DIVISION S-4—SOIL FERTILITY & PLANT NUTRITION

Evaluating Chemical and Physical Indices of Nitrogen Mineralization Capacity with an Unequivocal Reference

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ABSTRACT

After decades of searching for a rapid method to estimate the N mineralization capacity of soil, there is still no consistent recommendation. It is legitimate to examine the causes for the often-conflicting results in literature. The efficacy of various references that have been used as benchmarks for assessing chemical and physical indices in the literature is critically reviewed in this paper. Gross N mineralization and consumption during waterlogged and aerobic incubations were estimated in a wide range of soils. It was found that equivalent to 17 to 90 and 23 to 59% of the mineralized N was consumed during the waterlogged and aerobic incubations, respectively. As net N production rate represents the balance between N-producing and N-consuming processes, it appears difficult to find a simple method that could be used to predict the net effect of several concurrent processes. We used the gross N mineralization as a reference criterion for N mineralization ability. Total organic N, water-soluble organic N, alkali-hydrolyzable N, acid-hydrolyzable N, hot salt-hydrolyzable N and N in the light organic matter fraction were assessed against this reference criterion. All indices except light fraction N were significantly related to gross N mineralization. Water-soluble organic N had the highest correlation of all the indices tested. None of the chemically hydrolyzed N fractions consistently showed closer relationships with N mineralization than total organic N, suggesting that these chemical methods are ineffective in extracting a biologically labile fraction of soil organic N.

Accurate prediction of the amount of inorganic N released from soil organic matter is essential for the development of farming practices that maximize N use efficiency and minimize adverse impacts of N on the environment. It is thought that an appreciable portion of soil organic matter is chemically and/or physically stabilized and resistant to microbial degradation, whereas a part of the organic N is more labile and plays a prominent role as a source of substrate for N mineralization (Stanford and Smith, 1972; Parton et al., 1987; Jenkinson et al., 1987). To develop a method that accurately estimates the size of the labile organic N pool has been a goal of scientists in decades past, and a number of chemical and physical methods have been proposed (Bremner, 1965; Keeney, 1982). Unfortunately, none of these methods has been consistently successful (Dahnke and Vasey, 1973; Keeney, 1982). The dispute over these methods has led to claims that chemical methods are likely to be unable to selectively extract the fraction of biologically labile soil organic N (Bundy and Meisinger, 1994).

Though the concept of a mineralizable N pool has been defined for decades, there is no direct and absolute measure of such a pool to be used for assessment of chemical or physical methods. Stanford and Smith (1972) proposed a long-term (30-wk) incubation method to measure the "potentially mineralizable N, N_0". However, the concept of N_0 and its determination procedures have been questioned (Smith et al., 1980; Cabrera and Kissel, 1988). Thus, the validity of each chemical or physical method has to be inferred from its correlation with a biological "reference" criterion that is supposed to reflect the relative N mineralization capacity of soil (Keeney, 1982). The accuracy of the reference directly affects the conclusions drawn from the correlation studies. Nevertheless, little attention has been paid to the reliability of the references used by different authors in their evaluation studies.

Commonly used references include the amount of mineral N accumulated during a period of aerobic or waterlogged incubation, potentially mineralizable N calculated from long-term incubation, or N uptake by plants grown in greenhouse or field experiments (Keeney, 1982). All of these indices estimate the net rate of mineral N production; no correction is made for mineral N consumption by immobilization reactions, gaseous N losses, clay fixation, or leaching. Consequently, these approaches may seriously underestimate soil N mineralization capacity because mineral N consumption occurs simultaneously with mineralization.

Furthermore, N uptake by plants in greenhouse or field experiments does not discriminate between mineral N initially present in soil and N produced from the decomposition of organic matter during the plant growing season. Under field conditions, crops may take up significant, yet various amounts of mineral N from deep soil layers (Bundy and Meisinger, 1994), while N availability indices are usually tested using the surface soil where organic matter is high. Hence assessing readily mineralizable N indices by correlating against crop N uptake may lead to incorrect conclusions.

Soil moisture and temperature also affect the mineralization rate of organic matter (Cassman and Munns, 1980; Goncalves and Carlyle, 1994). Under field conditions, the amount of N taken up by plants is the net effect of many environmental factors that affect organic N release and plant growth. Therefore, N uptake by plants may not uniquely reflect the size and quality of

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the labile organic N pool. It is impractical to expect a single chemical method to cover the effects of environmental conditions. The effect of other soil or environmental factors on N mineralization should be considered and calibrated separately.

Controversy over the chemical methods may also have derived from data analysis that inappropriately correlates the references against chemical methods. For example, potentially mineralizable N or the amount of N produced from organic N mineralization in a period has been correlated against N availability indices that include initial mineral N present in the soil (e.g., Serna and Pomares, 1992; Jalil et al., 1996). This practice could not be rationalized unless all the soils had been under similar climatic conditions and management practices, collected at the same time and processed with similar procedures, and therefore the initial mineral N in soil could reflect the relative N mineralization capacity of soils. On the other hand, crop N uptake from soils that contained variable amounts of initial (NH_4 + NO_3)-N has been correlated against the amount of hydrolyzed organic N by chemical methods (e.g., Cornforth and Walmsley, 1971; Hong et al., 1990; Serna and Pomares, 1992; McTaggart and Smith, 1993). In such cases, the correlation between plant N uptake and the chemically extractable organic N may be confounded by the amount of mineral N present in soil unless the amount of mineral N was proportional to the amount of chemically extracted organic N. Removal of the confounding effect of mineral N is required in order to improve the results of evaluation (Chalk and Waring, 1970).

