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Legume and opportunity cropping systems in central Queensland. 2*. Effect of legumes on following crops[†]

R. D. Armstrong[AE], *K. McCosker, G. Millar, B. Kuskopf, S. Johnson*[B], *K. Walsh*[B],
M. E. Probert[C], *and J. Standley*[D]

Queensland Department of Natural Resources, LMB 6, Emerald, Qld 4720, Australia.
[A] Current address: Victorian Institute for Dryland Agriculture, Private Bag 260,
Horsham, Vic. 3401, Australia.
[B] Biology Department, Central Queensland University, Rockhampton, Qld 4702, Australia.
[C] CSIRO Tropical Agriculture, St Lucia, Qld 4067, Australia.
[D] Leslie Research Centre, PO Box 2282, Toowoomba, Qld 4350, Australia.
[E] Corresponding author; email: roger.armstrong@nre.vic.gov.au

Abstract Poor yields and low grain protein in cereal crops resulting from declining soil fertility, especially nitrogen (N), are major threats to the grains industry in central Queensland. The effect of 4 different pasture-ley legumes [siratro (*Macroptilium atropurpureum* cv. Siratro), lucerne (*Medicago sativa* cv. Trifecta), lablab (*Lablab purpureus* cv. Highworth), and desmanthus (*Desmanthus virgatus* cv. Marc)] on grain yield and quality of sorghum crops was compared with that of a pulse (mungbean; *Vigna radiata* cv. Satin) or continuous cropping with grain sorghum (*Sorghum bicolor*).

Legume leys consistently resulted in large increases in grain yield (188–272%), N uptake by sorghum (145–345%), and grain protein (0.21–7.0% increase in grain protein) in sorghum test-crops compared with continuous sorghum crops to which no fertiliser N had been added. The positive effect of legumes persisted up to 3 sorghum test-crops after only 1 year of legumes, although by the third year the effect was comparatively small. Mungbean and lablab generally produced the largest benefit in sorghum test-crops in the first year after legumes, whereas desmanthus and lucerne produced the least benefit. Adding fertiliser N (up to 75 kg N/ha) significantly improved grain yields and N uptake of sorghum test-crops in 3 of 4 years. However, responses to fertilisers were less than those resulting from legumes, which was ascribed to increased availability of legume N to sorghum.

Legumes progressively increased soil nitrate in all subsequent sorghum test-crops (compared with continuous sorghum crops), rising from 6.8–18.9 kg NO_3-N/ha after 1 year of legumes to 24.2–59.6 kg NO_3-N/ha after 3 years of legumes. There was little difference between the legumes in their ability to increase soil nitrate, with the exception of desmanthus, which consistently resulted in the lowest amount of soil nitrate for subsequent test-crops and lowest uptake of N by these crops.

Plant-available water content (PAWC) at planting of the sorghum test-crop was only significantly ($P < 0.05$) affected by previous species in 1997, when it was lowest in plots previously sown to siratro and lucerne and highest in sorghum and mungbean plots. In both 1996 and 1997, plots sown to sorghum had significantly higher PAWC at anthesis and grain maturity when previous plots were sorghum rather than legumes.

Additional keywords: cracking clays, nitrogen, grain sorghum, protein, water use efficiency.

Introduction

Although pasture-ley legumes offer the potential to dramatically improve liveweight gains by cattle through the provision of high quality (protein) feed (Graham *et al.* 1986), their adoption in Central Queensland (CQ) will depend primarily on their ability to improve grain yields and quality of subsequent crops. Soil fertility, especially nitrogen (N), has declined significantly in cracking clay soils of the northern

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[†] Some of the data contained in this paper were presented at the 9th Australian Agronomy Conference (Armstrong *et al.* 1998).

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Australian grain belt (Dalal and Mayer 1986), leading to decreased grain yields and protein concentrations (Dalal *et al.* 1991). In CQ, for example, Garside *et al.* (1992) found protein concentration in the grain of sorghum was as low as 4.4%. This decline in soil N was due primarily to continuous cropping with little use of N fertilisers or legumes in the rotations. Legumes can also benefit following cereal crops by controlling diseases and insect pests and improving soil structure (Reeves *et al.* 1984).

A number of studies in the southern section of the northern Australian grain belt have found that legume-leys can significantly improve the growth of subsequent cereal crops, mainly through their effect on soil N supply (e.g. Littler and Whitehouse 1987; Holford and Crocker 1997; Weston *et al.* 1997). Several studies have also shown that pulses can improve the growth of subsequent cereal crops (e.g. Doughton and Mackenzie 1984; Herridge *et al.* 1995; Holford and Crocker 1997). However, some legumes in this region can have a detrimental effect on subsequent crops, principally via reducing soil water availability (e.g. Holford and Doyle 1978).

There has been growing interest in the use of legumes to redress declining soil N in CQ (Garside *et al.* 1992). In this region, over 630 000 ha of land is used for cropping but grain yields are generally lower than in southern (Queensland) regions (Spackman and Garside 1995), due principally to low and unreliable rainfall and higher evaporative rates which decrease the effectiveness of this rainfall. However, the effect of legumes may be less pronounced in CQ than in southern regions due to both lower inputs of N resulting from poorer legume growth and decreased yields of subsequent crops due to greater water stress.

Several potential ley-legume species have recently been examined in terms of dry matter production, N fixation capacity, and use of soil water over several seasons when grown on a cracking clay soil in CQ (Armstrong *et al.* 1999*a*). This paper reports the effect of these ley-legumes on the growth of following grain sorghum crops. The effect of these ley-legumes is compared with that of a pulse (mungbean) or continuous cropping with cereals.

Materials and methods

Details about the site, general management of the legume and sorghum phases, and rainfall received are presented in Armstrong *et al.* (1999*a*).

Experimental design

The trial was a randomised block design with 3 replicates. Six treatments, comprising 2 cropping systems and 4 pasture-ley legumes, were grown from 1994 onwards prior to the sorghum test-crops: (*i*) grain sorghum, (*ii*) pulse crop (mungbean, *Vigna radiata* cv. Satin), (*iii*) siratro (*Macroptilium atropurpureum* cv. Siratro, a summer-growing perennial), (*iv*) lucerne (*Medicago sativa* cv. Trifecta, a winter perennial), (*v*) lablab (*Lablab purpureus* cv. Highworth, a summer annual forage crop), and (*vi*) desmanthus (*Desmanthus virgatus* cv. Marc, a summer perennial). The main plots were 91 m long (7 × 13-m lengths) and 9 m wide (5 × 1.8-m planter widths), except for continuous grain sorghum, which was 6 planter widths. Each planter width was 3 rows at 60-cm spacing.

Data for the legume plots (growth, N uptake, and changes in soil water and nitrate) are presented in Armstrong *et al.* (1999*a*).

