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Soil nitrogen availability in the cereal zone of South Australia. II. Buffer-extractable nitrogen, mineralisable nitrogen, and mineral nitrogen in soil profile under different land uses

Z. H. Xu[AB], *M. Amato*[C], *J. N. Ladd*[C], *and D. E. Elliott*[AD]

[A] Cooperative Research Centre (CRC) for Soil and Land Management, PMB 2, Glen Osmond, SA 5001.
[B] Present address: Queensland Forestry Research Institute, Queensland Department of Primary Industries, MS 483, Fraser Rd, Gympie, Qld 4570.
[C] CSIRO Division of Soils and CRC for Soil and Land Management, Private Bag No. 2, Glen Osmond, SA 5064.
[D] Retired.

Abstract

Mineral nitrogen (nitrate-N+ammonium-N) and its distribution in soil profiles to 60 cm depth at sowing in 3 growing seasons, 1990–1992, were assessed for 123 field experimental sites in South Australia. The sites were used to test N fertiliser responses with cereal crops following different land uses. More than 90% of the variation in mineral N at cereal sowing was attributable to nitrate-N in the 60-cm soil profiles. Coefficients of variation (CV) for nitrate-N ranged from 37 to 45%, less than half of the CV values (88–113%) for ammonium-N. More than 70% of mineral N in soil to 60 cm depth was accounted for by mineral N in the top 20 cm of soil, and 49% by mineral N in the top 10 cm of soil. The amounts of mineral N in the 60-cm soil profiles at sowing ranged from 24 to 180 kg N/ha (median 75) at sites following pastures, and from 22 to 113 kg N/ha (median 69) following grain legumes, significantly higher than 17 to 116 kg N/ha (median 47) following cereals. Only 26% of the variation in mineral N of soils (0–60 cm depth) could be predicted by soil total N, mineralisable N assessed by the aerobic incubation method, and previous land use.

Ammonium-N extracted by phosphate-borate buffer from soils sampled at 0–10 and 10–20 cm depths was directly related to soil total N and N mineralised after soil incubation, but not to mineral N accumulating at sowing in the soil profiles to 60 cm depth. Utilisation of a soil containing ^{15}N-labelled organic residues, and sampled to 100 cm depth at sowing in 5 successive growing seasons, revealed a positive relationship between the ^{15}N atom% enrichments of soil profile mineral N, mineralisable N from soil incubations, and plant N. Enrichments of soil profile mineral N and plant N were almost identical. However, the enrichment of buffer-extractable ammonium-N was comparatively low and unresponsive to the time of soil sampling, and unrelated to the other soil and plant N pools. Thus, buffer-extractable N was unrepresentative of plant-available N.

Additional keywords: ammonium-N, buffer extraction, nitrate-N, previous land use, soil mineral N, soil N availability.

Introduction

Soil mineral N at sowing or shortly before sowing is a direct, useful index of soil N availability for plant uptake and has been recognised as one of the important soil variables for predicting cereal growth and its response to application of N fertiliser (Strong 1981; Keeney 1982; Holford and Doyle 1992). Many studies have

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reported on soil mineral N at sowing following different land uses and its impact on cereal response to N fertiliser in South Australia (SA) (Russell 1968; French 1978*a*, 1978*b*; Xu and Elliott 1993). Mineral N in soil profiles at sowing, and soil N mineralised in incubation assays, have been closely related to cereal growth and its response to the addition of fertiliser N in many agricultural production systems (Keeney 1982; Stanford 1982; Dalal and Mayer 1990). In SA, soil mineral N at sowing is largely derived from mineralisation of soil organic N and decomposition of plant residues. Little or no N fertiliser is applied to pastures or grain legumes grown in rotation with cereals, and even under continuous cereal cropping, soils generally receive low application rates of N fertiliser (McDonald 1989).

Whilst mineralisation of soil organic matter N is often the most important process contributing to the accumulation of soil mineral N (French 1978*a*; Keeney 1982; Stanford 1982; Ladd *et al.* 1981, 1983, 1986), mineralisation of N from decomposing plant residues (particularly legume residues) may also contribute a significant minority of N for uptake by subsequent crops (Ladd *et al.* 1981, 1983; Ladd and Amato 1986; Amato *et al.* 1987; Xu *et al.* 1993*a*, 1993*b*, 1993*c*). Soil and plant residue properties, and climatic conditions (and hence soil temperature and moisture conditions), are major factors affecting mineralisation of N from organic sources (Gonzalez-Prieto *et al.* 1992; Xu *et al.* 1996). All of these factors may be influenced by management practices (Keeney 1982; Stanford 1982). Thus, the amounts of soil mineral N at sowing may differ greatly with previous land use (Haynes *et al.* 1993; Xu and Elliott 1993). In general, more soil mineral N is available at the beginning of a growing season for N nutrition of cereals following either legume crops or legume-based pastures than after cereals or non-legume break crops (King 1984; Evans *et al.* 1991). Soil mineral N and its value for predicting crop demand for additional N fertiliser can vary widely, depending on the method and time of soil sampling in relation to the stage of crop development (Keeney 1982; Stanford 1982). Moreover, soil mineral N is closely related to the depth of soil profile sampled (Strong *et al.* 1986; Holford and Doyle 1992). In Australia, mineral N in soil profiles to 60 cm depth at sowing has generally proved to be an important soil parameter for predicting cereal growth and its response to N fertiliser application. In many cases, mineral N in the surface soil (top 20–30 cm) at sowing has been found to be as useful as that in the 60 cm soil profile (Dalal and Mayer 1990; Xu and Elliott 1993).

