DIVISION S-4—SOIL FERTILITY & PLANT NUTRITION

Short-Term Effects of Nitrogen Fertilization on Soil Organic Nitrogen Availability

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ABSTRACT

Long-term N fertilization affects soil organic N reserves, N mineralization potential, and crop response to applied N, but little information is available on the influence of short-term N fertilizer (STN) management on soil organic N availability and crop response. This study was conducted to determine if STN changes soil N supplying capability to corn (*Zea mays* L.) after 3 yr of differential N fertilization on a Fayette silt loam soil (fine-silty, mixed, mesic Typic Hapludalf) in Wisconsin. Various rates of N fertilizer (0–402 kg N ha^{-1}) were applied to corn in 1983, 1984, and 1985, and their residual effects on corn response were evaluated in 1986. Soil profile NO_3-N levels in spring 1986 were very low in all plots (48 ± 4 kg ha^{-1} [90 cm]$^{-1}$), yet grain yields and N uptake were significantly increased by STN applications. Corn N uptake was linearly related to the total amount of N returned to soil in crop residues during the previous 3 yr. Increased organic N availability under high STN management was equivalent to a 78 kg N ha^{-1} rate, or 47% of the N fertilizer required for optimum crop yields. In aerobic incubations (40 wk) of spring 1986 soil (0–30 cm), STN additions increased N release only in the first few weeks. Kinetics of N mineralization were best described by a two-component model in which the active fraction (N_A) of soil organic N was highly correlated with corn N uptake (r = 0.88). Simulation of field conditions showed that 95% of N_A is available before crop maturity. A phosphate-borate buffer organic N availability index was significantly and consistently related to STN treatments. Relative increases in total soil organic N corresponded with the 3-yr N balance between fertilizer additions and grain removals, and were about 10 times larger than mineralizable N. These results indicate that immobilization of excess mineral N into stable soil organic N during decomposition of crop residues should be considered in determining the environmental risk of N fertilization. Although labile organic N is a small fraction of the total fertilizer N contribution to soil N, its quantification should allow a more accurate assessment of crop N needs.

MANY SITE-SPECIFIC factors influence the total amount of N supplied by soil to a cereal crop, but their relative importance depends on the specific soil–crop system. For Midwest production situations where corn follows corn, the most important sources of available N are usually residual soil NO_3–N and N mineralized during the growing season from soil organic matter including crop residues and recent organic amendments such as manure (Meisinger, 1984; Schepers and Mosier, 1991). Efficient use of N fertilizers requires a careful accounting for all these sources on an annual basis because they directly affect the amount of supplemental N needed for optimum crop production, and the year-to-year variation can be substantial (Bock and Hergert, 1991; National Research Council Committee on Long-Range Soil and Water Conservation, 1993; Vanotti and Bundy, 1994a,b). Although substantial research effort has been devoted to find a chemical or biological test that accurately quantifies labile soil organic N pools (Bremner, 1965a; Keeney, 1982; Bundy and Meisinger, 1994), a major problem is that the N mineralized or extracted in laboratory tests is poorly correlated with field measurement of N availability (Fox and Piekielek, 1984; Meisinger, 1984; McCracken et al., 1989; Hong et al., 1990; Rice and Havlin, 1993). Inefficient use of N fertilizer is likely when the N supply from organic sources is unknown. Efficient N use is important because N fertilization represents a significant cost to producers, and because excess N may cause NO_3^- contamination of groundwater.

Soil organic matter, including the microbial biomass, is a dynamic nutrient reservoir that functions as both a source of and sink for N through the competing effects of mineralization and immobilization (Boone, 1990). Addition of N fertilizers to corn under N-limiting conditions leads to increased crop production and, in turn, increased crop residues. Fertilizer N may enter the soil organic fraction via crop residues, or by microbial immobilization during decomposition of these residues (Stanford, 1973; Hauck, 1981). When crop residues are returned to the soil, N fertilization can increase organic N reserves and N-supplying capacity of the soil. This effect has been documented in long-term cropping studies after many years of repeated N fertilization (El-Haris et al., 1983; Janzen, 1987; McCracken et al., 1989; Jenkinson, 1991; Vanotti et al., 1995). Mineralization of stored N may in turn influence the N fertilizer needs of subsequent crops. Results of a continuous corn × N rate experiment in Wisconsin (Motavalli et al., 1992) showed that the N furnished from organic sources after discontinuing long-term (25-yr) N fertilizer additions significantly increased corn N uptake and grain yield, and decreased the response to added N during seven consecutive years in which the effect was evaluated. Olson and Swallow (1984) found that ≈50% of the total N fertilizer (50–100 kg N ha^{-1} yr^{-1}) applied to wheat (*Triticum aestivum* L.) in a 5-yr field experiment was still accounted for within the organic matter fraction in the soil system. Fertilizer N, once incorporated into soil organic matter, becomes increasingly stable with time,

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Abbreviations: STN, short-term N; N_A, active N fraction; AC-N, autoclave N availability index; PBB-N, phosphate–borate buffer N availability index; ANI-N, anaerobic incubation N availability index; NFEV, N fertilizer equivalent value.

but may need >5 yr to equilibrate with indigenous soil N (Allen et al., 1973). Compared with native humus N, a higher proportion of organic residual N during the early stages of humification occurs in amino acid and amino sugar forms (Allen et al., 1973; Smith et al., 1978), and it is more susceptible to mineralization (Freney and Simpson, 1969; Legg et al., 1971; Smith et al., 1978). Though these studies have provided valuable information on the fate of fertilizer N and potential availability of organic residual N to crops, only limited information is available on the short-term effect of N fertilization on soil organic N availability and crop response.

In this study, we evaluated the residual effects of fertilizer N applied to corn during a 3-yr period on subsequent corn grain production, N uptake, crop residue turnover, and soil N mineralization potential. Further, we evaluated chemical and biological indices for their ability to detect and predict the effects of STN fertilization and residue history on N availability and crop response.

