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Comparison of legume-based cropping systems at Warra, Queensland. I. Soil nitrogen and organic carbon accretion and potentially mineralisable nitrogen

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Abstract

Effects on soil nitrogen accretion and potentially mineralisable nitrogen were studied as part of a long-term field experiment established in 1986 to test alternative legume-based systems for restoring fertility in a Vertisol. Organic C accretion was also measured to ascertain the changes in organic matter content. The systems, which were studied only during 1989 and 1990, were a grass+legume ley (purple pigeon grass, Rhodes grass, lucerne, annual medics) of 4 years duration followed by wheat; a 2-year rotation of wheat (lucerne undersown) and lucerne; a 2-year rotation of wheat (medic undersown) and medic; a 2-year rotation of chickpea and wheat; and continuous wheat as control.

Soil total N and organic C significantly increased in the 0–10 cm soil layer only under the grass+legume ley. There was no significant change in the soil C/N ratio. Plant residues contained from 52 to 104 kg N/ha in 1990 at the end of the legume phase, with high values for root N in the grass+legume ley. A comparison of N accretion versus fixation at the end of the legume-based systems in 1990 showed that net accumulation of N exceeded fixation in soil under lucerne and grass+legume leys; in the latter, net accumulation of 779 kg N/ha over 3·75 years was measured compared with 384 kg N/ha for N_2 fixation. Part of the accumulation of N may have been due to uptake of NH_4-N from the deep subsoil. Although values for soil mineral N (0–120 cm) were low at the end of all the legume-based systems, a deep subsoil (120–300 cm) accumulation of NH_4-N was found in all treatments.

The nitrogen mineralisation potentials (N_o) for 0–10 cm depth samples taken at the end of the legume phase in 1989 were higher in all the legume-based systems (105–182 mg N/kg) than the wheat control (57 mg N/kg). The rapid biological tests of N availability, both waterlogged and aerobic incubation, were more sensitive to treatment differences than N_o in the surface and subsoil (range 12–78 mg N/kg for 0–10 cm soil for the waterlogged procedure). The rapid chemical tests, hot KCl extraction and the autoclave index, showed small treatment effects and did not appear to be useful availability indices. The pasture management (grazed *v.* mown and removed) had no significant effect on total N, organic C and N availability indices in this alkaline Vertisol during the study period.

Additional keywords: legumes, pasture leys, cropping systems, accumulation, availability.

Introduction

Hossain *et al.* (1995*a*) showed that nitrogen fixation in the legume-based systems at Warra using the enriched ^{15}N dilution procedure was 56 kg N/ha·year for a medic ley, 83 kg N/ha·year for lucerne ley and a mean of 80 kg N/ha·year for a grass+legume ley during a favourable growing period in this semi-arid

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environment. An important subsequent question is the extent to which N_2 fixation improves the soil N status and whether the improvement is sustainable in the longer term in the particular legume-based cropping system.

In southern Australia, the benefits of rotations involving legumes and cereal crops in terms of improved cereal grain yields and gains in soil organic N have been well documented (Greenland 1971; Clarke and Russell 1977). There has been little work in Queensland on the effect of legumes on soil N status in various cropping systems apart from Whitehouse and Littler (1984) who found that 2–4 years of lucerne-based pasture increased organic C, total N and mineralisable N on a moderately fertile (total N, 0·132%), black earth on the Darling Downs.

The experiments reported in this series of papers are part of a major study established by officers of the Queensland Department of Primary Industries (Dalal *et al.* 1991, 1995) to test alternative management strategies for their effectiveness in restoring or maintaining soil fertility in a fertility depleted Vertisol at Warra, southern Queensland. The objective for the work reported in this paper was to compare accretion of soil N and organic C of a number of legume-based cropping systems with that of continuous conventional till wheat. Since N-supplying capacity of the legume-based systems could even be proportionally greater than the total soil N, comparisons were also made of potentially mineralisable N (mineralisation potentials and availability indices) of these systems.

Materials and methods

Experiment site

Site details appear in an account of the Warra experiment by Dalal *et al.* (1991, 1995) and Hossain *et al.* (1995*a*). The soil is a deep and uniformly textured clay, described as thermic, Typic Chromustert. Soil reaction is alkaline (pH 8·2) at the surface (0–10 cm) and to a depth of about 1 m, but below this depth it becomes strongly acid (pH 5·0).

Treatments and cultural practices

Treatments investigated in this study are listed in Table 1 and these are fully described by Dalal *et al.* (1995).