Therefore, an index that unequivocally reflects the rate of N release from organic matter and whose magnitude is not affected by other processes that input or remove available mineral N should provide an accurate reference to evaluate the chemical methods of measuring readily mineralizable organic N. The gross amount of N mineralization (total release of NH_4 from organic matter through microbial activities) should meet these requirements better than any indices used to date. In this paper, we evaluate the suitability of total organic N, water-soluble organic N, alkali-hydrolyzable N, acid-hydrolyzable N, hot salt-hydrolyzable N, and light fraction N as indices of the biologically labile organic N pool, using the gross amount of N mineralized during aerobic and waterlogged incubations under constant temperature as a reference criterion.

MATERIALS AND METHODS

Nineteen soils were taken from three eastern states and the Capital territory of Australia to provide a wide range in total organic C content, C/N ratio, pH, and texture. Properties of each soil are given in Table 1. The soils were air-dried and ground to pass a 2-mm sieve and stored in sealed plastic drums until used.

Gross N mineralization and consumption were determined in both aerobic and waterlogged incubations. In the aerobic incubation, 5 g of soil were mixed with 15 g of quartz sand, moistened with 3 mL of $^{15}NH_4Cl$ solution (23.4 μg N; 98.63 atom % ^{15}N excess), and incubated at 30°C in plastic jars covered with Parafilm. The jars were flushed with air every other day and replenished with water to maintain at constant moisture content.

In the waterlogged incubation, 5 g of soil were added to a 30-mL polythene tube that contained 12.5 mL of $^{15}NH_4Cl$ solution (23.4 μg N with 98.63 atom % ^{15}N excess). The tubes were swirled for a few seconds, then sealed tightly with a stopper and placed in an incubator maintained at 30°C.

After 2 wk, aerobic samples were added with 22 mL of 2.3 *M* KCl, while waterlogged samples with 12.5 mL 4 *M* KCl, and extracted by shaking for 1 h. The soil suspensions were centrifuged, and the supernatant filtered through prewashed filter papers. Mineral N in the KCl extracts was analyzed by steam distillation. Isotope ratio analyses were performed using a magnetic-deflection mass spectrometer (Sira 10, VG Isogas, Middlewich, UK).

Total and ^{15}N-labeled NH_4 and mineral N in soil at the beginning of the experiment were determined by extracting

Table 1. Properties of soils used for incubations.

Soil	Location†	Great Soil Group		Clay	Silt	Organic C	pH¶	C/N
		Australian‡	U.S.§	g kg^{-1}				
1	Coreinbob, NSW	Solodic	Natrixeralf	50	500	15	5.0	12
2	Gombalin, NSW	Red Earth	Palexeralf	130	500	11	5.1	11
3	Gombalin, NSW	Red Earth	Palexeralf	130	300	11	5.5	13
4	Gombalin, NSW	Red Earth	Palexeralf	130	510	19	5.5	12
5	Waurn Ponds, Vic	Rendzina	Xeroll	420	580	61	7.8	10
6	Norillee, Qld	Black Earth	Haplustert	760	150	16	8.6	15
7	Mywybilla, Qld	Black Earth	Haplustert	720	130	12	7.3	17
8	Derrimut, Vic	Red Brown Earth	Rhodoxeralf	410	180	26	5.3	10
9	Bacchus Marsh, Vic	Alluvial	Xerofluvent	290	500	35	5.9	12
10	Drysdale, Vic	Black Earth	Haploxerert	450	230	77	5.6	14
11	Tarwin, Vic	Alluvial	Xerofluvent	80	30	50	5.5	12
12	Narrabri, NSW	Grey Clay	Haplustert	360	80	11	8.0	11
13	Walpeup, Vic	Solonised Brown	Palexeralf	30	20	7	7.9	12
14	Waurn Ponds, Vic	Terra Rossa	Haploxerept	420	190	37	7.7	11
15	Waurn Ponds, Vic	Rendzina	Xeroll	410	200	51	8.0	10
16	Gombalin, NSW	Red Earth	Palexeralf	140	500	14	5.4	12
17	Creswick, Vic	Krasnozem	Palexerult	350	630	49	5.5	15
18	Gombalin, NSW	Red Earth	Palexeralf	120	500	27	5.7	13
19	Coreinbob, NSW	Solodic	Natrixeralf	60	500	14	5.0	13

† NSW, New South Wales; Vic, Victoria; Qld, Queensland; ACT, Australian Capital Territory.
‡ Stace et al. (1968).
§ Soil Survey Staff (1999).
¶ pH in 1:5 soil/water suspension.

the soils 0.5 h after the addition of labeled NH_4 using the same procedures described above.

Gross amount of N mineralization (m) and consumption (i) during the incubations was calculated with the following equations (Shen et al., 1984):

$$m = (AT_2 - AT_1) + (AL_1 - AL_2)(AT_a/AL_a) \quad [1]$$

In the waterlogged incubation,

$$i = (AL_1 - AL_2)(AT_a/AL_a) \quad [2]$$

In the aerobic incubation,

$$i = (AL_1 - AL_2)(AT_a/AL_a) - (NT_2 - NT_1) \quad [3]$$

where AL represents labeled NH_4–N; AT refers to total NH_4–N; and NT stands for total (NO_2 + NO_3)-N. Subscripts 1, 2, and a denote the initial, the final, and the arithmetic mean N concentrations of a pool, respectively.

Indices of readily mineralizable organic N in soil were determined prior to incubation treatments and expressed on an over-dry basis.

