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Soil nitrogen availability in the cereal zone of South Australia. I. Soil organic carbon, total nitrogen, and nitrogen mineralisation rates

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Abstract

Assessments of soil nitrogen (N) availability were undertaken using soils sampled at 0–10 and 10–20 cm depths from 123 experimental sites where the responses of cereal crops to N fertilisers were tested, throughout the cereal zone of South Australia. Rates of N mineralisation and percentage N mineralisation, as determined by a laboratory aerobic incubation method, were related to soil properties.

Mineralisable N (N mineralised during a 4-week incubation) of 0–10 cm soil varied from 14 to 121 kg N/ha with a median of 50 kg N/ha, and that of 10–20 cm soil, from 5 to 42 kg N/ha (median 19 kg N/ha). Mineralisable N in 0–10 cm soil accounted for 90% of total mineralisable N in 0–20 cm soil. The percentages of N mineralised were generally higher in 0–10 cm soil (0·8–12·5%, median 3·4%) than in 10–20 cm soil (0·4–8·3%, median 2·3%). Soil organic carbon (OC) and total N could be well estimated from each other, and from soil pH, bulk density, and field capacity, with coefficients of determination (R^2) ranging from 0·64 to 0·78. Overall, either mineralisable N or percentage N mineralisation rate in the surface soils could be well estimated from soil OC, total N, C to N ratio, bulk density, field capacity, and pH (R^2, 0·78–0·86 for mineralisable N, and 0·67–0·91 for percentage N mineralisation rate).

Additional keywords: mineralisable N, N mineralisation rate, organic C, soil N availability, total N.

Introduction

The availability of nitrogen (N) to cereal crops is closely related to plant biomass, grain yield, and grain N content. Both mineralisable N and percentage N mineralisation rate in surface soils, as assessed by the laboratory aerobic incubation of soils under controlled conditions (Keeney and Bremner 1966), are useful indices of soil N availability (Bremner 1965; Keeney 1982). Compared with those derived from the laboratory aerobic incubation, N mineralisation rate determined by the incubation conducted in the field may be better related to plant uptake of soil N (Sierra 1992). The assessment of soil N availability is necessary for the effective management of N fertilisers in improving crop production (Taylor *et al.* 1978; Stanford 1982; Xu and Elliott 1993).

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A stable isotope of the ^{15}N tracing technique has been used to assess mineral N released from decomposition of plant residues and soil organic matter (Stanford *et al.* 1973; Ladd *et al.* 1983, 1985; Amato *et al.* 1984, 1987; Xu *et al.* 1993*a*, 1993*b*). Since both the *in situ* incubation methods and the ^{15}N tracing technique are time-consuming and expensive for assessing soil N availability, their use in making N fertiliser recommendations in agricultural production has, in practice, been limited (Keeney 1982). Soil N availability indices that are commonly favoured are those which can be estimated with reasonable accuracy and reliability from soil chemical and physical properties. We measured mineralisable N and percentage N mineralisation rate by the laboratory aerobic incubation method, using soils sampled from 2 depths (0–10 and 10–20 cm) at each of 123 sites in the South Australian (SA) cereal zone, and estimated mineralisable N and percentage N mineralisation rate from soil pH, total N, organic carbon (OC), bulk density, and field capacity.

Materials and methods

Soil sampling

The soils were sampled from 123 field experimental sites that had been used for testing responses of cereal crops to applications of N fertilisers during the 3 cropping seasons 1990–92 in South Australia. Site locations are listed in Appendix I. A general description of major soils and climatic conditions in the SA cereal zone has been reported previously (Russell 1967). Detailed soil properties and descriptions can be obtained from the authors upon request.

Six replicate cores (each 5 cm diam., 60 cm depth) were taken from each experimental site at, or shortly before, sowing over 4–6 weeks at the beginning of each growing season, when the sites were progressively sown with wheat and/or barley. The cores were separated into 0–10, 10–20, 20–40, and 40–60 cm depths, and bulked for determination of mineral N (ammonium N and nitrate N) content of the soil profile (Part 2; Xu *et al.* 1996). Soils of 0–10 and 10–20 cm were used for soil characterisation, and the N mineralisation incubation assay as described below.

Soil N availability assay

Soil subsamples were air-dried prior to their use in the aerobic incubation assay (Keeney and Bremner 1966). Mineral N, present in moist soil at sowing and analysed before air-drying, was used as an estimate of mineral N at the beginning of the incubation. Air-dried soil (10 g) and oven-dried 30–60 mesh quartz sand (30 g), washed with deionised water, were well mixed in a 75-mL plastic container before addition of 6 mL distilled water. The container with the moistened mixture of soil and sand was tightly covered with Glad Wrap and sealed with a rubber band, and then incubated at 30°C for 4 weeks. The incubated soil–sand mixture was extracted with 50 mL of 2 M KCl solution and shaken for 1 h, and the mineral N content of the extract was determined. Mineralisable N was calculated as the difference in mineral N present in soil before and after incubation, and then converted to kg N/ha by using the soil bulk density; percentage N mineralisation rate was determined by dividing the mineralisable N by soil total N.

