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# Australian Journal of Experimental Agriculture

Volume 37, 1997

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*Australian Journal of Experimental Agriculture*, 1997, **37**, 667–76

# Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage or legumes

# 4. Nitrogen fixation, water use and yield of chickpea

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**Summary.** Continuous cereal cropping in southern Queensland and northern New South Wales has depleted native soil nitrogen fertility to a level where corrective strategies are required to sustain grain yields and high protein content. The objective of this study was to examine the performance of chickpea in chickpea–wheat rotations in terms of yields, water use and $N_2$ fixation. The effects of sowing time and tillage practice have been studied.

Chickpea grain yields varied from 356 kg/ha in 1995 to 2361 kg/ha in 1988; these were significantly correlated with the total rainfall received during the preceding fallow period and crop growth. Almost 48% of total plant production and 30% of total plant nitrogen were below-ground as root biomass.

Mean values of water-use efficiency for grain, above-ground dry matter, and total dry matter were 5.9, 14.2 and 29.2 kg/ha.mm, respectively. The water-use efficiency for grain was positively correlated with the total rainfall for the preceding fallow and crop growth period although cultural practices modified water-use efficiency. The potential $N_2$ fixation was estimated to be 0.6 kg nitrogen/ha.mm from 1992 total dry matter nitrogen yields assuming all of the nitrogen contained in chickpea was derived from the atmosphere.

Sowing time had a much larger effect on grain yield and $N_2$ fixation by chickpea than tillage practice (conventional tillage and zero tillage) although zero tillage generally increased grain yields. The late May–early June sowing time was found to be the best for chickpea grain yield and $N_2$ fixation since it optimised solar energy use and water use, and minimised frost damage. Nitrogen fixation by chickpea was low, less than 40% nitrogen was derived from atmosphere, representing less than 20 kg nitrogen/ha.year. The potential for $N_2$ fixation was not attained during this period due to below-average rainfall and high soil $NO_3$-N accumulation because of poor utilisation by the preceding wheat crop. Increased soil $NO_3$-N due to residual from fertiliser N applied to the preceding wheat crop further reduced $N_2$ fixation. A simple soil nitrogen balance indicated that at least 60% of crop nitrogen must be obtained from $N_2$ fixation to avoid continued soil nitrogen loss. This did not occur in most years.

The generally negative soil nitrogen balance needs to be reversed if chickpea is to be useful in sustainable cropping systems although it is an attractive cash crop. Sowing time and zero tillage practice, possibly combined with more appropriate cultivars, to enhance chickpea biomass, along with low initial soil $NO_3$-N levels, would provide maximum $N_2$ fixation.

## Introduction

In the major cereal grain growing areas of north-eastern Australia, continuous cereal cropping has caused severe depletion of soil nitrogen (N) on a range of Vertisols (Dalal and Mayer 1986). This has led to decreasing grain protein concentrations and yield (Dalal *et al.* 1991). As a result, N fertiliser use has increased in the region (Strong *et al.* 1996), and there is currently much interest in sustainable cropping systems involving legumes as a source of N.

Chickpea (*Cicer arietinum* L.) has been used in short-term rotation with cereals in northern New South Wales (Marcellos 1984) and southern Queensland (Doughton *et al.* 1993). However, long-term performance and effects of chickpea on chickpea–cereal rotations are unknown. Also, it is uncertain whether the productivity of cereal crops and N status of fertility-depleted brigalow lands (Vertisols) can be sustained by chickpea in rotation with cereal grain crops. This primarily depends on net N input to soil from $N_2$ fixation by chickpea. This will occur only when the quantity of $N_2$ fixed exceeds the amount of N removed in grain (Evans *et al.* 1989; Beck *et al.* 1991; Horn *et al.* 1996*b*), and N lost through other processes.

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Evans *et al.* (1989) observed that $N_2$ fixation by chickpea primarily depended on biomass production, provided $NO_3$-N levels at sowing were low (Doughton *et al.* 1993). In the present study, we report the: (i) grain, biomass and N yields of chickpea grown in rotation with wheat (1987–95); (ii) $N_2$ fixation by chickpea in the long-term rotation; (iii) effect of cultural practices, such as time of sowing and zero tillage, and fertiliser N applications to the previous wheat crop on chickpea grain yield and $N_2$ fixation; and (iv) water-use efficiency (WUE) of chickpea.

## Materials and methods

### *Experiment 1. Long-term field experiment*

A long-term field experiment was established in 1986 at Warra (26º47'S, 150º53'E), Queensland. Soil at the site is a Vertisol (fine, mixed, hyperthermic, typic Chromustert) that originally supported predominantly brigalow (*Acacia harpophylla*) and belah (*Casuarina cristata*) vegetation and had been under continuous cereal cropping since 1935. The soil (0–10 cm) contained 56% clay, 17% silt, 27% sand, 0.74% organic carbon and 0.072% soil total N, with pH 8.6. The properties of the soil profile are given in Dalal *et al.* (1995).

Mean monthly rainfall, and mean monthly maximum and minimum temperatures are shown in Dalal *et al.* (1995) for 1987–94. The mean maximum temperature was 27ºC in January and mean minimum temperature 12ºC in July (1987–95). Annual rainfall varied from 396 mm in 1986 to 760 mm in 1988 (mean annual rainfall 685 mm, 1890–1987).