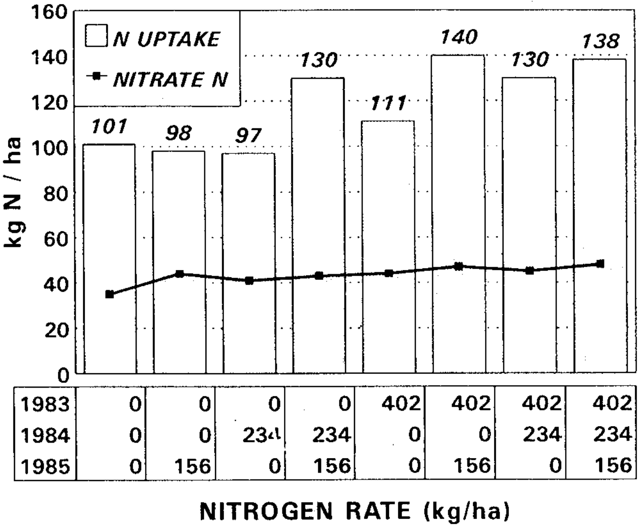
MATERIALS AND METHODS

Field Study Description

Field studies to determine the residual effects of STN on soil N availability and corn production were conducted from 1983 to 1986 at the Univ. of Wisconsin Agricultural Research Station near Lancaster, WI (42°51'N, 90°42'W). The soil is a well-drained Fayette silt loam. Corn was grown at the site for 3 yr prior to initiation of this work.

Fertilizer N was applied for corn at rates of 0, 134, 268, or 402 kg N ha^{-1} before planting in 1983. The treatments were arranged in a randomized complete block design with four replications and included above-optimum N rates to evaluate the extent of profile NO_3-N accumulation and overwinter retention in subsequent years (Bundy and Malone, 1988). In spring 1984, four N rates (0, 78, 156, and 234 kg N ha^{-1}) were applied in each of the 1983 N treatments by splitting the original plots. An additional split N treatment of 0, 78, and 156 kg N ha^{-1} was superimposed on each of the 1984 treatments in spring 1985. This provided a split-split plot design, with 1983 N treatments as main plots, 1984 N treatments as subplots, and 1985 N treatments as sub-subplots. No fertilizer N was applied in 1986, the residual year of the experiment, except for three sub-subplots that were used to determine corn response to N fertilizer applied in 1986. In this study, N rates of 78, 156, and 234 kg N ha^{-1} were applied to plots that received low STN treatments (134 kg N ha^{-1} in 1983 and 0 or 78 kg N ha^{-1} in 1984 and 1985). Nitrogen treatments were broadcast applied as NH_4NO_3 and were incorporated into the top 15 cm of soil by tillage within 24 h after application.

Corn production practices and dry matter, grain yield, and total plant N measurement procedures were previously described (Bundy and Malone, 1988). Grain yields are reported at a grain moisture content of 155 g kg^{-1}. Stover dry matter was calculated as the difference between total aboveground dry matter yield and grain yields (0% moisture). Aboveground corn N uptake and grain N removal were calculated from the total dry matter and grain yields, respectively, and the corresponding N concentrations. The amount of stover N returned to soil was calculated as the difference between total aboveground N uptake at physiological maturity and grain N removal from the field plot.



1983	0	0	0	0	402	402	402	402
1984	0	0	234	234	0	0	234	234
1985	0	156	0	156	0	156	0	156

Fig. 1. Short-term N treatment effect on 1986 corn N uptake (zero N in 1986) and spring soil NO_3-N content (0–90-cm depth). Each value is the average of four field replicates.

Soil Inorganic Nitrogen Availability

To determine the amounts of inorganic N in soil profiles, preplant soil samples were obtained from each plot in the spring before N application (16–23 April) in 1983 through 1986, and in the fall after harvest (14–24 October) in 1983 through 1985. Soil samples were taken in 30-cm increments to a total depth of 90 cm, using procedures described by Bundy and Malone (1988). Soil samples were stored at −10°C until they were dried at 30 to 35°C in a forced-draft dryer. The dry soils were ground to pass a 2-mm screen and stored in sealed plastic bags for further determinations. Inorganic N was extracted with 2 *M* KCl (Bremner and Keeney, 1966), and NO_3-N and exchangeable NH_4-N were determined by automated analysis (Bundy and Meisinger, 1994). The amounts of NO_3-N and NH_4-N in 30-cm profile depth increments were calculated using the assumption that 1 ha (30 cm of soil) weighs 4.48 × 10^3 Mg. Values for exchangeable soil NH_4-N are not reported because the amounts detected each year were uniformly low and were not affected by treatment. A detailed analysis of residual profile NO_3-N effects on corn response to applied N for 1984 was previously reported (Bundy and Malone, 1988).

Soil Organic Nitrogen Availability

The short-term effects of N fertilization on soil N availability to corn were evaluated using chemical and biological methods on surface (0–30-cm depth) soil samples collected in spring 1986 from eight field treatments that received the highest or zero N rate in each of the previous 3 yr (1983–1985). These STN rates are shown in Fig. 1. Laboratory analyses were performed separately on the four field replicate samples from each N treatment. The chemical methods used were: (i) total soil organic N, (ii) NH_4-N hydrolyzed by 0.01 *M* $CaCl_2$ after overnight (16 h) autoclaving at 121°C (Keeney, 1982), and (iii) steam distillation with pH 11.2 phosphate-borate buffer (Gianello and Bremner, 1988). The biological methods used were: (i) NH_4-N produced during a 1-wk waterlogged (anaerobic) incubation (Keeney, 1982), and (ii) inorganic N production during long-term (40-wk) aerobic incubation (Bundy and Meisinger, 1994). Values reported for the autoclave (AC-N), the phosphate borate buffer (PBB-N), and the anaerobic incubation

(ANI-N) indices were calculated by subtracting initial soil exchangeable NH_4–N from the total NH_4–N extracted by these methods. Inorganic N production during aerobic incubation was determined by leaching with 100 mL of 0.01 *M* $CaCl_2$ and 25 mL of a minus-N nutrient solution (Stanford and Smith, 1972) after 0, 1, 2, 3, 4, 6, 8, 11, 14, 18, 22, 26, 30, 34, and 40 wk of incubation at 35°C and a soil water tension of 80 kPa. Total soil organic N was measured on soil, crushed to pass a 0.15-mm (100-mesh) screen, using tube digestion (Nelson and Sommers, 1972) and colorimetric analysis of NH_4-N in the digest (Schuman et al., 1973).