The grass+legume 86–89/wheat, grass+legume 87–90/wheat, and grass+legume 88–91/wheat were planted in January 1986, 1987 and 1988, respectively. Lucerne was planted with wheat in alternate years during May–July. The annual medics were planted with wheat only once because of their self-generating nature.

Annual dry matter and N yields were measured in cuts in December, March, June and September for the grass+legume pasture and lucerne, and in June and September for the annual medics. At each cut, surplus plant material, mown at 10 cm height, was removed in the ungrazed experiment. In an adjoining grazed experiment, in each duplicate ley treatment (each plot, 25×6·75 m), one or two sheep were used for grazing for up to 20 days, coinciding with the pasture cuts in the ungrazed experiment. Dry matter yields were measured by using sheep enclosures (2×1 m).

Grass+legume pastures, and lucerne and annual medics were terminated by blade ploughing (allowing minimum soil inversions) in mid October each year. This allowed water recharge of the soil profile during summer–autumn.

Chickpea was planted in alternate years using phytophthora (*Phytophthora megasporium*) to tolerant lines or cv. Barwon. The control treatment was continuous conventional till (CT) wheat (cv. Hartog). Conventional till operations (2–4) were performed using tined implements to about 10 cm depth for weed control during the fallow and to prepare a seed bed for planting chickpea or wheat. All crop residues were retained. Basal P, S and Zn at rates of 10, 10, and 1 kg/ha, respectively, were applied annually to all plots.

Table 1. Treatment sequences from the Warra experiment

GL, grass+legume pasture consisting of purple pigeon grass (*Setaria incrassata* Stapf cv. Inverell), Rhodes grass (*Chloris gayana.* Kunth cv. Katambora), a mixture of medics (snail, *Medicago scutellata* L. Mill. cvv. Sava and Kelson; barrel, *M. truncatula* Gaertn cvv. Jemalong, Cyprus, Paraggio and Sephi); lucerne, *M. sativa* L. cv. Trifecta

W_L, lucerne undersown with wheat; W_M, medic undersown with wheat, self-regenerating medic thereafter; L, lucerne ley; M, medic ley; CP, chickpea; W, wheat (cv. Hartog)

No wheat crops were sown in 1986 and 1991

	Treatment	Calendar years									
		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
		Grass+legume ley/wheat rotation (4 years/4 years)									
1	Grass+legume 86–89/wheat	GL	GL	GL	GL	W	–	W	W	W	W
2	Grass+legume 87–90/wheat	–	GL	GL	GL	GL	–	W	W	W	W
3	Grass+legume 88–91/wheat	–	W	GL	GL	GL	GL	W	W	W	W
		Legume ley/wheat rotation (1year/1year)									
4	Lucerne/wheat	–	W_L	L	W_L	L	–	L	W_L	L	W_L
5	Lucerne/wheat	–	W	W_L	L	W_L	L	W_L	L	W_L	L
6	Medic/wheat	–	W_M	M	W	M	–	M	W	M	W
7	Medic/wheat	–	W	W_M	M	W	M	W	M	W	M
		Grain legume/wheat rotation (1 year/1 year)									
8	Chickpea/wheat	–	W	C	W	C	–	W	C	W	C
9	Chickpea/wheat	–	C	W	C	W	–	C	W	C	W
		Conventional till (CT) wheat cropping									
10	Wheat	–	W	W	W	W	–	W	W	W	W

Soil and plant residue sampling

Soil samples were collected from the pasture treatments at the end of the ley phase in October 1989 (treatments 1, 5, 7), and 1990 (treatments 2, 4, 6) and in November 1989 and 1990 after harvest, from the chickpea (9 and 8, respectively) and control CT wheat (treatment 10) plots. Samples were taken at 10 cm intervals to 30 cm depth, and, below this depth, at 30 cm intervals to 300 cm using a hydraulically operated sampler with a 50 mm diameter stainless steel tube down to 120 cm depth and a 25 mm diameter tube down to 300 cm depth. Five samples were collected from each plot from 0 to 30 cm depths, and two samples from 30 to 300 cm depths. These were mixed for their respective depths to obtain composite plot samples. A subsample at field moisture content was extracted with 2 M KCl for mineral N analysis. The remainder of the soil was dried at 25°C for 7 days and ground to pass a 2 mm sieve (0·25 mm for organic C and total N determinations). Field bulk density was calculated from the oven-dried soil weight contained in the field volume of the soil sample. The bulk density measured at field moisture content was adjusted for normal shrinkage up to moisture content at field capacity. Adjusted bulk densities were not significantly different between the various treatments.