Various assays based on chemical extractions and incubation techniques have been used to rank the capacity of soils to mineralise organic matter N or to supply plant-available N (Jenkinson 1968; Robinson 1975; Keeney 1982; Stanford 1982; Haynes 1986). Chemical extraction methods are less expensive and more convenient to use and yet may be significantly related to mineralisable N, determined by biological incubation methods and plant N uptake (Gianello and Bremner 1986*a*, 1986*b*). McTaggart and Smith (1993) and Smith and Li (1993) reported that soil N extracted by hot dilute KCl solution was well related to N uptake by barley crops grown in both glasshouse and field experiments, whereas Hong *et al.* (1990) reported that neither hot KCl extractable ammonium-N nor phosphate–borate extractable ammonium-N, as measured in assays described by Gianello and Bremner (1986*b*), was a good predictor of N-supplying capacity for their range of soils. Further, studies by Stockdale and Rees (1994), using soils containing ^{15}N immobilised in microbial organic residues, demonstrated that hot KCl-extractable ammonium-N was derived from a soil pool quite dissimilar from that supplying plant-available N. Other studies (Gonzalez-Prieto *et al.* 1994; Groot and Houba 1995) have demonstrated inconsistencies in the relationships between N availability indices estimated by chemical extraction methods, biological incubation methods, and plant N uptake in the field.

In Part 1 (Xu *et al.* 1996), we reported the study on soil organic carbon, total N, and N mineralisation rates assessed by a laboratory aerobic incubation method for soils sampled at 0–10 and 10–20 cm depths from 123 experimental sites in the cereal zone of SA. In the present study we determined amounts of mineral N in 123 soil profiles to 60 cm depth, sampled at times of sowing cereal crops over the 3 cropping seasons 1990–1992 following different land uses in SA, and examined the relationship between mineral N in the 60-cm soil profile and mineralisable N/percentage N mineralisation rate as reported in Part 1. We also evaluated a buffer extraction method of Gianello and Bremner (1988) to assess soil N availability, using 28 representative soils sampled at 0–10 and 10–20 cm depths across the SA cereal zone. Finally, we used a soil containing ^{15}N-labelled organic matter to compare isotope compositions of soil profile mineral N, buffer-extractable ammonium-N, mineralisable N in incubated soil, and plant N over 5 successive years.

Materials and methods

Soils and soil properties

Detailed chemical and physical properties of the soils sampled at 0–10 and 10–20 cm depths from the 123 field experimental sites are given in Part 1. A general description of major soils and climatic conditions in the SA cereal zone has been given by Russell (1967). Detailed soil properties and descriptions can be obtained from the authors upon request. Briefly, properties of the soils at 0–10 cm depth ranged widely: pH 5·0–8·9 (median 8·1); total N% 0·031–0·238 (0·120); organic carbon% 0·38–2·43 (1·20); bulk density (g/cm^3) 1·10–1·77 (1·36); and field capacity (% H_2O) 1·9–42·1 (20·9). The corresponding values for the soils at 10–20 cm depth were total N% 0·013–0·181 (0·065); organic carbon% 0·20–2·02 (0·60); bulk density (g/cm^3) 1·02–1·77 (1·36); and field capacity (% H_2O) 2·6–54·2 (25·4). Of these soils, 28 (site nos 1–14, 16–19, 21–25, 27, 29, 30, 32, and 33, as listed for the 1991 samplings in Part 1, Appendix I) were selected as representative of the major cereal-producing regions of SA and used to evaluate the buffer extraction method of Gianello and Bremner (1988).

In addition, an Alfisol (red brown earth) located at a field site near Kapunda, SA, was sampled to 100 cm depth from quadruplicated plots at sowing in each of 5 successive years, following an initial application of ^{15}N-nitrate at sowing of a wheat crop grown in 2-year rotations with lupin crops. The experiment formed part of a major study of N cycling in cereal–legume rotations at the Kapunda site (J. N. Ladd and M. Amato, unpublished data). Detailed properties of the Alfisol profile are described by Jocteur Monrozier *et al.* (1991).

Soil sampling for measurements of mineral N at sowing

The procedures for sampling and measurement of mineral N in soil profiles to 60 cm depth at sowing are described in Part 1. Field-moist soils were subsampled to determine moisture contents and concentrations of mineral N (ammonium-N and nitrate-N) before air-drying for other laboratory analyses. At 40 experimental sites, sampling occurred in the year following pastures of different quality and productivity, ranging from poor grassy pastures to high-yielding, legume-dominated pastures. All pasture sites were subjected to various intensities of grazing. At 30 sites, sampling followed different legume crops of various grain yields, and at 53 sites, sampling followed wheat, barley, or oats crops of different grain yields. Detailed information about the location of sites is given in Part 1.

Chemical and statistical analysis

Total N, profile mineral N, and mineralisable N released by the aerobic incubation method were determined for the 123 soils by the methods reported in Part 1. Buffer-extractable ammonium-N from 28 of the 123 soils was determined by steam distillation of duplicate subsamples (4 g air-dried soil) from the 0–10 and 10–20 cm profile depths with 40 mL of a phosphate–borate buffer, pH 11·2, for 8 min (Gianello and Bremner 1988). Ammonium-N of each distillate was titrated with 50 mM H_2SO_4, and corrected for an amount initially present in soil, and extracted with cold 2 M KCl solution.

For the Alfisol containing ^{15}N-labelled organic matter, mineral N of the soil profile to 100 cm depth, and mineralisable N released by soil incubation (10 days, 25°C), were determined on soil extracts (40–50 g soil/125 mL 2 M KCl). Prior to commencement of the incubation assay, water contents of the field-moist soil from the 0–10 cm depth were adjusted to the equivalent of 40% of its water-holding capacity and pre-incubated for 7 days at 25°C. Mineral N (ammonium-N+nitrate-N) of the extracts was estimated by steam distillation in the presence of MgO and Devarda's alloy, as described by Bremner (1965). Plant N was determined by Kjeldahl digestion of plant tops harvested at the late-flowering growth stage, oven-dried (80°C, overnight), and ground (<2 mm) in a Tecator mill. Ammonium-N of the digests was steam distilled and estimated as described above.

