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Comparison of legume-based cropping systems at Warra, Queensland. II.* Mineral nitrogen accumulation and availability to the subsequent wheat crop

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Abstract

Mineral nitrogen release following legume-based cropping systems for restoring the fertility of a Vertisol and the yield response and N uptake of subsequent wheat crops was studied. Legume phases of pastures, including a 4 year grass+legume ley, and lucerne and medic leys (~1 year) were terminated in October 1988 or 1989 and rotated with wheat. Chickpea–wheat rotations matched those of lucerne and medic leys. Mineral N accumulations during a subsequent fallow period were determined by core sampling to 1·5 m in October, February and May. Grain yield and N uptake of wheat enabled comparisons of the fertility restorative effects of the various systems relative to continuous wheat cropping.

Averaged for two fallow periods, increases in mineral N down to 1·2 m depth were 93, 91, 68, and 37 kg/ha following grass+legume, lucerne and medic leys, and chickpea, respectively, compared with the continuous wheat treatment.

Wheat yields were generally lower in 1989 (1·85–2·88 t/ha) than in 1990 (2·08–3·59 t/ha) following all leys and crops due to seasonal conditions. There was a grain yield increase of 0·11 and 0·52 t/ha in 1989 and 1·23 and 1·26 t/ha in 1990 following lucerne and medic leys, respectively and 0·85 t/ha in 1990 following a 4 year grass+legume ley. Following chickpea there was a yield increase of 0·81 and 1·36 t/ha in 1989 and 1990 respectively.

Nitrogen uptake by wheat was increased by 40 and 49 kg/ha in 1989 and 48 and 58 kg/ha in 1990 following lucerne and medic leys respectively and 63 kg/ha in 1990 following a 4 year grass+legume ley. Following chickpea N uptake by wheat was increased by 27 and 32 kg/ha in 1989 and 1990 respectively. Grain protein concentration of wheat was substantially higher following all pasture leys (11·7–15·8%) than following wheat (8·0–9·4%) or chickpea (9·4–10·1%). Therefore, there was substantial evidence of the effectiveness of pasture leys in soil fertility restoration, as reflected in mineral N, yield response and N uptake by subsequent wheat crops.

Additional keywords: pasture leys, legumes.

Introduction

The incorporation of legumes is considered essential in crop rotations for sustainable agriculture in temperate zones (Power 1989) although their roles in subtropical and tropical zones require further study (Prasad and Goswami 1992). Hossain *et al.* (1996) reported results from a long-term field experiment which compared the effects of legume-based systems for restoring fertility of a vertisol at Warra, in south-eastern Queensland. In a fertility-depleted soil, measurements

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of N_2-fixed by pasture and grain legumes ranged from 56 to 83 kg/ha·year with higher amounts for pasture legumes than for a grain legume (Hossain *et al.* 1995). Soil N status was significantly improved after the legume phase in all legume-based systems as indicated by total N as well as several N availability indices (Hossain *et al.* 1996). These included nitrogen mineralisation potential (N_o), biological N availability indices (waterlogged and aerobic incubation) and rapid chemical indices (hot KCl extraction and autoclave index).

We report in this paper the quantities of mineral N accumulated during the fallow period (October or November to May or July) following the legume phase of rotation systems included in the long-term field experiment. Legume phases compared in this study were (1) grass+legume ley for 3·75 years; (2) 17 months of lucerne established with a wheat crop; (3) 17 months of medic established with a wheat crop; or (4) a preceding chickpea crop instead of wheat. Comparisons of the fertility restorative effects of various legume-based cropping systems relative to that of continuous wheat cropping were made from yield response and N uptake by wheat following each legume phase.

Materials and methods

Details of the experimental site and treatments are given by Dalal *et al.* (1991, 1994) and Hossain*et al.* (1996). Measurements were taken from four replicates of nine treatments in a field experiment of plot size 6·75×25 m; two grass+legume pastures of 3·75 years duration, two phases of a medic-wheat and a lucerne-wheat rotation, two phases of a chickpea-wheat rotation and continuous wheat. Crop and pasture sequences for 1986–1995 have been shown previously by Hossain *et al.* (1996) for each treatment. Plant material was cut to a height of 10 cm and removed from the pasture treatments four times annually in March, June, September and December. Chickpea and wheat grains were harvested annually at maturity.