Soil analysis and statistical method

Soil total N (regular Kjeldahl method), OC (Walkley–Black method), and pH(1:5 H_2O) were analysed as described by Xu *et al.* (1993*b*). Soil bulk density was measured by the coring method (Xu and Elliott 1993), and soil field capacity was determined by the method of Cassel and Nielsen (1982). Soil nitrate-N and ammonium-N were analysed by colorimetric methods (Keeney and Nelson 1982). Statistical analysis and graphing were conducted with the 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 1 or more treatments), and then comparing the aggregate mean of each group with that of the others.

Table 1. Summary statistics of soil chemical and physical properties of 123 experimental sites in the cereal zone of South Australia

1, 0–10 cm; 2, 10–20 cm

Descriptive statistics	pH (1:5 H_2O) 1	Total N (%) 1	2	Organic C (%) 1	2	Bulk density (g/cm^3) 1	2	Field cap. (% H_2O) 1	2
Mean	7·7	0·117	0·066	1·23	0·65	1·37	1·37	20·7	25·8
s.d.	1·0	0·039	0·028	0·37	0·29	0·13	0·15	8·7	9·9
s.e.	0·1	0·003	0·003	0·03	0·03	0·01	0·01	0·8	0·9
CV (%)	13·0	33·2	42·6	30·5	44·7	9·24	10·7	42·0	38·4
Min.	5·0	0·031	0·013	0·38	0·20	1·10	1·02	1·9	2·6
Median	8·1	0·120	0·065	1·20	0·60	1·36	1·36	20·9	25·4
Max.	8·9	0·238	0·181	2·43	2·02	1·77	1·77	42·1	54·2

Results

Soil properties

A comparison between soils sampled at 0–10 and 10–20 cm depths of OC, total N, C to N ratio, bulk density, and field capacity respectively, is shown in Figs 1–5. Soil properties are summarised in Table 1.

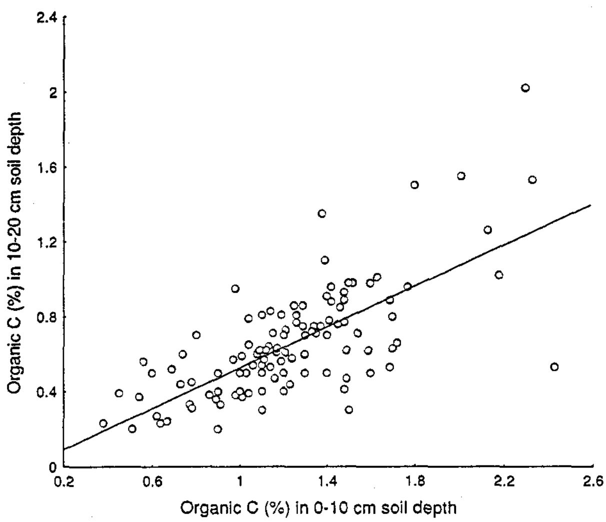

Fig. 1. Relationship between soil OC percentages in 0–10 and 10–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = -0 \cdot 02 + 0 \cdot 545x$
($R^2 = 0 \cdot 49$, $n = 123$,
$P < 0 \cdot 001$, r.s.d. $= 0 \cdot 21$)

Properties of soils at 0–10 cm depth ranged widely: pH 5·0–8·9 (median 8·1); total N% 0·031–0·238 (0·120); OC% 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). For soils at 10–20 cm depth, the range and median value were total N% 0·013–0·181 (0·065); OC% 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). There were significant relationships in the soil properties between the 2 depths, with R^2 values of 0·49 for OC (Fig. 1), 0·73 for total N (Fig. 2), 0·65 for C to N ratio (Fig. 3), 0·49 for bulk density (Fig. 4), and 0·64 for field capacity (Fig. 5).