Water-dissolved organic N was extracted according to the method described by Burford and Bremner (1975). In this method, 15 g of soil and 30 mL of deionized water were added to a 50-mL centrifuge tube and shaken for 15 min. The soil suspension was then centrifuged at 2500 *g* for 10 min. The supernatant was decanted into another centrifuge tube and centrifuged at 12 000 *g* for a further 10 min. The supernatant from the second centrifugation was vacuum filtered through a 0.45-μm Millipore membrane (Millipore, Bedford, MA).

Total N in the extracts was measured using the method given by Cabrera and Beare (1993). Ten milliliters of extract was digested with 10 mL of oxidizing reagent (50 g of low-N $K_2S_2O_8$ and 30 g of H_3BO_4 in 1 L of 0.375 *M* NaOH) in a tightly sealed culture tube at 120°C for 30 min with an autoclave. Nitrate N content in the digested solution was determined colorimetrically with an Alpkem continuous flow automatic analyzer (O.I. Corp., College Station, TX). Soluble organic N was calculated by difference in mineral N between the digested and undigested water extract.

Total organic C and N in soil were determined by dry combustion using a LECO CNS-2000 analyzer (LECO Corp., St. Joseph, MI). Calcareous soils were pretreated with H_3PO_4 to remove carbonate (Jalil et al., 1996; Curtin and Wen, 1999). Total organic N was the difference between total N and the mineral N extracted with 2 *M* KCl at room temperature.

Separation of the light fraction of soil organic matter was based on the procedures described by Janzen (1987) and Skjemstad et al. (1990). In the procedure used, 10 g of soil were placed in a 50-mL plastic centrifuge tube and floated with 40 mL of $ZnBr_2$ (1.6 g cm^{-3} specific gravity) by agitating vigorously with a vortex homogenizer for 1 min. The soil suspension was centrifuged at 5600 *g* for 10 min, gently swirled to wash down the clay particles adhered on the tube wall, and then centrifuged for a further 20 min. The supernatant with floated particles was decanted onto a 0.45-μm Millipore membrane under suction. The remaining soil was floated again with the same procedure to ensure complete recovery of the light fraction. The light fraction on the filter membrane was rinsed with deionized water, dried at 70°C, weighed, and ground. The C and N contents in the light fraction was determined with an automated CN analyzer (Europa 20-20, PDZ Europa Ltd, Middlewich, UK).

Hot KCl-hydrolyzable N was determined with the method proposed by Gianello and Bremner (1986a). About 7.5 g of soil were heated in 50 mL of 2 *M* KCl in a sealed digestion tube at 100°C on a block digester. After 4 h, the tubes were removed from the digester and cooled to room temperature. The soil suspension was mixed for 1 min with a Vortex homogenizer and then filtered through Whatman no. 42 filter paper. Ammonium-N in the filtrate was determined colorimetrically by the Alpkem automatic analyzer. The KCl-hydrolyzable N was calculated by subtracting the quantity of NH_4–N extracted with 2 *M* KCl at room temperature from the amount in the heated extract.

Hydrochloric acid-hydrolyzable organic N was analyzed by modifying the method given by Xu et al. (1997). Ten grams of soil was weighed into a 70-mL digestion tube and 50 mL of 1 *M* HCl added. After swirling the mixture, the tube was weighed, covered with a small funnel, and heated on a block digester at 100°C. After 4 h, the tube was allowed to cool to room temperature and water added by weight to replenish loss during digestion. The soil suspension was mixed thoroughly and filtered through Whatman no. 42 filter paper. A 20-mL aliquot of the filtrate was pipetted into a 50-mL beaker, neutralized to pH 6.5 with 2 *M* NaOH, and transferred quantitatively to a 100-mL volumetric flask and diluted with deionized water. The NH_4–N was then analyzed with the Alpkem automatic analyzer. The HCl-hydrolyzable N was obtained by subtracting the initial NH_4–N from the total amount of NH_4–N after hydrolysis.

Analysis of NaOH-hydrolyzable organic N was performed using the method described by Wang and Li (1991). A 200-mL wide-mouth plastic container with 4 g of soil and a 50-mL plastic beaker with 10 mL of 2% H_3BO_3–indicator solution were placed in a 1-L glass jar. Then 10 mL of 1 *M* NaOH were added to the container with soil and the glass jar was immediately closed with a lid fitted with a rubber gasket. The jar was placed in an incubator maintained at 40°C for 24 h. The amount of NH_4–N released was determined by titration of the H_3BO_3–indicator solution with standard 0.0025 *M* H_2SO_4. The NaOH-hydrolyzable N was the difference in the amount of NH_4–N before and after NaOH treatment.

Statistical analyses of data were performed using the regression analysis procedures of Genstat 5, Release 4.1 (Payne, 1997). The correlation between two variables was tested at significance levels of $P < 0.05$ and $P < 0.01$.

RESULTS AND DISCUSSION

Gross Amount of Nitrogen Mineralization and Consumption

During the 2 wk of waterlogged incubation, 41 to 231 mg N kg^{-1} soil were mineralized (Fig. 1) for all 19 soils. At the same time, 14 to 64 mg kg^{-1} of NH_4–N were consumed by immobilization and other processes. The amount of NH_4–N consumption in different soils accounted for 17 to 90% of the gross amount of N mineralized.