Each year the datum plot was progressively moved 13 m along the main plot to allow a grain sorghum test-crop to be planted across all treatments. The site had been planted to wheat in 1993 prior to planting the first legume treatments in 1994. In 1995, the first datum plot grew a sorghum test-crop after 1 year of legumes (or sorghum) (Table 1). In 1996 the datum area comprised a plot where sorghum was planted after 2 years of legumes (or sorghum) whilst the test-crop plots of the previous year were replanted to sorghum again to examine residual effects. Similarly in 1997, the datum area comprised the sorghum test-crop after 3 years of legumes (or sorghum), the second sorghum crop after 2 years of legumes (or sorghum), and the third sorghum test-crop after 1 year of legumes (or sorghum). N response by sorghum in 1994 (the year the trial commenced) was measured by applying the 4 N rates to a portion of the main plot so as not to interfere with subsequent measurements in the following years.

The effect of fertiliser N on the sorghum test-crop was examined in the first season immediately following legumes or continuous sorghum. Four rates of N fertiliser (0, 25, 50, and 75 kg N/ha as ammonium nitrate, subsequently designated as N0, N25, N50, and N75) were applied at sowing in plots 13 m long by 1.8 m wide after sorghum, and 2 rates (0, 50 kg N/ha, designated as N0 and N50) after legumes. These fertiliser rates were only applied to the first sorghum crop after legumes (or sorghum) (Table 1). This occurred in 1995, 1996, and 1997. In subsequent years (i.e. the second or third sorghum crop after legumes or sorghum), no fresh N was applied. From 1994 to 1996 the N was applied by dropping the fertiliser directly in front of the planting tyne which resulted in a light incorporation. For the 1996–97 crop, the fertiliser was applied through a disc opener at approximately 3–5 cm.

Crop management

Pasture legumes in plots due to be planted to a sorghum test-crop in the following year were sprayed out with herbicides in late July–early August each year. Fallowing commenced immediately after harvest in the sorghum and mungbean plots. The growth of weeds and regrowth of previous crops were controlled by spraying with glyphosate and fluroxypyr and mechanical cultivation using chisel plough and harrows.

Due to ongoing drought the entire trial was bedded up and flood irrigation applied on 14 January 1994 and 1 February 1995 to permit planting, and no further irrigation was applied during the trial until late January 1997 when 35 mm was applied as spray irrigation across the entire trial to ensure grain fill of the sorghum test-crop.

Sorghum was planted using a cone seeder with parallelogram planting units on 60 cm row spacing. Due to poor sorghum establishment in 1994, the sorghum was sprayed with glyphosate and fresh seed resown on 31 January 1994. Seventy-five mm of rain over the next 3 days ensured germination. The grain sorghum cultivar Tulloch was sown to aim for 65 000 established plants/ha on 31 January 1994 and reached grain maturity on 16 May 1994; cv. Barrier was sown on 20 February 1995, and then hand-thinned to 100 000 plants/ha and reached grain maturity on 13 June 1995; cv. Bronco was sown on 19 January 1996 to achieve 90 000 plants/ha and reached grain maturity on 22 April 1996; cv. MR31 was sown on 14 December 1996 to achieve 75 000 plants/ha and reached grain maturity on 19 March 1997.

Data collection

Sorghum yields were measured at flowering and grain maturity by cutting one 3.0-m length in the central row of each plot where N fertiliser had been applied or two 3.0-m lengths in N0 plots. Harvested

Table 1. Treatments used in field trial

Datum plot	1994	1995	1996	1997
1	Treatments[A]	1st test-crop[B] (residual N)[C]	2nd test-crop (residual N)	3rd test-crop
2	Treatments	Treatments	1st test-crop	2nd test-crop (residual N)
3	Treatments	Treatments	Treatments	1st test-crop

[A] Main cropping system/pasture legume treatments: sorghum, mungbean, siratro, lucerne, lablab, or desmanthus.

[B] Sorghum test crop. The first test crop following sorghum was split for 4 fertiliser N rates (0, 25, 50, 75 kg N/ha) or following legumes for 2 fertiliser N rates (0, 50 kg N/ha).

[C] Subsequent sorghum test crops measured residual effects of fertiliser N applied to the 1st test crops. In 1996, the yields for the 2nd test crop were only measured for the N0 and N50 rates; in 1997, the yields for the 3rd test crop were only measured for the N0 rate.

plant material was dried at 70°C for 48 h, ground to <2 mm, and retained for chemical analysis. At physiological maturity, grain was separated from the stover after drying and both components weighed, ground (<2 mm), and retained for N analysis.

Soil analyses

Water content of the soil was determined at sowing only for the N0 treatments of the first sorghum test-crop following a legume (or sorghum) at sowing, flowering, and grain maturity. Nitrate content of the soil in these plots was determined at planting and grain maturity. Four 3.5-cm-diameter soil cores were taken from each plot (2 for water, 2 for soil nitrate). Cores for water were divided into 10-cm increments to 30 cm, then 15-cm increments to decomposing basalt or 120 cm (whichever was encountered first); nitrate cores were divided into 10-cm increments to 30 cm then 30-cm increments to 120 cm. Soil nitrate samples were dried at 40°C before grinding (<2 mm), whereas soil water samples were dried at 105°C. Plant-available water content (PAWC) of the soil was determined by converting gravimetric soil water concentrations to volumetric by adjusting for the bulk density measured at the upper storage limit using a lower storage limit for each treatment determined by repeated sampling during the trial. Measurements of bulk density were made using 100-mm-diameter cores at the end of 1994 in microplots watered to the upper storage limit (D. Yule, pers. comm.). Estimates of lower storage limits ignored soil in the surface 20–30 cm, which was affected by air drying. Lower storage limits were found to be generally consistent between 30 and 105 cm depth. Soil water and nitrate data were subsequently pooled into 30-cm sections for statistical anlaysis.

Chemical analysis

Soil nitrate concentrations were determined by automated colorimetric analysis (Best 1976) following extraction in 2 M KCl at a soil extractant ratio of 1 : 10 (Bremner 1965*b*). Total amounts of nitrate-N were converted to an area basis (kg/ha) using the bulk density estimated at the end of 1994. Total N in plant material was determined by automated colorimetric analysis (Crooke and Simpson 1971) following Kjeldahl digestion (Bremner 1965*a*).

Calculations

Protein concentration of sorghum grain was reported on an oven dry basis and was calculated as %N in grain × 6.25.

In-crop mineralisation (ICM) of nitrogen was calculated as:

$$\text{ICM (kg N/ha)} = (C_N \times 1.3) + SN_M - SN_P \qquad (1)$$

where C_N is the uptake of N by sorghum (above-ground) (kg N/ha), and SN_P and SN_M are the amounts of soil nitrate-N in the profile at planting and grain maturity (kg N/ha), respectively. A correction factor of 1.3 was applied to above-ground N uptake, comprising stover plus grain, to account for the likely proportion of plant N located below ground (McNeill *et al.* 1997). This calculation assumes no loss of N (via volatilisation, denitrification, or leaching).