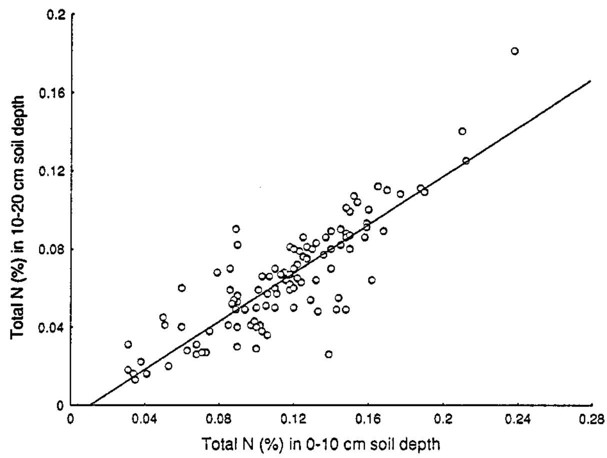

Fig. 2. Relationship between soil total N percentagtes in 0–10 and 10–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = -0 \cdot 006 + 0 \cdot 618x$
$(R^2 = 0 \cdot 73,\ n = 123,$
$P < 0 \cdot 001$, r.s.d. $= 0 \cdot 015)$

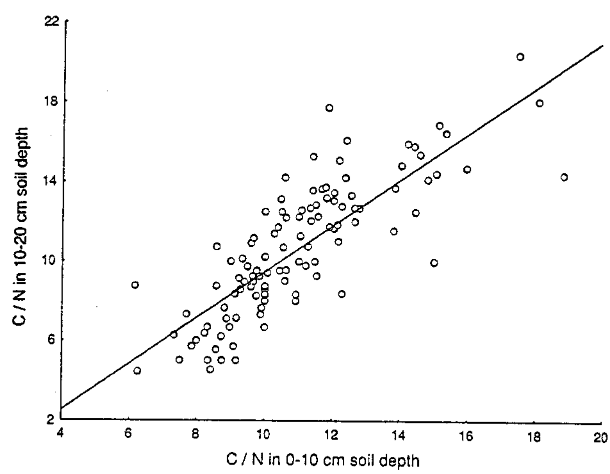

Fig. 3. Relationship between soil C to N ratios in 0–10 and 10–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = -2 \cdot 12 + 1 \cdot 16x$
$(R^2 = 0 \cdot 65, n = 123,$
$P < 0 \cdot 001$, r.s.d. $= 1 \cdot 90)$

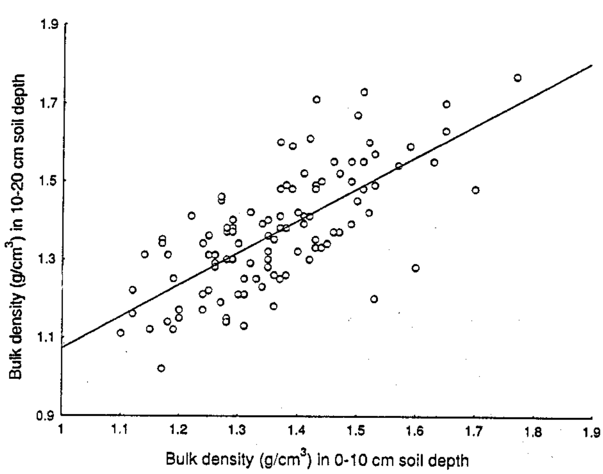

Fig. 4. Relationship between soil bulk densities in 0–10 and 10–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = -0 \cdot 26 + 0 \cdot 816x$
$(R^2 = 0 \cdot 49,\ n = 123,$
$P < 0 \cdot 001$, r.s.d. $= 0 \cdot 10)$

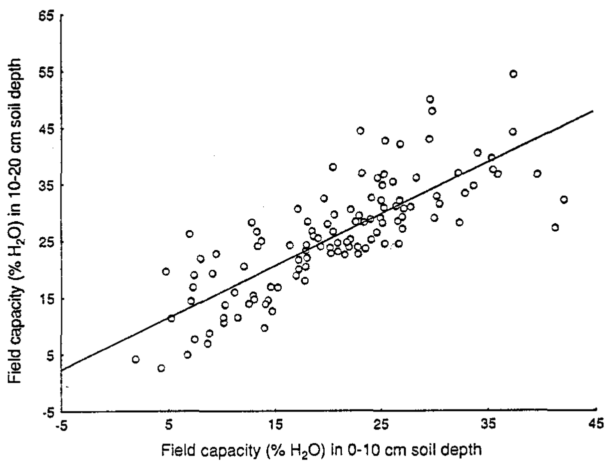

Fig. 5. Relationship between soil field capacities in 0–10 and 10–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = 6{\cdot}95 + 0{\cdot}910x$
($R^2 = 0{\cdot}64, n = 123,$
$P < 0{\cdot}001$, r.s.d. $= 5{\cdot}94$)