Distillates from buffer extracts of the Alfisol from 0–10 cm depth, or from digests of plants grown on the Alfisol, and which contained ammonium-^{15}N, were amended with KCl to 2 M final concentration. Aliquots (50 mL) of the distillates and of the 2 M KCl extracts of soils sampled from the soil profile and laboratory incubations were transferred to sealable plastic containers, amended with 0·5 g each of MgO and Devarda's alloy, and incubated at 25°C for 6 days (Brooks *et al.* 1989). Ammonia, diffused from the alkaline solutions, was collected on a glass filter disc impregnated with 10 mL 2·5 M $KHSO_4$ and suspended above the solutions in the sealed containers. The discs were then dried over H_2SO_4 and placed in tin capsules. The ^{15}N atom% enrichments of adsorbed ammonium-N were determined using an ANCA mass spectrometer (Europa Scientific).

Statistical analysis and graphing were conducted with STATISTICA (StatSoft 1994). As described by Gomez and Gomez (1984), between-group or single-contrast comparisons were made by classifying treatments into s (where $s > 2$) meaningful groups (each group consisting of one or more treatments), and then comparing the aggregate mean of each group with that of the others.

Results

Mineral N in soil profiles at sowing

Amounts of nitrate-N, ammonium-N, and mineral N (nitrate-N+ammonium-N) in soil profiles to 60 cm depth at sowing are summarised in Table 1. Nitrate-N (kg N/ha) ranged from 1 to 114 (median 22) at 0–10 cm depth, from 2 to 39 (10) at 10–20 cm, from 0 to 62 (10) at 20–40 cm, and from 0 to 22 (5) at 40–60 cm depth. Total nitrate-N in the 60-cm soil profile varied from 15 to 160 kg N/ha, with a median value of 51 kg N/ha. Ammonium-N (kg N/ha) ranged from 0 to 31 (median 1) at 0–10 cm, from 0 to 6 (1) at 10–20 cm, from 0 to 15 (1) at 20–40 cm, and from 0 to 15 (1) at 40–60 cm. Mineral N (kg N/ha) ranged from 2 to 133 (median 25) at 0–10 cm, from 2 to 39 (11) at 10–20 cm, from 0 to 77 (12) at 20–40 cm, and from 0 to 36 (7) at 40–60 cm. Total mineral N in the 60-cm soil profile ranged from 17 to 180 (median 57) kg N/ha.

Table 1. **Mineral N (NO_3^--N+NH_4^+-N, kg N/ha) distribution in soil profiles at sowing of 123 experimental sites in the cereal zone of South Australia**

Descriptive statistics	0–10 cm	10–20 cm	20–40 cm	40–60 cm
		NO_3^--N		
Mean	24·7	12·0	12·8	7·0
s.d.	16·2	8·4	10·2	5·8
s.e.	1·5	0·8	0·9	0·5
CV (%)	65·6	69·5	79·9	82·9
Min.	0·7	1·8	0·0	0·0
Median	22·3	9·7	9·8	5·3
Max.	113·8	38·6	61·7	22·1
		NH_4^+-N		
Mean	2·4	1·1	2·0	2·2
s.d.	4·4	1·3	2·4	2·7
s.e.	0·4	0·1	0·2	0·2
CV (%)	181·4	117·7	121·4	124·3
Min.	0·0	0·0	0·0	0·0
Median	1·0	0·8	1·3	1·4
Max.	31·1	6·1	15·4	14·7
		NO_3^--N+NH_4^+-N		
Mean	27·1	13·1	14·8	9·2
s.d.	17·1	8·5	11·4	7·5
s.e.	1·5	0·8	1·0	0·7
CV (%)	63·3	65·1	76·7	81·3
Min.	1·9	2·3	0·0	0·0
Median	24·8	10·7	11·8	7·3
Max.	132·5	39·1	77·0	36·0

In general, median values for nitrate-N were 90–91% of the respective amounts of mineral N in the surface soils (0–10 and 10–20 cm depths), decreasing to 73–83% at greater depths (20–40 and 40–60 cm of the soil profiles). The CV for the amounts of nitrate-N increased with the depth, from 66% at 0–10 cm to 83% at 40–60 cm; the CV for total mineral N increased from 63% at 0–10 cm to 81% at 40–60 cm. The CV values for the amounts of ammonium-N (181% at 0–10 cm and 118–124% at soil depths below 10 cm) were generally much higher than those for nitrate-N or mineral N.

At 0–10 cm, nitrate-N was much better related to mineral N ($R^2 = 0{\cdot}94$) than was ammonium-N ($R^2 = 0{\cdot}11$). Similarly, at 10–20 cm, 98% of the variation in mineral N was explained by nitrate-N, compared with only 4% by ammonium-N. Nitrate-N at 20–40 cm accounted for 96% of the variation in mineral N at the same depth, compared with 30% explained by the corresponding ammonium-N. About 90% of the variation in mineral N in 40–60 cm soil was attributable to nitrate-N at the same depth, with the corresponding ammonium-N accounting for 53%. Whilst nitrate-N in each depth of the soil profile consistently accounts for >90% of the variation in mineral N at the same depth, it is interesting to note that the relationships between ammonium-N and mineral N at greater depths (20–40 and 40–60 cm) are significantly better ($R^2 = 0{\cdot}30$–$0{\cdot}53$) than those at the more shallow depths (0–10 and 10–20 cm) ($R^2 = 0{\cdot}04$–$0{\cdot}11$).