Gross N mineralization and consumption under aero-

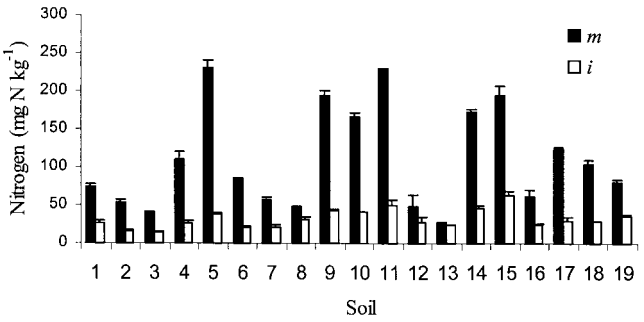

Fig. 1. Gross amount of N mineralized (m) and consumed (i) from 19 Australian soils during waterlogged incubation for 2 wk at 30°C. Vertical bars represent standard errors of three replicates.

bic conditions could not be calculated for 7 of the 19 soils because the labeled NH_4 and total NH_4 pools had been nearly emptied by nitrification by the end of the aerobic incubation. If large amount of labeled NH_4 had been added, it would have overcome this problem, but might have caused other complications in the rates of N mineralization and consumption. Of the remaining 12 soils, gross N mineralization ranged from 33 to 256 mg kg^{-1} (Fig. 2). Gross mineral N consumption varied from 8 to 67 mg kg^{-1}. The amount of mineral N consumed was equivalent to 23 to 59% of the gross amount of N mineralized in the aerobic incubation.

Net amount of N production provides a direct and sensible index for N-supplying ability of soil to crops, and research efforts to identify a simple method to predict net N production of soil have lasted for decades (Keeney, 1982). As the net rate represents a balance between the quantity of N mineralized and the amount of N consumed, it may be unlikely to find a single chemical or physical method that could predict the convergence of the combined effects of a few concurrent processes that are regulated by different mechanisms and affected by edaphic factors (e.g., C/N) in different ways. However, it may be likely to estimate the mineralizability of organic matter with a chemical approach, as the biological decomposability of soil organic matter should be a function of its chemical composition. Gross N mineralization unequivocally measures the mineralizability of the organic N pool, while net N production may possibly be negative, zero, or little even though the simultaneous processes of mineralization and immobilization are going on vigorously (Tusneem and Patrick, 1971). Gross mineralization should, therefore, be a better reference than net N production for evaluating chemical or physical indices of readily mineralizable organic N.

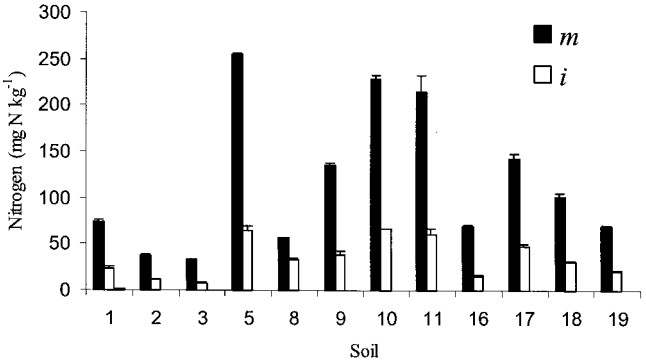

Fig. 2. Gross amount of N mineralized (*m*) and consumed (*i*) from 12 Australian soils during aerobic incubation for 2 wk at 30°C. Vertical bars represent standard errors of three replicates.

Relationships between the Chemical or Physical Indices and the References

With the exception of light fraction N, all indices of N mineralization capacity were significantly correlated with the gross amount of N mineralization during both waterlogged and aerobic incubations (Fig. 3: $r^2_{0.01} = 0.33$; and Fig. 4: $r^2_{0.01} = 0.50$). The relationships were generally weaker under waterlogged than under aerobic conditions. This was probably because waterlogging altered the edaphic environment for microbes and their substrate supply. However, the ranking of these indices in terms of their correlations with the references was consistent in waterlogged and aerobic incubations.

Total Organic Nitrogen

The total organic N of the 19 soils used in the waterlogged incubation ranged from 570 to 6100 mg kg^{-1}. For the 12 soils used in the aerobic incubation, it ranged from 850 to 6100 mg kg^{-1}. Total organic N explained

