

## Effect of Management Systems on Nitrogen Mineralization and Nitrification in Soils

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**Abstract:** Nitrogen (N) management and spatial variability of soils have received considerable attention in recent years. The effect of long-term cropping systems on net N mineralization was studied in soils obtained from replicated plots from two sites: Galva-Webster Research Center (CWRC site) at Kanawha and Galva-Primghar Research Center (GPRC site) at Sutherland in Iowa, USA. Each experiment consisted of three cropping systems: continuous corn (CCCC), corn-soybean-corn-soybean (CSCS), and corn-oats-meadow-meadow (COMM), and treated before corn with (+N) and without (0N) ammoniacal fertilizer. Other studies involved assessing the effect of eight lime application rates (0–17,920 kg ha<sup>-1</sup> effective calcium carbonate equivalent, ECCE) on net N mineralization and nitrification in soils at the Northeast Research Center (NERC site) at Nashua, Iowa. The means of cumulative N mineralized at 30°C for 24 weeks in soils from the CWRC and GPRC sites, expressed as percentage of organic N, were generally greater in N-treated plots than in control plots. The greatest amounts of N mineralized were in soils from the COMM rotation plots. Application of the log transformation of the data to calculate the potential mineralizable N ( $N_o$ ) and the first-order constants ( $k$ ) showed that the data obeyed the exponential equation model. Expressed as percentages of total organic N in soils, the cumulative amounts of N mineralized ranged from 2.7 to 3.4% at 20°C and from 5.8 to 7.5% at 30°C. The cumulative amounts of N mineralized at 20°C and 30°C in soils from the plots under CSCS rotation were not affected by lime application. The  $Q_{10}$  values of N mineralization ranged from 1.9 to 2.2. Increasing the rate of lime application decreased the  $N_o$  values at 20°C, but not at 30°C. Liming soils markedly increased the nitrification rate, from 27% of the  $NH_4^+$ -N added for untreated soils (0 kg ECCE ha<sup>-1</sup>) to 76% for the soil treated with

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17920 kg ECCE ha<sup>-1</sup>. N mineralization and nitrification rates varied among the replicated plots.

**Keywords:** Organic N in soils, cropping systems, lime application, soil pH, N mineralization, nitrification

## INTRODUCTION

Recent interest in soil and fertilizer management of agricultural systems has focused on issues related to improving soil health and quality and minimizing possible deleterious effects on soil erosion and eutrophication of natural ecosystems. The need for application of N fertilizer has focused the attention on the importance of N mineralization and nitrification in soil as affecting surface and groundwater qualities. Because crop residues are primary sources of organic matter, crop management and fertilizer regimen can exert a significant influence on soil quality and, therefore, on the processes involved (Campbell et al. 1991). In general, soils under monoculture systems contain significantly lower concentrations and qualities of soil organic C, less structure stability, and reduced amounts of microbial biomass and activities than soils under crop rotations, especially those involving alfalfa (*Medicago sativa* L.) or meadow (Deng and Tabatabai 2000). The possible effects of crop rotations on chemical, physical, and biological properties are related to the amounts of C inputs and diversity of plant residues returned to soils (Moore, Klose, and Tabatabai 2000). Other studies on the effect of N fertilization have shown that, although soil pH decreases with ammoniacal fertilizer before corn (*Zea mays* L.) in cropping systems, the rate of nitrification is greater in N-treated than in untreated soils; this finding suggests either that fertilizer with ammonium or ammonium-forming fertilizer increases the microbial populations responsible for nitrification in soils and/or that such treatments increase the efficiency of the nitrifiers by inducing the enzymes responsible for conversion of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  (Tabatabai, Fu, and Basta 1992).