Relationships among soil properties

Organic C in the surface soils can be reasonably estimated from the other properties, as shown below:

$$OC_1 = 0{\cdot}322 + 8{\cdot}72(TN_1) - 0{\cdot}00541(FC_1) \quad (1)$$

$$(R^2 = 0{\cdot}69,\ n = 123,\ P < 0{\cdot}01,\ \text{r.s.d.} = 0{\cdot}211)$$

$$OC_2 = 0{\cdot}239 + 7{\cdot}08(TN_2) - 0{\cdot}332(BD_2) - 0{\cdot}00492(FC_2) + 0{\cdot}0688(pH) \quad (2)$$

$$(R^2 = 0{\cdot}64,\ n = 123,\ P < 0{\cdot}01,\ \text{r.s.d.} = 0{\cdot}177)$$

where OC_1(%), TN_1(%), and FC_1(% H_2O) are OC, total N, and field capacity in the 0–10 cm soil depth; OC_2(%), TN_2(%), BD_2(g/cm^3), and FC_2(% H_2O) are OC, total N, bulk density, and field capacity in the 10–20 cm soil depth, and pH is pH(1 : 5 H_2O) in the 0–10 cm soil depth; and r.s.d. is residual standard deviation.

Soil total N can also be well estimated from the soil OC, bulk density, field capacity, and pH:

$$TN_1 = 0{\cdot}0768 - 0{\cdot}0474(BD_1) + 0{\cdot}00124(FC_1) + 0{\cdot}0644(OC_1) \quad (3)$$

$$(R^2 = 0{\cdot}78,\ n = 123,\ P < 0{\cdot}01,\ \text{r.s.d.} = 0{\cdot}0182)$$

$$TN_2 = 0{\cdot}0331 + (9{\cdot}77 \times 10^{-4})(FC_2) + 0{\cdot}0657(OC_2) - 0{\cdot}00459(pH) \quad (4)$$

$$(R^2 = 0{\cdot}65,\ n = 123,\ P < 0{\cdot}01,\ \text{r.s.d.} = 0{\cdot}0167)$$

where BD_1 (g/cm^3) is bulk density in the 0–10 cm soil depth.

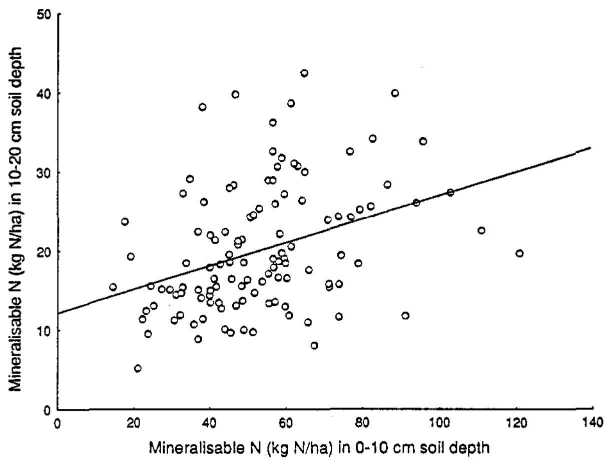

Fig. 6. Relationship between mineralisable N concentrations (mineral N released in a 4-week incubation) in 0–10 and 10–20 cm soil depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = 12{\cdot}2 + 0{\cdot}149x$
($R^2 = 0{\cdot}14$, $n = 123$,
$P < 0{\cdot}001$, r.s.d. $= 7{\cdot}2$)

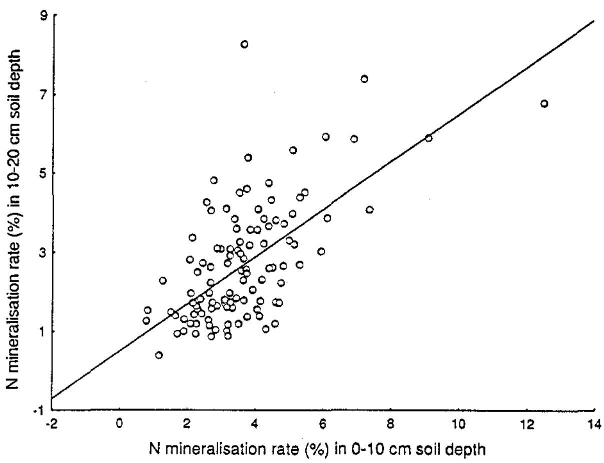

Fig. 7. Relationship between percentage N mineralisation rates in soils of 0–10 and 10–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = 0{\cdot}50 + 0{\cdot}601x$
($R^2 = 0{\cdot}40$, $n = 123$,
$P < 0{\cdot}001$, r.s.d. $= 1{\cdot}14$)

Table 2. Summary statistics of the N mineralised and N mineralisation rate as determined by the aerobic incubation of the surface soil (0–10 and 10–20 cm depths)

Descriptive statistics	Mineralisable N (kg N/ha)		N mineralisation rate (%)	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Mean	52·7	20·0	3·60	2·66
s.d.	19·3	7·8	1·56	1·48
s.e.	1·7	0·7	0·14	0·13
CV (%)	36·6	38·8	43·4	55·5
Min.	14·4	5·2	0·79	0·38
Median	49·8	18·5	3·43	2·29
Max.	120·7	42·4	12·49	8·26