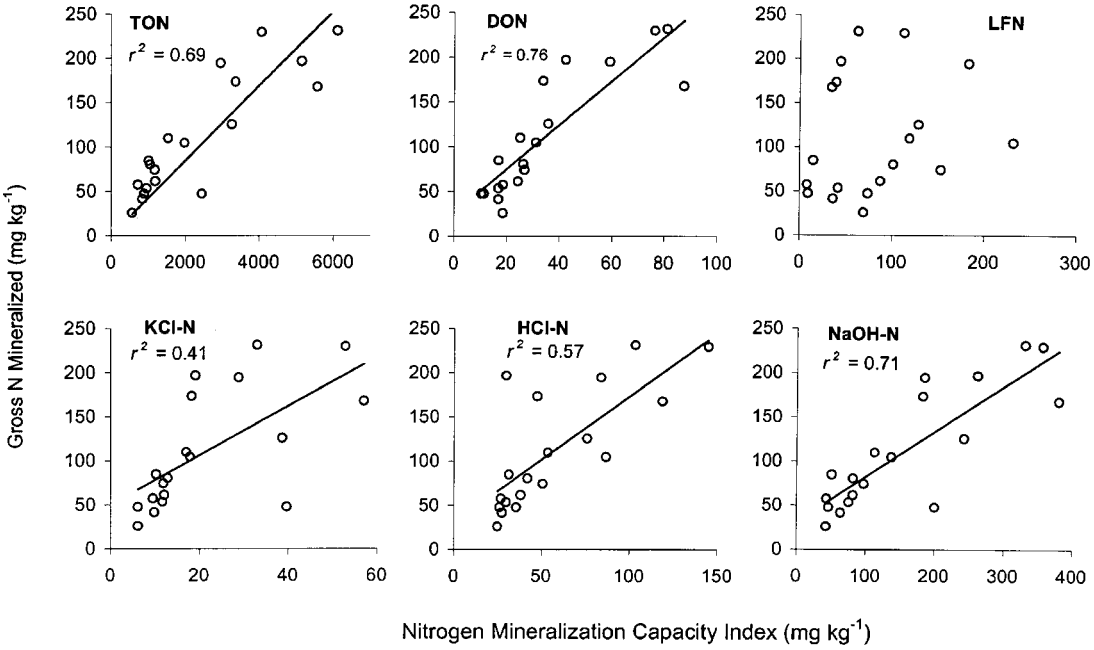

Fig. 3. Relationships between gross amount of N mineralization during waterlogged incubation for 2 wk at 30°C and indices of readily mineralizable organic N. TON: total organic N; DON: water-soluble organic N; LFN: light fraction N ($r^2 = 0.04$, $P > 0.05$); KCL-N: KCl-hydrolyzable N; HCl-N: HCl-hydrolyzable N; and NaOH-N: NaOH-hydrolyzable N. $r^2_{0.01} = 0.33$ for the relationship of all measurements with gross N mineralized.

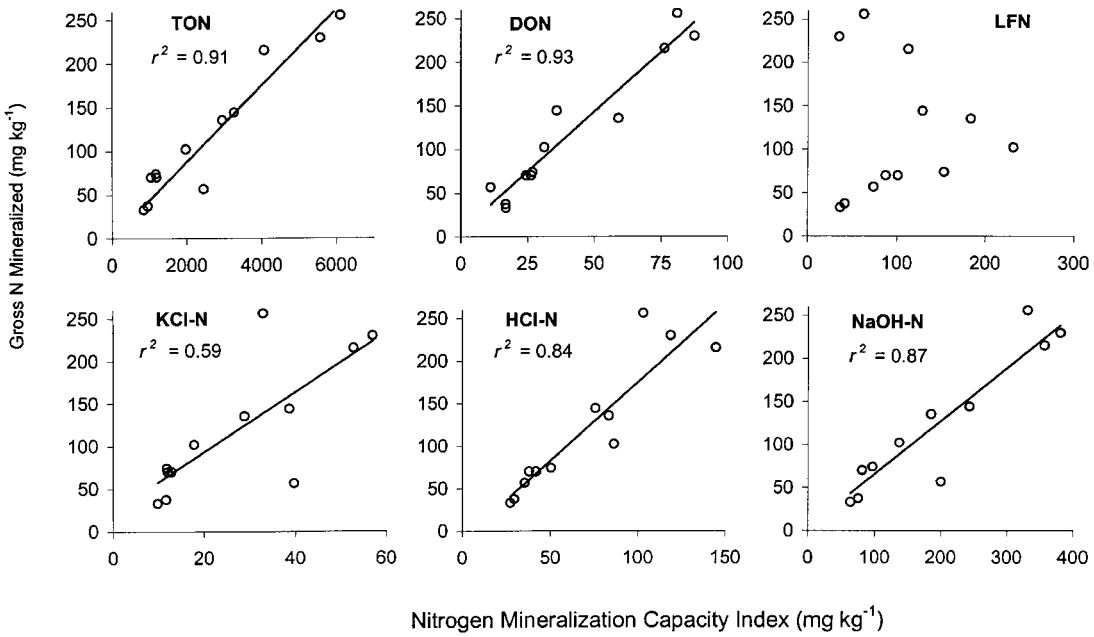

Fig. 4. Relationships between gross amount of N mineralization during aerobic incubation for 2 wk at 30°C and indices of readily mineralizable organic N. TON: total organic N; DON: water-soluble organic N; LFN: light fraction N (r^2 = 0.0007, $P > 0.05$); KCl-N: KCl-hydrolyzable N; HCl-N: HCl-hydrolyzable N; and NaOH-N: NaOH-hydrolyzable N. $r^2_{0.01}$ = 0.50 for the relationship of all measurements with gross N mineralized.

69 and 91% of the variations in the gross amount of N mineralized from different soils during waterlogged and aerobic incubations, respectively (Fig. 3 and 4).

During the 2-wk period of incubation, 1.9 to 8.4 and 2.3 to 6.7% of total organic N was mineralized under waterlogged and aerobic conditions, respectively. The variations between the individual soils suggested significant differences in soil organic matter quality and/or possibly in other edaphic factors that might limit the rate of N decomposition. Hence only an approximate prediction of N mineralization can be obtained from knowledge of total organic N as a single index. Furthermore, its close correlation with N mineralization did not necessarily mean that the entire organic N in soil was mineralizable. Rather, it should be understood that the ability for a soil to supply substrate for mineralization was proportional to its total organic N content.

It has frequently been found that total N (sometimes including a part or all mineral N) is closely related to other N availability indices such as chemical tests, net N mineralized during incubation, or crop N uptake in greenhouse experiments (Chalk and Waring, 1970; Keeney, 1982; Sollins et al., 1984; Serna and Pomares, 1992). However, Curtin and Wen (1999) reported a poor relationship between total N and potentially mineralizable N obtained by periodically leaching the soils in a 24-wk aerobic incubation, where considerable amount of soluble organic N could have been removed from soil by leaching. Fox and Piekielek (1984) and Hong et al. (1990) reported that total N, which was determined by routine Kjeldahl digestion and did not always adequately recover the variable amount of NO_3–N, was poorly correlated with field-measured N-supplying capacity that was estimated by subtracting a universal percentage (75%) of the fertilizer N from the total plant N uptake (Hong et al., 1990). The relationship between total N and N-supplying capacity in these field studies could have been confounded by the variation in the amounts of profile NO_3 and fertilizer use efficiencies among different sites. It would be advisable to include all mineral N in total N content when correlating against reference criteria, such as plant uptake, that are affected by initial mineral N level. However, if the reference criteria, such as potentially mineralizable N, measure only N released from organic matter, total organic N (excluding mineral N) should be used.