A 2-year rotation of chickpea and wheat (*Triticum aestivum* L.) was established in a randomised block design with 4 replications in 25 by 6.75 m plots. Chickpea was sown at about 5 cm depth in 25-cm rows at 60 kg/ha using phytophthora (*Phytophthora megaspermum*)-tolerant lines (462-1 in 1987 and 1988, and 571-5 in 1989) or cv. Barwon (1990–95). Wheat cultivar Hartog was also sown at about 5 cm depth in 25-cm wide rows at 40 kg/ha in May and June plantings or 50 kg/ha in July plantings. Both chickpea and wheat were sown on 30 May 1987, 26 May 1988, 20 June 1989, 3 July 1990, 26 June 1992, 22 July 1993, 17 June 1994 and 22 June 1995.

*Crop measurement and analyses.* Total dry matter yields of wheat and chickpea at anthesis were estimated by removing plants from the central 2 rows, 1 m long, and drying at 70–80ºC. Wheat and chickpea grain yields at maturity were measured from machine harvesting 1.75 by 23 m of the central areas of all plots. Grain yields were adjusted to 12% water content. Root lengths were measured by the line intersection method (Newman 1966) following ultrasonic dispersion and sieving (mesh size, 0.211 mm) of soil cores sampled at anthesis, and root biomass was estimated from root length and root weight (mean value 3 mg/m).

Whole, above-ground plants and roots from anthesis samplings, straw and grain were analysed for N concentration in Kjeldahl digests using automated ammonium analysis (Crooke and Simpson 1971).

Nitrogen fixation by chickpea was estimated (based on above-ground biomass) in 1988 and from 1992 to 1995 by isotopic dilution method using $^{15}N$ natural abundance technique (Ledgard and Peoples 1988) since this technique has been found to be stable over the wide range of $N_2$-fixed values (Doughton *et al.* 1995). Milk thistle (*Sonchus oleraceus* L.) was used as a reference plant (Horn *et al.* 1996*b*).

The percentage of $N_2$ derived from the atmosphere (%Ndfa) by chickpea was calculated as follows (Ledgard and Peoples 1988):

$$\%\text{Ndfa} = \frac{100 \times (\delta^{15}\text{N reference plant} - \delta^{15}\text{N chickpea})}{(\delta^{15}\text{N reference plant} - B)}$$

where $\delta^{15}N$ reference plant (milk thistle) and $\delta^{15}N$ chickpea are the parts per 1000 $^{15}N$ enrichment (in excess of 0.3663 atom % $^{15}N$ in atmosphere) of N in milk thistle and chickpea tops, and $B$ is the $\delta^{15}N$ of fixed $N_2$ for chickpea tops (–2.10, Doughton *et al.* 1993). The amount of $N_2$ fixed (kg/ha) was calculated from the above-ground chickpea crop N yield (kg/ha) and %Ndfa.

*Soil sampling and analyses.* Soil profile $NO_3$-N concentrations and water contents were measured from the soil samples collected in May (presowing), September or October (anthesis) and November (after harvest) each year. Five soil cores of 50 mm diameter were collected from each plot to a depth of 30 cm, then 2 cores to 150 cm depth, and divided into 10 cm layers down to 30 cm depth and below that 30 cm layers. The soil samples were bulked, sealed in plastic bags, and stored at 4°C until analysis. Soil was dried at 35 ± 5ºC in a forced draught oven and ground to <2 mm for colorimetric determination of $NO_3$-N (Best 1976) after extraction of 10 g of soil in 100 mL of 2 mol KCl/L.

Gravimetric soil water (g/g) was determined by drying soil samples at 105°C for 48 h, and volumetric water content (mm/layer) and plant available water were calculated as described by Strong *et al.* (1996).

Water-use efficiency (kg/ha.mm) of the chickpea grain yield was calculated from grain yield (kg/ha) divided by water utilised (mm), where water utilised by the chickpea crop is soil water in May before sowing minus soil water in November at harvest (0–120 cm) plus in-crop rainfall. Similar calculations were made for WUE of total dry matter and N yields.

### *Experiment 2. Chickpea sowing time, tillage practices and fertiliser residual nitrogen*

The experimental design and cultural practices have

**Table 1. Experiment 2. Chickpea sowing dates**

| Year | Early sowing | Mid sowing | Late sowing |
|---|---|---|---|
| 1992 | 1 May | 27 May | 7 August |
| 1993 | 28 April | 8 June | 21 July |
| 1994 | 28 April | 7 June | 8 July |
| 1995 | 2 May | 7 June | 10 July |

been described in detail by Horn *et al.* (1996*a*, 1996*b*). Briefly, the field experiment was established in May 1992, adjacent to the long-term experiment (experiment 1), after a 12 month fallow period which followed a sorghum crop. The field design was a randomised complete block with 4 replications of 22.5 by 6.75 m plots. Treatments consisted of 3 factors: tillage (conventional tillage and zero tillage after the 1992 crop harvest), phase of rotation (chickpea or wheat), and sowing time of chickpea (Table 1). After the chickpea crop, each plot of 6.75 m width was split into 3 subplots, 2.25 m wide, for fertiliser N (as urea) application to wheat at sowing at rates of 0, 25 and 75 kg N/ha.

Crop cultivars, crop and soil sampling, and analytical methods were as for experiment 1.

### *Statistical analysis*

Significant differences between treatments were assessed using ANOVA (Research Experiment Management System, Queensland Department of Primary Industries).

## Results

### *Experiment 1. Long-term chickpea yields*

Chickpea grain yield in the chickpea–wheat rotation varied from 356 kg/ha in 1995 to 2361 kg/ha in 1988 (Table 2). Total above-ground biomass yield varied from 793 kg/ha in 1995 to 5487 kg/ha in 1988 (Table 2). The mean percentage of grain yield to above-ground dry matter yield was 41% although it varied widely, from 20% (frost-damaged crop) in 1987 to 52% in 1989.