Pasture phases were terminated by ploughing in October 1988 and 1989 after cutting in September to a height of 10 cm. Thus only small quantities (<500 kg/ha) of above ground plant material were incorporated during pasture termination for all except medic pasture. Due to the prostrate nature of medics approximately 2500 kg/ha of above ground material was present in 1989 and 1990 when medic pastures were terminated. For all treatments, soil was tilled for 2 to 3 times to destroy weeds and to allow soil moisture to accumulate over the summer fallow until wheat (cv. Hartog) was sown at the rate of 40 kg/ha on 20 June 1989 and 2 July 1990. Annual rainfalls for October to September and quarterly totals are shown in Fig. 1. Rainfall for 1987–88, 1988–89 and 1989–1990 was similar or higher than the long-term average for the site. Rainfall in the summer quarter (January–March) was below average but in the autumn (April–June) and winter (July–September) quarters rainfalls were above average during these years. Rainfall for 1990–91 was below the long-term average with particularly low rainfall in the autumn and winter periods.

Wheat sampling and grain analysis

At maturity, wheat plants were removed from 2 m of row to measure a grain to straw ratio and a straw N content. Grain yield was measured by machine harvesting with an experimental plot header from 1·75 m (7 rows×20 m) in the centre of each plot. A 2 kg grain sample was retained for N analysis. Straw yield (t/ha) was determined by dividing machine-harvested grain yield (t/ha) by the grain to straw ratio. The nitrogen concentrations of grain and straw were determined by a Kjeldahl procedure (Ekpete and Cornfield 1964).

Soil sampling and analysis

Soil samples were collected in October 1989 and 1990 following grass+legume, lucerne and medic leys and in November 1989 and 1990 following chickpea and wheat crops just after grain harvest and prior to any tillage. In addition, soil samples were collected in February and May in both 1990 and 1991, May 1992 and July 1990 before crops were sown. Samples

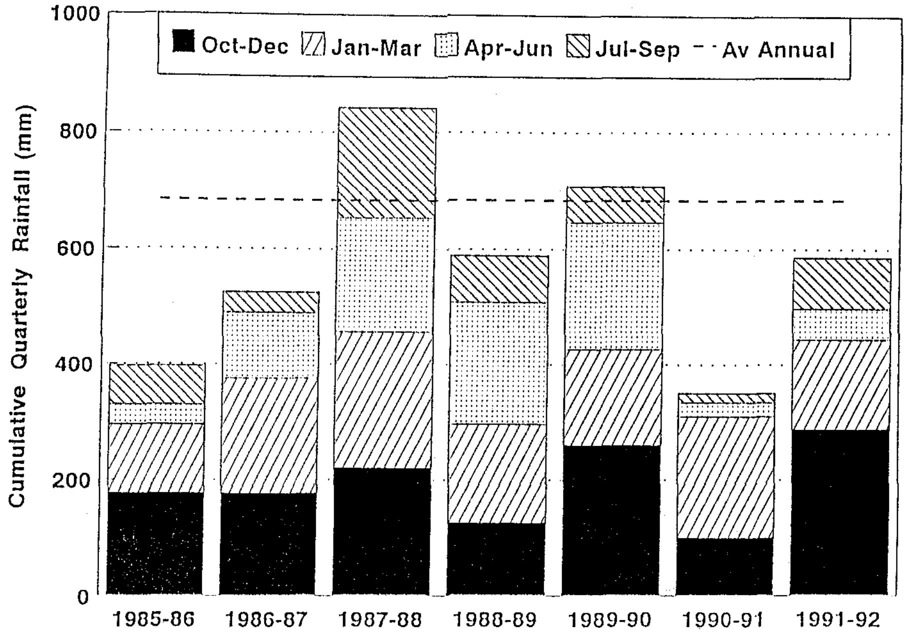

Fig. 1. Cumulative quarterly rainfall (mm) for October–September at the experimental site at Warra in south-east Queensland; mean annual rainfall (~100 years) for a site 10 km away is 686 mm.

were taken at 0·1 m intervals to 0·3 m, and 0·3 m intervals to 1·5 m by an hydraulically operated core sampler with a 50 mm diameter cutting edge. Five sampling sites per plot down to 0·3 m depth, and two samples from layers below 0·3 m were composited by layer, sealed in plastic bags in the field and stored below 4°C until further processing.