We used the autoclave, phosphate–borate buffer distillation, and anaerobic incubation procedures with the goal of obtaining a rapid, relative indication of N availability that may be used as a test to predict available N released from soil organic N under field conditions. Long-term incubations were performed to provide the base information needed to interpret data from both field and N availability index measurements. Total soil organic N, viewed as a net source of or sink for N, provided valuable information on the fertilizer N balance in soil.

Several mineralization models were applied to the cumulative net N mineralization data to describe changes in soil organic N pools as affected by N fertilization histories. The first-order model (Stanford and Smith, 1972), shown in product-appearance form, is the single exponential equation

$$N_m = N_o[1 - \exp(-k_o t)] \qquad [1]$$

where N_m is the amount of N mineralized at time t, N_o is the initial amount of potentially mineralizable N, and k_o is the specific rate of decomposition. Because net N mineralization may reflect the contribution of several soil organic N pools with differing susceptibilities to decomposition, several researchers have incorporated a more labile pool of N_o into Eq. [1]. This is illustrated by the double exponential equation (Molina et al., 1980)

$$N_m = N_A[1 - \exp(-ht)] + N_R[1 - \exp(-kt)] \qquad [2]$$

and a special case of the two-component model (Bonde and Rosswall, 1987)

$$N_m = N_A[1 - \exp(-ht)] + Ct \qquad [3]$$

where N_A and N_R represent the more available and more recalcitrant soil organic-N fractions decomposing at specific rates h and k, respectively, and C in the second term of Eq. [3] is a zero-order rate constant corresponding to the resistant fraction ($C = N_R k$). Equation [3] is most appropriate for describing the mineralization kinetics of data showing a rapid curvilinear increase in cumulative N mineralization followed by a slow linear increase that persists to the end of the incubation experiment.

Statistical Analysis

Equations [1] to [3] were fit to N mineralization data by nonlinear regression analysis (SAS Institute, 1988). The mineralization model giving a valid description of the data was selected on the basis of mean square error and F tests as described by Deans et al. (1986). Analysis of variance was used to determine significant differences among the various N rate treatments. Significant treatment effects were evaluated using linear correlation and regression analysis (Draper and Smith, 1981).

RESULTS AND DISCUSSION

Nitrogen Fertilization Effect on Crop Productivity and Soil Nitrate

The effects of N applied during 1983, 1984, and 1985 on corn grain and stover dry matter production, stover N concentration, and profile NO_3–N levels found at harvest (fall sampling) and in the following spring are shown in Table 1. Grain yields were significantly increased by applied N in all years. Total N uptake and the amount of N returned to soil in aboveground crop residues were usually increased by applied N. Although substantial amounts of residual NO_3–N were found in soil at harvest time in all 3 yr, the relative amounts of profile NO_3–N that remained within the soil profile over winter varied considerably among years. Equations in Table 1 indicate that ≈45% of the profile NO_3–N found in fall 1983 was recovered in spring 1984, but only ≈14 and 6% of the fall NO_3–N were recovered in the spring of 1985 and 1986, respectively. The minimum profile NO_3–N level of 40 to 50 kg N ha^{-1} observed in this study is similar to a "background" residual N level usually found in medium- to fine-textured soils (Schepers and Mosier, 1991; Bundy and Meisinger, 1994).

Nitrogen losses through leaching and denitrification, or transformation into organic compounds, may explain the substantial decreases in profile NO_3 observed during the period between growing seasons. Wet conditions during this overwinter period in all 3 yr of the study favored NO_3 losses from the root zone (October–April precipitation in 1983–1984, 1984–1985, and 1985–1986 was 368, 487, and 358 mm, respectively, relative to a 30-yr mean of 342 mm), especially during the fall 1984 to spring 1985 period. Alternatively, a significant fraction of fall NO_3–N may have been incorporated into the soil organic N fraction during the decomposition of corn residues, thus limiting the potential for NO_3^- leaching. The possibility of immobilization of the residual mineral N found in the fall and overwinter retention in soil organic matter is supported by the relatively low N concentration of the corn residues returned to the soil in all 3 yr (Table 1). Although N fertilization increased stover N concentration, the values found were usually below the established threshold N content of 10 to 20 g kg^{-1} that leads to depletion of mineral N in the soil during residue decomposition (Iritani and Arnold, 1959; Bartholomew, 1965; Allison, 1973; Vigil and Kissel, 1991).

We estimated the amount of additional N needed for decomposition of corn residues (above that contained in these residues) based on the following assumptions: (i) a critical residue N concentration of 16 g kg^{-1} is required to satisfy the needs of soil microorganisms during most crop residues' decomposition (Paul and Clark, 1989, p. 137), and (ii) roots comprise 20% of the total plant biomass and N concentrations in roots and stover are equal (Stanford, 1973). The results of these calculations (Table 1) show that, except for the low N treatments, the amounts of soil NO_3 available at the end of the 1983–1985 growing seasons were adequate to meet the N demands of microorganisms. These results also suggest

Table 1. Effect of N applied in 1983, 1984, and 1985 on corn grain yield, total N uptake, stover N returned to soil, and the amount of soil profile NO_3-N in the fall and the following spring.

N rate	Grain yield	Total N uptake	Stover: Dry matter	Stover: N	Stover: N concentration	Inorganic N needs for residue decomposition†	Profile NO_3-N (0-90 cm): Fall	Profile NO_3-N (0-90 cm): Following spring
kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
					1983			
0	5.15	118	7.08	43	6.1	98	52	63
134	6.64	119	6.75	26	3.8	120	93	117
268	5.80	134	8.33	49	5.8	119	193	167
402	6.13	162	8.26	70	8.0	93	358	213
$P > F$‡	0.02	0.11	0.08	0.22	0.27		0.01	0.02
CV, %	9	19	24	58	48		50	39
					1984§			
0	7.63	137	8.02	45	5.5	122	74	64
78	8.53	165	8.39	55	6.5	117	111	74
156	8.46	181	8.35	66	7.8	100	157	80
234	8.73	176	7.74	56	7.2	102	147	70
$P > F$	0.01	0.01	0.50	0.05	0.01		0.01	0.01
CV, %	8	11	17	35	25		42	39
					1985¶			
0	7.07	155	7.58	76	9.6	70	59	45
78	7.84	188	8.50	93	10.4	69	93	47
156	7.99	209	8.76	107	12.3	47	121	52
$P > F$	0.01	0.01	0.01	0.01	0.01		0.01	0.01
CV, %	15	22	25	41	35		70	35