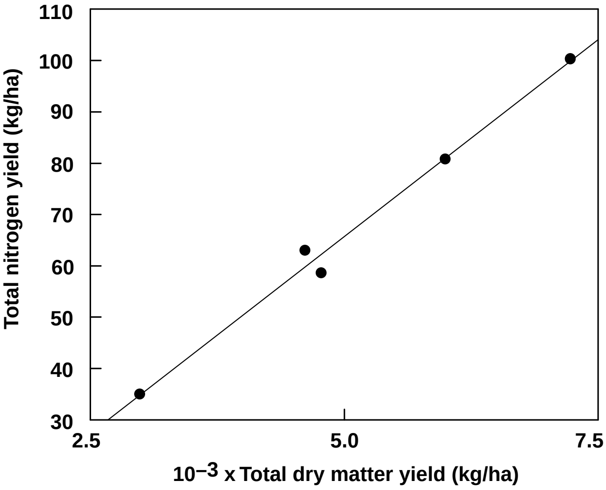

**Figure 1.** Relationship between total dry matter (above ground and below ground) yield and total nitrogen yield in chickpea. Equation of the line is:

$$y = -10.99 + 0.015x \quad (R^2 = 0.99, P<0.01).$$

Below-ground root biomass varied much less than the above-ground biomass (Table 2); it varied from 2027 kg/ha in 1990 to 3558 kg/ha in 1993. Almost half (48%) of the total dry matter produced by chickpea was root biomass.

### *Experiment 1. Chickpea nitrogen yield*

Similar to grain yield, grain N yield also varied widely, from 13.2 kg N/ha in 1995 to 93.1 kg N/ha in 1988 (Table 2). The N yield of the above-ground biomass varied 6-fold, with a minimum of 17.4 kg N/ha in 1995 and a maximum of 108.4 kg N/ha in 1988.

**Table 2. Chickpea grain yield (at 12% moisture), above-ground dry matter yield (AGDM), below-ground dry matter yield (BGDM), grain N yield, above-ground dry matter N yield (AGDM-N), below-ground dry matter N yield (BGDM-N) and total dry matter N yield (TDM-N) (kg/ha) from 1987 to 1995**

1986 and 1991 were drought years and no results were obtained

| Year | Grain yield | AGDM | BGDM | Grain N yield | AGDM-N | BGDM-N | TDM-N |
|---|---|---|---|---|---|---|---|
| 1987 | 535 | 2653 | n.d. | 22.5 | 64.2 | n.d. | n.d. |
| 1988 | 2361 | 5487 | n.d. | 93.1 | 108.4 | n.d. | n.d. |
| 1989 | 1153 | 2212 | n.d. | 45.3 | 50.7 | n.d. | n.d. |
| 1990 | 1195 | 2749 | 2027 | 37.0 | 42.4 | 16.2 | 58.6 |
| 1992 | 1859 | 4226 | 3004 | 61.0 | 76.0 | 24.3 | 100.3 |
| 1993 | 923 | 2439 | 3558 | 34.1 | 52.3 | 28.5 | 80.8 |
| 1994 | 1055 | 2329 | 2288 | 35.1 | 44.7 | 18.3 | 63.0 |
| 1995 | 356 | 793 | 2194 | 13.2 | 17.4 | 17.6 | 35.0 |

n.d. not determined.

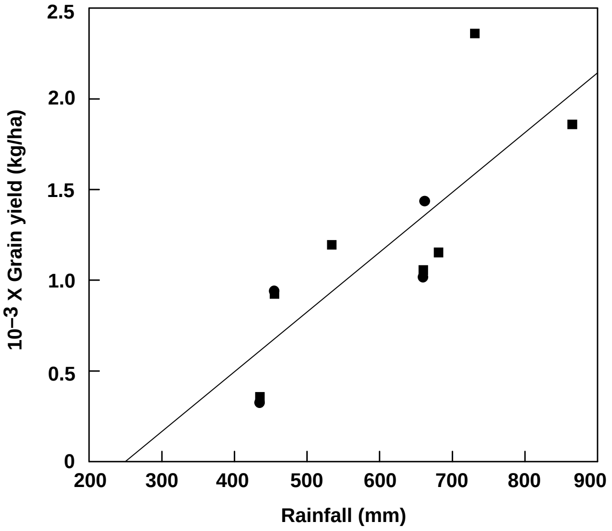

**Figure 2.** Effect of total rainfall received during the preceding fallow period (usually 6 months but 18 months for 1987 and 1992 crops following 1986 and 1992 droughts) and crop growth on chickpea grain yield. ■ Experiment 1; ● experiment 2. Equation of the line is:

$$y = -823 + 3.3x \quad (R^2 = 0.64, P<0.01).$$

Nitrogen contained in the root biomass was estimated from 1990 to 1995 (Table 2). During this period mean root biomass N was 31 ± 10% of the total plant dry matter N yield, a value similar to that for lupin (28%, Russell and Fillery 1996). The total N yield of chickpea was closely correlated (Fig. 1) with dry matter yield (below-ground and above-ground biomass), and signifies a mean N concentration of 1.5% in chickpea biomass.

