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Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes
5. Wheat yields, nitrogen benefits and water-use efficiency of chickpea–wheat rotation

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Summary. In this study, the benefits of chickpea–wheat rotation compared with continuous wheat cropping (wheat–wheat rotation) were evaluated for their effects on soil nitrate nitrogen, wheat grain yields and grain protein concentrations, and water-use efficiency at Warra, southern Queensland from 1988 to 1996.

Benefits in terms of wheat grain yields varied, from 17% in 1993 to 61% in 1990, with a mean increase in grain yield of 40% (825 kg/ha). Wheat grain protein concentration increased from 9.4% in a wheat–wheat rotation to 10.7% in a chickpea–wheat rotation, almost a 14% increase in grain protein. There was a mean increase in soil nitrate nitrogen of 35 kg N/ha.1.2 m after 6 months of fallow following chickpea (85 kg N/ha) compared with continuous wheat cropping (50 kg N/ha). This was reflected in additional nitrogen in the wheat grain (20 kg N/ha) and above-ground plant biomass (25 kg N/ha) following chickpea.

Water-use efficiency by wheat increased from a mean value of 9.2 kg grain/ha.mm in a wheat–wheat rotation to 11.7 kg grain/ha.mm in a chickpea–wheat rotation. The water-use efficiency values were closely correlated with presowing nitrate nitrogen, and showed no marked distinction between the 2 cropping sequences. Although presowing available water in soil in May was similar in both the chickpea–wheat rotation and the wheat–wheat rotation in all years except 1996, wheat in the former used about 20 mm additional water and enhanced water-use efficiency. Thus, by improving soil fertility through restorative practices such as incorporating chickpea in rotation, water-use efficiency can be enhanced and consequently water runoff losses reduced.

Furthermore, beneficial effects of chickpea in rotation with cereals could be enhanced by early to mid sowing (May–mid June) of chickpea, accompanied by zero tillage practice. Wheat of ‘Prime Hard’ grade protein (≥13%) could be obtained in chickpea–wheat rotation by supplementary application of fertiliser N to wheat.

In this study, incidence of crown rot of wheat caused by *Fusarium graminearum* was negligible, and incidence and severity of common root rot of wheat caused by *Bipolaris sorokiniana* were essentially similar in both cropping sequences and inversely related to the available water in soil at sowing. No other soil-borne disease was observed. Therefore, beneficial effects of chickpea on wheat yields and grain protein were primarily due to additional nitrate nitrogen following the legume crop and consequently better water-use efficiency.

Introduction

Major cereal growing areas of southern Queensland and northern New South Wales have recently experienced declining crop yields and grain protein concentrations (Martin *et al.* 1988; Dalal *et al.* 1991). For example, mean protein concentrations in wheat (*Triticum aestiuum* L.) in southern Queensland have fallen below 10% since 1980, thus preventing farmers from obtaining ‘Prime Hard’ status (13%) for their wheat crop. For improving the wheat grain yield and grain protein, the 2 management options are applications of nitrogenous fertiliser in a wheat monoculture (Holford *et al.* 1992; Strong *et al.* 1996) or inclusion of a legume in rotation with wheat (Herridge *et al.* 1995). Cropping

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systems with legumes, especially pastures, have been used successfully in southern Australia (Donald 1965) although application of such rotation systems in Queensland has been limited, except for the pasture legume, lucerne (*Medicago sativa* L.) (Littler and Whitehouse 1987), and the grain legume, chickpea (*Cicer arietinum* L.) (Doughton 1988).

Although chickpea has been widely used in cereal rotations (Ahlawat *et al.* 1981; Doughton *et al.* 1993), long-term effects of chickpea–wheat rotation on soil nitrogen (N) and wheat grain yields and grain protein concentrations have rarely been studied. Marcellos (1984) found that after one season of chickpea crop grown on an Alfisol in Tamworth, New South Wales, wheat yield in the following year increased from 1.5 t/ha in the wheat–wheat sequence to 3.0 t/ha in the chickpea–wheat sequence. The N benefits were equivalent to an application of 50 kg N/ha as ammonium nitrate. Strong *et al.* (1986*a*) reported a significant increase in nitrate-N concentration following 6 months of fallow after a chickpea crop. Similarly, Hossain *et al.* (1996*a*) measured a significantly higher mineral nitrate-N concentration after chickpea than after wheat.

Agronomic efficiency of N benefits from chickpea have been calculated in terms of fertiliser N equivalents in short-term rotations (Marcellos 1984; Strong *et al.* 1986*b*). However, it is not known whether the effects of a long-term chickpea–wheat rotation would differ from a short-term rotation.

The benefits from a chickpea–wheat rotation may be enhanced by optimising sowing time and tillage practices for chickpea (Horn *et al.* 1996*a*, 1996*b*; Dalal *et al.* 1997) and supplementary N application to the following wheat crop (Marcellos 1984).

Other benefits of legumes include control of cereal diseases. For example, Reeves *et al.* (1984) found that incidence of take-all (*Gaeumannomyces graminis*) in wheat was negligible following a lupin (*Lupinus angustifolius*) crop compared with 36% incidence in continuous wheat cropping. Also, the incidence and severity of crown rot of wheat, caused by *Fusarium graminearum*, appeared to have been reduced by rotation with chickpea in southern Queensland (Wildermuth *et al.* 1992).

The objectives of this study were to investigate the effects of a long-term chickpea–wheat rotation (1987–96) on soil nitrate-N and soil water, and wheat grain yield and grain protein concentration grown on a Vertisol. The incidence and severity of crown rot in wheat assessed at anthesis is reported. The effects of chickpea sowing time, tillage practices and supplementary N application to the wheat crop following chickpea to boost grain yield and protein were also examined in 2 associated experiments.

Materials and methods

Experiment 1. Long-term field experiment

A long-term field experiment was established in 1986 on a Vertisol (Typic Chromustert) that had lost 70% of total soil N (0–10 cm depth) after 50 years of continuous cereal cropping (Dalal and Mayer 1986). The soil originally supported predominantly brigalow (*Acacia harpophylla* L.) and belah (*Casuarina cristata* L.) vegetation. The field experiment was situated north of Warra (26°47'S, 150°53'E), Queensland.