Water use efficiency (WUE) for grain production was calculated as:

$$\text{WUE (kg grain/ha.mm)} = G/(W_P - W_M + R) \qquad (2)$$

where G is grain yield (kg/ha), W_P and W_M are PAWC at planting and maturity (mm), respectively, and R is the in-crop rainfall (1994 = 477.2, 1995 = 74.1, 1996 = 52.2, 1997 = 192.9 mm). The 1997 in-crop rainfall included 35 mm added as spray irrigation.

Statistical methods

Analyses of variance were used to evaluate the statistical significance of the treatment effects. Results from each datum plot by year (or time of sampling) combination were analysed separately. Examination of residuals indicated that the only variates where variances differed between treatments were in-crop N mineralisation in 1997 and soil nitrate-N at planting in 1996; a logarithmic transformation of these data was required.

The effects of the different cropping systems/legumes grown prior to the sorghum test-crops and nitrogen fertiliser rate applied to the test-crops after legumes, together with their interaction, were evaluated for grain yields, nitrogen uptake, and protein concentration.

Soil data for PAWC and nitrate-N were analysed on both a layer (0–30, 30–60, 60–90, 90–120 cm) by species basis and also on a total profile basis. Where appropriate, least significant differences (l.s.d. at $P = 0.05$) between treatment means are presented.

Results

Grain yield and crop uptake of N

Grain yields in sorghum test-crops varied markedly with season and treatments, ranging from 1933 to 3598 kg/ha in 1994, 1171 to 2754 in 1995, 854 to 2424 in 1996, and 1325 to 3844 kg/ha in 1997. Legumes significantly ($P < 0.05$) improved the grain yield (Fig. 1) and crop uptake of N (Fig. 2) of following sorghum test-crops compared with plots previously planted to sorghum in all years (1995–1997), in the absence of applied N. The grain yield response ranged from 29–113% (0.34–1.32 t/ha) in 1995 to 38–272% (0.50–2.28 t/ha) in 1997. Mungbean and lablab produced the largest grain yield responses in the first sorghum test-crop after legumes and desmanthus and lucerne the lowest in all years (Fig. 1*a*, *c*, *f*); siratro produced intermediate effects in 1995 but equalled that of the annual legumes in subsequent years.

Legumes still produced significant yield responses in both the second sorghum crop after legumes in 1996 (range 44–236%, Fig. 1*b*) and the second and third sorghum crop after legumes in 1997 (31–313%, Fig. 1*e*; 21–62%, Fig. 1*d*, respectively), although this effect was not as great proportionately as in the first crop after legumes.

In 1996, annual legumes had a greater effect than perennial legumes on grain yields of the second sorghum crop, whereas in 1997 this order was reversed in both the second and third sorghum crop after legumes.

Adding fertiliser N significantly improved grain yields of the sorghum test-crop in all crops except 1996. Although fertiliser N did not affect grain yields in 1996, a subsequent sorghum test-crop in 1997 showed significant yield responses across all species treatments (average 17%) to the residues of this N added the previous year (Fig. 1*e*).

Grain protein

Grain protein was always lower in sorghum after sorghum compared with sorghum after legumes (range 1.4–2.1 protein percentage units in 1996 and 2.0–5.0 protein percentage units in 1997). The exception was in 1995, when previous species had no significant ($P > 0.05$) effect (Fig. 3). Lucerne, siratro, and lablab increased grain protein concentrations the most and mungbean and desmanthus the least. The effect of prior legumes on grain protein concentrations of sorghum test-crops was highest in the first crop after legumes and decreased in subsequent sorghum crops, except in 1995 when there was no significant effect.

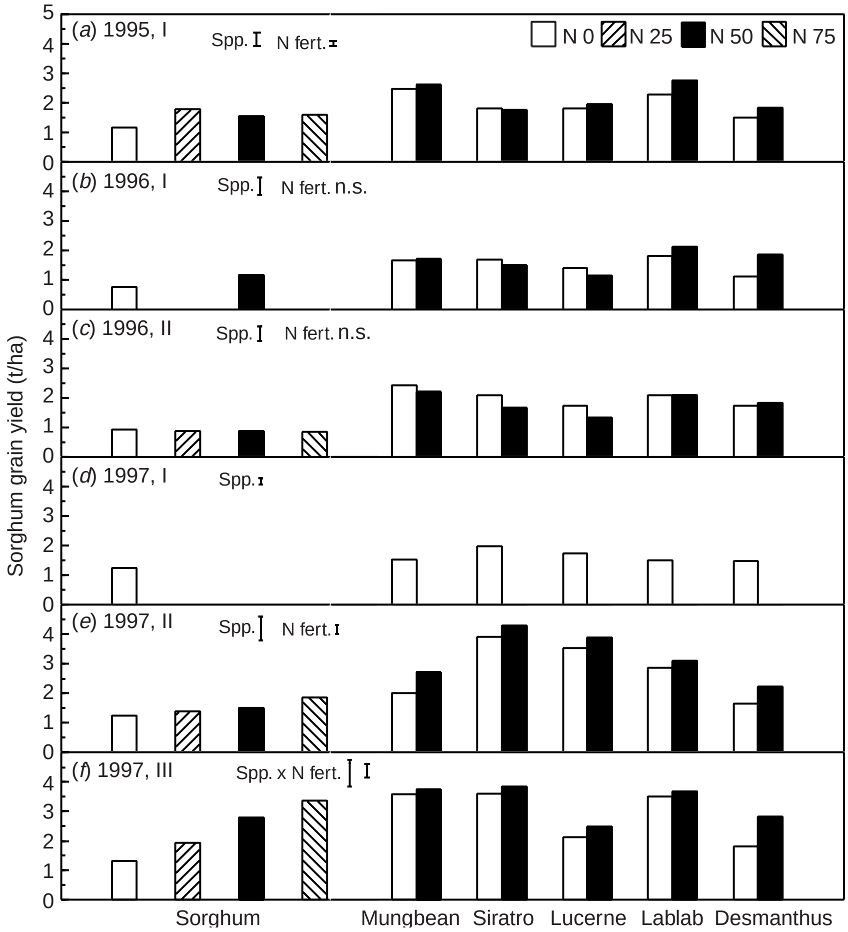

Fig. 1. Grain yield of sorghum test-crop in response to different species (legumes or sorghum) and various rates of N fertiliser. (*a*) 1995: First sorghum crop after 1 year of legumes; (*b*) 1996: second sorghum crop after 1 year of legumes; (*c*) 1996: first sorghum crop after 2 years of legumes; (*d*) 1997: third sorghum crop after 1 year of legumes; (*e*) 1997: second sorghum crop after 2 years of legumes; and (*f*) 1997: first sorghum crop after 3 years of legumes. Sorghum on sorghum had 4 rates of N fertiliser applied (0, 25, 50, 75 kg N/ha), whereas sorghum on legumes had 2 rates (0, 50 kg N/ha). Fertiliser was only applied to the first test-crop after legumes (or sorghum), i.e. (*a*), (*c*), and (*f*) so response of sorghum to N fertiliser in (*b*) and (*e*) represents response to residual N fertiliser. Numeral following year indicates the datum plot (i.e. Area I, II, or III). Vertical bar indicates l.s.d. ($P = 0.05$) for interaction between previous crop and N fertiliser, or main effect of species (Spp.) or N fertiliser (N fert).