Soil moisture content was determined by drying a subsample at 105°C for 24–48 h. The field bulk density (Mg/m^3) was calculated from the oven-dried soil weight contained in the field volume of the soil sample. A subsample of soil at field moisture content was extracted in 2 M KCl for mineral-N (NH_4^+ and NO_3^-) analyses. The remainder of the soil sample was dried at 25°C in a forced-draught oven for 7 days, ground to pass through 2 mm sieve and stored in sealed plastic containers at room temperature.

For mineral N the 2 M KCl extract (1 : 3, soil : solution ratio) was steam distilled with MgO and Devarda's alloy (Bremner 1965).

Other soil analyses including nitrogen mineralisation potential (N_o), rapid tests of N availability (waterlogged and aerobic incubation) and rapid chemical tests (hot KCl extraction and autoclave index) are described by Hossain *et al.* (1996).

Statistical analysis used were as described by Hossain *et al.* (1996).

Results

Nitrate-N accumulation during the fallow period after various crop and pasture systems

In October, following continuous wheat or leys, small quantities (<12 kg/ha·1·2 m) of nitrate-N were present in all treatments (data not shown). In chickpeas however the amount was greater (19 kg/ha·1·2 m) due to a significant rainfall event preceding crop harvest.

By February, mineral N accumulation (Figs 2 and 3) tended to be higher following the leys than following wheat or chickpeas, with more following chickpeas than wheat. By May more mineral N had accumulated following all treatments.

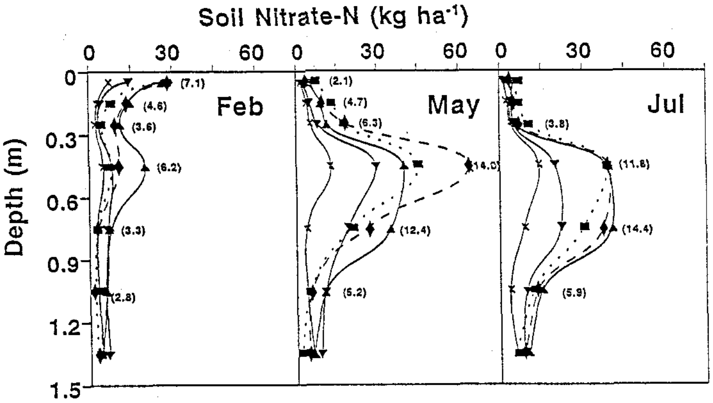

Fig. 2. Soil nitrate N at various depths and times in the profile during the fallow period, October 1989 to July 1990. Treatments: ■ grass legume 86–89/wheat; ◆ lucerne/wheat; ▲ medic/wheat; ▼ chickpea/wheat; × CT wheat. Values in parentheses for particular depths represent l.s.d. ($P = 0{\cdot}05$). In October less than 17 kg/ha·1·5 m was present in any system.

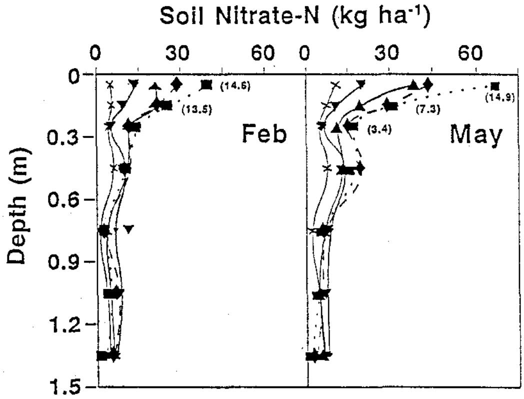

Fig. 3. Soil nitrate N at various depths and times in the profile during the fallow period, October 1990–May 1991, following leys, chickpea and wheat crops (see Fig. 2 for treatment descriptions). Values in parentheses for particular depths represent l.s.d. ($P = 0{\cdot}05$). In October less than 29 kg/ha·1·5 m was present in any system.