Rates of N mineralisation and percentage N mineralisation

Mineralisable N and percentage N mineralisation rate in the 0–10 and 10–20 cm depths of soil from each of the 123 experimental sites are shown in Figs 6 and 7. In general, the relationship between mineralisable N concentrations in the 0–10 and 10–20 cm depths of soil ($R^2 = 0 \cdot 14$) was weaker than that between percentage N mineralisation rates in both soil depths ($R^2 = 0 \cdot 40$). As summarised in Table 2, mineralisable N in the 0–10 cm soil varied from 14 to 121 kg N/ha·4 weeks, with a median of 50 kg N/ha·4 weeks, compared with that of the 10–20 cm soil which ranged from 5 to 42 kg/ha·4 weeks (median 19 kg N/ha·4 weeks). Percentage N mineralisation rate was generally higher in the 0–10 cm soil depth [range 0·79–12·5% per 4 weeks (median 3·43% per 4 weeks)] than in the 10–20 cm soil [range 0·38–8·26% per 4 weeks (median 2·29% per 4 weeks)].

Effects of soil properties on the N mineralisation rates

Percentage N mineralisation rate in both 0–10 and 10–20 cm depths of soil increased linearly with the soil C to N ratio, and decreased with soil total N; in the 10–20 cm soil, percentage N mineralisation rate decreased linearly as soil pH increased:

$$\mathrm{RMN_1} = 0 \cdot 401(\mathrm{RCN_1}) - 6 \cdot 81(\mathrm{TN_1}) \tag{5}$$

$$(R^2 = 0 \cdot 91,\ n = 123,\ P < 0 \cdot 01,\ \text{r.s.d.} = 1 \cdot 21)$$

$$\mathrm{RMN_2} = 3 \cdot 35 - 19 \cdot 9(\mathrm{TN_2}) + 0 \cdot 243(\mathrm{RCN_2}) - 0 \cdot 253(\mathrm{pH}) \tag{6}$$

$$(R^2 = 0 \cdot 67,\ n = 123,\ P < 0 \cdot 01,\ \text{r.s.d.} = 0 \cdot 86)$$

where $\mathrm{RMN_1}$(%) and $\mathrm{RCN_1}$ are percentage N mineralisation rate and C to N ratio, respectively, in the 0–10 cm soil, and $\mathrm{RMN_2}$ (%) and $\mathrm{RCN_2}$ are the corresponding variables in the 10–20 cm soil. The R^2 value of 0·91 in Eqn 5 was calculated when the equation was not forced through the origin; the intercept was, however, dropped from the equation since the coefficient was not statistically significant.

Mineralisable N in the 0–10 cm soil can be well estimated by taking account of soil OC, total N, bulk density, C to N ratio, and percentage N mineralisation rate; 86% of the variation in mineralisable N was explained by these variables:

$$\mathrm{NPMN_1} = 79 \cdot 4(\mathrm{OC_1}) + 12 \cdot 4(\mathrm{RMN_1}) + 37 \cdot 0(\mathrm{BD_1}) - 8 \cdot 59(\mathrm{RCN_1}) - 396(\mathrm{TN_1}) \tag{7}$$

$$(R^2 = 0 \cdot 86,\ n = 123,\ P < 0 \cdot 01,\ \text{r.s.d.} = 7 \cdot 39)$$

where $\mathrm{NPMN_1}$ (kg N/ha) is mineralisable N in the 0–10 cm soil. The R^2 value of 0·86 in Eqn 7 was derived when the equation was not forced through the origin, but the intercept was dropped from the equation since the coefficient was not statistically significant. Of the variation in mineralisable N of the 10–20 cm soil, 78% was attributable to soil OC, C to N ratio, percentage N mineralisation rate, bulk density, and field capacity:

$$\begin{aligned}\mathrm{NPMN_2} = &-27 \cdot 3 + 18 \cdot 6(\mathrm{BD_2}) - 1 \cdot 25(\mathrm{RCN_2}) \\ &+ 0 \cdot 162(\mathrm{FC_2}) + 5 \cdot 66(\mathrm{RMN_2}) + 24 \cdot 2(\mathrm{OC_2})\end{aligned} \tag{8}$$

$$(R^2 = 0 \cdot 78,\ n = 123,\ P < 0 \cdot 01,\ \text{r.s.d.} = 3 \cdot 69)$$

where $NPMN_2$ (kg N/ha) was mineralisable N in the 10–20 cm soil. Overall, 90% of the mineralisable N in the top 20 cm soil ($NPMN_1$+$NPMN_2$) could be accounted for by the mineralisable N in the 0–10 cm soil ($NPMN_1$), as shown in Fig. 8.