*Experiment 1. Effect of rainfall and water-use efficiency*

Except for the 1987 crop season, grain yield was significantly correlated with total rainfall received during the fallow period (usually 6 months but 18 months for 1987 and 1992 chickpea crops following 1986 and 1991 droughts) and crop growth (Fig. 2). The chickpea crop in 1987 was severely damaged by frost in early September. Similarly above-ground dry matter yield (kg/ha) was related to the total rainfall during fallow and crop growth:

$$\text{Dry matter yield (kg/ha)} = -1270 + 7.50 \times \text{rainfall (mm)} \quad (R^2 = 0.52, P<0.05)$$

but not as well as it was with grain yield. Total amount of plant-available water in the soil profile at sowing and the rainfall during crop growth were poorly correlated with chickpea grain yield and dry matter yield.

Grain N yield was also related to the total amount of rainfall:

$$\text{Grain yield (kg/ha)} = -58.5 + 0.15 \times \text{rainfall (mm)} \quad (R^2 = 0.63, P<0.05).$$

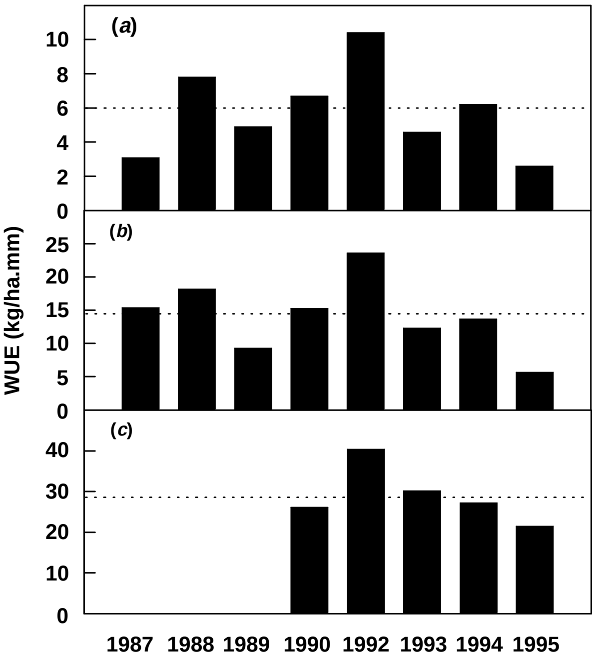

**Figure 3.** Water-use efficiency (WUE) of chickpea in the long-term chickpea–wheat rotation from 1987 to 1995. (*a*) WUE of grain production, (*b*) WUE of above-ground dry matter production, and (*c*) WUE of total dry matter (TDM) production. WUE of TDM (above ground and below ground) was not determined from 1987 to 1989.

Except for 1993, both below-ground biomass N and total dry matter N increased with increasing combined rainfalls received during fallow and crop growth periods.

Water-use efficiency of chickpea grain production varied from 2.6 kg grain/ha.mm in 1995 to 10.4 kg grain/ha.mm in 1992, with a mean value of 5.9 ± 2.5 kg grain/ha.mm (Fig. 3). The mean values of WUE for above-ground dry matter and total biomass (both below ground and above ground) production were 14.2 ± 5.4 and 29.2 ± 7.0 kg/ha.mm, respectively (Fig. 3).

*Experiment 2. Effect of sowing time, tillage and residual fertiliser nitrogen on chickpea yield*

Horn *et al.* (1996*a*) presented results for the first 2 seasons (1992 and 1993), which were estimated from a much smaller sampling area (2 by 0.5 m) than used in the present study (22.5 by 1.75 m). Thus, the results in this study usually had much smaller error of yield measurements than in the former study.

Sowing times significantly affected the chickpea grain yields in 1992, 1993 and 1994 (Table 3). In both 1992 and 1993, chickpea grain yields were highest at mid sowing and lowest at late sowing although no significant differences in grain yield were measured in

**Table 3. Effect of sowing time and tillage practice on chickpea grain yield (at 12% moisture) and grain harvest index from 1992 to 1995**

| Treatment | Grain yield (kg/ha) 1992 | 1993 | 1994 | 1995 | Harvest index 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|
| Sowing time (S) | | | | | | | | |
| Early (S1) | 1272 | 1420 | 961 | n.d. | 0.45 | 0.43 | 0.34 | n.d. |
| Mid (S2) | 1434 | 2484 | 849 | 421 | 0.51 | 0.48 | 0.53 | 0.41 |
| Late (S3) | 931 | 1095 | 787 | 440 | 0.39 | 0.36 | 0.47 | 0.44 |
| l.s.d. (*P* = 0.05) | 127 | 124 | 90 | n.s. | 0.09 | 0.03 | 0.05 | n.s. |
| Tillage (T) | | | | | | | | |
| Conventional tillage (T1) | n.a. | 1507 | 904 | 319 | n.a. | 0.41 | 0.46 | 0.36 |
| Zero tillage (T2) | n.a. | 1826 | 827 | 542 | n.a. | 0.44 | 0.44 | 0.48 |
| l.s.d. (*P* = 0.05) | n.a. | 101 | 74 | 71 | n.a. | 0.02 | n.s. | 0.07 |
| Means (S x T) | | | | | | | | |
| T1 x S1 | n.a. | 1343 | 1005 | n.d. | n.a. | 0.40 | 0.34 | n.d. |
| T1 x S2 | n.a. | 2240 | 962 | 324 | n.a. | 0.49 | 0.56 | 0.35 |
| T1 x S3 | n.a. | 939 | 744 | 314 | n.a. | 0.32 | 0.47 | 0.38 |
| T2 x S1 | n.a. | 1497 | 917 | n.d. | n.a. | 0.47 | 0.33 | n.d. |
| T2 x S2 | n.a. | 2729 | 735 | 518 | n.a. | 0.47 | 0.51 | 0.47 |
| T2 x S3 | n.a. | 1251 | 829 | 566 | n.a. | 0.39 | 0.47 | 0.50 |
| l.s.d. (*P* = 0.05) | | 176 | 127 | n.s. | | 0.05 | 0.07 | 0.09 |

n.a., not applicable; n.d., not determined; n.s., not significant.