The soil characteristics, mean monthly maximum and minimum temperatures, and mean monthly rainfall, for 1987–94 at the field site, treatment details, soil and plant sampling and analysis, and statistical analysis techniques are given by Dalal *et al.* (1995) and Strong *et al.* (1996). The soil at the field experiment site has been cultivated for cereal cropping since 1935. The soil is very deep, ranging from dark greyish brown to dark brown cracking clay, alkaline from the surface to 0.6 m depth and acid below 0.9 m. Parent material is alluvial clayey sediments formed from light grey shales, siltstones, and fine medium sandstones. The slope at the site is <0.1%. The soil (0–10 cm) contains 56% clay, 17% silt and 27% sand, 0.74% organic C and 0.072% total soil N, and pH (1 : 5, soil : H_2O) 8.6.

Annual rainfall varied from 396 mm in 1986 to 760 mm in 1988. Mean rainfall during the fallow period (usually from November to May inclusive), from 1987 to 1996, was 556 mm. Rainfall from sowing to anthesis varied from 11 mm in 1994 to 169 mm in 1988 although total rainfall during crop growth (usually from June to October inclusive) varied less, from 97 to 217 mm (Table 1). The mean maximum air temperature in January was 27°C and minimum 12°C in July, with a mean annual temperature of 20.7°C.

A 2-year rotation of chickpea (*Cicer arietinum* L. cv. Barwon) and wheat (*Triticum aestivum* L. cv. Hartog) was established in a randomised block design with 4 replications (plot size, 25.0 by 6.75 m). The chickpea–wheat rotation, representing both phases of the

Table 1. Rainfall during the fallow period (usually November–May), from sowing to flowering (in-crop anthesis), from sowing to harvest (total in-crop rainfall, usually June–October), and total rainfall (fallow period and total in-crop rainfall, usually November–October)

Period	Fallow (mm)	In-crop anthesis (mm)	Total in-crop (mm)	Total (mm)
1987–88	592	169	212	804
1988–89	472	99	217	689
1989–90	542	66	134	676
1990–92	790	76	108	898
1992–93	432	108	143	575
1993–94	607	11	97	704
1994–95	317	48	178	495
1995–96	566	61	189	755

rotation, comprised treatments 8 and 9, and continuous wheat cropping (wheat–wheat rotation) was treatment 10 in Dalal *et al.* (1995). Detailed cultural practices of chickpea production are given in Dalal *et al.* (1997). Wheat was sown at about 5 cm depth in rows with 25 cm spacing at the rate of 40 kg/ha in late May and June or 50 kg/ha in July (1990 and 1993).

Crop measurement and analysis

Total dry matter yield of wheat at the time of anthesis was estimated by removing plants from a 1 m long section of the central 2 rows of each plot and drying them at 70–80°C. Wheat grain yields were measured from machine harvesting 1.75 m by about 23 m of the central areas of all plots, and grain yields were adjusted to 12% water content. Harvest index (grain weight/total dry matter weight) was determined using the plants removed from 1 m length of the 2 central rows. Total dry matter yield was calculated by dividing machine harvested grain yield by harvest index. Whole plants from anthesis samplings, and straw and grain from the final harvest were analysed for N concentrations using Kjeldahl digestion followed by automated ammonium analysis (Crooke and Simpson 1971).

Soil sampling and analyses

In May (presowing), September or October (anthesis) and November (after harvest) each year, 5 soil cores, using a 50-mm diameter tube sampler, were collected from each plot to a depth of 30 cm, and then 2 cores to 150 cm depth; these were divided into 10 cm layers down to 30 cm depth, and below that at 30 cm depth intervals. The cores were bulked, sealed in plastic bags, and stored at 4°C until analysis.

Soil was dried at 35 ± 5°C in a forced draught oven and ground to <2 mm for colorimetric determination of nitrate (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; volumetric water content (mm/layer) was calculated using a bulk density adjusted for the soil moisture of the layer sampled. Plant-available water was calculated as described by Strong *et al.* (1996).

Water-use efficiency (WUE; kg/ha.mm) for the wheat crops was calculated from grain yield divided by water utilised (mm), where water utilised by the wheat crop is soil water in May before sowing minus soil water (0–1.2 m) in November at harvest plus in-crop rainfall.

Disease assessment

An assessment was made for the incidence and severity of common root rot caused by *Bipolaris sorokiniana* (Sacc. In Sorok.) Shoem. and crown rot caused by *Fusarium graminearum* Schw. Group 1. Fifty wheat plants with their roots were randomly collected from each plot at anthesis and the subcrown internode of each plant was examined for the extent of lesions due to common root rot. The plants were separated into 6 disease categories based on subcrown internode surface covered by lesions: 1, no lesion; 2, 1 or 2 lesions covering <10%; 3, lesions covering 10–25%; 4, lesions covering 25–50%; 5, lesions covering 50–99%; 6, lesions covering 100%. Disease severity was calculated from the formula:

$$\text{Disease severity (\%)} = \frac{(2\ N_1 + 5\ N_2 + 10\ N_3) \times 100}{10 \times \text{total number of plants}}$$

where N_1 is the number of plants in categories 2 and 3, N_2 is the number of plants in category 4, and N_3 is the number of plants in categories 5 and 6 (Wildermuth *et al.* 1992).

Incidence of crown rot was assessed by examining the first internode of tillers for honey brown to dark brown discolouration.

Experiment 2. Fertiliser nitrogen response by wheat

A study (to equate the chickpea N benefits to the subsequent wheat crop in terms of N fertiliser equivalent rates) was carried out adjacent to the long-term experiment from 1987 to 1996. The cereal cropping history of this area was exactly the same as the long-term experiment and since 1987 it was sown to wheat each year without fertiliser N application. On a new randomly allocated area each year, fertiliser N, as urea, was applied at 0, 25, 50, 75, 100 (1988 only), 125 (1989 only) and 150 kg N/ha. The experimental design was a completely randomised block with 4 replications and plot size was 12.5 by 2.25 m.

Crop management, crop measurements, soil sampling and analysis, and statistical analysis have been described previously (Strong *et al.* 1996). Fertiliser N response curves were obtained by linear or quadratic regressions of wheat grain N yield on N fertiliser application rate. From these curves, the equivalent amount of fertiliser N required to give the grain N yield of unfertilised wheat following chickpea in the long-term field experiment was estimated.

Experiment 3. Time of sowing of previous chickpea crop

This study was conducted adjacent to the long-term experiment site (experiment 1) from 1992 to 1995 to study the effects of sowing time and tillage practices on grain yield of chickpea, and its effects on subsequent wheat grain yields and grain protein contents.