Similarly, lime application to soils normally leads to a significant increases in pH and, thus, in the rate of chemical and biochemical reactions and in microbial processes (McLean 1971). Such changes result in significant alterations in the solubility of many chemical compounds, improvement of plant roots and development, including microbial dynamic and diversity and, therefore, significant changes in enzyme activities (Acosta-Martínez and Tabatabai 2000). Changes in soil moisture and temperature induced by crop management practices have a large impact on microbial biomass and mineralizable carbon (C) and N (Deng and Tabatabai 2000; Ross 1987) and on the ability of soils to supply nutrients to plants from organic matter decomposition (Bonde and Rosswall 1987). Little information is available about the effect of such practices on net N mineralization and nitrification in soils. Studies of lime application to soils and the interaction of fertilizer

N with crop rotation practices are needed to establish crop N requirements and efficient use of N (El-Haris et al. 1983). Such information is needed to determine management practices for better strategies in manipulating the soil-plant systems for improved water, soil, and environmental quality. This study was undertaken to evaluate the effect of long-term crop rotation, N fertilization, and lime application on N mineralization and nitrification in soils of three such sites in Iowa.

## MATERIALS AND METHODS

### Soils and Their Properties

The soils were the surface soil (0–15 cm) samples collected from three long-term cropping systems at the Clarion-Webster Research Center (CWRC) in Kanawha, Galva-Primghar Research Center (GPRC) in Sutherland, and Northeast Research Center (NERC) in Nashua, Iowa that were initiated in 1954, 1957, and 1984, respectively. The soils from the first two sites were taken from two plots (6 × 12 m) each of the following cropping systems; continuous corn (CCCC), corn (*Zea mays* L.)-soybean (*Glycine max* L.)-corn-soybean (CSCS), and corn-oats-meadow-meadow [a mixture of alfalfa (*Medicago sativa*) and red clover (*Trifolium pratense* L.)] (COMM) and annual N fertilizer treatments: 0 or 180 kg N ha<sup>-1</sup> for CCCC and CSCS, and 130 kg N ha<sup>-1</sup> for COMM rotation at the CWRC site, and 0 or 200 kg N ha<sup>-1</sup> for CCCC and CSCS, and 130 kg N ha<sup>-1</sup> for COMM at the GPRC site. All N applications were done before corn, and all soil samples from each site consisted of the same soil type: Webster silty clay loam (Fine-loamy, mixed, mesic Typic Haplaquoll) at the CWRC site and Galva silty loam (Fine-silty, mixed, mesic Typic Hapludoll) at the GPRC site. The soils were collected from at least eight locations in the plot, mixed, and stored under field-moist conditions at 4°C. Samples were taken from untreated N-treated (with ammoniacal or urea N fertilizer) plots. Duplicate samples were obtained in June 1987 by sampling two plots receiving the same treatment (same rotation and fertilization). The chemical and physical properties of the soil samples were previously reported by Basta and Tabatabai (1992).

The soil samples from the NERC site (lime treatment site at Nashua) were Kenyon loam (Fine-loamy, mixed, mesic Typic Hapludoll). In this field experiment, agricultural limestone from local quarry was broadcast at the following rates: 0, 1,120, 2,240, 4,480, 6,720, 8,960, 13,440, and 17,920 kg effective calcium carbonate equivalent (ECCE) ha<sup>-1</sup> in 1984. The treatments were arranged in a randomized complete block design with four-field replications. The size of each plot was 6 × 15 m. Corn and soybeans were grown in alternate years, with annual application of fertilizers to maintain high nutrient levels of N, phosphorus (P), and potassium (K). Soil surface

samples (0–15 cm) were taken after corn harvest from all the field replicates 7 years after lime application by pooling six to eight core-samples (7.6-cm diameter). All laboratory experiments were done in duplicates, including controls. Selected chemical properties, including pH, organic C, and organic N contents, were previously reported by Acosta-Martínez and Tabatabai (2000).