1995. Early-sown chickpea crop was severely damaged by frost in 1995. In 1994, there was a slight decrease in chickpea grain yield with delayed sowing.

Tillage practices affected grain yields in 1993, 1994 and 1995 (Table 3). In 1993 and 1995, chickpea grain yields increased by 21 and 70%, respectively, under zero tillage practice compared with conventional tillage. However, in 1994, it was slightly lower (9%) under zero tillage than conventional tillage. Thus, chickpea generally benefited from the practice of zero tillage.

In 1993, there was a significant interaction between sowing time and tillage practice (Table 3). For example, mid sowing under zero tillage doubled the chickpea yield (2729 kg/ha) compared with early sowing under conventional tillage (1343 kg/ha). Also, yield decreases from late sowing were much less under zero tillage than under conventional tillage. In 1994, mid sowing under zero tillage resulted in lower yield compared with early sowing under both conventional tillage and zero tillage. However, grain yield differences were small.

Fertiliser N applied to the previous wheat crop did not significantly affect chickpea grain yield (data not shown).

Grain harvest index was consistently highest for mid sowing in 1992, 1993 and 1994 (Table 3). Also, it was higher under zero tillage practice in 1993 and 1995 than under conventional tillage. There were significant sowing time x tillage interactions in 1993, 1994 and 1995. The differences in harvest index due to different sowing times were less under zero tillage than under conventional tillage.

Chickpea grain protein concentrations were lowest from mid sowing in 1992 and 1993 (Table 4), most likely due to dilution of N concentration by yield. Grain N yields were not significantly affected by sowing times in 1995 (Table 4). However, grain N yield from mid sowing in 1993 was 67% higher than the early sowing and 13% lower in 1994, mainly because of lower grain yields from mid sowing under zero tillage.

In 1993, grain N yield was higher from mid sowing (75 kg N/ha) than either early (45 kg N/ha) or late (40 kg N/ha) sowing. In 1994, however, grain N yield was highest from the early sowing (Table 4); which was essentially a reflection of grain yield. Zero tillage increased grain N yield in 1993 and 1995 but there was no tillage practice effect in 1994. Generally, grain N yield followed a similar pattern to that of grain yield. Fertiliser N applied to the previous wheat crop had no significant effect on grain N yield of chickpea (data not shown).

Nitrogen harvest index, the proportion of total above-ground N yield in grain removed from the field, was highest from mid sowing in 1993 and 1994 (Table 4). Significant effects of tillage were observed only in 1995 when N harvest index was higher under zero tillage (0.77) than conventional tillage (0.61).

Previous N fertiliser application of 75 kg N/ha to wheat significantly reduced both the N derived from the atmosphere (%Ndfa) as well as the amount of $N_2$ fixed

**Table 4. Effect of sowing time and tillage practice on chickpea grain protein, grain N yield and grain N harvest index from 1992 to 1995**

| Treatment | Grain protein (%) | | | | Grain N yield (kg/ha) | | | | N Harvest index | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1992 | 1993 | 1994 | 1995 | 1992 | 1993 | 1994 | 1995 | 1992 | 1993 | 1994 | 1995 |
| Sowing time (S) | | | | | | | | | | | | |
| Early (S1) | 22.8 | 19.8 | 20.9 | n.d. | 46 | 45 | 32 | n.d. | 0.74 | 0.78 | 0.64 | n.d. |
| Mid (S2) | 21.6 | 18.8 | 20.8 | 26.3 | 50 | 75 | 28 | 18 | 0.78 | 0.83 | 0.84 | 0.70 |
| Late (S3) | 22.7 | 23.1 | 19.7 | 23.0 | 34 | 40 | 25 | 16 | 0.60 | 0.62 | 0.75 | 0.68 |
| l.s.d. ($P = 0.05$) | 1.0 | 0.7 | 0.5 | 0.9 | 4 | 4 | 3 | n.s. | 0.13 | 0.05 | 0.06 | n.s. |
| Tillage (T) | | | | | | | | | | | | |
| Conventional tillage (T1) | n.a. | 20.9 | 20.4 | 24.9 | n.a. | 49 | 30 | 13 | n.a. | 0.73 | 0.74 | 0.61 |
| Zero tillage (T2) | n.a. | 20.3 | 20.5 | 24.4 | n.a. | 58 | 27 | 21 | n.a. | 0.76 | 0.74 | 0.77 |
| l.s.d. ($P = 0.05$) | | 0.5 | n.s. | n.s. | | 3 | n.s. | 2 | | n.s. | n.s. | 0.08 |
| Means (S x T) | | | | | | | | | | | | |
| S1 x T1 | n.a. | 19.7 | 20.5 | n.d. | n.a. | 42 | 33 | n.d. | n.a. | 0.77 | 0.65 | n.d. |
| S2 x T1 | n.a. | 19.3 | 21.0 | 26.7 | n.a. | 69 | 32 | 14 | n.a. | 0.86 | 0.85 | 0.62 |
| S3 x T1 | n.a. | 23.5 | 19.5 | 23.2 | n.a. | 35 | 23 | 12 | n.a. | 0.54 | 0.75 | 0.61 |
| S1 x T2 | n.a. | 19.9 | 21.3 | n.d. | n.a. | 47 | 31 | n.d. | n.a. | 0.79 | 0.65 | n.d. |
| S2 x T2 | n.a. | 18.4 | 20.5 | 25.9 | n.a. | 80 | 24 | 21 | n.a. | 0.81 | 0.82 | 0.78 |
| S3 x T2 | n.a. | 22.7 | 19.7 | 22.8 | n.a. | 45 | 26 | 20 | n.a. | 0.69 | 0.75 | 0.75 |
| l.s.d. ($P = 0.05$) | | 0.9 | 0.6 | n.s. | | 6 | 4 | 3 | | 0.08 | n.s. | n.s. |

n.a., not applicable; n.d., not determined; n.s., not significant.