The effect of fertiliser N varied with season: it had no effect in 1994 (data not presented) or 1996, but significantly improved protein concentrations in test-crops planted after both sorghum and legumes in 1995 and 1997. However, the effect of fertiliser N on grain protein concentrations was generally much less marked than the effect of previously growing legumes on the first sorghum test-crop after legumes.

Soil nitrate

The amount of soil nitrate in the profile (0–1.2 m) in plots sown to sorghum was highest at planting in January 1994 (37 kg NO_3-N/ha) and then remained low in sorghum on sorghum treatments (<23 kg/ha) throughout the remainder of the trial (Fig. 4). Legumes significantly ($P < 0.001$) increased the amount of soil nitrate at planting of the sorghum test-crops compared with plots continuously sown to sorghum in all years (1995–97). This effect increased as the trial progressed, from an extra 6.8–18.9 kg NO_3-N/ha (compared with continuous sorghum) after 1 year of legumes in 1995, to 24.2–59.6 kg NO_3-N/ha after 3 years of legumes in 1997. Most of this additional soil nitrate was located in the top of the soil profile (0–60 cm). Of the legumes tested, desmanthus consistently had the smallest effect on soil NO_3-N. In 1996 and 1997 there was no significant difference between the other 4 legumes in the total NO_3-N in the 1.2 m profile.

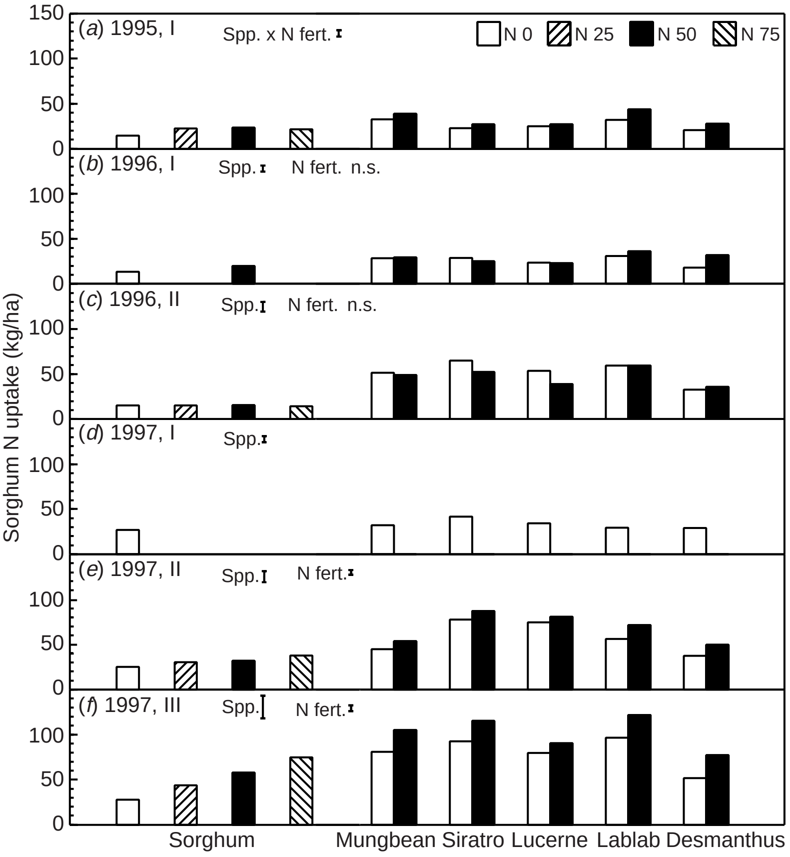

Fig. 2. Nitrogen content of above-ground sorghum test-crop (grain + stover) in response to different species (legumes or sorghum) and various rates of N fertiliser. (*a*) 1995: First sorghum crop after 1 year of legumes; (*b*) 1996: second sorghum crop after 1 year of legumes; (*c*) 1996: first sorghum crop after 2 years of legumes; (*d*) 1997: third sorghum crop after 1 year of legumes; (*e*) 1997: second sorghum crop after 2 years of legumes; and (*f*) 1997: first sorghum crop after 3 years of legumes. Sorghum on sorghum had 4 rates of N fertiliser applied (0, 25, 50, 75 kg N/ha), whereas sorghum on legumes had 2 rates (0, 50 kg N/ha). Fertiliser was only applied to the first test-crop after legumes (or sorghum) i.e. (*a*), (*c*) and (*f*) so response of sorghum to N fertiliser in (*b*) and (*e*) represents response to residual N fertiliser. Numeral following year indicates the datum plot (i.e. Area I, II, or III). Vertical bar indicates l.s.d. ($P = 0.05$) for interaction between previous species and N fertiliser, or main effect of species (Spp.) or N fertiliser (N fert).

The amount of nitrate remaining in the profile at grain maturity of the sorghum test-crops varied with year and depth. Usually, only very low amounts of nitrate remained in the profile (<17 kg NO_3-N/ha). The exception was 1996 when up to 27 NO_3-N/ha remained in plots of some legume species, most of which was located in the top 30 cm of soil.

Soil N mineralisation during the sorghum test-crops was strongly influenced by previous species (Table 2). It was generally lowest in plots previously sown to sorghum and highest in siratro.

Plant-available water

Plant-available water content at planting of sorghum test-crops was only significantly ($P < 0.05$) affected by previous species in 1997, when it was lowest in plots previously sown to siratro and lucerne (<106 mm) and highest in sorghum and mungbean plots (>156 mm) (Fig. 5). The extra PAWC of sorghum and mungbean plots was mainly located in the deeper sections of the profile (90–120 cm).

The effect of different species on the PAWC of soil during growth of the subsequent sorghum test-crops varied with year. In 1995, there was no significant effect ($P > 0.05$) of previously growing different species. However, at anthesis and grain maturity in both 1996 and 1997, plots previously sown to sorghum had significantly higher PAWC than plots sown to legumes. For example, in 1997, sorghum on sorghum plots contained 67 mm PAWC at grain maturity compared with <13 mm in legume plots.