The experimental design and cultural practices have been described in detail by Horn *et al.* (1996*a*, 1996*b*) and Dalal *et al.* (1997). Briefly, the field experiment was established in May 1992, following a cultivated fallow since May 1991, when sorghum was harvested. The design was a randomised complete block with 4 replications in plots each 22.5 by 6.75 m. The treatments were tillage [conventional tillage (CT) and zero tillage (ZT) after 1992 crop harvest], 2 crops (wheat and chickpea), and 3 sowing times of chickpea (28 April–2 May, 27 May–9 June, 4 July–7 August).

Table 2. Experiment 1. Grain yield and grain protein concentrations of wheat in chickpea–wheat or wheat–wheat rotation from 1988 to 1996 (no crop was planted in 1991 due to drought)

Year	Grain yield (kg/ha)			Grain protein (%)		
	Chickpea–wheat	Wheat–wheat	l.s.d. ($P = 0.05$)	Chickpea–wheat	Wheat–wheat	l.s.d. ($P = 0.05$)
1988	4620	3076	1311	9.4	8.3	n.s
1989	2875	2073	467	10.1	8.0	1.2
1990	3586	2234	243	9.4	8.3	1.0
1992	4230	3476	543	12.4	10.8	0.7
1993	2198	1883	n.s.	11.8	9.6	1.1
1994	1604	1023	152	10.1	8.7	1.1
1995	1761	1198	220	12.1	11.8	n.s.
1996	3023	2265	756	10.1	10.2	n.s.
Mean	2942	2117	125	10.7	9.4	0.5

Crop cultivars, crop and soil sampling, and analytical methods used in this experiment were the same as in the long-term experiment described earlier.

Experiment 4. Tillage practices and fertiliser nitrogen application to wheat following chickpea

The experiment was conducted in an area adjacent to the experiment 1 site. The ZT and CT treatments were applied in 1986 at the same time as experiment 1 was established and wheat (cv. Hartog) was grown until 1990 in a randomised block design with 4 replications (plot size, 12.5 by 2.25 m) (Strong *et al.* 1996*a*). After the drought of 1991, a chickpea (cv. Barwon) crop was grown in 25% of the plots each in 1992, 1993, 1994 and 1995, while wheat (cv. Hartog), was grown on the remainder. Following a chickpea crop, wheat was grown and fertiliser N as urea was freshly applied each year at 0, 25, 50, 75 and 150 (CT only) kg N/ha. Crop management, crop measurements and analysis were the same as those described for experiment 1.

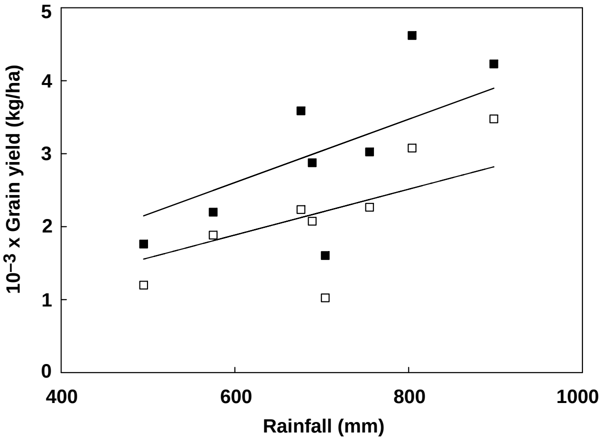

Figure 1. Relationship between total rainfall and wheat grain yield in chickpea–wheat rotation (■) and wheat–wheat rotation (□).
Equations of the lines are:
Chickpea–wheat rotation:
Grain yield (kg/ha) = 4.3 (± 0.4) x rainfall (mm) ($r = 0.76$, $P<0.05$); intercept is not significantly different from zero at $P = 0.05$.
Wheat–wheat rotation:
Grain yield (kg/ha) = 3.1 (± 0.3) x rainfall (mm) ($r = 0.80$, $P<0.05$); intercept is not significantly different from zero at $P = 0.05$.

Statistical analysis

Analysis of variance was performed to assess the effect of soil and crop management practices on soil nitrate-N, available water, dry matter, grain yields and grain protein concentrations, N yields, disease incidence and severity, and WUE using standard statistical techniques (Snedecor and Cochran 1967).

Results

Experiment 1. Wheat grain yields and grain protein concentrations

Wheat grain yields in the chickpea–wheat rotation varied from 1604 kg/ha in 1994 to 4620 kg/ha in 1988; the corresponding wheat grain yields in the wheat–wheat rotation in the same seasons were 1023 and 3076 kg/ha respectively (Table 2). Except for the 1993 season, wheat grain yields were significantly higher in the chickpea–wheat rotation than in the wheat–wheat rotation. The percentage increases in wheat grain yields in the chickpea–wheat rotation compared with the wheat–wheat rotation ranged from 22% in 1992 to 61% in 1990, with a mean increase of about 40% or 825 kg/ha during 1988–96. Neither the absolute increase nor the percentage increase in grain yield of wheat from the chickpea–wheat rotation were related to total rainfall (fallow period + in-crop rainfall) although wheat grain yield increased with total rainfall at the rate of 4.3 ± 0.4 kg grain/ha.mm rainfall for the chickpea–wheat rotation and 3.1 ± 0.3 kg grain/ha.mm rainfall for the wheat–wheat rotation (Fig. 1). Thus, wheat following chickpea had almost 40% better rainfall-use efficiency than continuous wheat cropping. This appears to be due to better utilisation of rainfall received from sowing to anthesis, as shown by the following relationships:

Chickpea–wheat rotation:

$$\text{Grain yield (kg/ha)} = 4.8\ (\pm\ 1.6)x_1 + 15.3\ (\pm\ 4.7)x_2 - 809 \quad (R^2 = 0.80;\ P<0.05)$$

Wheat–wheat rotation:

$$\text{Grain yield (kg/ha)} = 4.0\ (\pm\ 1.1)x_1 + 10.9\ (\pm\ 3.3)x_2 - 850 \quad (R^2 = 0.83;\ P<0.05)$$

where x_1 and x_2 are the amounts of rainfall (mm) received during the fallow period and from sowing to anthesis respectively.

Grain protein concentrations of wheat following chickpea increased significantly in most years; exceptions were 1988, 1995 and 1996 (Table 2). Mean grain protein concentration increased from 9.4% in the wheat–wheat rotation to 10.7% in the chickpea–wheat rotation for 1988–96. Therefore, there was a substantial increase in grain yield and a small but significant increase in grain protein concentration by including chickpea in rotation with wheat.