Litter and root samples (plant residues) were collected in October 1990 from grass+legume (treatment 2), lucerne (treatment 4) and medic (treatment 6) leys. Two 50×30 cm quadrats were sampled in each plot, litter was removed by hand and soil was excavated from 0 to 10 cm depth for root measurements. The excavated soil was soaked for 24 h and then washed through a 2 mm and then a 0·5 mm sieve. Litter and root material were dried at 60–70°C and ground to pass a 1 mm sieve for N analysis. Root biomass below 10 cm depth was estimated from total root lengths measured by the line intersection method (Newman 1966), by ultrasonic dispersion of soil cores (composites) and from root weight (3 mg/m root length).

Analytical procedures

Soil organic carbon was determined by the Walkley–Black method adapted for spectrophotometric determination (Sims and Haby 1971). Total N was determined by the Kjeldahl method modified to include NO_3-N (Dalal *et al.* 1984) and in plant material by the salicylic acid method (Ekpete and Cornfield 1964). For mineral N, the 2 M KCl extract (1:3 soil:solution ratio) was steam distilled with MgO and Devarda's alloy (Bremner 1965). Mineralisable N in soil was determined by incubation under waterlogged conditions at 40°C for 7 days (Waring and Bremner 1964) and by aerobic incubation for 2 weeks at 30°C (Keeney and Bremner 1967). Autoclave N was measured by the procedure of Keeney (1982) and hot KCl N by the method of Gianello and Bremner (1986).

The nitrogen mineralisation potential (N_o) was measured by the procedure of Stanford and Smith (1972) except that twice the amount of quartz sand was used to increase the rate of leaching and the incubation temperature was increased to 40°C (Campbell *et al.* 1981). Cumulative mineralised N (N_t) was measured at 1, 2, 4, 8, 12, 16, 22, and 30 weeks, and N_o was calculated using the relationship

$$N_t = N_0 + (N_0 - N_e) \exp(-kt)$$

where N_e is mineralised N initially (t=0).

Statistical analysis

Analysis of variance was performed to assess the treatment and time effects on soil total N, organic C, carbon to nitrogen ratio, mineral N, and potentially mineralisable N by standard statistical techniques (Steel and Torrie 1980).

Results

Effect of pasture management

Soil organic C and total N concentrations, and the amounts of mineralisable N did not differ significantly between the mown and removal (the ungrazed pasture) and the grazed pasture in both 1989 (Fig. 1) and 1990. Consequently, soil organic C and total N concentrations and mineralisable N obtained from the ungrazed pastures only are reported. Furthermore, soil organic C and total N concentrations were averaged for both 1989 and 1990 since the year effect was not significant.

Soil organic carbon and total nitrogen

Organic C contents at three depths are given in Table 2. Using CT wheat as the control, the only significant treatment effect was the higher organic C in the grass+legume ley, especially in the 0–10 cm layer. The grass+legume ley contained 2·7 t/ha more organic C than the CT wheat, that is, an accumulation of 720 kg/ha·year of organic C during 3·75 years of the pasture phase.

Similarly, total soil N for 1989 and 1990 (Table 3) was substantially higher in the grass+legume ley in the surface (0–10 cm) soil compared with other legume treatments and the wheat control. Total soil N amounts for 0–20 and 0–30 cm were also significantly higher. Although the soil under the remaining legume treatments was not significantly higher in N concentration than that in the CT wheat, the total amounts of N in the lucerne treatments were significantly higher for 0–10, 0–20, and 0–30 cm depths.