Crop water-use efficiency

Water-use efficiency of the sorghum test-crops ranged from 3.4 to 12.5 kg grain/ha.mm water (Table 3). WUE of sorghum planted after sorghum was generally lower than that of sorghum planted after legumes in all years except 1995, when there was no significant difference between treatments. Adding fertiliser N significantly increased the WUE of sorghum on sorghum crops in the one year (1997) that this was measured.

Discussion

Grain production in CQ is primarily limited by low and unreliable rainfall (Spackman and Garside 1995). Previous studies of pasture-leys in CQ (Armstrong *et al.* 1997) demonstrated that a short legume phase could significantly benefit a subsequent cereal crop (wheat). This study demonstrated that improvements in soil mineral N in the legume phase (Armstrong *et al.* 1999) could directly translate not only to significant improvements in grain yields (Fig. 1), N uptake (Fig. 2), and quality of sorghum (Fig. 3), but also to increasing the efficiency of use of low and unreliable rainfall (Table 3). Furthermore, this benefit can extend up to several sorghum crops. Adding fertiliser N also resulted in increased production and WUE but this effect was more dependent on rainfall patterns than when legumes had been previously grown. The design used for the experiment confounds the effects of season (mainly rainfall and its distribution) and length of legume phase on the growth of the sorghum test-crops. However, this does not invalidate the comparisons made in any given year between the various cropping/ley systems in terms of the growth of the following test-crops.

Table 2. In-crop N mineralisation (kg/ha) during first sorghum test-crop following different species

Treatment	1994	1995	1996	1997^A
Sorghum (N0)	10.8	14.2	24.3	13.5
Mungbean	—	21.8	23.1	26.4
Siratro	—	33.9	51.6	53.0
Lucerne	—	23.0	31.2	42.7
Lablab	—	25.0	37.3	49.3
Desmanthus	—	32.0	26.1	25.3
l.s.d. ($P = 0.05$)		6.2	n.s.	31.2

n.s., not significant ($P > 0.05$).

^{A} ANOVA was not significant at $P = 0.05$. However, residual indicated that transformation was required. Log-transformed data were significant ($P < 0.032$).

N nutrition and soil water

The use of flood irrigation in 1995, necessitated by the prolonged drought, and the high rainfall (>250 mm) in the fortnight prior to planting in 1996 ensured that there were no significant effects of prior legumes on the PAWC of sorghum test-crops at planting in those 2 crops. Consequently, we were able to demonstrate the significant benefit that legumes can have on subsequent grain crops without the confounding influence of differences in planting soil water. The inclusion of legumes can benefit subsequent crops in a number of ways, including disease and weed break and improved soil

Table 3. Water use efficiency (kg grain/ha.mm) for sorghum crops following different species

1994 sorghum followed wheat in 1993. Sorghum is N0 (no added fertiliser N) treatment, except for 1997 when both N0 and N75 values are listed

Treatment	N fertiliser (kg N/ha)	Water use efficiency 1994	1995	1996	1997
Sorghum	0	3.4	7.0	6.0	4.7
Sorghum	75	—	—	—	11.2
Mungbean	0	—	11.2	14.0	10.6
Siratro	0	—	10.3	11.8	12.1
Lucerne	0	—	9.0	10.5	7.2
Lablab	0	—	11.6	12.5	11.2
Desmanthus	0	—	11.0	10.3	5.8
l.s.d. ($P = 0.05$)			n.s.	3.7	3.3

n.s., not significant ($P > 0.05$).

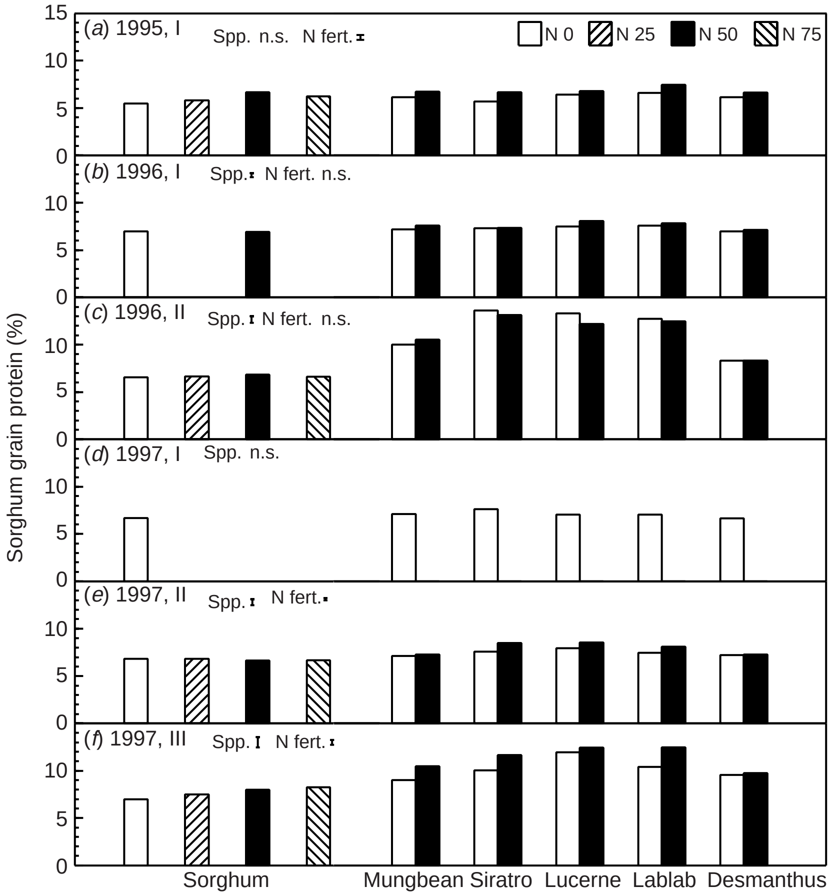

Fig. 3. Grain protein content of sorghum test-crop in response to different species (legumes or sorghum) and various rates of N fertiliser. (*a*) 1995: First sorghum crop after 1 year of legumes; (*b*) 1996: second sorghum crop after 1 year of legumes; (*c*) 1996: first sorghum crop after 2 years of legumes; (*d*) 1997: third sorghum crop after 1 year of legumes; (*e*) 1997: second sorghum crop after 2 years of legumes; and (*f*) 1997: first sorghum crop after 3 years of legumes. Sorghum on sorghum had 4 rates of N fertiliser applied (0, 25, 50, 75 kg N/ha), whereas sorghum on legumes had 2 rates (0, 50 kg N/ha). Fertiliser was only applied to the first test-crop after legumes (or sorghum), i.e. (*a*), (*c*), and (*f*), so response of sorghum to N fertiliser in (*b*) and (*e*) represents response to residual N fertiliser. Numeral following year indicates the datum plot (i.e. Area I, II, or III). Vertical bar indicates l.s.d. ($P = 0.05$) for interaction between previous species and N fertiliser, or main effect of species (Spp.) or N fertiliser (N fert).

structure (Weston *et al.* 1997). Although not specifically monitored in this experiment, there was no obvious sign that disease affected the growth of the sorghum test crops. Legumes appeared to benefit sorghum crops principally through better N nutrition, as exemplified by significant increases in crop uptake of N and grain protein (Figs 2 and 3).