Grain nitrogen and above-ground plant nitrogen yields

Grain N yield varied from 28.4 kg/ha in 1994 to 91.8 kg/ha in 1992 for wheat in the chickpea–wheat rotation; the corresponding values in the wheat–wheat rotation were 15.6 and 65.8 kg/ha (Table 3). For 1988–96, mean grain N yields were 55.5 and 35.5 kg/ha for wheat in the chickpea–wheat rotation and the wheat–wheat rotation, respectively, resulting in a net increase of 20 kg N/ha in wheat grain following a chickpea crop. Similar trends were observed for above-ground plant N yields, resulting in a net increase of 25.1 kg N/ha following a chickpea crop for 1988–96 (Table 3). No significant relationship was observed between the total amounts of N of the previous chickpea crop (Dalal *et al.* 1997) and increased amounts of wheat grain N and plant N yields following a chickpea crop.

Soil nitrate nitrogen and wheat nitrogen yields

Soil nitrate-N concentrations in the profile in May (after about 6 months of clean fallow in all years except 1992 when the fallow period was 18 months) were significantly greater following chickpea than wheat down to 1.2 m depths in 1988 and 1992 (Fig. 2). In other years, there was generally a trend towards increased nitrate-N concentrations at all depths following chickpea. In the relatively dry seasons of 1994 and 1995, significantly higher nitrate-N at 120–150 cm depth was found following chickpea than wheat. Total nitrate-N in the 0–1.2 m depth was significantly greater in all years except 1995 (Table 4). Mean nitrate-N from 1988 to 1996 was 34.6 kg N/ha greater following chickpea than wheat. Soil nitrate-N following chickpea exceeded that following wheat by more than 50 kg N/ha in 1988 and 1992. Crop rotations preceding these soil nitrate measurements were different from those for other years. Chickpea grown in 1987, preceding the 1988 measurement, followed an 18-month fallow period and suffered yield reduction due to frost injury, and an 18-month fallow period followed chickpea grown in 1990, which preceded the 1992 measurement.

In both crop rotations, wheat grain N yields were closely correlated with the amounts of nitrate-N in the soil profile at sowing in May (Fig. 3). However, in 1994 and 1995, when rainfall from sowing to anthesis was less than 50 mm, which resulted in none or poor secondary root development, the relationship between grain N yield and soil nitrate-N was different. Similar relationships were observed between above-ground wheat biomass N yields and soil nitrate-N at sowing in May (data not shown). The same relationship fitted results for wheat in both rotations, therefore, the differences in plant N yields between wheat following chickpea and the wheat–wheat rotation were primarily due to the amounts of nitrate-N in the soil profile at sowing.

Soil-available water contents and water-use efficiency

Soil-available water following chickpea was either similar to or higher than under continuous wheat cropping (Table 4). In 1988 and 1993, more water was found at 0.6–1.2 m depths following chickpea than continuous wheat cropping (Fig. 2). On the other hand,

Table 3. Experiment 1. Grain nitrogen yield and total nitrogen yield of above-ground biomass of wheat in chickpea–wheat or wheat–wheat rotation from 1988 to 1996 (no crop was planted in 1991 due to drought)

Year	Grain nitrogen yield (kg/ha)			Total nitrogen yield (kg/ha)		
	Chickpea–wheat	Wheat–wheat	l.s.d. (P = 0.05)	Chickpea–wheat	Wheat–wheat	l.s.d. (P = 0.05)
1988	75.9	44.5	9.4	88.4	52.2	19.0
1989	51.4	29.1	14.6	62.1	34.7	16.4
1990	59.2	32.5	3.2	74.0	41.9	8.0
1992	91.8	65.8	14.6	121.8	81.6	16.8
1993	45.4	31.6	6.0	55.0	36.5	5.9
1994	28.4	15.6	4.5	38.6	20.6	11.0
1995	37.5	24.8	5.2	47.1	31.3	8.7
1996	54.2	40.6	n.s.	64.3	51.3	n.s.
Mean	55.5	35.5	2.2	68.9	43.8	3.4