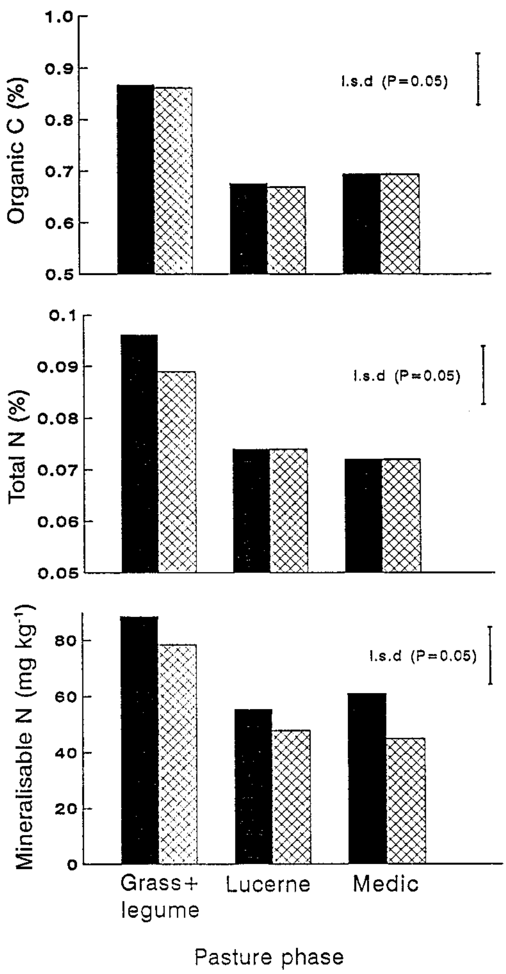

Fig. 1. Comparison of the pasture management effects of grazing, and mown and removed on soil organic C, total N and mineralisable (waterlogged incubation) N at 0–10 cm depth at the end of the pasture phase. Pasture phases include grass-legume 86–89/wheat, lucerne/wheat (treatment 5), and medic/wheat (treatment 7) rotations. Closed bars, mown at 10 cm height and removed four times a year. Cross-hatched bars, grazed by sheep for up to 2 months duration four times a year. Medic was mown and removed or grazed during winter and spring.

Table 2. Profile distribution of organic C in the soil after the legume phase and wheat harvest

Values are means for 1989 and 1990

	Treatment	Organic C (%)			Organic C (t/ha)[A]		
		0–10 cm	10–20 cm	20–30 cm	0–10 cm	0–20 cm	0–30 cm
1,2	Grass+legume/wheat	0·88	0·59	0·49	11·7	19·8	26·5
4,5	Lucerne/wheat	0·71	0·55	0·46	9·5	17·1	23·5
6,7	Medic/wheat	0·70	0·54	0·46	9·3	16·7	23·1
8,9	Chickpea/wheat	0·70	0·53	0·44	9·2	16·2	22·0
10	CT wheat	0·69	0·54	0·46	9·0	16·2	22·3
	l.s.d. ($P = 0\cdot05$)	0·05	n.s.	n.s.	0·7	1·2	1·7

n.s., not significant.

[A] Cumulative amounts of organic C obtained by summation of the amounts at each depth interval.

There were no significant treatment effects on the carbon: nitrogen ratio. However, the carbon to nitrogen ratio in the CT wheat treatment (9·8) was always higher than the legume treatments, especially in the grass+legume ley (8·8; data not shown).

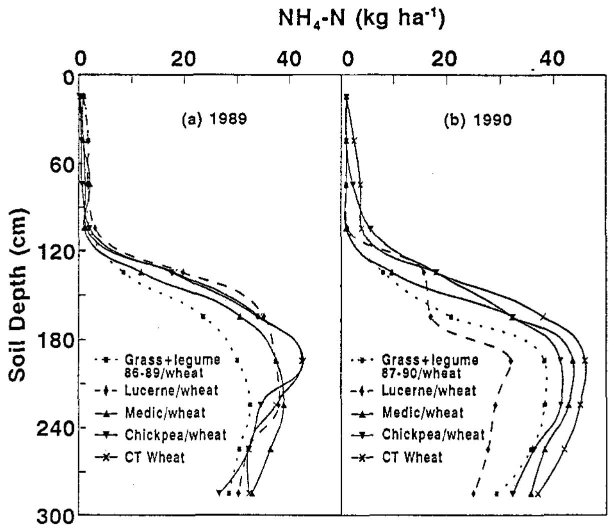

Fig. 2. Ammonium N (NH_4-N) in the profile at the end of the legume phase in 1989 and 1990, respectively, for grass+legume 86–89/wheat, grass+legume 87–90/wheat, lucerne/wheat, medic/wheat, and chickpea/wheat rotations and continuous conventional tilled (CT) wheat. The NH_4-N values of various treatments at any given depth are not significantly different at $P = 0{\cdot}05$.

Mineral nitrogen in the profile

At the termination of the pasture phases and after chickpea and wheat harvests, mineral N to a depth of 1·2 m was low, with about two-thirds occurring as NO_3-N (data not shown). The soil in the pasture treatments contained on average 17 kg/ha and that in chickpea and CT wheat treatments contained 27 and 19 kg/ha of mineral N, respectively.

The NH_4-N contents were low down to 120 cm in both experiments but then increased to a peak at 210 cm with a small decline to 300 cm (Fig. 2). Below 120 cm, NH_4-N values were generally lower for the grass+legume and lucerne leys than for wheat. Nitrate-N content was generally low (<5 kg/ha) and tended to decrease with depth in the pasture treatments and was negligible below 1·5 m in all treatments (data not shown).