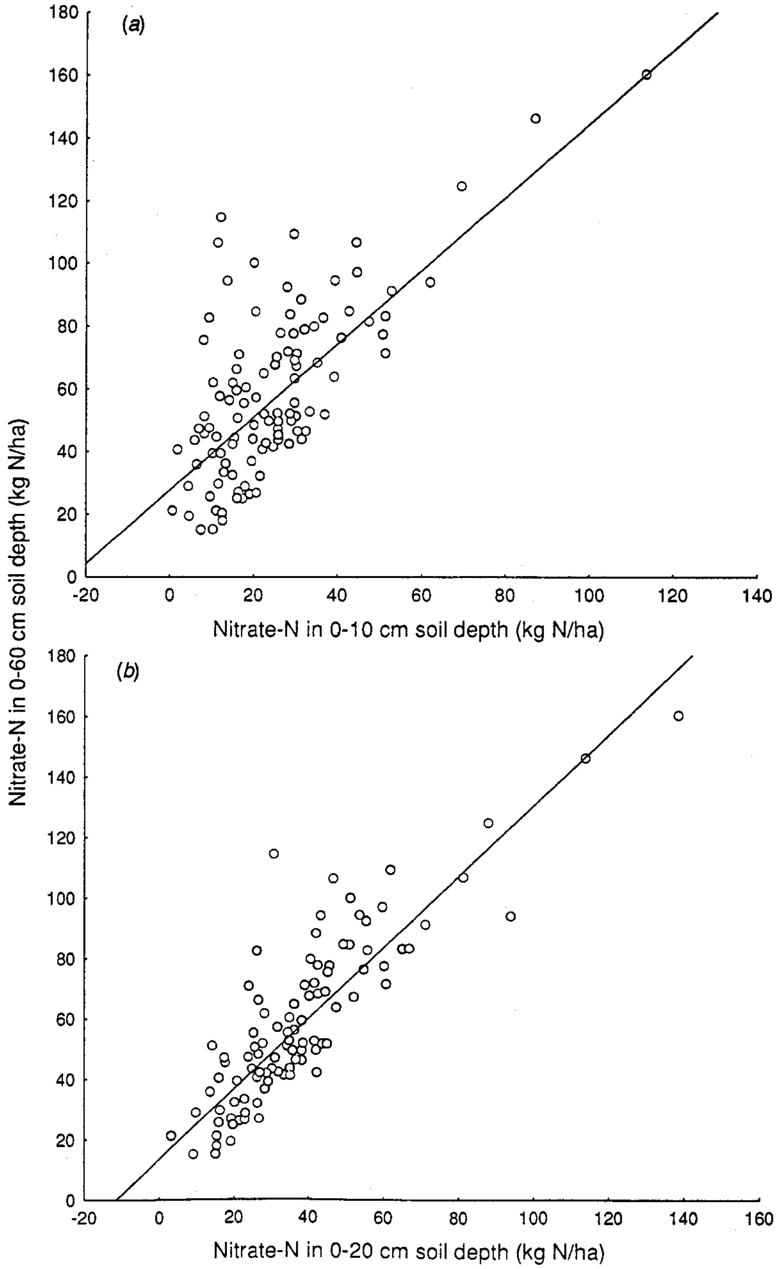

Fig. 1. Relationships between (a) nitrate-N in 0–10 cm soil depth and nitrate-N in 0–60 cm soil depth:

$$y = 27{\cdot}7 + 1{\cdot}17x \ (R^2 = 0{\cdot}48,\ n = 123,\ P < 0{\cdot}001,\ \text{r.s.d.} = 19{\cdot}5);$$

and (b) nitrate-N in 0–20 cm soil depth and nitrate-N in 0–60 cm soil depth:

$$y = 13{\cdot}5 + 1{\cdot}17x \ (R^2 = 0{\cdot}74,\ n = 123,\ P < 0{\cdot}001,\ \text{r.s.d.} = 13{\cdot}9).$$

Previous land use and mineral N in soil profiles

Of the nitrate-N in soil profiles to 60 cm depth, most was present in the top 20 cm of soil (Fig. 1*a* and *b*) and was significantly affected by seasonal conditions and previous land use:

$$N_{NN60} = 29\cdot4 + 1\cdot10N_{NN10} - 0\cdot0546C_{90v.91,92} - 0\cdot186C_{91v.92} + 0\cdot0974C_{PGv.CE} \quad (1)$$

$$(R^2 = 0\cdot58,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 18\cdot0)$$

$$N_{NN60} = 15\cdot5 + 1\cdot12N_{NN20} - 0\cdot147C_{91v.92} + 0\cdot0542C_{PGv.CE} \quad (2)$$

$$(R^2 = 0\cdot77,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 13\cdot2)$$

where N_{NN10}, N_{NN20}, and N_{NN60} are nitrate-N (kg N/ha) at soil depths of 0–10, 0–20, and 0–60 cm, respectively, $C_{90v.91,92}$ is the single contrast of sites in 1990 (+60) *v.* those in 1991 and 1992 (−63), $C_{91v.92}$ is the single contrast of sites in 1991 (+32) *v.* those in 1992 (−28), $C_{PGv.CE}$ is the single contrast of sites following either pastures or grain legumes (+53) *v.* those after cereals (−70), and r.s.d. is the residual standard deviation. In Eqn 1, 48% of the variation in N_{NN60} was explained by N_{NN10}; 4% by both $C_{90v.91,92}$ and $C_{91v.92}$, suggesting that the extent of nitrate-N detected in the 60-cm soil profiles was in the order 1990 < 1991 < 1992; and 6% by $C_{PGv.CE}$, indicating that more nitrate-N was recorded in the 60-cm soil profiles following either pastures or grain legumes, compared with cereals. In Eqn 2, 74% of the variation in N_{NN60} could be explained by N_{NN20}, 1% by $C_{91v.92}$, and 2% by $C_{PGv.CE}$.

In most cases, <10% of total mineral N at sowing in the 60 cm soil profiles was present as ammonium-N. Most of the ammonium-N in the 60 cm soil profile (N_{AN60}, kg N/ha) was detected in the surface soil layer (Fig. 2*a* and *b*). A small but significant effect of seasonal conditions was detected on ammonium-N in the 60-cm soil profiles:

$$N_{AN60} = 4\cdot40 + 1\cdot36N_{AN10} - 0\cdot0516C_{91v.92} \quad (3)$$

$$(R^2 = 0\cdot58,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 5\cdot40)$$

$$N_{AN60} = 2\cdot79 + 1\cdot41N_{AN20} - 0\cdot0366C_{91v.92} \quad (4)$$

$$(R^2 = 0\cdot74,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 4\cdot28)$$

where N_{AN10} and N_{AN20} are ammonium-N (kg N/ha) at soil depths of 0–10 and 0–20 cm, respectively. In Eqn 3, 56% of the variation in N_{AN60} could be explained by N_{AN10}, and 2% by $C_{91v.92}$. In Eqn 4, 73% of the variation in N_{AN60} could be explained by N_{AN20}, and 1% by $C_{91v.92}$. There was less ammonium-N in the 60-cm soil profiles detected in 1991 than in 1992.