Relationship between the amount of profile NO_3-N found in spring and fall:

NO_3-N spring 1984 = 61.2 + 0.448 NO_3-N fall 1983 $r^2 = 0.76^{**}$ ($n = 16$)

NO_3-N spring 1985 = 54.7 + 0.141 NO_3-N fall 1984 $r^2 = 0.14^{**}$ ($n = 62$)

NO_3-N spring 1986 = 41.9 + 0.062 NO_3-N fall 1985 $r^2 = 0.14^{**}$ ($n = 192$)

** Significant at the 0.01 level.

† Additional N required by soil microorganisms to decompose stover and roots.

‡ $P > F$ = probability that tabular F ratio exceeds F ratio calculated by analysis of variance.

§ Averaged across 1983 N treatments.

¶ Averaged across 1983 and 1984 N treatments.

that the supplemental amounts of N required by microorganisms for residue decomposition are similar across N fertilization rates. Bartholomew (1965) noted that this effect should be expected because, as shown in our data, N fertilization of cereal crops generally increases both the total residue production and the N content of the residue material, which compensate each other. This effect may limit residue N turnover and N fertilizer availability to the following crop in soils with relatively low soil NO_3-N levels receiving low N rates (Table 1).

Residual Effects of Short-Term Nitrogen Fertilization on Crop Productivity

The residual effects of 1983, 1984, and 1985 N fertilization on 1986 corn response (unfertilized plots) are shown in Table 2. Corn grain and N yields were significantly increased by STN treatments. However, the quantities of profile NO_3-N found in 1986, and its variation among STN treatments, were too small to account for the observed crop responses (Fig. 1, Table 2), suggesting that N fertilizer applied in the preceding 3 yr contributed significantly to the soil's mineralizable N fraction released in 1986. Comparison between corn N uptake from fertilized (Table 3) and unfertilized (Fig. 1) plots allowed estimation of the fertilizer value of this labile pool of soil organic matter. We found that the average net amount of N mineralized during the 1986 corn growing season in those soils that received high STN treatments was equivalent to ≈78 kg N ha^{-1}, or 47% of the observed N rate required for optimum crop yields (167 kg ha^{-1}).

Table 2. Residual effects of 1983, 1984, and 1985 N rates on 1986 corn grain yield, plant N uptake and concentration, and spring profile soil NO_3-N content.†

N rate‡	Grain yield	Total N uptake	Plant N concentration	Profile NO_3-N spring 1986§
kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
		Main effect of 1983 N rates¶		
0	5.15	105	7.6	45
134	5.72	114	7.9	46
268	5.93	127	8.5	52
402	6.14	126	8.4	48
$P > F$#	0.01	0.01	0.01	0.01
		Main effect of 1984 N rates¶		
0	5.56	116	7.8	44
78	5.43	112	7.9	47
156	5.48	114	8.0	49
234	6.38	129	8.5	50
$P > F$	0.01	0.01	0.01	0.02
		Main effect of 1985 N rates¶		
0	5.10	105	7.8	45
78	5.62	117	8.0	47
156	6.32	129	8.5	52
$P > F$	0.01	0.01	0.01	0.01

† CV = 15, 21, 12, and 21% for corn grain yield, total N uptake, plant N concentration and profile NO_3-N, respectively.

‡ No fertilizer N applied in 1986.

§ Profile NO_3-N to the 90-cm depth.

¶ Main effects are averages across N rates applied in the other 2 yr.

$P > F$ = probability that tabular F ratio exceeds F ratio calculated by analysis of variance.

Table 3. Effect of N applied in 1986 on corn grain yield and total N uptake.

1986 N rate	Profile NO_3-N spring 1986	Grain yield	Total N uptake	Plant N concentration
kg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	g kg^{-1}
0	36	4.35	101	7.8
78	41	6.92	137	7.8
156	43	8.97	206	10.0
234	40	9.39	223	11.4
$P > F$†		0.01	0.02	0.01
CV, %		14	29	18

‡Selected regression equation:
Grain yield (Mg ha^{-1}) = 4.43 + 0.0296 N rate (kg ha^{-1}) if N rate < 167
Grain yield (Mg ha^{-1}) = 9.37 if N rate ≥ 167 $r^2 = 1.00^{**}$ (n = 4)

** Significant at the 0.01 level.
† $P > F$ = probability that tabular F ratio exceeds F ratio calculated by analysis of variance.
‡ Linear-plus-plateau response model.

This observation illustrates the potential effect of short-term N fertilization on site-specific variation of soil N supplying capacity and fertilizer needs of subsequent crops. It also emphasizes the need for a laboratory test that can provide an index of the availability of soil N and allow refined assessment of crop N needs.

Residual Effects of Short-Term Nitrogen Fertilization on Soil Nitrogen Mineralization

Table 4 shows the effect of STN treatments on N mineralized during long-term aerobic incubation of spring 1986 soil samples (0–30-cm depth). Significant differences between STN treatments usually occurred after the first 4 wk of incubation. The two-component mineralization model (Eq. [3]) offered the best description of the kinetics of N mineralization on data for all STN treatments evaluated. Optimized parameter values thus obtained (Table 4) show that differences in N mineralization between STN treatments are largely due to contributions from a readily available N pool (N_A) of uniform composition, as revealed by the absence of significant differences in the associated rate of decomposition, h. In contrast, the rate constant C, representing the more resistant mineralizable N pool, was not affected by STN treatments (Table 4). This is also illustrated in Fig. 2, which shows that differences in soil N mineralization between STN treatments became nearly constant after about 8 wk of incubation. Bonde et al. (1988) provided evidence that microbial biomass constitutes a significant part of the potentially mineralizable N pool. They reported mineralization rate constants for the available microbial biomass (h_b = 0.36–0.61 wk^{-1}) similar to those corresponding to the available fraction, N_A, of soil organic N (h = 0.45–0.56 wk^{-1}). These rate constants are essentially the same as those obtained in our study using comparable methodology (Table 4).