by chickpea (Table 5) although above-ground dry matter N yields were not affected (data not shown). Tillage practice had no significant effect on either %Ndfa or the amount of $N_2$ fixed in 1993, 1994 and 1995 (data not shown). The effects of sowing time on %Ndfa and the amount of $N_2$ fixed were inconsistent. For example, in 1993, sowing time had no effect on %Ndfa (Horn *et al.* 1996*b*). In 1994, early-sown chickpea had the highest Ndfa value (31.8%), followed by mid sowing (26.2%) and late sowing (14.5%) whereas, in 1995, the respective Ndfa values were 13.6, 16.2 and 20.7% [l.s.d. ($P = 0.05$) = 4.7]. In both 1994 and 1995, %Ndfa values of mid-sown chickpea were similar to the highest %Ndfa observed in this study.

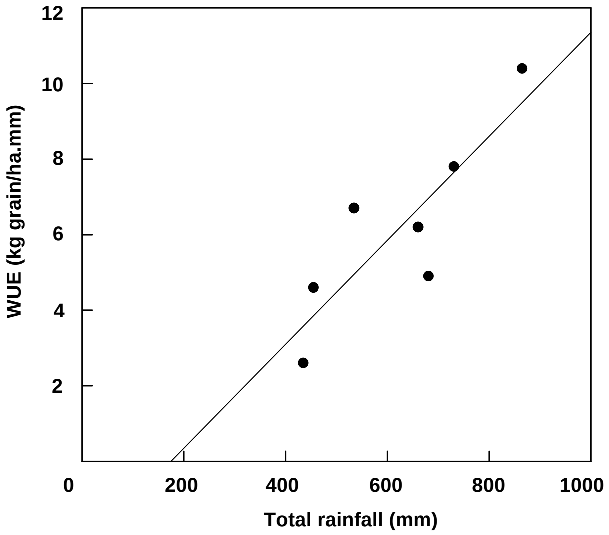

**Figure 4.** Relationship between water-use efficiency (WUE) of chickpea grain yield and total amount of rainfall from 1988 to 1995. The frost-damaged 1987 chickpea crop was excluded. Equation of the line is:

$$y = -2.4 + 0.0138x \quad (R^2 = 0.74, P<0.01).$$

Soil $NO_3$-N levels adversely affected both %Ndfa and $N_2$ fixed by chickpea. For example, in May 1994, $NO_3$-N levels in the 0–120 cm layer were 85 and 140 kg N/ha following previous no N and fertiliser N application of 75 kg N/ha to wheat, respectively. Essentially similar trends in $NO_3$-N levels were observed in May 1995; the respective values were 73 and 123 kg N/ha. Tillage practice had no significant effect on $NO_3$-N levels.

## Discussion

### *Long-term chickpea yields*

Chickpea grain yields in the long-term chickpea–wheat rotation primarily reflected the amount of rainfall received during the fallow period preceding the crop and in-crop rainfall. However, WUE for grain production varied widely, from a low value of 2.6 in 1995 to 10.4 in 1992 with a mean value of 5.9 kg grain/ha.mm. Beech and Leach (1988) reported WUE values of 4.9 kg grain/ha.mm for a 1980 crop at Dalby. In the current study, WUE was linearly correlated with the total amount of rainfall during the preceding summer fallow and crop growth (Fig. 4). Herridge *et al.* (1995) observed differences in WUE at 2 sites, 8.5 at Windridge

**Table 5. Effect of sowing time, tillage practice and fertiliser N applied to previous wheat crop on N derived from the atmosphere (%Ndfa) and $N_2$ fixed by chickpea (based on above-ground biomass; kg/ha) in 1994 and 1995**

There were no significant interactions of tillage, S x T and N x S x T

| Treatment | 1994 season | | 1995 season | |
|---|---|---|---|---|
| | Ndfa | $N_2$ fixed | Ndfa | $N_2$ fixed |
| Fertiliser N | | | | |
| N1 (0 kg/ha) | 33.2 | 12.5 | 18.1 | 4.5 |
| N2 (75 kg/ha) | 15.1 | 6.3 | 15.6 | 3.7 |
| l.s.d. ($P = 0.05$) | 9.9 | 3.8 | n.s. | n.s. |
| Sowing time (S) | | | | |
| Early (S1) | 31.8 | 13.8 | 13.6 | n.d. |
| Mid (S2) | 26.2 | 10.4 | 16.2 | 4.1 |
| Late (S3) | 14.5 | 6.3 | 20.7 | 4.8 |
| l.s.d. ($P = 0.05$) | 12.2 | 4.6 | 4.7 | n.s. |
| N x S interaction | | | | |
| N1 x S1 | 39.8 | 16.5 | 23.0 | n.d. |
| N1 x S2 | 36.3 | 14.0 | 19.6 | 4.5 |
| N1 x S3 | 23.6 | 9.4 | 11.6 | 2.3 |
| N2 x S1 | 23.7 | 10.6 | 4.9 | n.d. |
| N2 x S2 | 16.1 | 6.4 | 13.1 | 3.6 |
| N2 x S3 | 5.4 | 2.5 | 28.9 | 7.7 |
| l.s.d. ($P = 0.05$) | n.s. | n.s. | 8.2 | 2.1 |
| N x T interaction | | | | |
| N1 x T1 | 28.7 | 12.3 | 13.2 | 2.9 |
| N1 x T2 | 37.7 | 13.9 | 22.9 | 6.3 |
| N2 x T1 | 13.5 | 6.2 | 17.5 | 3.6 |
| N2 x T2 | 16.6 | 6.8 | 13.8 | 3.7 |
| l.s.d. ($P = 0.05$) | n.s. | n.s. | 6.6 | n.s. |