Plant residues in the pasture treatments

In both years, plant residues (litter and root materials) were very low in the chickpea and wheat treatments. For the pasture treatments in 1990, the dry weight of litter material was the highest. Total amounts of plant residues were highest for the grass+legume ley (5932 kg/ha) and lowest for lucerne (3408 kg/ha). Root material in the top 10 cm depth was much higher for the grass+legume ley (2164 kg/ha) than either for lucerne (605 kg/ha) or medic (429 kg/ha). Root biomass in the 10–150 cm depth, although much higher, followed a similar trend (Dalal *et al.* 1995). Nitrogen concentration of plant residues ranged from 1·33 to 2·24% N, with no consistent treatment effects. Total N content of plant

Table 3. Profile distribution of organic N in the soil after the legume phase and wheat harvest
Values are means for 1989 and 1990

	Treatment	Total N (%)			Total N (kg/ha)		
		0–10 cm	10–20 cm	20–30 cm	0–10 cm	0–20 cm	0–30 cm
1,2	Grass+legume/wheat	0·096	0·065	0·054	1279	2168	2911
4,5	Lucerne/wheat	0·077	0·061	0·051	1023	1859	2560
6,7	Medic/wheat	0·073	0·059	0·051	974	1786	2491
8,9	Chickpea/wheat	0·073	0·057	0·047	957	1710	2348
10	CT wheat	0·071	0·060	0·048	915	1711	2356
	l.s.d. ($P = 0{\cdot}05$)	0·007	n.s.	n.s.	88	147	198

n.s., not significant.

Table 4. Comparison of amount (kg/ha) of soil total N, plant residue N, and N accumulation with N_2 fixed at the end of the legume phase in 1990 after four years of mixed pasture or 2 cycles of legume–wheat rotation

Treatment no.[A]	Total N in soil (0–30 cm)	Plant residue N[B]	Product N removal	Total N[C]	Net accretion[D]	Total N_2 fixed[E]	Accretion cf. fixation
2	2872	104	289	3265	779	384	+395
4	2663	52	232	2947	461	200	+261
6	2451	67	234	2752	266	108	+158
8	2353	Nil	259	2612	126	144	−18
10	2303	Nil	183	2486	0	—	—

[A] Treatment number: 2, grass and legume 87–90/wheat; 4, lucerne/wheat; 6, medic/wheat; 8, chickpea/wheat; 10, CT wheat.
[B] Plant residue N (litter+root+fine material) retained in the field at the end of the legume phase in 1990. Root material is from 0–10 cm depth only; below 10 cm depth it is included in total soil N.
[C] Total N = soil+plant+product.
[D] Net accumulation of total N in legume treatments for 4 years compared with wheat control.
[E] Derived by assuming fixation over 4 years for the legume treatments was at the same rate as for the 2 years studied (Hossain *et al.* 1995*a*).

residues ranged from 52 kg/ha for lucerne to 104 kg/ha for the grass+legume ley (Table 4). Below 10 cm depth, N in the root material would have been included in the total soil N (Table 3).

Nitrogen mineralisation potential (N_o)

Cumulative N mineralised from surface soil samples in 1989 (Fig. 3) showed a consistent pattern across all treatments, with an initial flush followed by a fairly constant rate during the remaining incubation period. The N_o values were highest for soil from the grass+legume leys (Table 5) and intermediate for the remaining legume treatments with much lower values for continuous wheat. For subsurface soil samples (10–20 cm), values for N_o were much lower than for the surface soil (Table 6) but showed a similar treatment pattern.

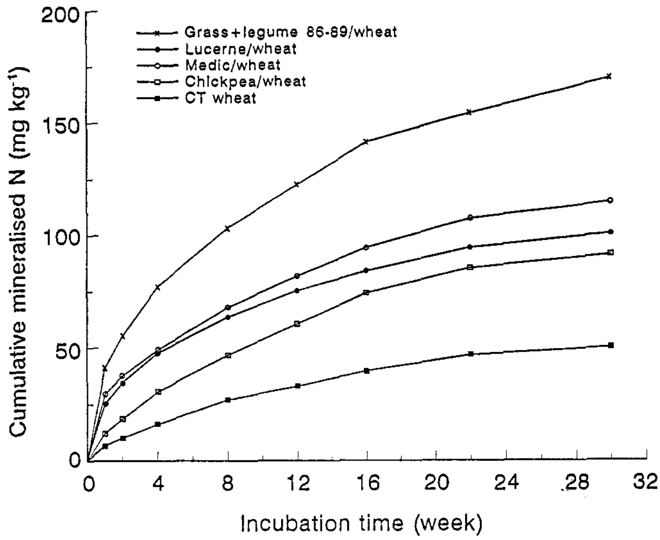

Fig. 3. The effect of legumes in different cropping systems and continuous CT wheat on cumulative mineralised N in the 0–10 cm depth in 1989.