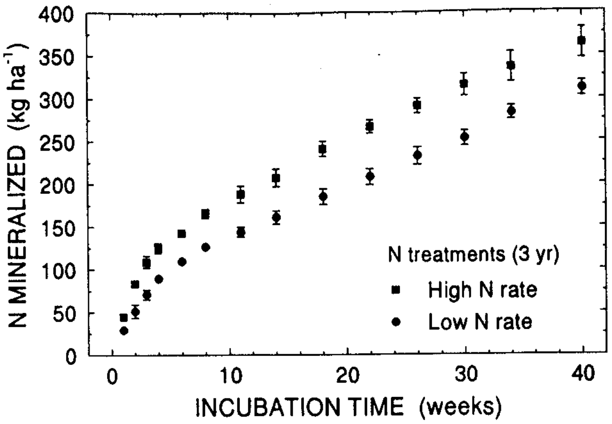


Fig. 2. Residual effects of short-term N fertilization on soil N mineralization during aerobic incubation at 35°C and 80 kPa soil water tension. Data show cumulative net mineralization (mean values ± standard error, n = 4) of soils (0–30-cm depth) sampled in spring 1986 that received the highest (792 kg ha^{-1}) or lowest (0 kg ha^{-1}) N additions from 1983 to 1985.

Our finding that N fertilization contributes largely to N_A with little effect on the more resistant mineralizable

Table 4. Effect of 1983, 1984, and 1985 N fertilizer treatments on soil N mineralization in laboratory incubations and on the available N fraction of soil organic matter.†

	Cumulative net N mineralization (N_{min})‡							$N_{min} = N_A[1 - \exp(-ht)] + Ct$§		
N rate	1 wk	2 wk	3 wk	4 wk	6 wk	8 wk	40 wk	N_A	h	C
	kg N ha^{-1}								wk^{-1}	kg N ha^{-1} wk^{-1}
					Main effect of 1983 N rates¶					
0	37	63	84	98	115	135	313	98	0.42	5.4
402	41	69	92	108	127	150	345	125	0.42	5.7
$P > F$#	0.11	0.14	0.08	0.02	0.01	0.01	0.01	0.01	0.98	0.38
					Main effect of 1984 N rates					
0	37	60	79	96	115	136	322	106	0.42	5.5
234	41	72	96	111	128	150	336	117	0.42	5.6
$P > F$	0.04	0.01	0.01	0.01	0.01	0.01	0.09	0.12	0.98	0.33
					Main effect of 1985 N rates					
0	38	64	84	97	115	136	319	101	0.44	5.6
156	40	68	91	109	128	149	339	122	0.40	5.4
$P > F$	0.16	0.27	0.12	0.01	0.01	0.01	0.03	0.06	0.51	0.27
CV, %	15	17	15	11	6	8	7	21	43	20

† Soil samples collected in spring 1986, 0- to 30-cm depth.
‡ Cumulative net N mineralization by aerobic leaching-incubation procedure.
§ Equation [3].
¶ Main effects are averages across N rates applied in the other 2 yr.
# $P > F$ = probability that tabular F ratio exceeds F ratio calculated by analysis of variance.

Table 5. Linear correlation coefficients (r) between grain yield and total N uptake of 1986 unfertilized corn or N residue history, and soil N mineralization (n = 32).†

	Grain yield 1986	N uptake 1986	Total N returned to soil in crop residues	
			1985 only	1983-1985
N_A-N‡	0.85	0.88	0.63	0.75
Cumulative net N mineralization				
1 wk	0.55	0.75	0.48	0.64
2 wk	0.58	0.74	0.59	0.71
3 wk	0.71	0.78	0.66	0.81
4 wk	0.78	0.79	0.68	0.80
6 wk	0.75	0.72	0.66	0.77
8 wk	0.74	0.76	0.59	0.76
40 wk	0.59	0.67	0.43	0.71

Selected regression equations:§

Grain yield = 1.796 + 0.0357 N_A-N

N uptake = 24.5 + 0.855 N_A-N

Grain yield = −0.203 + 0.057 N mineralized at 4 wk

N uptake = −36.0 + 1.492 N mineralized at 4 wk

N_A-N = 45.5 + 0.302 stover N (3 yr)

N mineralized at 4 wk = 64.8 + 0.190 stover N (3 yr)

† 1986 soil samples, 0- to 30-cm depth. All correlation coefficients significant at the P = 0.01 level.

‡ Available soil N fraction, Eq. [3].

§ Grain yield in Mg ha^{-1}; N uptake, N_A-N, stover N, and mineralized N in kg ha^{-1}.

N fraction (Table 4) is consistent with results obtained by El-Haris et al. (1983) and Bonde and Rosswall (1987) in studies of the influence of previous N fertilization (4–8 yr) on soil mineralization. However, much longer studies (25 yr) in Wisconsin (Vanotti et al., 1995) showed a marked effect of N fertilization history on the resistant mineralizable N pool as well.

The N_A soil fraction derived from laboratory incubation data was highly correlated with the field-measured N supplying capability of soil, which is represented by the total N uptake of unfertilized corn (Table 5, Fig. 1 and 3). The slope coefficient in this linear relationship suggests that 85% of the N_A fraction contributed directly to the N needs of the growing crop (Table 5). The role that N_A has in corn N nutrition was further evaluated by simulating the dynamics of this component under field conditions. For this purpose, the laboratory-obtained rate constant of mineralization h (mean at 35°C = 0.42 wk^{-1} or 0.06 d^{-1}) was adjusted for lower-than-optimum field temperatures using a Q_{10} (temperature coefficient) of 2 between 0 and 35°C (Stanford et al., 1973), with the following equation:

$$h' = h\,10^{(-1.053605 + 0.030103T)} \qquad [4]$$

where T is the observed mean daily temperature and h' is the corresponding (adjusted) mineralization rate constant. The portion of N_A mineralized under field conditions during the 1986 growing season was estimated on a daily basis using Eq. [4] and the computational method described by Stanford et al. (1973). As reference, we also estimated the N uptake demand function for 1986 using the equation given by Watts and Hanks (1978), adjusted for the actual growing degree days (base 10°C) observed from 1 May (planting) through 17 September (physiological maturity). Results of these calculations (Fig. 4) indicate that 95% of the N contained in the N_A fraction would be mineralized before the crop reached physiological maturity, and most of the N released from this fraction was readily available to meet crop demands during the period of rapid N uptake in July and August.

