	0-irrig	6989a	5010b	2800c	781e	6164a
	+ irrig	10618a*	7559b*	7007b*	1973c*	8532a*
Grain yield (kg/ha)	0-irrig	3042a	2203b	802c	242c	2445a
	+ irrig	4366a*	2837b	2446c*	1065d*	2938b
Harvest index	0-irrig	0.44a	0.44a	0.29c	0.31c	0.40b
	+ irrig	0.41a	0.38c*	0.35b*	0.54a*	0.34b*

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

* indicates significant ($t_{0.05}$) difference between means for pairs of irrigated and non-irrigated treatments.

Table 5. Radiation use efficiency (RUE) and water-use efficiency (WUE) for non-irrigated soles crops of wheat and chickpea and of mixed crops, and land equivalent ratio (LER) for the mixed crop at Roseworthy in 1995

Variables[b]	Cropping systems[a]		
	Wheat-s	Chickpea-s	Mixture
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] Means in the same rows followed by different letter(s) are statistically different at $p \leq 0.05$; *na*, not applicable

[b] subscripts d and g denote calculations based on DM and grain yields, respectively.

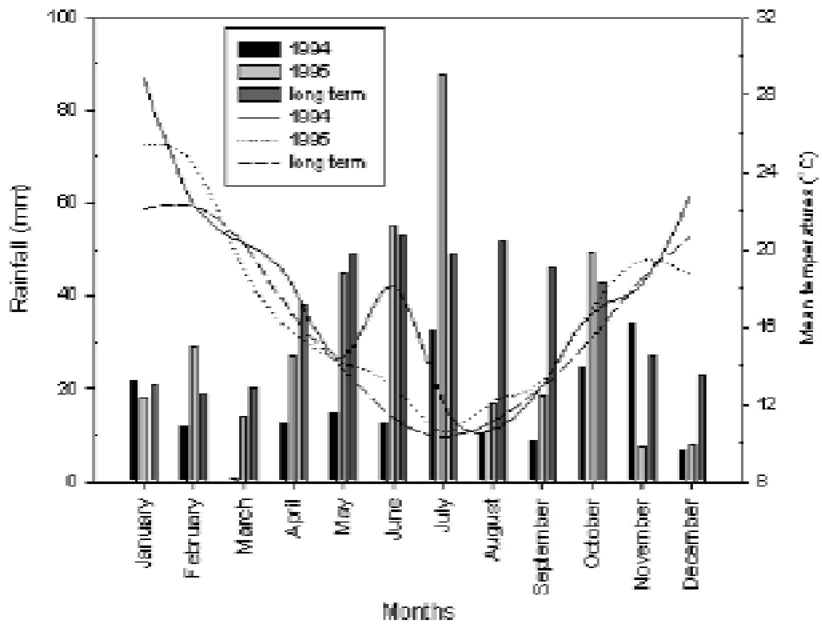

Fig. 1. Values for monthly rainfall (bars) and temperatures (lines) for 1994, 1995 and their long term averages at Roseworthy.