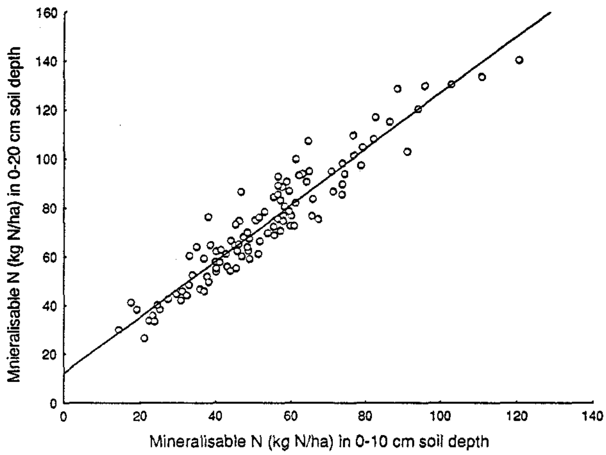

Fig. 8. Relationship between mineralisable N concentrations in 0–10 and 0–20 cm depths sampled from 123 experimental sites; the line shown is described by the regression equation
$y = 12\cdot2 + 1\cdot15x$
($R^2 = 0\cdot90$, $n = 123$,
$P < 0\cdot001$, r.s.d. = $7\cdot3$)

Discussion

Percentage N mineralisation rates determined by the aerobic incubation method of Keeney and Bremner (1966) can be estimated either from the soil C to N ratio, and total N in the case of 0–10 cm soil, or from the soil pH, C to N ratio, and total N in the case of 10–20 cm soil. A total of 91% of the variation in percentage N mineralisation rate of the 0–10 cm soil was explained by the soil C to N ratio and total N in that depth. This compared with 67% in the 10–20 cm soil explained by the soil pH in the 0–10 cm soil, C to N ratio, and total N in the 10–20 cm soil. In reviewing the soil N availability studies, Keeney (1982) indicated that results of biological tests of N availability were often closely related to soil total N, which in turn was well related to soil organic matter. This is supported by our findings from the aerobic incubation study. In general, percentage N mineralisation rate was higher in the 0–10 cm soil (median rate, 3·4%) than in the 10–20 cm soil (median rate, 2·3%), as also found by Soudi *et al.* (1990). The percentage N mineralisation rates of 0·8–12·5% (median 3·4%) in the 0–10 cm soil, and 0·4–8·3% (median 2·3%) in the 10–20 cm soil, are comparable with 1·63% (Gonzalez-Prieto *et al.* 1992) and 5–9% (Hatch *et al.* 1991) in other agricultural soils.

Mineralisable N in the 0–10 cm soil, as determined by the aerobic incubation method, increased linearly with soil OC, bulk density, and percentage N mineralisation rate, and decreased linearly with increasing soil C to N ratio and total N. Similarly, mineralisable N in the 10–20 cm soil increased with soil OC, percentage N mineralisation rate, bulk density, and field capacity, and decreased with increasing soil C to N ratio. It is commonly accepted that mineralisable N is positively related to percentage N mineralisation rate and soil OC, since OC is positively related to total N. However, it is difficult to explain why mineralisable N was further negatively related to total N and the C to N ratio in the 0–10 cm soil and to the C to N ratio in the 10–20 cm soil. It seems possible that the N mineralisation process during the aerobic incubation in this study might be more limited by the availability of C substrates, since the percentage N mineralisation rate was positively related to the C to N ratio. More research is clearly required to understand regulation mechanisms of the major factors in the N mineralisation process. The mineralisable N in the top 20 cm soil, which was an important soil variable affecting cereal grain yield and its response to N fertiliser application (Xu and Elliott 1993), can be well estimated from the mineralisable N in the top 10 cm of soil. Taylor *et al.* (1978) reported that the magnitude of the responses in wheat grain yield to application of N fertiliser was well related to the mineralisable N in the 0–10 cm soil. In reviewing soil N availability studies, Stanford (1982) indicated that an account of both available soil mineral N and mineralisable N could improve the prediction of crop growth response to N application. Xu and Elliott (1993) supported the use of both soil mineral N at sowing and mineralisable N in improving N fertiliser recommendations for cereal production in South Australia. Either percentage N mineralisation rate, or mineralisable N, is only one of the useful indices on soil N availability and will need to be considered together with other key variables in determining the N fertiliser recommendations for improving cereal production.

Conclusions

There were significant relationships among pH, OC, total N, bulk density, and field capacity in the top 20 cm depth of soils sampled from 123 experimental sites throughout the cereal zone of South Australia. Soil OC and total N in either the 0–10 or 10–20 cm depth could be well estimated from each other together with soil pH, bulk density, and field capacity. In addition, OC, total N, bulk density, and field capacity in the 0–10 cm soil were significantly related to the corresponding measurements in the 10–20 cm soil. Both percentage N mineralisation rate and mineralisable N assessed by the aerobic incubation method could be well estimated by combination of the soil OC, total N, C to N ratio, pH, bulk density, and field capacity. Most of the mineralisable N in the top 20 cm soil could be explained by the mineralisable N in the 0–10 cm soil.