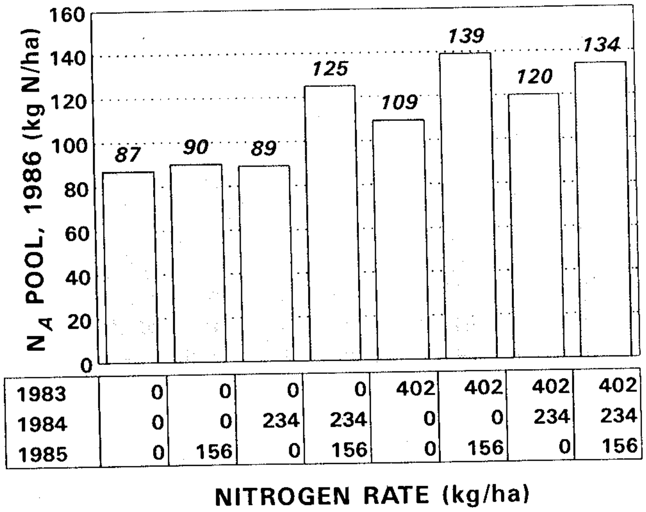


Fig. 3. Short-term N treatment effect on the N content of a readily available soil organic fraction (N_A) derived from laboratory incubation data (0–30-cm soil collected in spring 1986). Each value is the average of four field replicates.

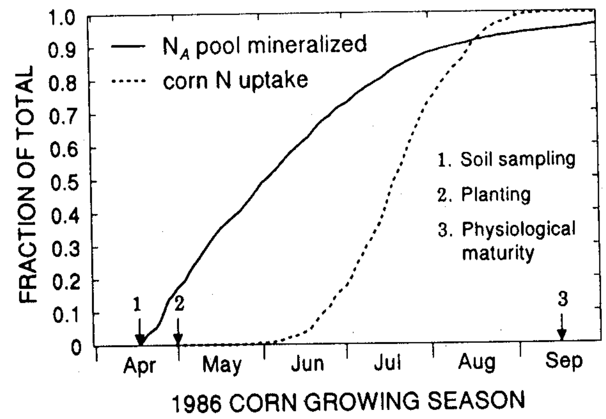


Fig. 4. Computed N turnover of the readily available soil organic N (N_A) pool vs. corn N uptake demands, based on mean daily temperatures observed during 1986.

The relationship between residue N returned to soil and N mineralization in aerobic incubations or the N_A pool was better described when the residue contributions from all 3 yr were considered (Table 5), and total N recycled through crop residues was a good indicator of N availability per se (Fig. 5). Cumulative N mineralization was also highly correlated with the N supplying capability of soil (N uptake in 1986), the correlation improving with increased time of incubation up to 4 wk (Table 5). Additional N released after 4 wk diminished rather than augmented the predictability of N availability under field conditions. Similar trends were noted for 1986 corn grain yield and for crop residue history (Table 5). These results were expected, based on the apparent synchrony found between corn N needs and turnover of the N_A pool under field conditions (Fig. 4), and the fact that this pool is a mathematical representation of the

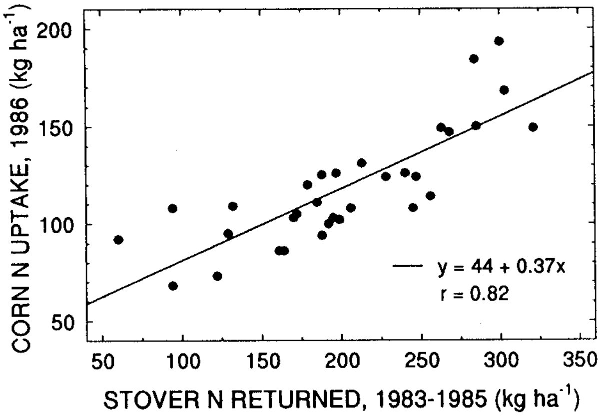


Fig. 5. Relationship between corn N uptake with no N applied in 1986 and the total amount of N returned to soil in the crop residues during the previous 3 yr.

mineralization data obtained during the initial stages of incubation (Fig. 2). Thicke et al. (1993) also reported that N released during the initial 1 to 2 wk of incubation was best correlated with N uptake of unfertilized corn at four Minnesota locations. These findings support the assertion (Bundy and Meisinger, 1994) that the N released during the first few weeks of incubation probably reflects the readily mineralizable or active fraction of soil organic matter, while that released later originates from a much larger but more stable soil organic matter pool. Therefore, the pattern of N mineralization during the first few weeks of incubation is critical for understanding the N availability status of soil.

Soil Organic Nitrogen Availability Indices

Low profile NO_3 levels in spring 1986 created optimum conditions to evaluate soil organic N availability tests, since these tests need to be calibrated against N-supplying capability under field conditions, and the presence of high amounts of residual inorganic N in the soil may overshadow the contributions of N mineralized during the growing season. The only N availability index that showed significant and consistent effects of past N fertilizer management was the PBB-N (Table 6). The ANI-N test was significantly affected by 1983 N rate treatments, but produced anomalous responses to 1984 and 1985 N rate treatments in view of the significant N uptake responses found among these treatments (Table 2). Further, the ANI-N and AC-N indices were not related with crop yield, crop N uptake, residue history, or aerobic mineralization measurements (Table 7, Fig. 6a). In comparison, the PBB-N index was highly correlated with both field indicators of N availability and laboratory-measured labile fractions of soil organic matter (Table 7, Fig. 6b).