Higher levels persisted following leys than following crops and more following chickpeas than wheat.

Profile distribution of accumulated nitrate N

Distribution patterns for NO_3^--N accumulation in the profile during the fallow period are shown in Figures 2 and 3. At the beginning of each fallow, NO_3^--N was very low throughout the profile in each treatment.

Trends in NO_3^--N for the February samplings in 1990 and 1991 showed a marked similarity except for the grass+legume treatment. In 1991, levels of NO_3^--N in grass+legume treatment were higher throughout the profile than in

1990. There was further increase in NO_3^--N by May each year with marked contrast between the distribution patterns in 1990 and 1991. In 1990, greatest accumulation of NO_3^--N occurred between 0·3 m and 0·9 m depths (Fig. 2) whereas in 1991 NO_3^--N accumulated in the top 0·2 m (Fig. 3). Wheat sowing was delayed in 1990 due to wet conditions and so treatments were resampled in July. There was no significant change in the quantity of soil NO_3^--N between May and July but there was a change in distribution pattern down the profile. Accumulation occurred mainly in the 0·6–0·9 m layer but some increase also occurred at 0·9–1·2 m depth (Fig. 2).

Relationship between N accumulation and N availability indices

The amounts of NO_3^--N accumulated in the field in 1989–90 to different depths (0·6, 0·9 and 1·2 m) were significantly correlated with some N availability indices of topsoils measured in the laboratory as well as total N and organic C (Hossain *et al.* 1996). Significant ($P < 0{\cdot}05$) correlations were obtained between NO_3^--N to different depths (0·6, 0·9, 1·2 m) and waterlogged ($r = 0{\cdot}82$–$0{\cdot}83$) or aerobic ($r = 0{\cdot}85$–$0{\cdot}86$) N. Although not significant, N_0 also showed good relationship ($r = 0{\cdot}64$–$0{\cdot}69$) with NO_3^--N. Chemical indices, organic carbon or total nitrogen showed very poor correlations ($r = 0{\cdot}15$–$0{\cdot}40$), with NO_3^--N in this study.

Wheat yields

Wheat yields following different legume systems in 1989 and 1990 are shown in Table 1. Wheat yields in 1989 following medic or chickpea were significantly ($P < 0{\cdot}05$) higher than the yield from continuous wheat or lucerne treatments.

In 1990, due to favourable seasonal conditions, wheat yields following different legume systems were higher than in 1989 for the corresponding treatments, ranging from 2·23 to 3·59 t/ha (Table 1). Grain yields following all legume treatments were significantly ($P < 0{\cdot}05$) higher than those following continuous wheat.

Grain protein

The protein concentration of wheat following different cropping systems ranged from 8·0% to 15·7% and 8·3% to 13·0% in 1989 and 1990 respectively (Table 1). Grain protein concentrations of wheat following the legume treatments were significantly ($P < 0{\cdot}05$) higher than for continuous wheat in 1989 and 1990. In both years grain protein concentrations of wheat following chickpea were higher than for continuous wheat but lower than following all leys.

In 1989, protein concentration of wheat after lucerne was significantly higher than other treatments. In 1990, protein content of wheat following the grass+legume ley was higher than for wheat, or following any other legume treatment. Similar wheat proteins were produced following either lucerne or medic leys.