In spite of the good correlation between total organic N and N mineralization obtained in this study (Fig. 3 and 4), we would not recommend total N (including mineral N) as a single index of N-supplying ability in a wide range of field conditions for two reasons. First, there is often a substantial amount of mineral N in the soil profile. The size of this mineral N pool significantly affects the amount of N uptake by plants (Bundy and Meisinger, 1994). Total N is usually tens or hundreds of times higher than the amount of mineral N and therefore may obscure the size of this immediately available N pool. Second, the N supplying ability of a soil is a function of many factors such as moisture, temperature, and N immobilization and loss. Trying to use a single index to predict available N supply under differing field conditions would oversimplify the N transformation and cycling in soil.

Water-Soluble Organic Nitrogen

The size of this N pool was much smaller than total organic N and ranged from 10 to 87 mg kg^{-1} for all 19 soils under waterlogged incubation and 11 to 87 mg kg^{-1} for the 12 aerobically incubated soils. Water-soluble organic N represented 0.5 to 3.3% of total organic N

for the 19 soils incubated under waterlogged conditions and 0.5 to 2.5% for the 12 soils incubated under aerobic conditions. Correlation coefficients between this index and N mineralization were slightly higher than that for total organic N (Fig. 3 and 4).

More research has been reported on soluble organic C than on soluble organic N. Many studies showed that soluble organic C is a very labile component of soil organic matter and serves as a key driver of microbial activity (Burford and Bremner, 1975; Davidson et al., 1987; Qualls and Haines, 1992; DeLuca and Keeney, 1993).

Water-soluble organic N contents in the soils before incubation were only 20 to 72 and 20 to 51% of the N mineralized during the 2 wk of waterlogged and aerobic incubations, respectively. Similar results were also found for soluble organic C (Burford and Bremner, 1975; Davidson et al., 1987). Some studies have shown that not all soluble organic matter is equally susceptible to biological decay (Boissier and Fontvieille, 1993; Boyer and Groffman, 1996; Jandl and Sollins, 1997). The significant, but not very high, correlation ($r^2 = 0.76$, $n = 19$) between this organic N pool and the gross amount of N mineralization for the waterlogged incubation gave an indirect indication of the variability in the quality of soluble organic N in different soils. If we accept that the water-soluble fraction is the immediate substrate for soil microorganisms (McGill et al., 1986; Curtin and Wen, 1999), the low percentage of mineralized N that it accounted for would imply that the biologically available pool was small at a given time, but it must have been replenished as it was consumed. Therefore, the dissolved organic N was not actually a direct measure of the size of the potentially mineralizable N pool, but was rather an indicator of the soil's capacity to supply substrate for mineralization.

It should be noted, however, that the soils used in this study were air-dried samples. The soluble organic C concentration after air-drying could increase by 2 to 10 times (Davidson et al., 1987) and has been shown to be highly correlated with microbial biomass C prior to drying (Christ and David, 1994). Therefore the dissolved organic fraction of air-dried soils might contain a substantial portion of killed soil biomass, which could result in better correlation with N mineralization rates.

Light Fraction Nitrogen

This part of organic N represented 0.6 to 13% of total organic N for both the 19 waterlogged and the 12 aerobically incubated soils, with values ranging from 8 to 231 mg kg^{-1} for the 19 soils, and 34 to 231 mg kg^{-1} for the 12 soils (on the basis of the whole soil). The C/N ratios for the light fraction were 13 to 38 for the 19 soils and 16 to 26 for the 12 soils, much higher than those of the total soil organic matter. There was no significant relationship between light fraction N and the amount of N mineralized during the 2-wk incubations (Fig. 3 and 4).

The role of light fraction N in terms of its contribution to N mineralization of the whole soil is in dispute. The rate of N loss from this fraction was reported to be much quicker than from heavy fraction N (the difference between total organic N and light fraction N) during laboratory incubation of two cultivated soils (Ford and Greenland, 1968) or upon cultivation of six virgin soils (Dalal and Mayer, 1987). Moreover, light fraction N was found to be closely related to the net amount of N production in soils of different crop rotations during an intermittently leached incubation (Janzen, 1987). In another leached incubation with cultivated soils, Curtin and Wen (1999) found that light fraction N was closely related with potentially mineralizable N calculated after 24 wk of incubation, but was not related to the net amount of N mineralized in the early stage of incubation.

Contrary to the above findings, results from one agricultural and two forest soils presented by Boone (1994) and a calculation from the data of six forest soils reported by Sollins et al. (1984) showed that light fraction N accounted for only a small part of total organic N, and that the net N production rate from this N pool (as mg N kg^{-1} light fraction N) was much lower than from heavy fraction N (as mg N kg^{-1} heavy fraction N). As a combined effect of its small percentage in total organic N and its slow rate of mineralization, light fraction N contributed only slightly to net N production of the whole soils. In another study with pine forest soil (Theodorou, 1990), light fraction N consisted of 57% of the total soil organic N, but contributed only 32% of the total amount of N accumulated in an aerobic incubation, also suggesting a slower mineralization rate from light fraction N than from heavy fraction N.