Table 6. Effect of previous N fertilization on three indices of soil organic N availability, 1986.†

N rate	Organic N availability index‡		
	Anaerobic incubation (ANI-N)	Autoclave (AC-N)	Phosphate-borate buffer (PBB-N)
	Kg ha^{-1}		
	Main effect of 1983 N rates§		
0	139	356	71
402	194	347	90
$P > F$¶	0.01	0.68	0.01
	Main effect of 1984 N rates§		
0	167	354	75
234	168	349	87
$P > F$	0.99	0.81	0.01
	Main effect of 1985 N rates§		
0	175	351	76
156	158	351	86
$P > F$	0.37	0.99	0.04

† Soil samples collected in spring 1986, 0- to 30-cm depth.
‡ CV = 31, 18, and 15% for ANI-N, AC-N, and PBB-N, respectively.
§ Main effects are averages across N rates applied in the other 2 yr.
¶ $P > F$ = probability that tabular F ratio exceeds F ratio calculated by analysis of variance.

The PBB-N values ranged from 32 to 107 kg N ha^{-1} (0–30-cm depth), and its linear relationship with crop yield parameters reflects the fact that all observations obtained in 1986 in the unfertilized plots occurred within the responsive zone. For example, grain yield and N uptake values in zero N rate plots ranged from 3.55 to 7.92 Mg ha^{-1} and 68 to 193 kg N ha^{-1}, respectively, which are lower than values obtained at non-limiting N rates applied in 1986 (9.39 Mg ha^{-1} and 223 kg N ha^{-1}; Table 3). The N fertilizer equivalent value (NFEV) for PPB-N was estimated from the yield response equation in Fig. 7 and the yield response function for fresh N rates in Table 3. The resulting algorithm, NFEV = 1.64(PBB-N − 54), provides a method for crediting PBB-N test values against current N fertilizer recommendations. For example, an N fertilizer credit of 75 kg ha^{-1} is anticipated for a PBB-N test value of 100 kg ha^{-1} (0–30 cm). This credit can then be used to adjust N recommendations for soil organic N contributions. It is not our intent to provide an algorithm with general applicability, since information from numerous soils and environments is required to develop such relationship, but rather to indicate the feasibility of using a laboratory soil test to predict N mineralization under field conditions, and to provide a possible method of evaluation. In this respect, the PBB-N test appears promising for predicting changes in N-supplying capability of soil induced by short-term N fertilizer management in corn fields.

The PBB-N test (Gianello and Bremner, 1988) is based on the findings (Tracey, 1952; Stevenson, 1982a) that the N in glucosamine is converted quantitatively to NH_3 when this compound is steam distilled with pH 11.2 phosphate–borate buffer for 3 min. Studies of N transformation during microbial decomposition of plant materials have shown that this process is accompanied by synthesis of hexosamines (Bremner, 1965b; Allen et al., 1973; Namdeo and Dube, 1973), and that most of this substance in soil is of microbial origin (Stevenson, 1982b). Therefore, it is possible that PBB-N selectively measures the microbial products of plant decomposition, including the structural components of fungal mycelia (chitin, a polymer of glucosamine). This possibility is supported by the close relationship we obtained between PBB-N test values and the N_A fraction (Table 7), which has a

Table 7. Linear correlation coefficients (*r*) between yield and N uptake of unfertilized corn, N residue history, available soil organic N fraction, or N mineralized at 4 wk (aerobic incubation), and three soil indices of N availability ($n = 32$).†

Availability index	Grain yield 1986	N uptake 1986	Total N returned to soil in crop residues		N_A-N‡	Cumulative N mineralized at 4 wk
			1985 only	1983 to 1985		
Anaerobic incubation (ANI-N)	0.25(NS)	0.15(NS)	0.08(NS)	0.16(NS)	0.11(NS)	0.09(NS)
Autoclave (AC-N)	0.24(NS)	0.19(NS)	0.06(NS)	0.09(NS)	0.18(NS)	− 0.08(NS)
Phosphate-borate buffer (PBB-N)	0.76**	0.80**	0.67**	0.79**	0.71**	0.79**
Selected regression equations:¶						
Grain yield = 1.801 + 0.0484 PBB-N						
N uptake = 12.9 + 1.327 PBB-N						
N_A-N = 20.1 + 1.086 PBB-N						
N_{min} (4wk) = 48.0 + 0.697 PBB-N						
PBB-N = 36.0 + 0.214 stover N (3 yr)						

** Significant at $P = 0.01$; NS = not significant at $P = 0.01$.

† Soil tests performed on 0- to 30-cm depth samples taken in spring 1986.

‡ N_A-N = available soil organic N fraction, Eq. [3].

§ Grain yield in Mg ha^{-1}; N uptake, stover N, and soil tests in kg N ha^{-1}.

rate of N turnover similar to the microbial biomass (Bonde et al., 1988).

Total Soil Organic Nitrogen Changes

Data in Table 8 show the 3-yr N balance between N fertilizer inputs to corn and N removed in harvested grain, and the total soil organic N measured at the beginning of the fourth growing season (April 1986). Total soil organic N levels were consistently increased by 1983 and 1985 N rate treatments, but only the effect of 1983 N rates was statistically significant. In general, changes in soil organic N followed the N balance between fertilizer additions and grain removals. For example, the average difference in total organic N between soils receiving the highest and zero N rate in 1983 through 1985 was 680 kg N ha^{-1} (0.152 g kg^{-1}), which is similar to the 689 kg N ha^{-1} difference in net N found between the same treatments (Table 8). On the other hand, there was little difference in total N returned to soil with crop residues to account for the marked changes in soil organic N. This implies that immobilization of excess fertilizer N by soil microorganisms was the primary N cycle process determining the relative increases in soil organic N and the fate of fertilizer N in this study. Boone (1990) suggested that only in a system with both energy-rich, N-poor organic substrates and high inorganic N inputs should soil organic matter be a net N sink, and such a system perfectly describes the conditions encountered in our study (Table 1).