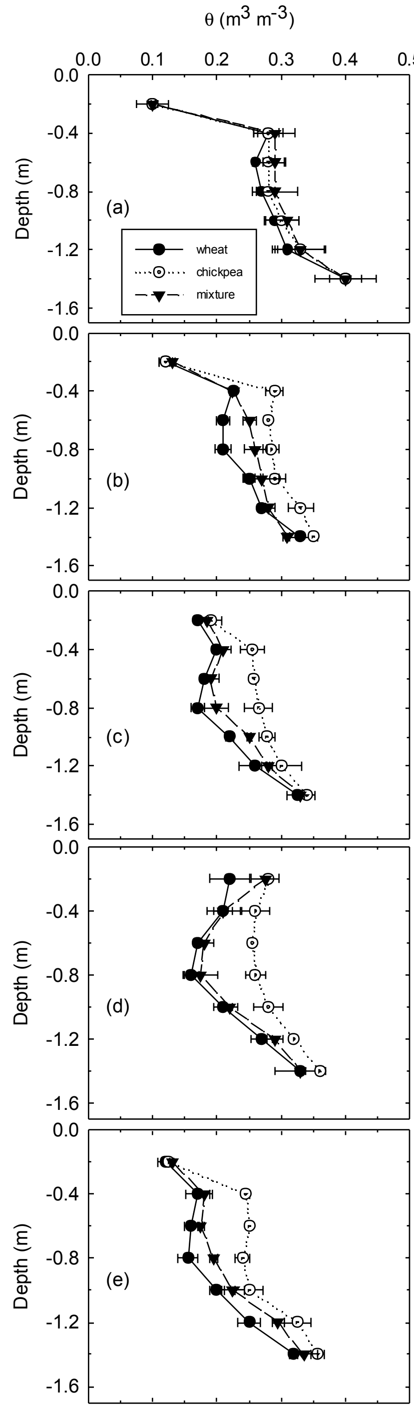

Fig. 2. Distribution of volumetric soil moisture content (θ) (± standared errors of means) in the 1.4m soil profile under wheat-s, chicpea-s and in mixed crops at Roseworthy in 1995: (a) 53, (b) 73, (c) 91, (d) 103 and (e) 116 days after sowing.

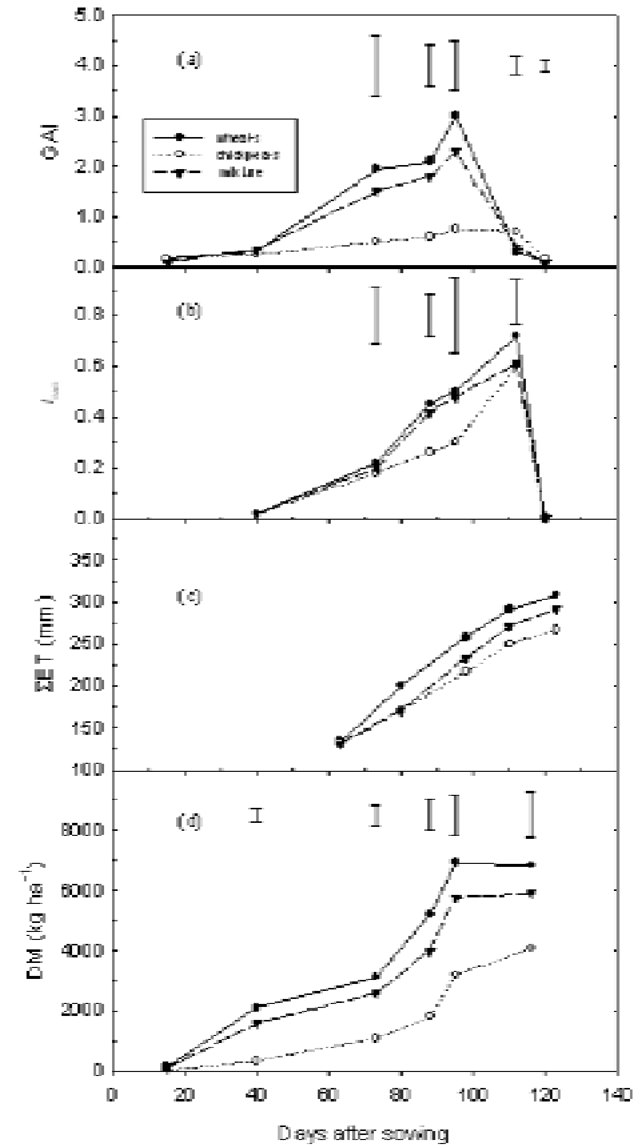

Fig. 3. Growth variables for sole crops of wheat (wheat-s) and chickpea (chickpea-s) and for the mixed crops at Roseworthy in 1995: (a) green area index (GAI), (b) fraction of PAR intercepted (i_{PAR}), (c) cumulative evaptranspiration (ET) and (d) dry matter .(DM) accumulation. Bars are LSD at p = 0.05, 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.

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13 September 2006

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This is for your consideration for publication in your reputable journal. I affirm that the manuscript is a honest account of original work undertaken by us and is not being considered for publication by any other journal.

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