Plant-available water content at planting of sorghum test-crops was only influenced by previous species in one season (1997). However, these differences persisted to strongly influence subsequent grain yields and N uptake of plots previously sown to lucerne but had little effect where siratro had grown. PAWC following the perennial legumes, siratro and lucerne, and to a lesser extent the perennial desmanthus and the annual forage crop lablab, was up to 54 mm (44%) less than in plots previously sown to the annual crops sorghum and mungbean. Dalal *et al.* (1991) noted that a major problem associated with the use of lucerne in ley pastures in cracking clay soils of southern Queensland is its tendency to severely deplete subsoil moisture which increases the likelihood of moisture stress in subsequent crops, a finding also noted in northern NSW by Holford and Crocker (1997). This effect also appeared to apply to other perennial legumes such as siratro, as indicated in the current study. However, in contrast to these studies the majority of soils used for cropping in CQ are comparatively shallow (*c.* 70 cm). Consequently,

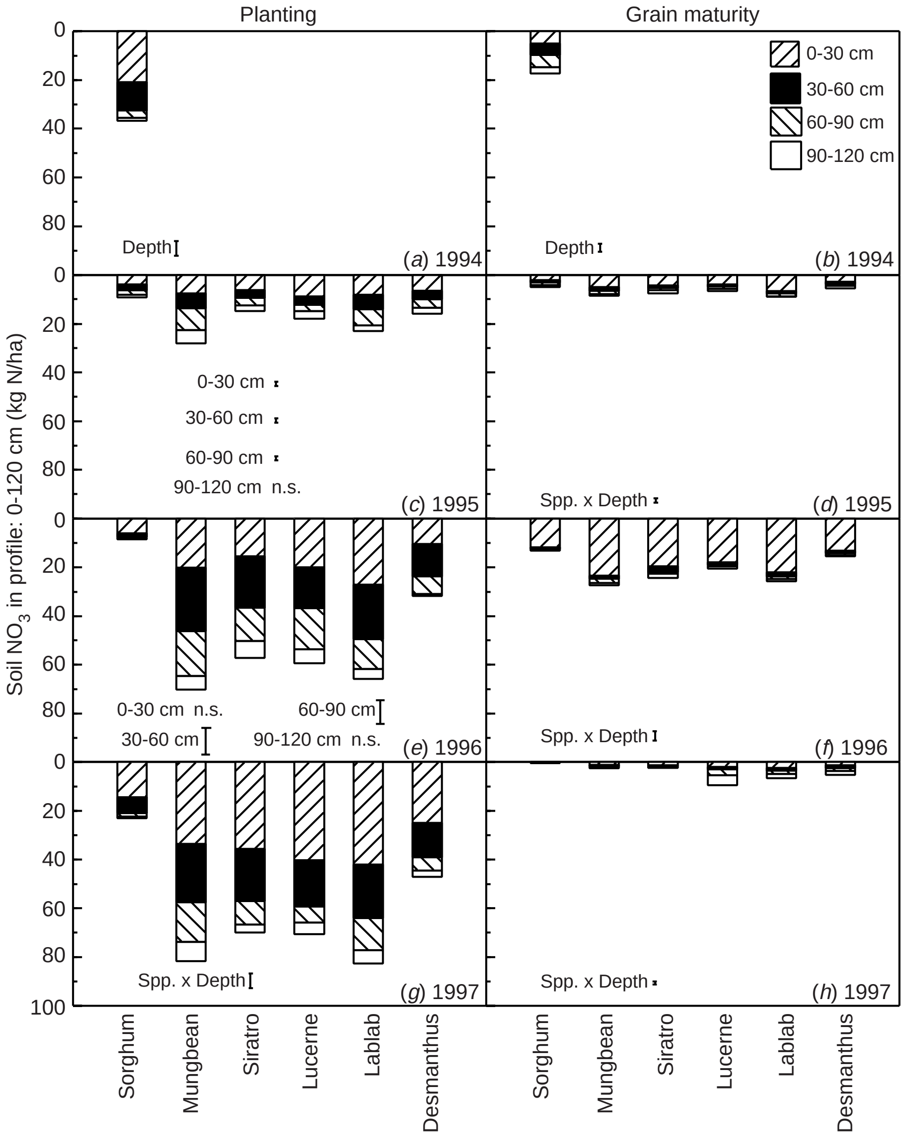

Fig. 4. Amount of soil nitrate (kg N/ha) in 0–30, 30–60, 60–90, and 90–120 cm sections of the soil profile at planting and grain maturity of sorghum test-crop after different crops (legumes and sorghum) in (*a,b*) 1994, (*c,d*) 1995, (*e,f*) 1996, and (*g,h*) 1997. Samples were taken from sections of plots where no N was added. Data presented are non-transformed. When log transformed, data for the 1996 planting in the 0–30 cm (l.s.d. = 14.3) and 90–120 cm (5.0) sections were significantly different ($P < 0.05$). The 1994 crop was planted after wheat grown in 1993. Vertical bar indicates l.s.d. ($P = 0.05$) for individual section of soil profile listed, interaction between species × depth, or main effect of depth. (n.s., not significant.)

differences between species in their ability to reduce soil water to lower matrix potential (Armstrong *et al.* 1999*a*) may be more important than effects on subsoil water.