The relative increases in total organic N were about 10 times larger than the differences in mineralized N found in the long-term incubation experiment. For example, the average difference in N released during the

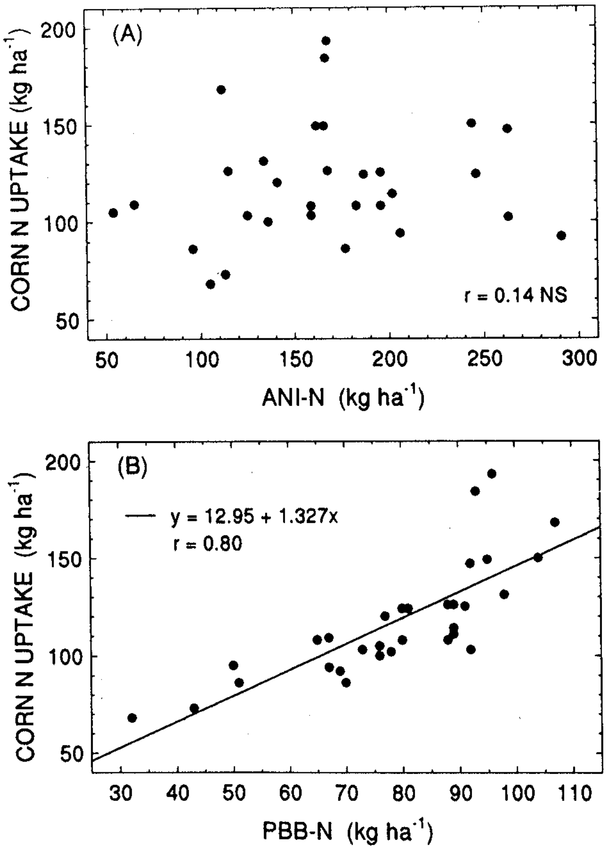


Fig. 6. Relationships between corn N uptake with no N applied in 1986 and (A) anaerobically mineralized N or (B) NH_4-N extracted with the phosphate-borate buffer distillation method.

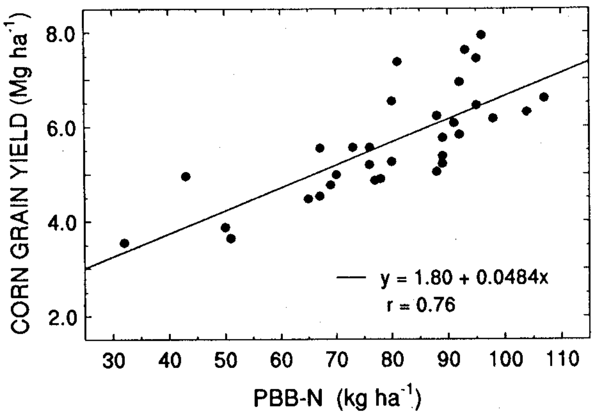


Fig. 7. Relationship between corn grain yield with no N applied in 1986 and NH_4-N extracted with the phosphate-borate buffer distillation method.

Table 8. Changes in total soil organic N after 3 yr of differential N fertilization (1983–1985).

N rate				Total crop residue returned to soil‡				
1983	1984	1985	Applied N†	Dry matter	N	Grain N	Net N§	1986 soil organic N¶
kg ha^{-1}				Mg ha^{-1}	kg ha^{-1}			g kg^{-1}
0	0	0	40	20.7 (1.1)#	125 (20)	200 (18)	−160	0.94 (0.07)
0	0	156	196	23.0 (0.5)	175 (18)	240 (9)	−44	0.97 (0.05)
0	234	0	274	22.9 (1.5)	170 (5)	274 (17)	0	0.94 (0.03)
0	234	156	430	24.8 (1.6)	237 (23)	283 (17)	147	0.97 (0.09)
402	0	0	442	23.7 (2.4)	182 (42)	283 (7)	159	1.03 (0.11)
402	0	156	598	24.7 (2.0)	220 (38)	315 (14)	274	1.10 (0.05)
402	234	0	676	26.7 (2.0)	249 (24)	300 (5)	376	1.06 (0.06)
402	234	156	832	26.7 (1.9)	263 (26)	303 (9)	529	1.09 (0.03)

† Applied N = N rate plus starter fertilizer (13.3 kg N ha^{-1} yr^{-1}).

‡ Aboveground measurements.

§ Net N = applied N − grain N harvest.

¶ 0- to 30-cm depth; main effects of 1983 N rates on soil organic N are significant at $P = 0.01$; effect of 1984 and 1985 N rates were not significant; CV = 12%.

Standard error of the mean of four field replicate samples given in parentheses.

40-wk incubation from soils that received the highest and zero N rates in 1983 through 1985 was 54 kg ha^{-1} (Fig. 2), which compares with the 680 kg ha^{-1} difference obtained for total soil organic N in the same soil samples. These results are consistent with previous work (Allen et al., 1973; Hauck, 1981; Olson and Swallow, 1984) showing that most of the fertilizer N incorporated into organic substances contributes mainly to a stable, passive soil N pool where remineralization will probably proceed for several decades.

CONCLUSIONS

Our results suggest that, in the long term, assessing the potential of soil–crop systems to incorporate excess N fertilizer into more stable organic fractions should be an important consideration. This is critical because the amount of N fertilizer currently used in U.S. corn production exceeds the amount of N harvested in grain by 50 to 60% (National Research Council Committee on Long-Range Soil and Water Conservation, 1993). Our N balance shows that most of this net excess N during a 3-yr period was probably sequestered into stable soil organic forms during decomposition of plant residues, limiting the risk of NO_3^- leaching. Thus, to determine the potential environmental risk of N fertilization, it is necessary to know the capacity of a soil to immobilize and store N. Our findings indicate that this capacity may be enhanced by readily decomposable, N-poor organic substrates such as corn residues.

To predict crop N fertilization needs, however, the effect of past N fertilization on labile soil organic fractions is much more important than its effect on total soil N, even when labile pools probably represent a relatively small fraction of the total fertilizer contribution to soil N. Results from this work indicate that an enhanced mineralizable N fraction due to short-term N fertilization practices may substitute for up to one-half the N fertilizer requirement for optimum yields. Thus, proper accounting for this N source could greatly reduce the uncertainty and risk associated with N fertilizer applications. Our results show that N released during the first few weeks of aerobic incubations was well correlated with corn N uptake. This relationship was not improved by considering N mineralized in longer term incubations. Our evaluation of several N availability indices showed that the PBB-N test was well correlated with labile fractions of soil organic N, and this test may be useful for predicting field changes in N-supplying capability of soil induced by short-term N fertilizer management in corn production. Additional research is needed to determine the suitability of this test for other soils and environments.

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