Nitrogen uptake

Nitrogen uptake (kg/ha) in the grain and straw of wheat was increased significantly ($P < 0{\cdot}05$) following all legumes compared with continuous wheat in 1989 and 1990 (Table 1). Relative increases in N uptake following legume treatments were much greater than relative increases in grain yield. Nitrogen uptake by wheat following leys was more than double that for continuous wheat

Table 1. Grain yield, N uptake, and grain protein concentration of wheat at 12% grain moisture in 1989 and 1990 following grass+legume (4 years), lucerne (1 year), medic (1 year) leys, chickpea, and continuous wheat

Treatment	Grain yield (t/ha)	Grain protein (%)	Total crop N uptake (kg/ha)
	1989		
Grass+legume	—[A]	—[A]	—[A]
Lucerne/wheat	1·86	15·7	65·9
Medic/wheat	2·70	13·2	80·5
Chickpea/wheat	2·88	10·1	61·3
CT wheat	2·07	8·0	34·2
l.s.d. ($P = 0{\cdot}05$)	0·26	0·8	9·7
	1989		
Grass+legume 86–89/wheat	3·38	13·0	106·4
Lucerne/wheat	3·43	11·7	86·0
Medic/wheat	3·59	12·1	104·9
Chickpea/wheat	3·59	9·4	73·0
CT wheat	2·23	8·3	41·3
l.s.d. ($P = 0{\cdot}05$)	0·27	0·8	8·8

[A] Still in pasture phase.

except in 1989 after the lucerne leys. Nitrogen uptake by wheat was also higher after chickpea but not as high as after the leys.

In 1989, N uptake by wheat following medic was higher than that following lucerne. In 1990, N uptake by wheat following medic and grass+legume leys was higher than following the lucerne ley.

Soil mineral N

Due to drought in 1991, wheat was not sown following termination of legume leys in October 1990 and so the fallow period was extended. As a result, large quantities of NO_3^--N had accumulated in the profile following all legume treatments by May 1992 when the values after all leys were significantly ($P < 0{\cdot}05$) higher than for continuous wheat (Table 2). The values were very high in comparison with values for May 1991 although net gains during the 12 months after May 1991 were less than the gains up to May 1991 after lucerne or medic leys. Total accumulation following medic (139 kg/ha) was the same as that following chickpea with much higher accumulations following lucerne (217 kg/ha) on grass+legume ley (282 kg/ha).

Discussion

Over 100 kg N/ha·year (range, 103–128) accumulated down to 1·2 m depth at the end of the fallow period following short (~1 year) lucerne or medic swards or long-term (3·75 years) grass+legume leys (Figs 2 and 3). These values are lower than those obtained by Whitehouse and Littler (1984) for a vertisol. They found that following 2 to 4 years of lucerne–prairie grass pasture 197–260 kg/ha mineral N was accumulated in soil to 0·6 m depth. Higher mineral N accumulation found by Whitehouse and Littler may be due to much higher indigenous soil total N content (0·13%) compared with the Warra soil (0·07%).

Table 2. Accumulation of mineral N (kg/ha) to 1·2 m (Oct. or Nov. 1990 to May 1992) during the extended fallow period following legume leys, chickpea, or wheat

Treatment	Oct. or Nov. 1990–May 1991[A]	May 1991–May 1992	Oct. or Nov. 1990–May 1992[A]
Grass+legume 87–90/wheat	147·3	134·9	282·2
Lucerne/wheat	123·3	94·0[B]	217·3
Medic/wheat	96·1	41·9[B]	138·0
Chickpea/wheat	69·4	69·6	139·0
CT wheat	37·9	50·8	88·7
l.s.d. ($P = 0 \cdot 05$)	33·6	51·2	46·6

[A] Figures include the low initial NO_3^--N values (<12 kg/ha) in Oct. 1990.
[B] Some lucerne and medic regrowth occurred in these plots during this period.

In spite of smaller legume benefits as measured by accumulated soil mineral N, legume benefit to wheat yield of 1·1–1·3 t/ha is higher than reported in a review of legume effects collated for this region by Lloyd *et al.* (1991). Holford (1980) found benefits from a legume ley in increased grain yield from four succeeding wheat crops which averaged 0·5 t/ha over crop yields of 1·4 to 1·7 t/ha on black earths and 1·1 t/ha on red-brown earths. Because of the higher than average autumn and winter rainfall in 1989 and 1990 at Warra yield increases may have been somewhat greater than expected over the long term. More bioassay information is required following the leys at Warra to adequately assess legume benefits (to soil mineral N and yields of subsequent crops) over a wider range of seasonal conditions.