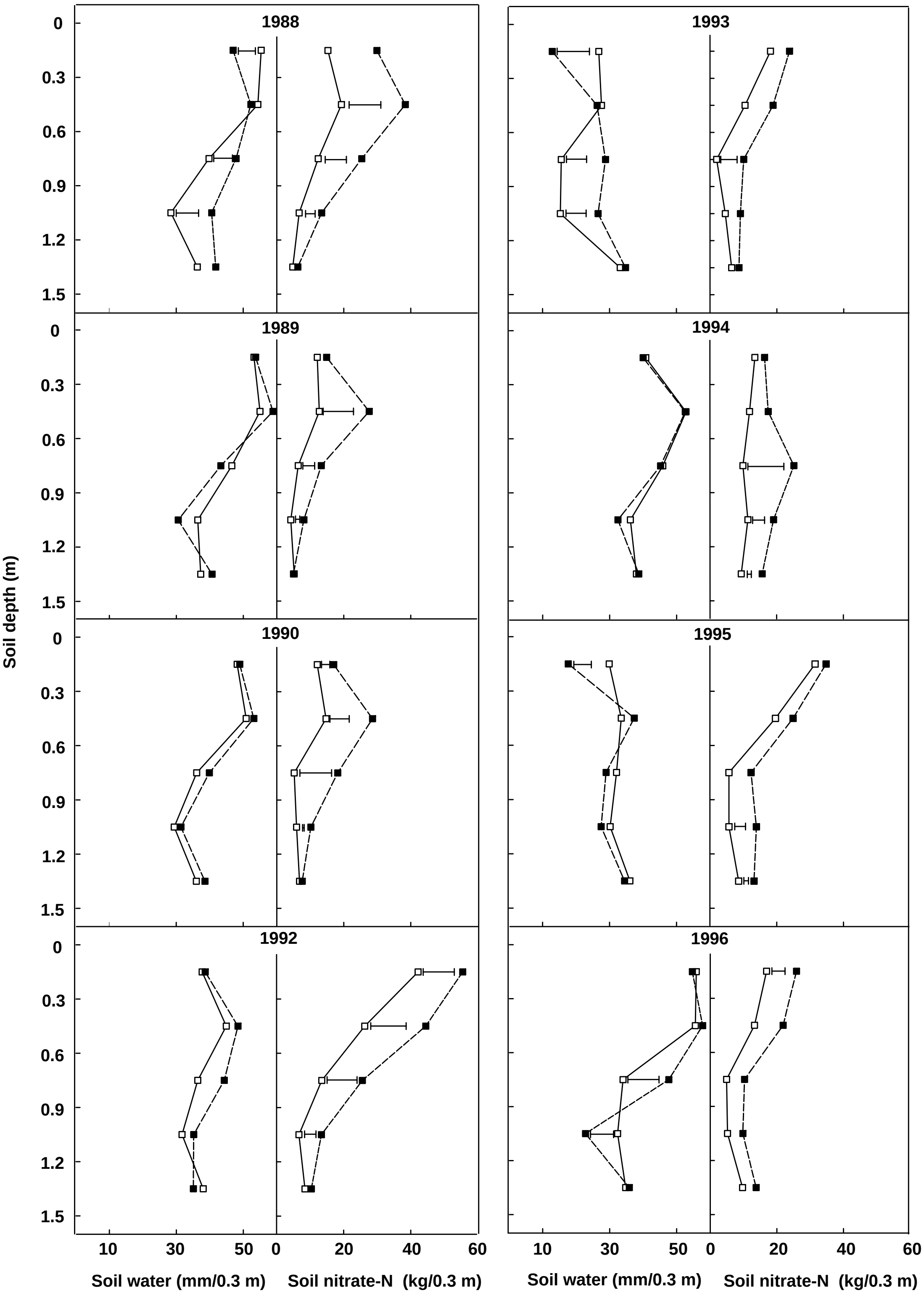

Figure 2. Soil depth distribution of available water and nitrate-N in May (presowing) following the fallow period after chickpea in chickpea–wheat rotation (■) and wheat–wheat rotation (□). Horizontal bars indicate l.s.d. at $P = 0.05$.

Table 4. Wheat crop presowing soil nitrate-N and available water (1.2 m depth) in May after chickpea (chickpea–wheat rotation) and wheat–wheat rotation following six months of clean fallow (no crop was sown in 1991 due to lack of sowing rain)

Year	Soil nitrate-N (kg/ha.1.2 m)			Available water (mm/1.2 m)	
	After chickpea (chickpea–wheat)	Wheat–wheat	l.s.d. (P= 0.05)	After chickpea (chickpea–wheat)	Wheat–wheat
1988	107.1	53.7	37.4	187.7	177.9
1989	63.9	35.4	15.4	195.3	195.3
1990	73.9	37.9	10.9	173.5	164.6
1992	139.0	88.7	25.5	166.5	150.7
1993	61.9	35.2	25.3	94.6	85.3
1994	78.2	46.6	29.7	170.3	175.7
1995	85.9	62.5	n.s.	121.5	123.8
1996	68.0	40.4	25.5	192.6*	168.3
Mean	84.7	50.1	8.9	162.8*	155.2

* $P<0.05$.

the top 0–0.3 m layer had lower soil-available water in 1988, 1993 and 1995, often resulting in similar amounts of soil-available water under both cropping systems (Table 4).

Water-use efficiencies of wheat varied from a low of 5 kg grain/ha.mm water in 1994 in the wheat–wheat rotation to a high of 17.5 kg grain/ha.mm water in 1992 in the chickpea–wheat rotation (Fig. 4). In all years, WUE of wheat in the chickpea–wheat rotation was higher than in the wheat–wheat rotation (Fig. 4); the difference was significant ($P<0.05$) in 4 of the 8 years of cropping, and for all years combined.

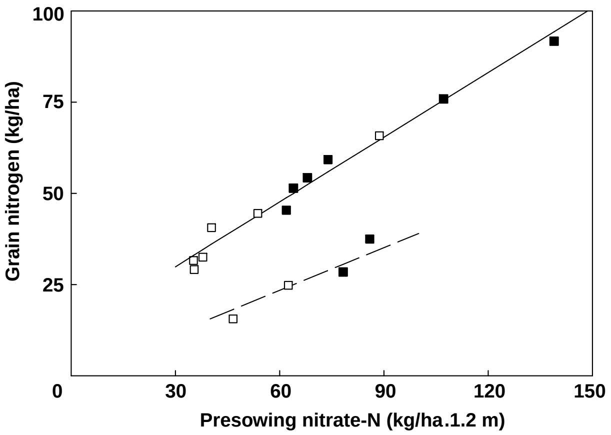

Figure 3. Relationship between the amount of nitrate-N at presowing and wheat grain N yield, from 1988 to 1996, in chickpea–wheat rotation (■) and wheat–wheat rotation (□).
The equations of the lines are:
For 1994–95 crops:

$$\text{Grain N (kg/ha)} = 0.39\ (\pm 0.02) \times \text{nitrate-N (kg/ha.1.2 m)}$$
$$(R^2 = 0.94,\ P<0.05);$$

intercept is not significantly different from zero at $P = 0.05$.
For 1988–93 and 1996 crops:

$$\text{Grain N (kg/ha)} = 12.2\ (\pm 2.0) + 0.59\ (\pm 0.03) \times \text{nitrate-N (kg/ha.1.2 m)}$$
$$(R^2 = 0.98,\ P<0.05)$$

In all cropping years, WUE was closely correlated with soil nitrate-N at sowing (Fig. 5). Almost 77% of the variation in WUE could be accounted for by the amount of soil nitrate-N present in the soil profile at sowing. Wheat following chickpea, therefore, utilised water more efficiently due primarily to increased amounts of nitrate-N in the soil.

In the dry years of 1994 and 1995, WUE was lower than in other years at similar nitrate-N in soil at sowing. Apparently, WUE was affected by poor root density, since secondary root development was restricted due to low in-crop rainfall after sowing.

Common root rot and crown rot

Common root rot occurred extensively in all years in

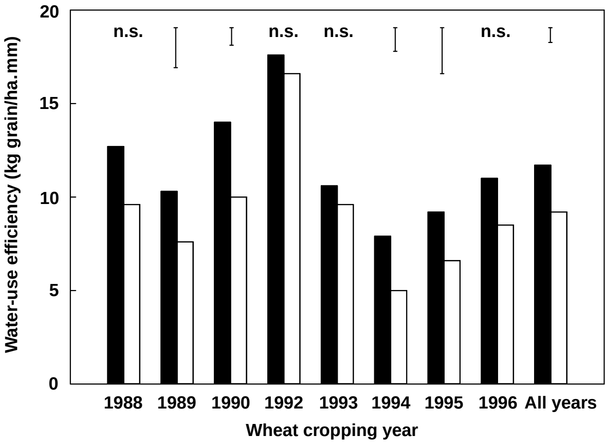

Figure 4. Water-use efficiencies of wheat in chickpea–wheat rotation (closed bars), and wheat–wheat rotation (without fertiliser N) (open bars). Vertical bars indicate l.s.d. at $P = 0.05$.