A previous study (Armstrong *et al.* 1999*a*) showed the better ability of the annual legumes lablab and mungbean and the perennial siratro to produce dry matter, accumulate N, and fix atmospheric N during the first 2 years after establishment, especially compared with desmanthus and to a lesser extent lucerne. In the current study, lablab, mungbean, and siratro also consistently benefited the growth and grain quality (protein) of the first sorghum crop after the legume phase more than lucerne and desmanthus. This appeared to be related to the amount of N in dry matter and N fixation in the preceding legume, which was significantly less in both

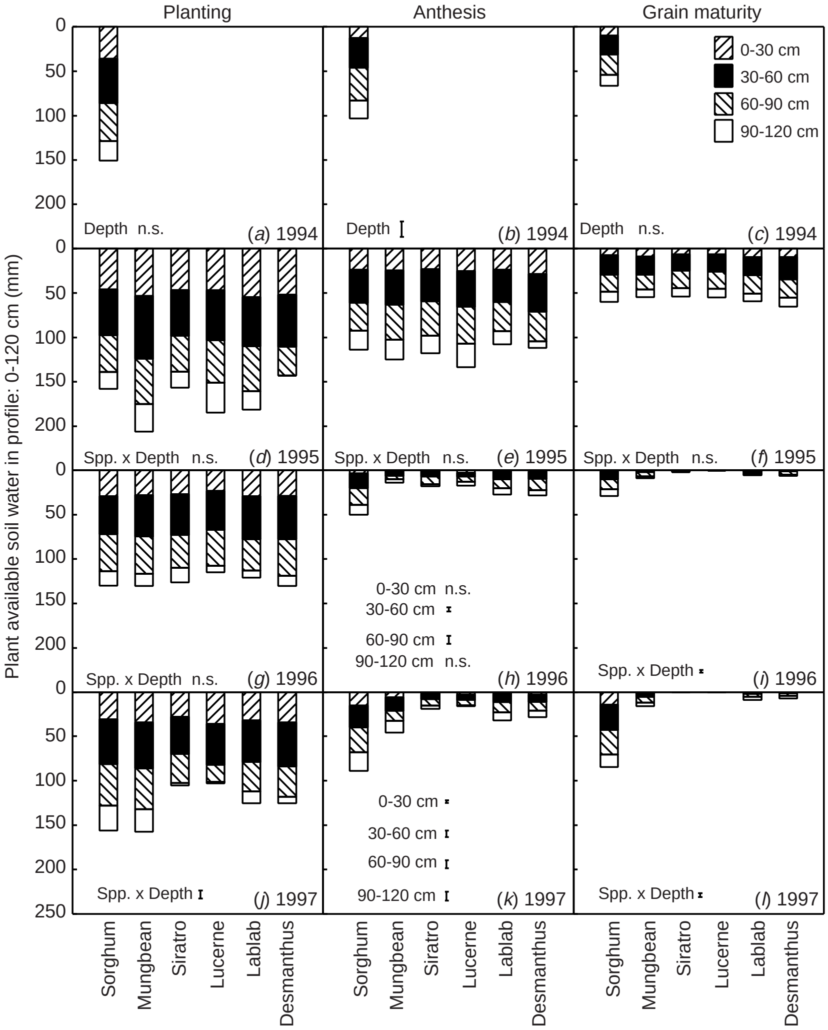

Fig. 5. Plant-available water content in 0–30, 30–60, 60–90, and 90–120 cm layers of the soil profile at planting, flowering, and grain maturity of sorghum test-crop after different crops (legumes and sorghum) in (*a–c*) 1994, (*d–f*) 1995, (*g–i*) 1996, and (*j–l*) 1997. Samples were taken from section of plots where no N was added. The 1994 crop was planted after wheat grown in 1993. Sor., sorghum; M/B, mungbean; Sir., siratro; Luc., lucerne; LL, lablab; Des., desmanthus. Vertical bar indicates l.s.d. ($P = 0.05$) for individual section of soil profile listed, interaction between species × depth, or main effect of depth. (n.s., not significant.)

desmanthus and lucerne in 1994 and desmanthus in 1995, compared with the other legumes (Armstrong *et al.* 1999*a*). The poor ability of desmanthus to promote growth in following sorghum test-crops was thus directly related to ineffective N fixation (low %Ndfa). This current study confirms the tentative findings of Armstrong *et al.* (1997) that suggested that siratro, lablab, and mungbean showed considerable promise in their ability to improve a subsequent cereal crop (wheat) but that lucerne and desmanthus had less potential to do so. Results obtained in CQ thus contrast with other studies on cracking clays in northern NSW by Holford and Crocker (1997), who found that lucerne was superior to annual pasture legumes (medic, clover) and pulses (chickpea) in its benefits to subsequent cereal (wheat) crops. However, Dalal *et al.* (1991) suggest that annual ley legumes may generally produce more beneficial effects on subsequent cereal crops than lucerne, primarily via having a less detrimental effect on soil water availability to the crop. This indicates that the benefits of lucerne as a ley species decrease in moving north, reflecting either a poorer growth potential of lucerne under tropical conditions (higher temperatures) or a greater effect of lucerne on soil water balances in areas with less effective rainfall.

Although the annual legumes had the greatest benefit on the first sorghum crop after legumes, the perennials (with the exception of desmanthus) subsequently produced greater benefits compared with the annual legumes in the second and third sorghum crops after as little as one year of legumes (Fig. 1*d*, *e*). Unfortunately, neither soil water nor nitrate was measured in the second and third sorghum crops after legumes. Although soil water limited the growth of the first sorghum crop after legumes in 1997, subsequent sorghum crops would have most probably had similar amounts of soil water as in continuous sorghum treatments as there was little difference in PAWC at grain maturity of the first sorghum test-crop (Fig. 5*f*). Whilst the effect of the legume phase persisted into the third sorghum crop (Fig. 1*d*), there were only small differences between treatments on an absolute basis, with all crops suffering from obvious N deficiency (Figs 2*d* and 3*d*). Further studies are required to evaluate the longer term effects of a long pasture-ley phase (e.g. 2–3 years).

Effect of rainfall

Rainfall is regarded as a major determinant of obtaining an economic response when applying N fertilisers to grain crops in CQ. All sorghum test-crops, with the exception of crops in 1997 following lucerne and siratro, had nearly full profiles of plant-available water at sowing. In this study, in-crop rainfall was well below average with totals of less than 75 mm in both 1995 and 1996, and 197 mm in 1997 (including 35 mm applied as irrigation) compared with the long-term January–April average of 310 mm at Emerald. Holford and Crocker (1997) suggest that fallow rainfall is comparatively more important than in-crop rainfall for wheat following legumes in northern NSW. Results from this study would support this conclusion. However, daily evaporation rates during the sorghum growing season in CQ are significantly higher than during the wheat season in NSW and rainfall events generally have to be >10–20 mm/day to be considered effective during summer (C. Carroll, pers. comm.).

Despite the low in-crop rainfall recorded, it was the timing rather than the total amount that appeared to have the greater effect on the sorghum crop. Rainfall at and immediately following flowering is regarded as critical for grain yield in sorghum (Holland and Herridge 1992). In this study the timing of rainfall also significantly influenced sorghum response to N fertiliser. Rainfall soon after planting, but before flowering, appeared to consistently increase sorghum's ability to obtain fertiliser N and produce significant yield responses. For example, significant rainfall (> 35 mm) occurred within a week after sowing in all years in which sorghum produced significant yield responses to N fertiliser (1994, 1995, 1997). In contrast, a similar sized rainfall event occurred at flowering in 1996 but no response to applied N was recorded (Fig. 1*c*).