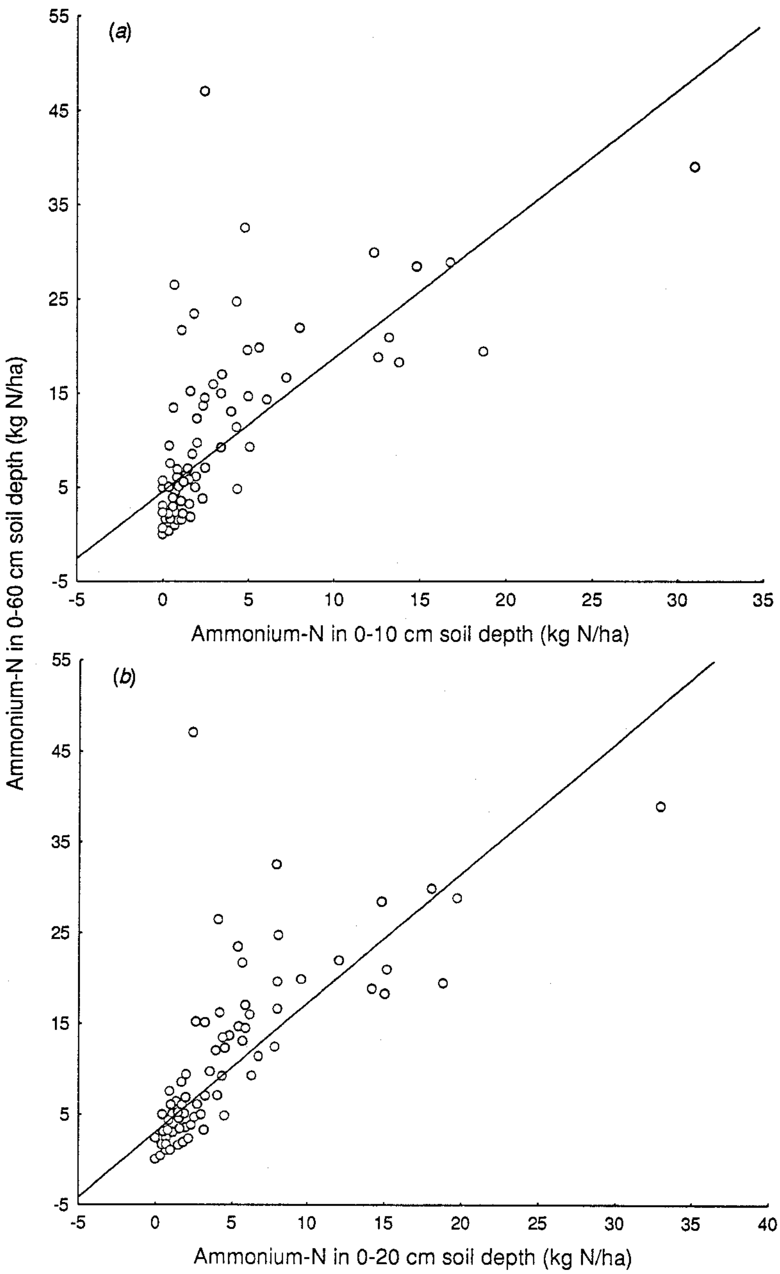

Fig. 2. Relationships between (*a*) ammonium-N in 0–10 cm soil depth and ammonium-N in 0–60 cm soil depth:

$$y = 4{\cdot}27 + 1{\cdot}42x\ (R^2 = 0{\cdot}56,\ n = 123,\ P < 0{\cdot}001,\ \text{r.s.d.} = 5{\cdot}49);$$

and (*b*) ammonium-N in 0–20 cm soil depth and ammonium-N in 0–60 cm soil depth:

$$y = 2{\cdot}66 + 1{\cdot}43x\ (R^2 = 0{\cdot}73,\ n = 123,\ P < 0{\cdot}001, \text{r.s.d.} = 4{\cdot}33).$$