Table 5. Nitrogen mineralisation potential (N_o), N_o/total N, and mineralisation rate constant (k) of surface soil (0–10 cm) in 1989

Values in parentheses are standard errors

	Treatment	N_o (mg/kg soil)	N_o/total N (%)	k (per week)
1	Grass+legume 86–89/wheat	182 (5)	19	0·081 (0·007)
5	Lucerne/wheat	107 (3)	15	0·087 (0·007)
7	Medic/wheat	129 (3)	18	0·070 (0·004)
9	Chickpea/wheat	105 (4)	14	0·070 (0·006)
10	CT wheat	57 (2)	8	0·071 (0·005)

Table 6. Nitrogen mineralisation potential (N_o), N_o/total N and mineralisation rate constant (k) of subsoil (10–20 cm) in 1989

Values in parentheses are standard errors

	Treatment	N_o (mg/kg soil)	N_o/total N (%)	k (per week)
1	Grass+legume 86–89/wheat	41 (2)	6	0·131 (0·021)
5	Lucerne/wheat	29 (1)	5	0·173 (0·043)
7	Medic/wheat	29 (1)	5	0·200 (0·048)
9	Chickpea/wheat	24 (1)	4	0·220 (0·060)
10	CT wheat	18 (1)	3	0·164 (0·040)

The proportion of N_o to total N was much higher in the surface soil than the subsoil for all treatments but usually with smaller differences between the grass+legume ley and the other legume treatments (Tables 5 and 6). Values for the mineralisation rate constant (k) did not show consistent treatment effects but were consistently higher and more variable in the subsurface soil than the surface soil.

Table 7. Rapid indices of soil N (mineral N, mg/kg) availability for different soil depths measured at the end of legume phase and wheat harvest in 1989

	Treatment	Waterlogged incubation	Aerobic incubation	Hot KCl extraction	Autoclave index
		0–10 cm			
1	Grass+legume 86–89/ wheat	78·5	41·1	14·5	45·4
5	Lucerne/wheat	47·9	25·4	9·8	36·7
7	Medic/wheat	45·0	29·7	11·6	38·8
9	Chickpea/wheat	27·0	12·2	11·2	36·6
10	CT wheat	12·1	7·4	8·9	37·1
	l.s.d. ($P = 0\cdot05$)	10·5	6·2	2·3	n.s.
		10–20 cm			
1	Grass+legume 86–89/ wheat	32·1	14·6	9·6	29·3
5	Lucerne/wheat	21·0	11·7	7·9	27·3
7	Medic/wheat	22·1	11·4	7·7	27·9
9	Chickpea/wheat	14·3	7·3	8·3	26·9
10	CT wheat	11·9	3·8	7·4	28·7
	l.s.d. ($P = 0\cdot05$)	6·5	3·5	n.s.	n.s.
		20–30 cm			
1	Grass+legume 86–89/ wheat	25·6	n.d.	7·3	25·3
5	Lucerne/wheat	17·5	n.d.	7·3	23·5
7	Medic/wheat	20·5	n.d.	7·8	25·1
9	Chickpea/wheat	13·3	n.d.	7·1	21·5
10	CT wheat	12·8	n.d.	6·1	23·5
	l.s.d. ($P = 0\cdot05$)	7·8	–	n.s.	n.s.

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

Rapid indices of nitrogen availability

Soil N availability indices using both waterlogged and aerobic incubation procedures showed a similar pattern but with much higher values for the waterlogged incubation method (Table 7). In the surface soil (0–10 cm), all the legume treatments were substantially higher than the CT wheat control and, within the legume treatments, the grass+legume ley was much higher than the lucerne or medic leys, which in turn were higher than chickpeas. Values for the 10–20 cm soil were much lower than for 0–10 cm but showed similar trends, with most of the legume treatments being significantly higher than the CT wheat control. Soil N availability for the waterlogged procedure at 20–30 cm depth showed values mostly lower than for 10–20 cm, with only the grass+legume ley being significantly higher than the wheat control.

The rapid chemical indices (hot KCl extraction and autoclave index) gave no significant treatment differences except for the hot KCl method for the 0–10 cm soil (Table 7) where the grass+legume ley had the highest value and this and medic ley were significantly higher than the CT wheat control. As with the incubation procedures, there was a general trend for values to decrease with soil depth.