### Nitrogen Mineralization

Nitrogen mineralization was studied as described by Deng and Tabatabai (2000) and Deng, Moore, and Tabatabai (2000). The protocol involved incubating a mixture of 20-g field-moist soil samples (on an oven-dry basis) and an equal weight of acid-washed silica sand (<20 mesh). The soil-sand mixture was mixed thoroughly after being moistened with fine spray of deionized water to obtain a homogeneous mixture and prevent segregation during transfer to a leaching tube. The mineral N initially present was removed by leaching with 100 mL of 5 mM  $\text{CaCl}_2$  and incubated at either 20°C or 30°C. The N mineralized during incubation was removed by leaching with 5 mM  $\text{CaCl}_2$  every 2 weeks for up to 24 weeks. The volume of the leachate was adjusted to 100 mL, and the inorganic N was determined by steam distillation (Mulvaney 1996).

The nonlinear regression approach described by Stanford and Smith (1972) was used to solve the equation for mineralizable N pool ( $N_o$ ) and first-order rate constant ( $k$ )

$$N_m = N_o[1 - \exp(-kt)],$$

where  $N_m$  is amount of N mineralized at a specific time ( $t$ ). The Statistical Analysis System computer language was used to calculate  $N_o$  and  $k$  (Barr et al. 1976).

### Nitrification

The method involved treating a 10-g of field-moist soil (on an oven-dried basis) in an 8-oz (250 mL) French bottle with 2 mL of solution containing 2000  $\mu\text{g}$  N as  $(\text{NH}_4)_4\text{SO}_4$ ; added dropwise to moisten the whole soil. Controls were included by treating the soil sample with 2 mL of deionized water. The bottle was sealed with a rubber stopper and incubated at 30°C. Every 2 days, the bottle was aerated. At the end of 10 days, the  $(\text{NO}_3^- + \text{NO}_2^-)$ -N produced were extracted with 50 mL of 2 M KCl and determined by steam distillation as described by Mulvaney (1996). Percentage nitrification was calculated from  $[(A-B)/C] \times 100$ , where A and B represent the amount of  $(\text{NO}_3^- + \text{NO}_2^-)$ -N produced in the soil treated with  $\text{NH}_4^+$ -N and water, respectively, and C is the amount of  $\text{NH}_4^+$ -N added.

## Statistical Analysis

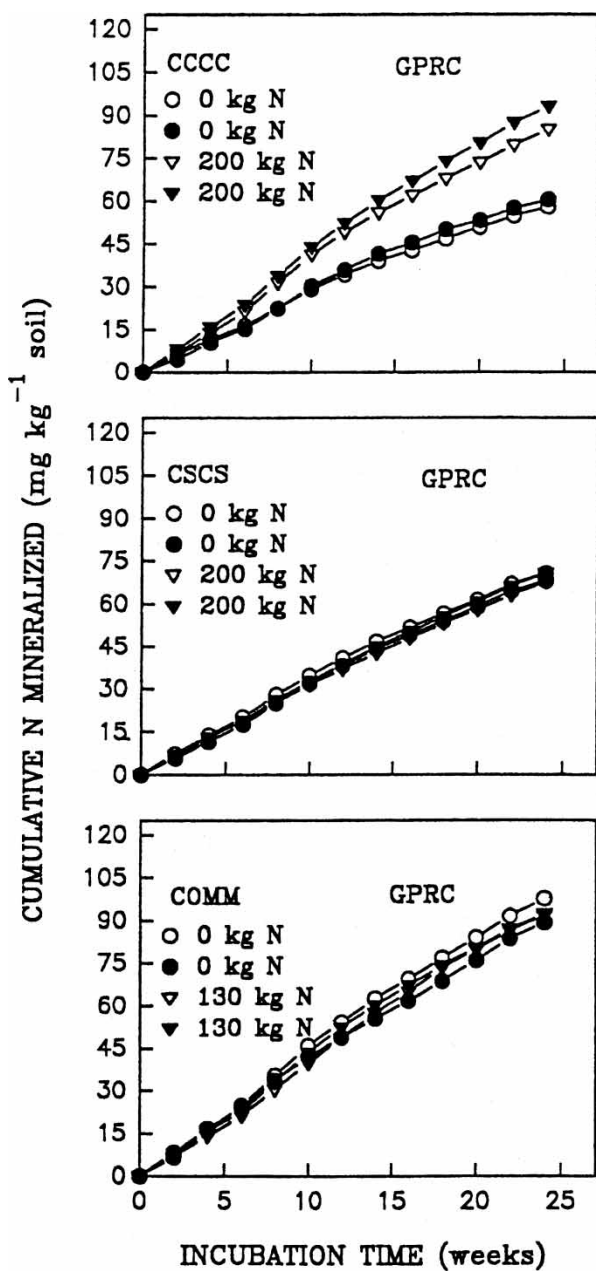
Statistical analyses were performed by using the General Linear Model procedure of the SAS system (1996). For all data points reported in the figures, the difference between the laboratory duplicates was smaller than the symbol size.