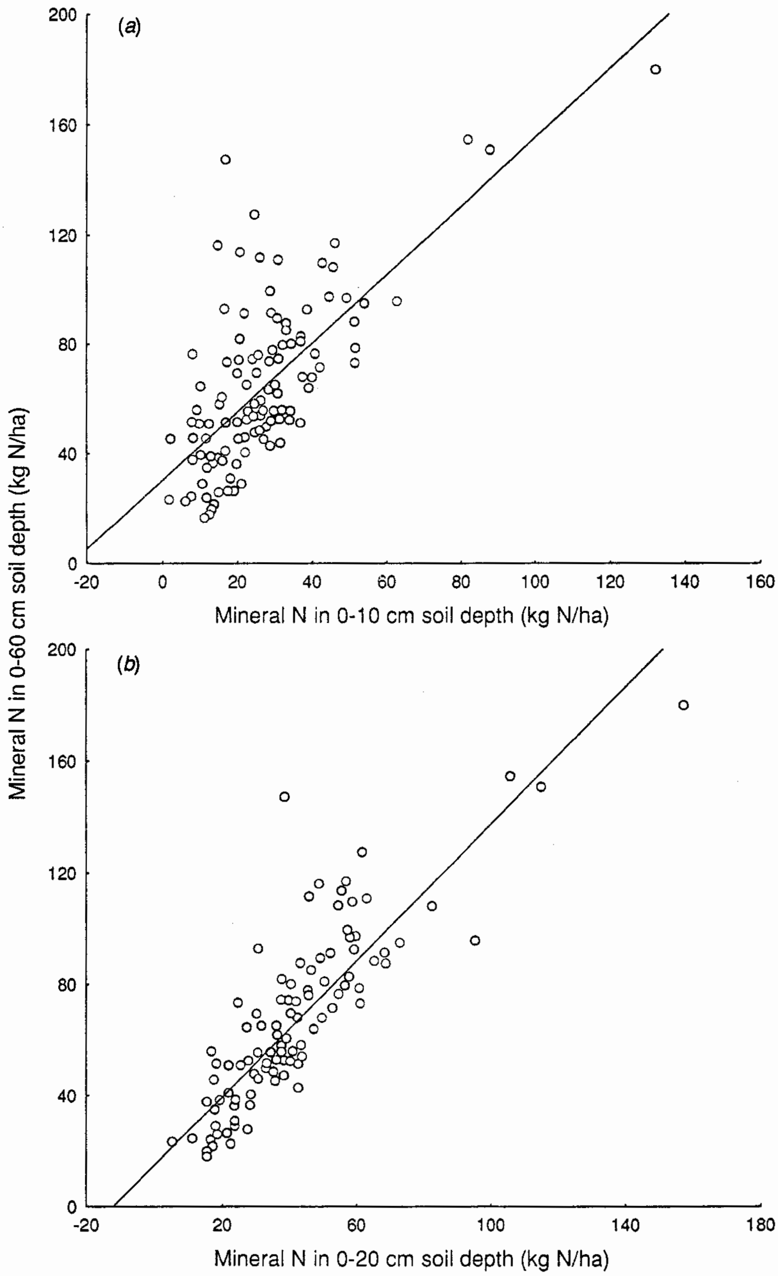

Fig. 3. Relationships between (a) mineral N in 0–10 cm soil depth and mineral N in 0–60 cm soil depth:

$$y = 30 \cdot 4 + 1 \cdot 25x \ (R^2 = 0 \cdot 49,\ n = 123,\ P < 0 \cdot 001,\ \text{r.s.d.} = 21 \cdot 9);$$

and (b) mineral N in 0–20 cm soil depth and mineral N in 0–60 cm soil depth:

$$y = 15 \cdot 0 + 1 \cdot 22x \ (R^2 = 0 \cdot 71,\ n = 123,\ P < 0 \cdot 001,\ \text{r.s.d.} = 16 \cdot 4).$$

Table 2. Mineral N (kg N/ha) in 60-cm soil profile at sowing following either a pasture or crop in the cereal zone of South Australia

Descriptive statistics	After pasture			After grain legume crop			After cereal crop		
	NO_3^--N	NH_4^+-N	Mineral N	NO_3^--N	NH_4^+-N	Mineral N	NO_3^--N	NH_4^+-N	Mineral N
Number of sites	40	40	40	30	30	30	53	53	53
Mean	69·9	9·2	79·1	62·3	8·6	70·9	43·0	6·0	49·0
s.d.	31·1	10·3	35·4	23·2	7·6	24·5	18·8	6·5	21·8
s.e.	4·9	1·6	5·6	4·2	1·4	4·5	2·6	0·9	3·0
CV (%)	44·5	112·7	44·8	37·2	88·2	34·6	43·7	108·1	44·5
Min.	21·1	0·0	24·0	20·3	0·0	21·6	15·0	0·0	16·6
Median	65·5	4·2	75·1	58·7	6·9	68·7	42·3	3·9	47·2
Max.	160·3	39·0	179·8	109·3	28·9	113·4	94·5	26·4	116·0

Distribution of total mineral N in the 60-cm soil profiles at sowing was similar to that of nitrate-N, as shown in Fig. 3*a* and *b* and the following equations:

$$N_{MN60} = 32\cdot8 + 1\cdot16N_{MN10} - 0\cdot256C_{91v.92} + 0\cdot0897C_{PGv.CE} \quad (5)$$

$$(R^2 = 0\cdot56,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 20\cdot4)$$

$$N_{MN60} = 17\cdot4 + 1\cdot16N_{MN20} - 0\cdot200C_{91v.92} + 0\cdot0500C_{PGv.CE} \quad (6)$$

$$(R^2 = 0\cdot75,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 15\cdot5)$$

where N_{MN10}, N_{MN20}, and N_{MN60} are mineral N (kg N/ha) in 0–10, 0–20, and 0–60 cm soil depths, respectively. In Eqn 5, 49% of the variation in N_{MN60} could be explained by the N_{MN10}; 5% by $C_{91v.92}$, indicating that less mineral N in the 60-cm soil profile was detected in 1991 than in 1992; and 2% by $C_{PGv.CE}$, demonstrating that more mineral N in the 60-cm soil profile was recorded from the sites following either pastures or grain legumes than those after cereals. In Eqn 6, 71% of the variation in N_{MN60} was attributable to N_{MN20}, 2% to $C_{91v.92}$, and 2% to $C_{PGv.CE}$.

Following pastures grown in the previous year, the amounts of mineral N in soil profiles to 60 cm depth at sowing ranged from 24 to 180 kg N/ha, with a median of 75 kg N/ha (Table 2). These values may be compared, respectively, with a range of mineral N 22–113 kg N/ha (median 69) following grain legumes, and 17–116 kg N/ha (median 47) following cereals. On average, previous growth of either pasture or grain legume resulted in an extra 20 kg N/ha or more in the soil mineral N pool when compared with that following previous cereal crops. Irrespective of the previous land use, the CV for nitrate-N in the 60-cm soil profile was 37–45%, which was less than half of the CV 88–113% for ammonium-N. However, the CV for mineral N following grain legumes was 34%, compared with 45% following either pastures or cereals.