Table 8. Linear correlation coefficients (r) among N availability indices for 0–10 and 10–20 cm soil sampled in 1989

Value of r required for $P = 0 \cdot 05$ is $0 \cdot 62$

Parameter	Waterlogged incubation	Hot KCl N	Autoclave index	Soil total N	Soil organic C	Aerobic N
N_o	0·93	0·69	0·80	0·91	0·92	0·92
Waterlogged incubation		0·67	0·67	0·82	0·80	0·97
Hot KCl N			0·69	0·76	0·75	0·64
Autoclave index				0·92	0·88	0·69
Soil total N						0·80
Soil organic C						0·78

Relationship among indices of nitrogen availability

Table 8 shows a correlation matrix for the indices of nitrogen availability for 0–10 and 10–20 cm samples taken in 1989. All the nitrogen availability indices were significantly correlated with each other ($P < 0 \cdot 05$). In particular, waterlogged and aerobic incubation N were highly correlated. However, generally low correlations were obtained where the rapid chemical methods were used.

Discussion

Ammonium-N in the profile

The low values for NH_4-N down to 120 cm depth at the termination of the legume phase in October 1989 and 1990 (Fig. 2) are to be expected as a result of plant N uptake and immobilisation of N due to the input of carbonaceous residues. For NH_4-N, the unusual result was the substantial increase beyond 120 cm in all treatments with a peak usually at 210 cm (Fig. 2). The origin of this NH_4-N is not clear.

Organic C and total N

The much greater accumulation of soil organic carbon and total nitrogen in the grass+legume leys compared with other legume treatments (Tables 2 and 3) is to be expected in view of the longer accretion time and the larger residue input of fibrous grass roots. Accumulation of C and N mostly in the 0–10 cm layer agrees with the results of other workers such as Whitehouse and Littler (1984). The surface increases in C and N are similar to those obtained by Holford (1981) for 3·5 years of grazed lucerne at Tamworth, NSW, and by Whitehouse and Littler (1984) after 4 years of grazed lucerne+prairie grass at Jondaryan, Queensland.

The much lower soil organic carbon and total nitrogen for the undersown lucerne and medic treatments compared with the grass+legume leys may be due to the shorter period of legume inputs in the former. There are few comparable data on these treatments, but Whitehouse and Littler (1984) did show a much greater effect from 1 year of lucerne+prairie grass pasture, possibly due to the influence of the associated grass in increasing soil organic matter and N_2 fixation. The lack of difference between the chickpea and continuous CT wheat treatments is not surprising in view of the low residue return from chickpea, agreeing with the results of Strong *et al.* (1986).

Net N accumulation

Net accumulation of soil and plant N after 4 years exceeded fixation for the lucerne and grass+legume leys treatments, particularly the latter treatment (Table 4). It would seem that non-symbiotic fixation may have been significant or that symbiotic fixation could have been underestimated (Hossain *et al.* 1995*a*), which appears likely since N_2 fixed in roots of the legumes was not measured. Alternatively there may have been NH_4-N uptake from the deeper layers (1·2–3·0 m) in the profile. Although the treatment differences in Fig. 2 were not significant, there was a significant depletion of water from the deeper layers (1·2–2·1 m) in the lucerne and grass+legume leys (Hossain 1993), providing circumstantial evidence for NH_4-N uptake and re-cycling. These results also suggest that net N loss during the pasture phase by mechanisms such as denitrification and leaching is not large. The nil net N accretion in the chickpea treatment, despite the relatively high fixation, agrees with results reported elsewhere for grain legumes (Evans *et al.* 1989) and for chickpea (Strong *et al.* 1986).

Net N accumulation is a useful measure of providing the long term sustainability of N in the various systems. For the grass+legume leys, trends in total N after the cropping phase have been reported by Dalal *et al.* (1995). Whitehouse and Littler (1984) suggested that it may take up to 9 years of wheat cropping to return total N to the level of that before the commencement of the legume phase of 3–5 years duration.

For the lucerne and medic leys in rotation with wheat, the positive accumulations indicate viable long term systems in terms of total N with greater gains for lucerne. The higher N_2 fixation for lucerne compared with medic may be associated with its longer growing period (Hossain *et al.* 1995*a*) and possibly higher N accretion from deeper layers. Chickpea, on the basis of total N trends, is shown to be little better than continuous CT wheat.