n.d., not determined; n.s., not significant.

and 5.8 at Glenhoma, presumably because the latter had lower summer rainfall since it had 42 mm less soil water than the former at sowing.

However, WUE can be modified by altering the chickpea sowing time and tillage practice. For example, in a related study, Horn *et al.* (1996*a*) showed that chickpea sown on 21 July 1993 had a WUE of only 4.1 kg grain/ha.mm compared with 10.5 kg grain/ha.mm for that sown on 8 June 1993. Similar results were obtained by Leach and Beech (1988) and Siddique and Sedgley (1986) who suggested that planting at an optimum time encourages better chickpea canopy development, thereby reducing soil evaporation in winter and chickpea transpiration in spring. Horn *et al.* (1996*a*) also observed that zero tillage practice further increased WUE, probably by reducing water loss through soil evaporation during the fallow period.

The mean value of WUE for above-ground dry matter (AGDM) production, 14.2 kg AGDM/ha.mm, compares favourably with that reported by Leach and Beech (1988), 15.0 kg AGDM/ha.mm for chickpea in 1979 at Dalby although in 1980 they observed a mean WUE of 26 kg AGDM/ha.mm. They attributed these differences to different amounts of soil moisture lost due to evaporation during the cropping season; in 1979 the soil evaporation loss was more than double that in 1980. If below-ground dry matter production is also included, mean WUE of the total dry matter (TDM) (29.2 kg TDM/ha.mm) was about twice that of AGDM and almost 5-fold that of grain yield and generally followed a similar pattern to that of AGDM and grain production.

The highest value of WUE for total dry matter production was 40.4 kg TDM/ha.mm in 1992. Assuming 1.5% N concentration in the dry matter (Fig. 1), WUE of N assimilation would be 0.6 kg N/ha.mm. However, the WUE of $N_2$ fixation would always be lower than the maximum value depending on chickpea biomass production and %Ndfa. This upper limit of WUE is 50% higher than that estimated (0.4 kg N/ha.mm) by Herridge *et al.* (1995). As they suggested, it may prove valuable to evaluate different legumes in terms of their WUE of $N_2$ fixation.

### *Effect of cultural practices on chickpea yield*

Changes in sowing time of chickpea significantly affected grain yield, harvest index (Table 3), grain protein, grain N yield, N harvest index (Table 4), Ndfa and $N_2$ fixed (Table 5) in most years of the study. Tillage practice mainly affected grain yield of chickpea. Sowing time regulates both the amounts of solar energy received (radiation and degree days) and stored soil water and rainfall used (Siddique and Sedgley 1986; Singh *et al.* 1987; Sivakumar and Singh 1987). The need to maximise radiation interception early in the season has to be counterbalanced with water use and frost damage, especially at flowering and pod setting. The consistently better chickpea grain yields from mid sowing compared with early and, especially, late sowing emphasises the importance of balancing 3 major aspects that affect chickpea crop performance.

The tillage practices had more effect on chickpea grain yield than $N_2$ fixation. This may have been due to below-average rainfall years from 1992 to 1995. The zero tillage practice enhanced grain yields by about 20% compared with conventional tillage. Almost identical results were obtained from zero tillage practice in an adjoining site during 1992–94 [conventional tillage, 1156 kg/ha; zero tillage, 1400 kg/ha; l.s.d. ($P = 0.05$), 94 kg/ha] although this site had been under zero tillage practice since 1986 (data not shown).

Tillage effects on $N_2$ fixation by chickpea were small. In general, zero tillage practice enhanced %Ndfa and $N_2$ fixation but the differences were not significant. Horn

**Table 6. Effect of sowing time, fertiliser N applied to previous wheat crop and tillage practice on N balance (kg/ha) in chickpea in 1994 and 1995**

Values in parentheses also include estimated 30% $N_2$ fixed in chickpea root biomass