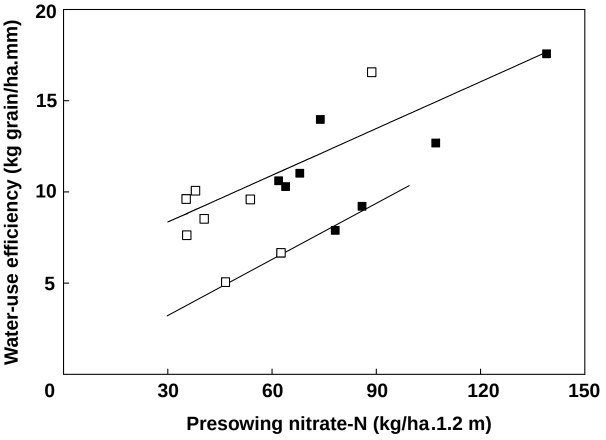

Figure 5. Relationship between amount of nitrate-N at presowing in May and water-use efficiency (WUE) of wheat in chickpea–wheat rotation (■), and continuous wheat–wheat rotation (□). The equations of the lines are:

For 1994–95 crops:

WUE (kg grain/ha.mm) = 0.105 (± 0.002) x nitrate-N (kg/ha.1.2 m) ($R^2 = 0.98$, $P<0.05$);

intercept is not significantly different from zero at $P = 0.05$.

For 1988–93 and 1996 crops:

WUE (kg grain/ha.mm) = 5.77 (± 1.10) + 0.086 (± 0.015) x nitrate-N (kg/ha.1.2 m) ($R^2 = 0.77$, $P<0.05$).

both the chickpea–wheat rotation and the wheat–wheat rotation (Table 5). Incidence and severity of common root rot were similar in both treatments in all years except 1994 and 1995. In these 2 years, common root rot was significantly higher in the chickpea–wheat rotation than in the wheat–wheat rotation.

For all years, both incidence and severity of common root rot were inversely related to the amount of available water at sowing irrespective of crop rotations. The incidence of common root rot was also inversely related to the amount of rainfall received from sowing to anthesis.

Crown rot was not detected until 1995; even then the disease levels were negligible in this and subsequent years.

Table 5. Incidence and severity of common root rot in wheat crop after chickpea (chickpea–wheat rotation, CpW) and wheat–wheat rotation (WW) at anthesis (no crop was sown in 1991 due to drought)

Year	Incidence (%)		Severity (%)	
	CpW	WW	CpW	WW
1989	38.6	31.7	18.8	17.3
1990	28.6	37.2	15.6	18.6
1992	39.6	35.8	22.8	21.3
1993	87.5	84.3	64.3	53.4
1994	73.4*	34.8	32.8*	8.6
1995	62.0*	41.2	38.6*	24.8
1996	41.7	34.6	20.0	19.4

* $P<0.05$.

Table 6. Fertiliser nitrogen equivalents and additional wheat grain nitrogen yield in chickpea–wheat rotation compared with wheat–wheat rotation

Fertiliser nitrogen equivalents in 1994 and 1995 could not be calculated due to poor fertiliser nitrogen uptake in these dry seasons

Crop year	Additional grain N yield (kg/ha)	Fertiliser N equivalent (kg/ha)
1988	53.4	114.6
1989	28.5	50.1
1990	36.0	57.9
1992	50.3	50.5
1993	26.7	47.3
1994	31.6	n.d.
1995	23.4	n.d.
1996	27.6	40.0

Experiment 2. Fertiliser nitrogen equivalents

Fertiliser N equivalents were calculated from the relationship between wheat grain N yield and freshly applied fertiliser N rates. Mean fertiliser equivalent values for 1989, 1990, 1992, 1993 and 1996 were 49.2 ± 6.4 kg N/ha (Table 6). In 1988, it was more than twice the mean value. Frost injury of the preceding chickpea crop at flowering and consequently low grain yield (535 kg/ha) and low amounts of grain N removed (22 kg N/ha) was the probable cause. Also, the chickpea crop in 1987 followed a long period of fallow (18 months) and therefore a large nitrate-N supply had accumulated by May 1987 (126 kg N/ha.1.2 m). In 1994 and 1995, fertiliser equivalents could not be estimated because fertiliser N applied to wheat at sowing between the rows was poorly used due to low in-crop rainfall. Additional wheat grain N yield (grain N intake) following chickpea usually exceeded 50% of the fertiliser N equivalents (Table 6).

Experiment 3. Effect of time of sowing of previous chickpea crop on wheat yield

Wheat yields were significantly lower following the early-sown chickpea crop than either mid sowing or late sowing in 1993 and 1995 although in 1994, wheat following the early-sown chickpea crop gave a better yield (Table 7).

Table 7. Effect of sowing time of previous chickpea crop on the following wheat crop

Previous chickpea sowing period	Wheat grain yield (kg/ha)			
	1993	1994	1995	Mean
Early sowing (28 Apr.–1 May)	2530	1737	1267	1845
Mid sowing (27 May–8 June)	2768	1544	1646	1986
Late sowing (8 July–7 Aug.)	2698	1590	1679	1989
l.s.d. ($P = 0.05$)	133	110	167	80