Distribution of N derived from fertiliser and legumes in soil

In this study, fertiliser N was applied at sowing to the surface 5 cm of soil. Because the surface soil can dry to permanent wilting point within a few days under the high evaporation rates encountered in the CQ environment (>9 mm/day during summer), the fertiliser N located in this position would remain unavailable to sorghum roots until sufficient rain occurred to leach it further into the soil profile. This highlights previous findings (Strong and Cooper 1980) of the increased effectiveness of fertiliser N when applied at sowing at greater depth (>10 cm) in environments where in-crop rainfall is either low or unreliable. However, unused fertiliser N was utilised by the next sorghum crop, as indicated by the significant grain and N uptake responses to N fertiliser applied in the previous year (Figs 1*e* and 2*e*).

The amount of soil nitrate in plots previously sown to legumes was not only significantly greater than in plots previously sown to sorghum but a large proportion of this extra N was located in the 30–60 cm and to a lesser extent 60–90 cm layers of the soil profile. The consistent ability (3 years out of 3) of legumes to produce higher grain yields and N uptake by sorghum test-crops compared with N fertiliser under identical soil moisture conditions at sowing and in-crop rainfall would indicate that legume N was much more effective than fertiliser N. This increased effectiveness corresponds to the ability of sorghum to utilise PAWC and soil nitrate located in the subsoil. The greater effectiveness of the legume N was especially evident in 1996 when an extra 49 kg N/ha as nitrate at sowing (averaged across legumes plots; Fig. 4*e*) resulted in considerably higher N uptake (20 kg N/ha) than was obtained from adding 75 kg N/ha as fertiliser (Fig. 2*c*). Other studies on cracking clay soils in Queensland (Littler and Whitehouse 1987) have also suggested that N derived from pasture was more efficient than fertiliser N for wheat growing in a Darling Downs cracking clay due to better profile distribution of the pasture N. Furthermore, denitrification may be responsible for significant losses of mineral N in these soils (Avalakki *et al.* 1995; Armstrong *et al.* 1996*a*); nitrate deeper in the profile is less liable to be lost.

The measurements made in this study cannot provide a definite answer on the processes that resulted in accumulation of nitrate N in the deeper soil layers following the legumes. The possibilities are that it was mineralised *in situ*, or mineralised in the topsoil, and was subsequently leached. McNeill *et al.* (1997) have reported that a significant proportion of legume N is located below ground and that this N can supply a major proportion of the N utilised by subsequent crops. Whereas topsoils dry very rapidly in this environment, subsoils (>30 cm) are consistently wetter throughout the fallow period. Thus there may be less legume residues on an absolute basis in the subsoil but the consistently better soil moisture conditions (during both the fallow and in-crop period) may result in higher rates of N mineralisation. However, it seems unlikely that the distribution of root N would be able to account for the observed, rather uniform, distribution of nitrate in the profile at planting. Increases in the total soil-N following legumes (especially lablab and mungbean) were small and occurred mainly in the top 5 cm of the soil profile (data not presented). Studies using ^{15}N-labelled fertiliser indicated that mineral N (NO_3/NH_4) leached only slowly in these heavy cracking clay soils (Armstrong *et al.* 1996*b*). But in contrast to that study where the labelled fertiliser was applied to soil that had already wetted up, here the accumulation of nitrate occurred during the fallow period when the profile was also being recharged with water. Under these circumstances there would be some opportunity for leaching of nitrate that had mineralised nearer the surface.

Grain quality

Including legumes in the rotation not only increased subsequent sorghum grain yields but also significantly improved grain quality (protein). Improving grain protein concentrations, via the use of N fertilisers or legumes, can increase the profitability of wheat crops grown in northern Australia (Strong *et al.* 1996). Currently, no premiums are paid for improved sorghum grain protein concentrations but this situation is likely to change as both domestic and export markets for stock feed increasingly demand higher quality commodities.

Without added N fertiliser, the grain protein concentrations of sorghum on sorghum crops were consistently low regardless of seasonal conditions, ranging between 5 and 7%, indicating that the site used in this study was probably of below average soil fertility compared with CQ as a whole. As Garside *et al.* (1992) found that grain protein concentrations declined progressively with age of cultivation since clearing, the positive effect of legumes on subsequent sorghum protein found in this study would indicate that greatest benefit of including legumes in the rotation will be found on soils cropped for the longest period. In CQ this will be primarily the open downs cracking clays rather than more recently cultivated brigalow and alluvial scrub soils.

Grain protein levels are also widely used as an indicator of the potential responsiveness of cereal crops to fertiliser N in northern Australia, with critical concentrations of 13.1% and 10.4% (at 0% moisture on a dry weight basis) recommended for wheat and sorghum, respectively (W. M. Strong, pers. comm.). However, in this study, grain protein concentrations were a poor indicator of the responsiveness of subsequent crops to fertiliser N, although they were a good predictor of yield responses to using legumes. Grain protein concentration, like yield, is highly dependent on both N nutrition and seasonal rainfall patterns. In this study the pattern of in-crop rainfall strongly limited the ability of fertiliser N to improve both grain yields and protein. However, this lack of rainfall had less effect in plots previously sown to legumes because of the better distribution of N in the soil profile.

Implications for agriculture and future research

The rate of adoption of pasture-ley legumes in CQ will depend on several factors including relative commodity prices for grain *v.* beef, possession of infrastructure and management skills to run a mixed cattle/grain enterprise, and the comparative degree of soil fertility decline. Economic analysis will be needed to help assess the comparative benefits of continuous cropping with the use of legumes (both pulse and ley) in farming systems of CQ.

Nitrogen derived from legumes is not free; there is a considerable cost in lost opportunities for grain production during the legume phase and this cost can extend to the cropping phase in terms of diminished soil water supplies, as occurred following lucerne and siratro in 1997. The contribution of N from the legume phase will reflect seasonal conditions, principally rainfall, during the pasture phase as this relates directly to the growth of the legume and amount of N fixed. However, in the case of a preceding pulse (e.g. mungbean), there may be further decline in soil N because more N is exported in the grain than is fixed.

In terms of ease of establishment, ability to rapidly produce cattle feed, supply N, and boost yields and quality of subsequent sorghum crops, lablab and siratro outperformed the other pasture legumes tested. Although mungbean had an immediate economic appeal in terms of high returns during the legume phase and a strong benefical effect on subsequent sorghum crops, this was at the expense of the soil N balance, a finding confirmed by measurements of changes in soil total N (Armstrong *et al.* 1999*b*). The benefit of lablab on soil N supplies diminished significantly after the second season due to declining rates of N fixation, which indicates that there may be little additional benefit in a second season if the primary aim is to increase soil fertility levels.

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