| Treatment | 1994 season | | | 1995 season | | |
|---|---|---|---|---|---|---|
| | $N_2$ fixed | Grain N removal | Soil N balance | $N_2$ fixed | Grain N removal | Soil N balance |
| Early sowing | 13.8 | 32.2 | –18.4 (–14.3) | n.d. | n.d. | n.d. |
| Mid sowing | 10.4 | 28.3 | –17.9 (–14.8) | 4.5 | 17.6 | –13.0 (–11.8) |
| Late sowing | 6.3 | 24.8 | –18.5 (–16.6) | 3.7 | 16.0 | –12.3 (–5.7) |
| l.s.d. ($P$ = 0.05) | 4.6 | 3.0 | 1.2 | n.s. | n.s. | n.s. |
| Fertiliser N (0 kg/ha) | 12.5 | 27.8 | –15.3 (–11.6) | 4.1 | 17.3 | –13.2 (–12.0) |
| Fertiliser N (75 kg/ha) | 6.3 | 29.6 | –23.3 (–21.4) | 4.8 | 16.6 | –11.8 (–10.4) |
| l.s.d. ($P$ = 0.05) | 3.8 | n.s. | 4.2 | n.s. | n.s. | n.s. |
| Conventional tillage | 9.3 | 29.5 | –20.2 (–17.4) | 3.5 | 12.8 | –9.3 (–8.3) |
| Zero tillage | 10.9 | 27.3 | –16.4 (–13.1) | 4.7 | 20.9 | –16.2 (–14.8) |
| l.s.d. ($P$ = 0.05) | n.s. | n.s. | n.s. | n.s. | 2.3 | 3.5 |

n.d, not determined; n.s., not significant.

*et al.* (1996*b*) also reported similar results for 1993. Zero tillage may have increased $N_2$ fixation except for below-average rainfall years that limited the chickpea biomass production and caused an accumulation of soil $NO_3$-N for chickpea crops (Horn *et al.* 1996*b*). Similarly, Herridge *et al.* (1995) observed no significant effect of tillage practice on $N_2$ fixation by chickpea in northern New South Wales.

### *Soil nitrogen balance*

The small amounts of $N_2$ fixed during this experiment were less than the amount of N removed by chickpea grain harvest (Table 6), thus confirming the findings of Horn *et al.* (1996*b*) for 1992 and 1993 seasons. Except for the available N supply, the major determinant of $N_2$ fixation by chickpea is the quantity of biomass produced (Hossain *et al.* 1995) and this was primarily influenced by the combined summer–autumn fallow rainfall and in-crop rainfall (Fig. 3). In the current study, low $N_2$ fixation was due to a combination of seasons of below-average rainfall, low biomass production and high supplies of available N. For example, the amounts of $N_2$ fixed calculated from the Doughton *et al.* (1995) relationship:

$$N_2 \text{ fixed (kg/ha)} = 89.73 - 0.202 \times NO_3\text{-N (kg/ha)},$$

(0–120 cm sowing depth), are 73 and 61 kg/ha in 1994 and 75 and 65 kg/ha in 1995 from nil fertiliser and fertiliser residual N from 75 kg N/ha treatments, respectively. The $N_2$ fixed in this experiment was <20% of the predicted values (Table 5). Horn *et al.* (1996*b*) concluded that chickpea biomass and $N_2$ fixation for a particular value of $NO_3$-N may decrease as rainfall decreases and potential evapotranspiration increases.

Even accounting for the N contribution by chickpea roots (about 30% of the total chickpea N, Table 6), the negative N balance is of concern in the long-term maintenance of soil total N. Evans *et al.* (1989) suggested that chickpea needs to obtain at least 60% of crop N from $N_2$ fixation before making a positive contribution to soil total N. Essentially similar conclusions can be drawn from the data of Beck *et al.* (1991) and Armstrong *et al.* (1997). However, the relationship is complex since soil $NO_3$-N concentration at sowing, legume biomass yield and grain N removal all affect the overall contribution to soil N (Horn *et al.* 1996*b*). Drought-affected chickpea crops depleted soil N between 1992 and 1995 (Table 6). However, at this site in 1988, 62% of crop N was derived from fixed $N_2$ contributing 72 kg N/ha in the above-ground chickpea biomass (Hossain *et al.* 1995), and an estimated 93 kg N/ha in total dry matter (assuming 30% root N contribution), which would balance the grain N export of the 1988 crop, 93.1 kg N/ha (Table 2). Similarly when chickpea fixed 65% of its total N, assuming 30% contribution by the root biomass (this study, and Russell and Fillery 1996), it probably provided a positive soil N balance of 13 kg/ha rather than a reported deficit of 11 kg N/ha (Armstrong *et al.* 1997).

In spite of generally negative soil total N balances from chickpea cropping, chickpea increases N supply to the succeeding cereal crop, both from soil $NO_3$-N left unused during legume growth and N mineralised from crop residues (Herridge *et al.* 1995). In a following paper, N benefits to the wheat crop from the prior chickpea crop, between 1987 and 1995, are presented and the profitability of chickpea–wheat rotation compared with traditional continuous wheat cropping is examined (R. C. Dalal, W. M. Strong, E. J. Weston and J. E. Cooper unpublished data).

## Conclusions

Long-term chickpea yields were related to the amount of rainfall received during the preceding fallow period and crop growth. However, sowing time and tillage practices modified grain yields significantly, presumably by optimising solar energy use, and water use and minimising frost damage. Generally, best grain yields are likely to be obtained from late May–early June sowing periods, especially under zero tillage practice, in this region. It appears that chickpea must receive at least 60% of its N needs from $N_2$ fixation to make any significant contribution to soil total N, and hence long-term sustainable production. Management of chickpea in chickpea–cereal systems should be such that it grows in conditions of low soil $NO_3$-N levels and adequate stored water at sowing in this semi-arid subtropical environment, thus enhancing the usefulness of chickpea crop in sustainable cropping systems.

## Acknowledgments

The authors thank J. Glasby, A. Pumfrey, A. J. King, C. J. Chicken and K. J. Lehane for assistance, and the former Wheat Research Committee for Queensland and the Grains Research and Development Corporation for financial support. We thank T. Reid for providing land for the field trials.

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Received 2 February 1997, accepted 12 June 1997