Acknowledgments

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References

Amato, M., Jackson, R. B., Butler, J. H. A., and Ladd, J. N. (1984). Decomposition of plant material in Australian soils. II. Residual organic ^{14}C and ^{15}N from legume plant parts decomposing under field and laboratory conditions. *Australian Journal of Soil Research* **22**, 331–41.

Amato, M., Ladd, J. N., Ellington, A., Ford, G., Mahoney, J. E., Taylor, A. C., and Walsgott, D. (1987). Decomposition of plant material in Australian soils. IV. Decomposition *in situ* of ^{14}C- and ^{15}N-labelled legume and wheat materials in a range of southern Australian soils. *Australian Journal of Soil Research* **25**, 95–105.

Bremner, J. M. (1965). Nitrogen availability indexes. *In* 'Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties'. (Ed. C. A. Black.) Agronomy Monograph 9. pp. 1324–45. (ASA: Madison, WI.)

Cassel, D. K., and Nielsen, D. R. (1982). Field capacity and available water capacity. *In* 'Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods'. (Ed. A. Klute.) Agronomy Monograph No. 9. pp. 901–26. (ASA–SSSA: Madison, WI.)

Gomez, K. A., and Gomez, A. A. (1984). 'Statistical Procedures for Agricultural Research.' (John Wiley: Singapore.)

Gonzalez-Prieto, S. J., Villar, M. C., Carballas, M., and Carballas, T. (1992). Nitrogen mineralisation and its controlling factors in various kinds of temperate humid-zone soils. *Plant and Soil* **144**, 31–44.

Hatch, D. J., Jarvis, S. C., and Reynolds, S. E. (1991). An assessment of the contribution of net mineralisation to N cycling in grass swards using a field incubation method. *Plant and Soil* **138**, 23–32.

Keeney, D. R. (1982). Nitrogen-availability indices. *In* 'Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties'. (Eds A. L. Page, R. H. Miller, and D. R. Keeney.) Agronomy Monograph No. 9. pp. 711–33. (ASA–SSSA: Madison, WI.)

Keeney, D. R., and Bremner, J. M. (1966). Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal* **58**, 498–503.

Keeney, D. R., and Nelson, D. W. (1982). Nitrogen—inorganic forms. *In* 'Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties'. (Eds. A. L. Page, R. H. Miller, and D. R. Keeney.) Agronomy Monograph No. 9. pp. 643–98. (ASA–SSSA: Madison, WI.)

Ladd, J. N., Jackson, R. B., Amato, M., and Butler, J. H. A. (1983). Decomposition of plant material in Australian soils. I. The effect of quantity added on decomposition and on residual microbial biomass. *Australian Journal of Soil Research* **21**, 563–70.

Ladd, J. N., Amato, M., and Oades, J. M. (1985). Decomposition of plant material in Australian soils. III. Residual organic and microbial biomass C and N from isotope-labelled legume material and soil organic matter, decomposing under field conditions. *Australian Journal of Soil Research* **23**, 603–11.

Russell, J. S. (1967). Nitrogen fertiliser and wheat in a semi-arid environment. 1. Effect on yield. *Australian Journal of Experimental Agriculture and Animal Husbandry* **7**, 453–62.

Sierra, J. (1992). Relationship between mineral N content and N mineralisation rate in disturbed and undisturbed soil samples incubated under field and laboratory conditions. *Australian Journal of Soil Research* **30**, 477–92.

Soudi, B., Sbai, A., and Chiang, C. N. (1990). Nitrogen mineralisation in semi-arid soils of Morocco: Rate constant variation with depth. *Soil Science Society of America Journal* **54**, 756–61.

Stanford, G. (1982). Assessment of soil nitrogen availability. *In* 'Nitrogen in Agricultural Soils'. (Ed. F. J. Stevenson.) Agronomy Monograph 22. pp. 651–88. (ASA–CSSA–SSSA: Madison, WI.)

Stanford, G., Legg, J. O., and Smith, S. J. (1973). Soil nitrogen availability evaluations based on nitrogen mineralisation potentials of soils and uptake of labelled and unlabelled nitrogen by plants. *Plant and Soil* **39**, 113–24.

StatSoft (1994). 'STATISTICA'. (StatSoft: Tulsa.)

Taylor, A. C., Storrier, R. R., and Gilmour, A. R. (1978). Nitrogen needs of wheat. 2. Grain yield response to nitrogenous fertiliser. *Australian Journal of Experimental Agriculture and Animal Husbandry* **18**, 118–28.