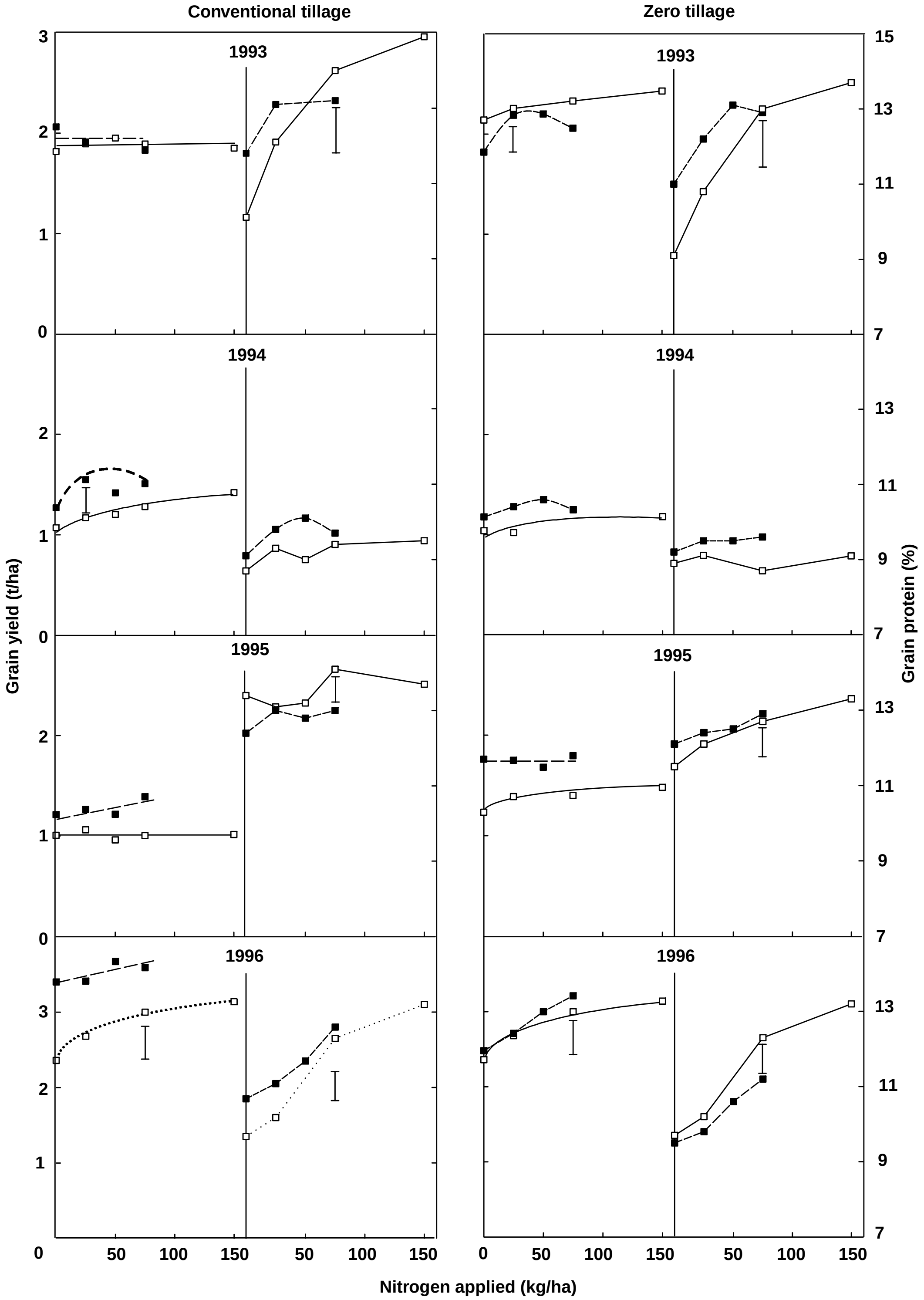

Figure 6. Wheat grain yield and grain protein from 1993 to 1996 in chickpea–wheat rotation (■) and wheat–wheat rotation (□) under conventional tillage and zero tillage, and different rates of fertiliser N applications. Height of bars indicate l.s.d. (*P* = 0.05) for fertiliser N response.

Mean wheat yields for 1993–95 were similar following the mid-sown and late-sown chickpea crops.

Effect of tillage practice and fertiliser nitrogen application on wheat following chickpea

Wheat yields increased significantly under zero tillage practice both in chickpea–wheat rotation and wheat–wheat rotation in 1993 [CT 1901 kg/ha, ZT 2179 kg/ha, l.s.d. (P = 0.05), 220 kg/ha] and 1995 [CT 1125 kg/ha, ZT 1561 kg/ha, l.s.d. (P = 0.05), 215 kg/ha] (Fig. 6). In the chickpea–wheat rotation, fertiliser N created small increases in wheat grain yield in 1993 (ZT) and 1994 (CT) with a modest application of 25 kg N/ha. Large grain yield increases occurred in 1996 (ZT) with N rates up to 75 kg/ha. Wheat grain protein concentrations were increased significantly in 1993 and 1996 in the chickpea–wheat rotation and in 1993, 1995 and 1996 in the wheat–wheat rotation for both tillage practices (Fig. 6). With supplementary fertiliser N applications of 75 kg N/ha to wheat following chickpea, 'Prime Hard' grade (≥13%) wheat was produced in 1993, 1995 and 1996 (Fig. 6).

Discussion

Wheat grain yields

In spite of the large seasonal variability experienced during 1987–96, wheat yields were significantly higher in the chickpea–wheat rotation than in the wheat–wheat rotation in all years except 1993 (Table 2). Mean yield increase of wheat in chickpea–wheat rotation during this period was 825 kg/ha or 40% compared with the wheat–wheat rotation. Marcellos (1984) measured an increase of 1465 kg/ha in wheat following a chickpea crop (CP156288) compared with a wheat–wheat rotation in northern New South Wales. Felton *et al.* (1998) recorded a mean wheat yield increase of 850 kg/ha following chickpea compared with continuous wheat during 1987–90. The results of Herridge *et al.* (1995) corroborate these findings from northern New South Wales. However, Strong *et al.* (1986*b*) in southern Queensland, obtained much smaller increases in wheat yields following chickpea (500 kg/ha in 1977 and only 330 kg/ha in 1978). The magnitude of wheat yield is likely to be dependent on several factors including seasonal conditions (both fallow period rainfall and in-crop rainfall), performance of the previous chickpea crop (plant biomass, grain yield, N accretion and grain N removal), soil fertility levels, tillage practices and disease incidence.

Cultural practices such as sowing time of the previous chickpea crop and tillage practices affected the yields of the following wheat crops. Since sowing time had a much larger effect on grain yield and N_2 fixation by chickpea than tillage practice (Dalal *et al.* 1997), yields of the following wheat crop were similarly affected (Table 7). Zero tillage improved wheat grain yields primarily by increasing total available water in the soil (Strong *et al.* 1996).

Grain protein concentrations

Grain protein concentrations of wheat following chickpea showed small but significant increases in 5 out of 8 crops, with a mean increase of 0.5% (Table 2). Felton *et al.* (1998) reported similar grain protein responses (0.6%). However, wheat protein did not attain 'Prime Hard' grade in any of the cropping seasons. Supplementary application of fertiliser N to wheat were required to increase protein concentrations of wheat to 'Prime Hard' classification (Fig. 6). However, residual fertiliser N left after the wheat crop decreased N_2 fixation by the following chickpea crop (Dalal *et al.* 1997). Obviously, better N management strategy is required to maximise not only N benefits from chickpea but also better grain yield and grain protein concentrations of the following wheat crop.