It has been suggested that the high C/N ratio of light fraction organic matter may result in immobilization of mineralized N (Sollins et al., 1984; Janzen et al., 1992), which may lead to weaker and inconsistent correlations between light fraction N and the net amount of N production (Janzen et al., 1992). Few investigations have examined the relationship between this N pool and the gross rate of N mineralization. In a 9-wk laboratory incubation study with two grassland soils from England, Monaghan and Barraclough (1995) found that macroorganic matter (>0.2 mm, $d < 1.0$ g cm^{-3}) added in amounts equivalent to 5.2 and 5.4% of the total soil N accounted for 15 and 45% of the gross N mineralized from the whole soil, suggesting faster mineralization rates of the light fraction N than heavy fraction N. However, when corrected to its natural contents in these soils, light fraction N contributed only 4.5 and 12% of the gross N mineralization for the whole soils. Our results extended their findings by using more soils that have a wider range of properties. The poor correlation between this N pool and the gross amount of N mineralization of the soils (Fig. 3 and 4) indicated that light fraction N cannot generally represents the N mineralization capacity of whole soils.

Hot Potassium Chloride-Hydrolyzable Nitrogen

The organic N extracted by hot KCl ranged from 6.2 to 57.0 mg kg^{-1} for the 19 soils, and 9.8 to 57.0 mg kg^{-1} for the 12 soils. Although the relationships between this part of organic N and N mineralization rate were

significant, the correlations ($r^2 = 0.41$ and 0.59 for waterlogged and aerobic incubations, respectively) were weak (Fig. 3 and 4).

Hot KCl-hydrolyzable N was initially tested by being correlated against the net amount of N released during 1-, 2-, or 12-wk waterlogged or aerobic incubations (Gianello and Bremner, 1986a, 1986b). Consistently strong correlations were obtained between this index and the references. However, their result has rarely been confirmed in later studies by other researchers. In three pot experiments, Smith and Li (1993) found that plant N uptake was reasonably well related ($r^2 = 0.64$–0.85, $n = 12$) to hot KCl-extractable N, with the initial ($NH_4 + NO_3$)-N being included in the test. Moderate relationship ($r^2 = 0.66$) between aboveground plant N uptake in field conditions and KCl-hydrolyzable N (not including initial mineral N) was reported by McTaggart and Smith (1993), but only when the data for 2 out of 10 sites were excluded. Poor correlation was obtained between KCl-hydrolyzable N and field-measured N supplying capacity by Hong et al. (1990). However, none of these field correlation studies took into account the variation of temperature and moisture among different sites and their effects on N mineralization. Recently, hot KCl-extractable organic N was reported to be poorly correlated to the net amount of N produced during long-term aerobic incubations (Groot and Houba, 1995; Jalil et al., 1996; Curtin and Wen, 1999).

Both Jalil et al. (1996) and Curtin and Wen (1999) found that the relationship between KCl-hydrolyzable N and the net amount of N released from organic matter during incubation (leached) was greatly improved when the initial NH_4–N was included in the KCl-hydrolyzable N. No rational basis was given for these findings, and they could not be confirmed by our results. The determination coefficients (r^2) would be 0.17 and 0.16 for waterlogged and aerobic incubations, respectively, when such addition and correlation analysis were carried out.

Curtin and Wen (1999) found that KCl-hydrolyzable N was reasonably well correlated with net N production during the first 2 wk, but poorly correlated with N accumulated during 24 wk of incubation. This led them to suggest that hot KCl may selectively release the most labile organic N. Nevertheless, this claim was contrasted by our results that total organic N more closely correlated with the gross amount of N mineralized during 2-wk incubations than did hot KCl-hydrolyzable N (Fig. 3 and 4).

Hydrochloric Acid-Hydrolyzable Nitrogen and Sodium Hydroxide-Hydrolyzable Nitrogen

The HCl method hydrolyzed 25 to 144 mg N kg^{-1} from the 19 soils used in waterlogged incubation and 27 to 144 mg N kg^{-1} from the 12 soils used in aerobic incubation. Hydrochloric acid-hydrolyzable N had higher r^2 values than KCl-hydrolyzable N, but lower than soluble organic N and total organic N, when regressed against the N mineralization rates (Fig. 3 and 4). This method was recently claimed to be promising for measuring the biologically active soil organic matter pool as estimated by the NCSOIL model (Xu et al., 1997). However, evidence for their assertion appeared to be insufficient, although data showed that this method extracted a chemically labile fraction of soil organic matter. The poorer correlation with N mineralization for HCl-hydrolyzable N than for total organic N implied that HCl-hydrolyzable N was not more biologically reactive than the whole soil organic N.

The amount of organic N hydrolyzed by the NaOH method was markedly greater than that measured by the other two chemical methods (KCl- or HCl-hydrolyzable N), ranging from 43 to 379 for all the waterlogged soils and 64 to 379 mg kg^{-1} for the aerobically incubated soils. The NaOH-hydrolyzable N explained 71 and 87% of the variations in N mineralization rates during waterlogged and aerobic incubations, respectively (Fig. 3 and 4). These percentages were consistently higher than those for KCl- or HCl-hydrolyzable N, but lower than those for water-soluble organic N.

This method was originally presented by Cornfield who observed a good relationship ($r^2 = 0.72$, $n = 48$) between NaOH-extractable N and the net amount of N produced during 3 wk of aerobic incubation. Cornfield (1960) included the initial NH_4–N in their test, but not in the net N production. Keeney and Bremner (1966) reported a poor correlation between this N pool and plant N uptake in pot studies. They also included the initial NH_4–N in the test of NaOH-extractable N, but excluded in the reference the amount of N absorbed by plants during the first 33 d of the experiment, which should consist of the initial available mineral N plus the mineralized N from the most labile organic N pool. Contrasting results were obtained in other evaluation studies of this index with pot and field experiments by Cornforth and Walmsley (1971) and Walmsley and Forde (1976). The reference used in their studies was plant N uptake or percentage yield. The initial NO_3–N in soil might have a significant effect on the value of these references, but was not included in the test of NaOH-hydrolyzable N.