Xu, Z. H., and Elliott, D. E. (1993). Effective management of N fertiliser use for wheat and barley production in a semi-arid environment. *In* 'Plant Nutrition—from Genetic Engineering to Field Practice'. (Ed. N. J. Barrow.) Developments in Plant and Soil Sciences Vol. 54, pp. 525–8. (Kluwer: The Netherlands.)

Xu, Z. H., Myers, R. J. K., Saffigna, P. G., and Chapman, A. L. (1993*a*). Nitrogen fertiliser in leucaena alley cropping. II. Residual value of nitrogen fertiliser and leucaena residues. *Fertilizer Research* **34**, 1–8.

Xu, Z. H., Saffigna, P. G., Myers, R. J. K., and Chapman, A. L. (1993*b*). Nitrogen cycling in leucaena (*Leucaena leucocephala*) alley cropping in semi-arid tropics. I. Mineralisation of nitrogen from leucaena residues. *Plant and Soil* **148**, 63–72.

Xu, Z. H., Amato, M., Ladd, J. N., and Elliott, D. E. (1996). Soil nitrogen availability in the cereal zone of South Australia. II. Buffer-extractable nitrogen, mineralisable nitrogen, and mineral nitrogen in soil profiles under different land uses. *Australian Journal of Soil Research* **34**, 949–65.

Appendix I. Locations of 123 N experimental sites in the cereal zone of South Australia

Year	Site No.	Location	Year	Site No.	Location
1990	1	Minlaton	1990	80	Cummins
1990	2	Minlaton	1991	1	Pinery
1990	3	South Kilkerran	1991	2	Brinkworth
1990	4	South Kilkerran	1991	3	Point Pearce
1990	5	Maitland	1991	4	Merriton
1990	6	Maitland	1991	5	Mallala
1990	8	Arthurton	1991	6	Minlaton
1990	9	Clinton Centre	1991	7	Maitland
1990	10	Moonta	1991	8	Spalding
1990	11	Bute	1991	9	Owen
1990	12	Alford	1991	10	Northfield
1990	13	Alford	1991	11	Lameroo
1990	14	Northfield	1991	12	Paskeville
1990	15	Northfield	1991	13	Kadina
1990	16	Freeling	1991	14	Alford
1990	17	Freeling	1991	16	Kadina
1990	18	Mallala	1991	17	Clinton Centre
1990	19	Owen	1991	18	Freeling
1990	20	Riverton	1991	19	Sandilands
1990	21	Waterloo	1991	21	Coomandook
1990	22	Saddleworth	1991	22	Coonalpyn
1990	23	Manoora	1991	23	Waterloo
1990	24	Mintaro	1991	25	Wolseley
1990	25	Hilltown	1991	27	Keith
1990	26	Spalding	1991	29	Lowen Vale
1990	27	Merriton	1991	30	Maitland
1990	28	Jamestown	1991	31	Mintaro
1990	29	Jamestown	1991	32	Georgetown
1990	30	Appila	1991	33	Clinton Centre
1990	31	Booleroo Centre	1992	1	Kadina
1990	32	Wolseley	1992	2	Clinton Centre
1990	33	Lowen Vale	1992	3	Mallala
1990	34	Keith	1992	4	Merriton
1990	35	Coonalpyn	1992	5	Manoora
1990	36	Coonalpyn	1992	6	Jamestown
1990	37	Coomandook	1992	7	Owen
1990	38	Coomandook	1992	8	Freeling
1990	39	Lameroo	1992	9	Maitland
1990	41	Pinnaroo	1992	10	Maitland
1990	42	Lameroo	1992	11	Mintaro
1990	43	Wynarka	1992	12	Maitland
1990	47	Cockaleechie	1992	13	Paskeville
1990	48	Cockaleechie	1992	14	Bute
1990	50	Cockaleechie	1992	15	Mintaro
1990	51	Tumby Bay	1992	16	Alford
1990	52	Tumby Bay	1992	17	Clinton Centre
1990	53	Yeelanna	1992	18	Lock
1990	54	Ungarra	1992	19	Cummins
1990	55	Tooligie Hill	1992	20	Sandilands
1990	56	Lock	1992	21	Coomandook
1990	57	Kimba	1992	22	Spalding
1990	59	Mangalo	1992	23	Ungarra
1990	61	Wanilla	1992	24	Cummins
1990	63	Wharminda	1992	25	Waterloo
1990	64	Kapinnie	1992	26	Jamestown
1990	66	Minnipa	1992	27	Saddleworth
1990	68	Ungarra	1992	28	Mintaro
1990	72	Elliston	1992	29	Waterloo
1990	73	Warramboo	1992	30	Kapinnie
1990	75	Cummins	1992	31	Northfield
1990	77	Tuckey	1992	32	Northfield
1990	79	Tooligie Hill			

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