Potentially mineralisable N

The availability of the nitrogen accumulated in soil organic matter to subsequent crops following the various legume-based treatments is a critical issue. The most accepted measurement is probably that of N_o (Stanford and Smith 1972). Although N_o and total soil N and soil organic C were highly correlated (Table 8), N_o showed much greater changes from the CT wheat control for the various legume-based treatments (Table 5). This contrasts with the findings presented by Dalal and Mayer (1987) who, in their study of soil fertility degradation due to cultivation, found N_o to be an index no more sensitive to reflect treatment effects than total soil N. For example, the N_o value in the chickpea treatment is approximately twice that of the wheat control in the soil surface (Table 5) but there is no difference in total soil N. The much higher N_o value for the grass+legume leys is to be anticipated in view of its much increased total soil nitrogen. The N_o value of 182 mg N/kg for the grass+legume ley compares favourably with a value reported by Dalal and Mayer (1987) of 217 mg N/kg for the 0–10 cm surface layer of a similar virgin soil, suggesting that 4 years of a grass+legume pasture can restore N_o to a level similar to that before cultivation.

The 'active' or more readily mineralisable N of the soil organic matter can be calculated as N_o/total N. The values obtained (Tables 5 and 6) show trends generally similar to N_o and values for the 0–10 cm surface in a similar range to those reported by Campbell *et al.* (1981) for the 0–15 cm surface soil of a range of cultivated Vertisols. The results for different treatments indicate a similar but much higher availability for the recently accrued N in all the legume treatments when a comparison is made with the CT wheat control. Such an increase in availability is to be expected following inputs from legumes, agreeing with the results of Waring and Gibson (1995). For the grass+legume leys, the 0–10 cm value of 19% is much higher than the value of 11% found by Dalal and Mayer (1987) for a similar virgin soil. No explanation can be offered for the higher k values in the 10–20 cm depth compared with the topsoil (Table 6).

Of the rapid indices of N availability, the chemical indices showed few significant treatment effects, especially for the autoclave index (Table 7), currently regarded as the recommended chemical procedure (Keeney 1982). Also, they were not as well correlated with N_o as the rapid incubation procedures. This agrees with Gibson (1988) and Dalal and Mayer (1990) who found the waterlogged method to be better correlated with N_o than the hot KCl method. However, Gianello and Bremner (1986) reported that hot KCl-N values were closely correlated with waterlogged and aerobic mineralisable N in Iowa soils and McCracken *et al.* (1989) found the autoclave index to be superior to waterlogged incubation. For the soils in the present study there is no question of the superiority of the rapid incubation procedures. For these procedures, the two methods gave a very similar rank order of treatments but with fewer significant effects for the aerobic procedure. This, combined with the greater simplicity and speed of the waterlogged procedure, indicates it to be the preferred incubation method agreeing with the recommendation of Keeney (1982).

Both the rapid incubation procedures were more sensitive with similar trends, although the chickpea treatment for the rapid procedures is substantially lower than the lucerne and medic treatments. A significant question is whether the rapid procedures are as satisfactory as the much longer procedure to estimate N_o in predicting release and subsequent crop uptake of N. This issue is addressed in Part II of this series of papers (Hossain *et al.* 1995*b*).

Effect of pasture management

The N inputs through legume and grass plant residues, litter and root materials were found to be essentially similar in both the ungrazed (mown and removed) and the grazed experiments. Since pastures in the ungrazed experiment were mown at 10 cm height, about 50% of the standing material remained after each mowing and removal. In the grazed experiment, the effect of faeces may be localised because they are voided non-uniformly and N losses from urine could be substantial, often exceeding 75% in alkaline soils (Vallis *et al.* 1982) such as from this Vertisol (pH 8·2–8·6).

The results obtained in this study provide opportunities to develop soil and crop management systems that result in better synchrony between N_2 fixation, organic C and N accretion, N mineralisation and N uptake by crop and also conservation of N not used by crop plants. For example, tillage management can be an important tool for the manipulation of organic N accumulation and release. The readily mineralisable N that accumulates in legume-based treatments as a result of the period of legume growth is more important to immediate crop growth than the total N build-up. However, the effectiveness of legume-N inputs to soil from different cropping systems needs consideration of the effect on soil water supply for the subsequent crop. This may indicate a significant advantage in using medics (albeit without summer weeds) compared with lucerne in this environment.

Conclusions

Total soil N and organic C in this Vertisol were increased by 4 year grass+legume leys only. This was primarily associated with additional root biomass yield produced by grass+legume leys (10 t/ha) compared with the other treatments (2–4 t/ha) (Dalal *et al.* 1995). However, potentially mineralisable N, including N mineralisation potentials and N availability indices was significantly enhanced by all legume-based treatments compared with CT wheat. Therefore, cereal crop(s) following the legume-based treatments are likely to benefit from the increased rapid N supply capacity of the soil. However, the improvement in soil organic matter (total soil N and organic C) is sustainable in the longer term in only the grass+legume ley based cropping system in these Vertisols.

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