Chalk and Waring used a partial correlation analysis to remove the confounding effect of the initial mineral N on the relationship between N mineralization capacity indices and plant N uptake. Wang and Li (1991) found that the relationships between NaOH-hydrolyzable N and plant N uptake in two pot experiments were significantly improved when the initial NO_3–N was included in the chemical index. Moreover, the correlation coefficients for NaOH-hydrolyzable N plus mineral N were much higher than those for the initial ($NH_4 + NO_3$)-N alone or total N (including NO_3–N). Their results indicated that both initial mineral N in soil and N mineralization during the plant-growing period played an important role in providing available N. If a single index is desired, a test that integrates initial mineral N and NaOH-hydrolyzable organic N would be a better index than total N (including mineral N), as the lower level of NaOH-hydrolyzable N was less likely to obscure the level of mineral N in soil.

CONCLUSIONS

Significant and variable amounts of mineral N were consumed during waterlogged and aerobic incubation

of soils. Gross N mineralization under controlled conditions provides an unequivocal measure of soil organic N mineralizability. Correlation studies with the gross amount of N mineralized as a reference demonstrated that the light fraction N content is not a reliable index for measuring the size of readily mineralizable organic N pool in the whole soils developed under different conditions. None of the three chemical methods tested in this study could represent the N mineralization capacity better than water-soluble organic N and total organic N. Further studies are needed to test the ability of water-soluble organic N to measure N mineralization capacity of field-moist soils over a longer period.

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Deep Banding Phosphorus and Potassium Fertilizers for Corn Managed with Ridge Tillage

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ABSTRACT

Broadcast fertilization leads to stratification of soil P and K in the ridge-till system, which may reduce fertilizer use efficiency. This study evaluated the response of corn (*Zea mays* L.) to broadcast or deep-band (15- to 20-cm depth) placements in 15 site–years. Fertilization rates were 0 to 56 kg P ha^{-1} and 0 to 132 kg K ha^{-1}. Soil-test P (STP) and K (STK) were higher in the top 15-cm layer of the ridges. Phosphorus increased early plant growth (V5 stage) in five sites, early P uptake in nine sites, and grain yield in seven sites. Yield was increased by P when STP was <22 mg P kg^{-1} (Bray-1) in the top 15-cm layer of ridges or <18 mg P kg^{-1} in the top 15 cm of ridges and valleys. The P placements seldom differed (the deep-band P was better in one site). Potassium increased growth in 6 sites, K uptake in 14 sites, and grain yield in nine sites. The deep-band K increased yield over the broadcast K in four sites. The yield response to broadcast K across sites was not correlated with STK, but the response to deep-band K was negatively and linearly correlated with STK from various sampling positions. Corn responded to deep-band K in soils with above-optimum STK according to current soil-test interpretations. The results showed that both placements usually were similarly effective for P, and that deep banding often was superior for K.

The ridge tillage system was rapidly adopted by Corn Belt producers during the 1980s. Producers were exploring various forms of conservation tillage to reduce costs, reduce soil erosion, reduce contamination of water supplies, and comply with soil-conservation requirements of government programs. The area in ridge-till corn in the North American Corn Belt, however, has remained constant or even decreased during the 1990s (CTIC, 1998). Although many reasons could explain this trend, a major one often mentioned by producers is the perception of serious problems with fertilizer management with ridge tillage. This is especially the case for K because K-deficiency symptoms are observed in corn leaves even when apparently soil test-based rates of broadcast K fertilizer are used.

Studies on fertilizer application for moldboard or chisel-plow tillage have shown that P fertilization seldom increases corn yield when soils test above ≈20 mg P kg^{-1} when the Bray-1 extractant is used (Olson et al., 1962; deMooy et al., 1973; Rehm et al., 1981; Rehm, 1986; Walker and Raines, 1988; Mallarino et al., 1991a; Mallarino and Blackmer, 1992; Webb et al., 1992). Studies with K for moldboard or chisel-plow tillage showed that fertilization seldom increases corn yield when soils test above ≈130 mg K kg^{-1} when the ammonium acetate extractant is used (Hanway et al., 1962; deMooy et al., 1973; Rehm et al., 1981; Walker and Raines, 1988; Mallarino et al., 1991a, 1991b), although results are more variable than for P mostly due to differences in sample processing (i.e., use of field moist or dried samples). Levels above these values are considered high for corn in many Corn Belt states and no P or K fertilization is recommended. These interpretations may or may not apply to ridge tillage, however. Ridge tillage leads to accumulation of P and K in the ridges, mainly due to tillage operations and limited movement of these nutrients in soils (Karlen et al., 1991; Rehm, 1992). Vertical and lateral nutrient stratification may reduce crop early growth and yield. Limited research suggests that commonly used soil sampling techniques and the broadcast fertilizer application may not be appropriate for ridge tillage (MacKay et al., 1987; Rehm, 1992). Ridge tillage mixes soil, fertilizer, and residues more than no tillage. The common practice is to build ridges when corn is 15 to 30 cm tall (often between the V5 and V6 growth stages) and to leave the ridges undisturbed until planting time of the next season when the field is leveled by a

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Abbreviations: LSD, least significant difference; STK, soil-test K; STP, soil-test P.