Soil profile mineral N and N availability parameters

Only 26% of mineral N in the 60-cm soil profile at sowing could be explained from the previous land use ($C_{PGv.CE}$), total N in the top 10 cm soil (TN_{10}, %), and mineralisable N in the top 20 cm soil (N_{PMN20}, kg N/ha):

$$N_{MN60} = 57\cdot8 + 198TN_{10} + 0\cdot247C_{PGv.CE} - 0\cdot226N_{PMN20} \quad (7)$$

$$(R^2 = 0\cdot26,\ n = 123,\ P < 0\cdot001,\ \text{r.s.d.} = 26\cdot6)$$

Buffer-extractable ammonium-N from both 0–10 and 10–20 cm depths of the 28 selected soils was directly and significantly related to the total N contents of the respective soils (Fig. 4*a*), and to the amounts of mineral N released during a 4-week aerobic incubation of the soils (Fig. 4*b*), but was not significantly related to the amounts of mineral N that had accumulated at sowing in the soil profiles

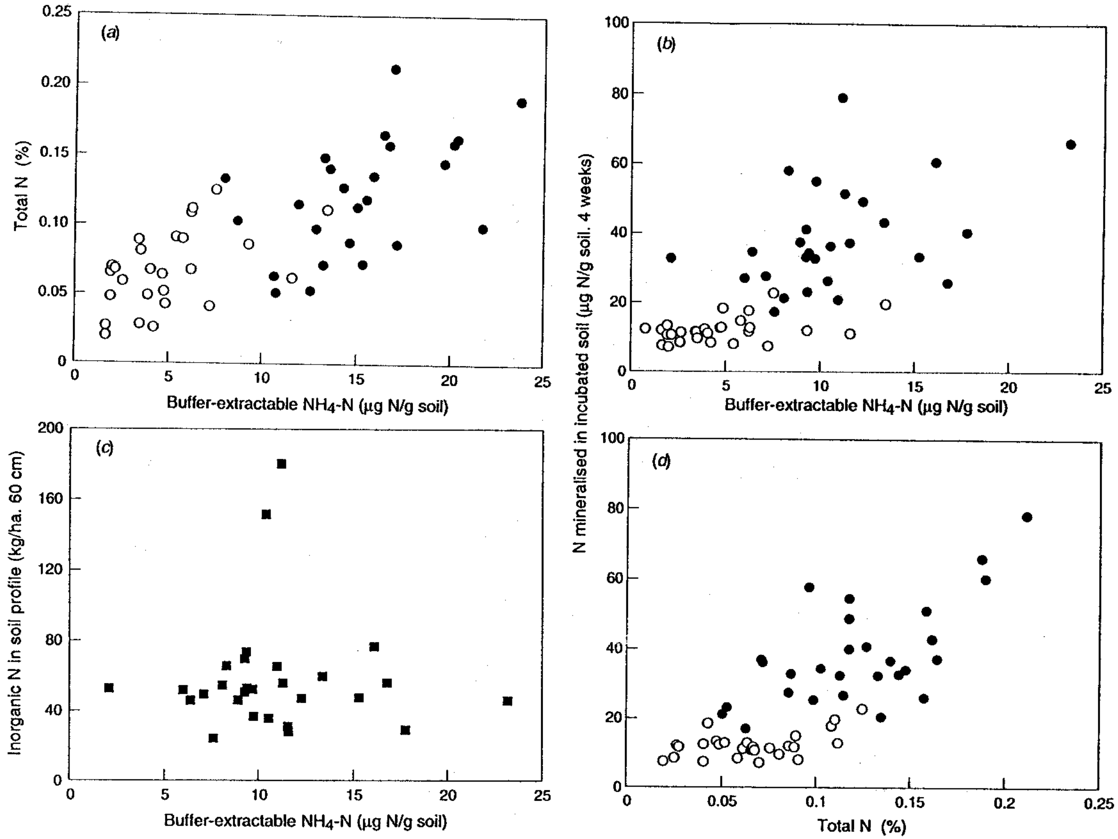

Fig. 4. Relationships between buffer-extractable ammonium-N (0–10, 10–20 cm) and (*a*) soil total N: 0–10 cm (●) $y = 0{\cdot}072 + 0{\cdot}005x$ ($P < 0{\cdot}01$), 10–20 cm (○) $y = 0{\cdot}044 + 0{\cdot}005x$ ($P < 0{\cdot}01$); and (*b*) mineral N in incubated soils: 0–10 cm (●) $y = 22{\cdot}5 + 1{\cdot}44x$ ($P < 0{\cdot}02$), 10–20 cm (○) $y = 9{\cdot}4 + 0{\cdot}55x$ ($P < 0{\cdot}02$). Relationships between (*c*) soil profile mineral N (0–60 cm depth) and buffer-extractable ammonium-N (0–10 cm), $P > 0{\cdot}05$; and (*d*) mineral N in incubated soils (0–10, 10–20 cm) and soil total N (0–10, 10–20 cm): 0–10 cm (●) $y = 10{\cdot}5 + 226{\cdot}1\ x$ ($P < 0{\cdot}001$), 10–20 cm (○) $y = 7{\cdot}44 + 68{\cdot}9x$ ($P < 0{\cdot}01$).

to 60 cm depth (Fig. 4*c*). Mineral N released during incubation of the 28 soils was directly related to soil total N (Fig. 4*d*), as reported by Xu *et al.* (1996) for the extended range of soils.

The ^{15}N atom% enrichments of mineral N in the Alfisol soil profile to 100 cm depth at sowing, of mineral N released by incubation of the soil from the 0–10 cm depth at sowing, and of plant top N harvested at flowering decreased progressively with each year of sampling. However, whereas in a given year ^{15}N enrichments of soil profile mineral N and plant N were almost identical, each was significantly higher than that of mineral N released in the incubated soil (Table 3). By contrast, the ^{15}N enrichment of the buffer-extractable N of the Alfisol, sampled at sowing to 0–10 cm depth, was relatively low and remained relatively constant and unrelated to the ^{15}N enrichment of the other pools over the field experiment.