Increase in mineralisable soil N was evident following lucerne, medic and chickpea as well as grass+legume leys. A direct relationship was found between the quantity of N assimilated into wheat grain and straw and mineralisable N as indicated by waterlogged N ($r = 0 \cdot 93$), aerobic N ($r = 0 \cdot 94$) or potentially mineralisable N ($r = 0 \cdot 94$). Even though total soil N contents were not significantly increased (Dalal *et al.* 1995), except after grass+legume ley, the increase in readily mineralisable N supplied sufficient N to improve grain yields and protein contents of subsequent cereal crops, on this fertility-depleted soil.

Year to year differences in distribution patterns of mineral N in the profile at the end of the summer and autumn fallow period was due largely to different fallow rainfall (Fig. 1); in the drought year of 1991 mineral N did not move down in the profile to the same extent as in 1990 (Figs 2 and 3). There was no indication of increases in NO_3^--N below 1·2 m by May at the end of either fallow period, and so leaching of NO_3^--N beyond the depth of sampling in May 1990 or May 1991 appears unlikely. Some downward movement of NO_3^--N in the profile was evident in 1990 when substantial rainfall (126 mm) was received between May and July when water storage was already high.

The much larger increases in NO_3^--N following grass+legume, lucerne and medic leys than following chickpea was probably due to the greater N_2 fixed by these forage legumes (Hossain *et al.* 1995) as well as a greater proportion of fixed N returned to soil (Hossain *et al.* 1996).

Actual net mineralisation following some pastures may have been greater than was apparent by the field measurements of N accumulated. There was no evidence of leaching below 1·2 m but denitrification may have occurred in 1990 because of the greater than normal rainfall in May and June when the soil profile was fully recharged. Microplot studies on these plots during this period in 1990 indicated considerable potential for the loss of mineral N from surface soil layers (0·3 m) particularly following the grass+legume ley (Islam 1992). However, similar NO_3^--N distribution pattern in subsoil layers suggested little loss of mineral N from layers below 0·3 m.

Results of Holford and Doyle (1978) indicated that in north-eastern Australia lucerne can extract available water down to 2 m depth and that 4 to 5 months of fallow after lucerne may not be long enough to completely recharge subsoil moisture. Even with the extended fallow period to July 1990 the additional rainfall may not have recharged soil moisture below 1·2 m following pasture phases.

The establishment of different legume-based cropping systems substantially increased production of high protein wheat. Grain yield, grain protein and N uptake by successive wheat crops were increased to different degrees following all legume treatments. Crop response was closely correlated with the amount of soil mineral N that became available during a 6–7 month fallow period following the legume phase either measured in the field or predicted from waterlogged, aerobic or potentially mineralisable N at the beginning of the fallow period.

While both pasture and grain legumes significantly increased wheat yields, N supply following grain legumes was insufficient to increase N uptake and grain protein contents of wheat to the levels achieved following pasture legume systems. The grain legume is grown primarily for its seed production and since it is desirable to maximise the harvest index, much N is removed in the grain legume seed. The high nitrogen harvest index and thus removal of biologically fixed N by grain legumes means that only a small proportion of fixed N may be left in or on the soil for succeeding cereal crops (Myers and Wood 1987). Very small increases in NO_3^--N were observed after chickpea between February and May samplings, particularly in 1991, reflecting the rapid mineralisable N inputs following grain legumes. Strong *et al.* (1986) demonstrated similar rapid release of mineral N following winter grain legumes in this environment. Inclusion of grain legumes in the rotation therefore, provides only the short term fertility benefit to the subsequent cereal crops.

Evidence of long term benefits of legume leys to fertility restoration presented in this and previous papers (Hossain *et al.* 1995, 1996) supports the contention of Whitehouse and Littler (1984) about continued residual benefits following pasture leys. Some financial returns would be needed during the long term grass+legume ley from grazing or hay to make pasture leys a viable economic option for cereal producers with fertility-degraded soils. Some economic comparisons of these systems have been presented (Dalal *et al.* 1991, 1994) but reliable comparisons can be made only after effects of these treatments are available over a longer term. Nevertheless, grass+legume and legume leys would appear to play a key role in future ecologically and economically sustainable farming systems for this region.

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