Nitrogen benefits

Total plant N and grain N yield benefits of rotations (wheat N yield in a chickpea–wheat rotation minus that in a wheat–wheat rotation) are less affected by seasonal conditions than grain yield. Mean plant N yield and grain N yield benefits were 25 and 20 kg N/ha respectively (Table 3). Armstrong *et al.* (1997) reported much larger increases in 1993 at Wagga Wagga, New South Wales. They found that wheat in a chickpea–wheat rotation had total plant N and grain N benefits of 55 and 50 kg N/ha, respectively, compared with wheat in a barley–wheat rotation. They obtained much higher biomass of the previous chickpea crop, 8.2 t/ha (Armstrong *et al.* 1997) *v.* 2.9 t/ha (Dalal *et al.* 1997), and hence, achieved more N_2 fixation. On the other hand, Keatinge *et al.* (1988) observed that the residual effects of legume crops, including chickpea, were about 10 kg N/ha, as measured by the difference in total crop N yield of barley in a legume–barley rotation and barley–barley rotation in a relatively dry area. Obviously, seasonal and location differences should also be considered in evaluating the residual benefits of legumes in dryland agriculture.

Chickpea N benefits, measured by the difference in total plant N yield and grain N yield of wheat in a chickpea–wheat rotation compared with a wheat–wheat rotation, are affected by the efficiency of N uptake by the cereal crop. For example, apparent N uptake efficiency of presowing nitrate-N by wheat in the grain and above-ground crop were only 39 and 64% in 1994 and 1995, the drier seasons with none or restricted secondary root development (in-crop rainfall to anthesis, <50 mm, Table 1), compared with values of 59 and 77% (Fig. 3) in years of normal secondary root development.

Agronomic benefits of a legume in rotation are usually measured as fertiliser N responses to the following cereal crop. Except for the 1988 crop, which followed a frost-damaged chickpea crop, and 1994 and 1995 seasons, which had limited in-crop rainfall up to anthesis, fertiliser N equivalent benefits of chickpea to the following wheat crop were about 50 kg N/ha (Table 6), a value similar to that reported for northern New South Wales (Marcellos 1984).

Currently the most sensitive method to measure the residual N benefits of a chickpea crop, from both N_2 fixation and N sparing (Dalal *et al.* 1994; Herridge *et al.* 1995; Hossain *et al.* 1996*b*; Marcellos *et al.* 1998), in northern New South Wales and Queensland, is probably the amount of nitrate-N present in the soil profile after the summer–autumn fallow period, provided chickpea accrued organic N and plant N has nitrified and nitrate-N losses due to leaching and denitrification are negligible.

Mean increase in the amount of nitrate-N after fallow at sowing in May was 34.6 kg N/ha following chickpea compared with continuous wheat cropping (Table 4). Marcellos *et al.* (1998) found similar nitrate-N increases following a chickpea crop, with mean values of 33 kg N/ha, from 1987 to 1990 in northern New South Wales. We estimate that chickpea root and stubble residues contributed on average 39.4 kg N/ha.crop. This is estimated from the net difference in the total above-ground and below-ground chickpea N yields (assuming 30% N in below-ground biomass according to Russell and Fillery 1996; Dalal *et al.* 1997), and grain N removal (Dalal *et al.* 1997). This value is essentially similar to the overall nitrate-N increase after chickpea, assuming that about 5 kg N/ha.crop may have been mineralised from wheat crop residues in the wheat–wheat rotation. Similar nitrate-N benefits following chickpea compared with wheat were reported by Marcellos (1984), Strong *et al.* (1986*a*), Hossain *et al.* (1996*b*) and Marcellos *et al.* (1998). Also, Herridge *et al.* (1995) reported 29–51 kg N/ha increased nitrate-N benefits in wheat crop following chickpea compared with a wheat–wheat rotation.

A salient feature of this study is the close relationship observed between the amount of nitrate-N in the soil profile at sowing and wheat grain N and plant N yields in both crop sequences (Fig. 3). The increase in available N was the dominant benefit following chickpea rather than a break in disease cycle or some other non-nitrogen rotation benefit, as suggested by Stevenson and van Kessel (1996). As mentioned earlier, the disease incidence and severity of common root rot of wheat was generally similar in both crop sequences and that of crown rot of wheat was negligible in this experiment.

Water-use efficiency

Average WUE of wheat in the chickpea–wheat rotation (11.7 kg grain/ha.mm) was 2.5 kg/ha.mm higher than in the wheat–wheat rotation (9.2 kg grain/ha.mm) (Fig. 4). Available water at sowing was essentially similar in all years except 1996, in both cropping sequences (Table 4). However, overall mean values of water use by wheat from 1988 to 1996 were almost 20 mm higher in the chickpea–wheat rotation (249.6 mm) than the wheat–wheat rotation [230.2 mm; l.s.d. ($P = 0.05$) 9.1 mm]. Thus, the wheat crop following chickpea utilised available water from soil more efficiently than continuously-grown wheat, primarily due to additional N from the previous chickpea crop. This is evident from the relationship between WUE by wheat and the amount of presowing nitrate-N, with no distinction between the crop rotations (Fig. 5).

In other experiments, WUE by wheat following a legume crop has been shown to be higher due to lower incidence and severity of soil-borne disease than in continuous wheat cropping (King 1984). Besides common root rot (Table 4) and low incidence or absence of crown rot of wheat in this study, the other known soil-borne disease in the region, root lesions caused by root lesion nematodes (*Pratylenchus thornei*) was absent from the experimental site.

Conclusions and relevance to sustainable farming system

Chickpea–wheat rotation provides an alternative to monoculture wheat cropping in the semi-arid subtropical eastern Australia. In the absence of severe disease incidence in this study, the main benefits of chickpea to wheat in rotation were increased grain yields and grain protein concentrations due to additional N and better WUE. This is critical in this environment where water is the most limiting factor in crop production. Wheat in the chickpea–wheat rotation not only used more water from the soil but it used it more efficiently than monoculture wheat (without fertiliser N application), primarily due to increased N supply following chickpea (Fig. 5). Consequently, less water runoff may be expected from such rotations, particularly if the soil surface protection by cereal residues is prolonged by reduced or zero tillage practices. Increased N supply can also be achieved by fresh application of fertilisers (Strong *et al.* 1996) although its utilisation by the crop can be limited by poor in-crop rainfall, for example, in 1994 and 1995 (Table 6).

In long-term sustainable farming systems, incorporating chickpea provides a small but significant N benefit to cereals in rotations. Such benefits can be increased by cultural practices such as optimum sowing time and zero tillage practice and by supplementary fertiliser N application to the following wheat crop to increase grain protein concentrations. However, increased organic matter accumulation in soil is less likely to be achieved from a chickpea–wheat rotation in this semi-arid subtropical environment (Dalal *et al.* 1995).

The economic analysis of a chickpea–wheat rotation and monoculture wheat cropping will be presented in a subsequent paper.

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