Table 3. $10^3 \times {}^{15}N$ atom% enrichments of soil profile mineral N (SPMN), buffer-extractable ammonium-N (BEAN), N mineralised during soil incubation (NMDSI), and plant N

Standard errors of the mean are in parentheses

Soil sampling	SPMN	BEAN	NMDSI	Plant N[A]
17.vi.86	222·7	31·1	112·4	n.a.
	(10·0)	(0·7)	(3·5)	
16.vi.87	118·9	27·7	75·6	121·2
	(10·0)	(3·3)	(5·1)	(3·3)
29.vi.88	91·0	30·2	54·9	n.a.
	(3·3)	(1·3)	(4·9)	
13.vi.89	65·8	30·3	42·3	66·8
	(7·5)	(2·3)	(1·0)	(1·5)
17.vii.90	52·5	22·0	45·0	54·3
	(8·3)	(1·1)	(2·7)	(2·0)

n.a., not applicable (^{15}N enrichments of lupin crop N, grown in 1986 and 1988, were diluted due to symbiotic N fixation).

[B] Wheat crops 1987 and 1989; oat crop 1990.

Discussion

Nitrate-N represented the great majority of mineral N in soil profiles to 60 cm depth. This is not surprising since rapid nitrification occurs in most dryland farming systems (Keeney 1982; Stanford 1982). Ammonium N and total mineral N are more closely associated in the deeper soil layers than in the top soil layer. This may be attributable to the weak, or the absence of, nitrification in the deeper soil, possibly due to a combination of the lack of nitrifiers and unfavourable conditions for nitrification. Nevertheless, only 30–53% of the variation in mineral N at depths of 20–40 and 40–60 cm is explained by ammonium-N. This may be attributed to the significant leaching of nitrate-N from the surface soils to the deep soil profiles.

The distribution of nitrate-N in the 60-cm soil profiles was similar to that of total mineral N, with most (74 and 71%, respectively) present in the top 20 cm of soil, and 48% of both nitrate-N and total mineral N of the profile present in the top 10 cm of soil. The depth of soil sampling required to assess adequately the quantity of nitrate-N or mineral N available for plant uptake is obviously dependent on effective rooting depth and seasonal climatic conditions. Nonetheless, a sampling depth of 60 cm has been reported as satisfactory in most agricultural ecosystems (Strong 1981; Dalal and Mayer 1990; Xu and Elliott 1993), and in many cases, a sampling depth of 15–30 cm for assessing soil N availability is as effective as 60 cm (Stanford 1982; Xu and Elliott 1993). Our present study suggests that nitrate-N in the top 20 cm can be used to estimate the soil mineral N pool at sowing or planting. Holford and Doyle (1992) reported satisfactory predictions of N fertiliser needs (within a season) by the use of 0–15 and 0–30 cm soil tests. Relationships varied across seasons. Shallow soil tests therefore have the inherent problem that distributions of mineral N within the soils of the northern region may vary from year to year. Perhaps this is not the case for soils of the southern region where rainfall is much more reliable and seasonal.

Mineral N in the soil profiles to 60 cm depth was significantly influenced by previous land use and seasonal climatic conditions. In general, an extra 20 kg N/ha (or more) of mineral N in the soil profiles had resulted from growth in the previous year of either a grain legume crop or a pasture, compared with that of a cereal crop. The median mineral N in the 60-cm soil profile at sowing following a pasture was 75 kg N/ha, which was similar to 69 kg N/ha after a grain legume crop. The amounts of soil mineral N following pastures ranged widely, from as low as 24 kg N/ha after a poor, grass-dominated pasture on sandy soil in a low rainfall area to as high as 180 kg N/ha following a good legume-dominated pasture on a fertile soil in a high rainfall area. In most cases, the proportion of legumes in pastures at the sites tested ranged from 40 to 60%. Thus, soil mineral N after an average pasture was not significantly different from that following a grain legume crop. On average, about 47 kg N/ha of mineral N was present in the 60-cm soil profile at sowing after a cereal crop. Similar contributions to the N nutrition of cereals from previous legume-based pastures and legume crops have also been reported by Strong *et al.* (1986) and Haynes *et al.* (1993). Evans *et al.* (1991) reported an extra 30–40 kg N/ha of soil mineral N to be available for uptake by a cereal following a grain legume crop, compared with that following a cereal crop.

Whereas the N availability parameters, total N, buffer-extractable N, and N mineralised by soil incubation were significantly interrelated, none was positively related to soil mineral N accumulating in soil profiles at sowing under practical field management conditions. This is not surprising since soil profile mineral N would be expected to range widely due to the variable influences of climate and management practices on the amounts of mineral N initialised and carried over from the previous growing season, on net rates of N mineralisation from soil organic matter and plant residues, and on N losses, potentially from leaching and denitrification in late autumn prior to sowing and from ammonia volatilisation under different grazing regimes. Thus, only 26% of the variation in the amounts of mineral N in the 60-cm soil profiles at sowing was explained by a combination of previous land use, total N in the top 10 cm soil, and mineralisable N in the top 20 cm soil. Important climatic variables (rainfall and temperature), and management variables (plant residue quality and quantity, intensity of grazing and residue treatment), were not included in the regression analysis.

Studies with the Alfisol containing ^{15}N-labelled organic residues demonstrated, in a field experiment over a 5-year sampling period, not only that the ^{15}N enrichments of soil profile mineral N at sowing and of plant N at subsequent harvest were almost identical, but also that each was related to, and higher than, that of mineral N released from soil sampled at sowing and incubated. Since the ^{15}N enrichment of mineralised N decreased with time, it is to be expected that the enrichments of mineral N of soil profiles formed over 6–7 months leading up to sowing would exceed that of N released from soil sampled and incubated at the end of the period. Further, whereas the results supported a common organic N pool from which the mineral N had been released, it would appear that plant N was derived mainly from mineral N that had already been released in the soil profile by sowing; there was no evidence to suggest dilution of plant N enrichment due to uptake of N of lower enrichment released during the growth season. By contrast, the ^{15}N enrichment of the buffer-extractable N, compared with that of the other N pools, was relatively low (average, 0·029%) and close to that of soil total organic N (average for 0–10 cm depth sampled at crop flowering, 0·026%; J. N. Ladd and M. Amato, unpublished data), thus demonstrating that the buffer-extractable N was not a parameter selective for plant-available N. These results were in total accord with studies by Stockdale and Rees (1994).

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