## RESULTS AND DISCUSSION

Studies of N mineralization in soils during incubation have been reported to follow one of four patterns: 1) immobilization of N during the initial period of incubation (Chae and Tabatabai 1986; Haque and Walmsley 1972); 2) a decline in the release of  $\text{NO}_3^-$  with time; 3) a constant and linear  $\text{NO}_3^-$  release with time over the duration of incubation (Tabatabai and Al-Khafaji 1980); or 4) a rapid release of  $\text{NO}_3^-$  during the first few days and a subsequent slow but linear  $\text{NO}_3^-$  release (Stanford and Smith 1972; Feigin et al. 1974).

### Effect of Cropping Systems on Nitrogen Mineralization

The cumulative amounts of N mineralized were initially slow but then increased rapidly; however, the mineralization patterns became somewhat linear after the 2nd week of incubation. The cumulative amounts of N mineralized in soils obtained from the GPRC site are plotted in Figure 1. The amount of N mineralized was affected by the cropping systems and N treatments (Table 1). The values, in general, varied among the soil samples of the two replicate plots. This was especially true for the CCCC cropping systems at the CWRC and GPRC sites and CSCS cropping systems at the CWRC site. Statistical analysis showed that the amounts of N mineralized in N treated and untreated soils under the COMM and CSCS cropping systems at the GPRC site were not significantly different (Figure 1 and Table 1). The means of cumulative N mineralized, expressed as percentages of organic N, were greater in N-treated than untreated plots under CCC and CSCS cropping systems at the GRPC site (Table 1). The greatest amount of N mineralized in the control plots (0 N treatment) was in the soils under COMM cropping systems. This shows the beneficial effect of legumes on soil organic matter and crop productivity in crop rotations (Deng and Tabatabai 2000). Such a rotation sequence may potentially provide available soil N through increase in soil organic matter, microbial biomass, and mineralizable N. Application of the log transformation of the data to calculate the potential mineralizable N ( $N_o$ ) and the first-order rate constants ( $k$ ) showed that, with one exception (untreated plots under CCCC at the CWRC site), the data obeyed the model proposed by Stanford and Smith (1972). Convergence of the nonlinear model did occur by using 50



**Figure 1.** Cumulative amounts of N mineralized in soils of four replicated field plots under various cropping systems at the GPRC site incubated at 30°C for 24 weeks.

Table 1. Effect of cropping systems on the cumulative amounts of N mineralized in soils incubated at 30°C for 24 weeks

Research center	Crop rotation <sup>c</sup>	N treatment kg ha <sup>-1</sup>	Cum. N mineralized <sup>a</sup> mg N kg <sup>-1</sup> soil			N mineralized <sup>b</sup>		
			R <sub>1</sub>	R <sub>2</sub>	Mean	R <sub>1</sub>	R <sub>2</sub>	Mean
Clarion-Webster at Kanawha	CCCC	0	63	66	64	2.5	2.6	2.6
	CSCS	180	125	138	132	4.5	5.5	5.0
		0	67	81	74	2.6	3.2	2.9
	COMM	180	106	141	123	4.0	5.1	4.6
LSD ( <i>p</i> < 0.05) <sup>d</sup> Galva-Pringhar at Sutherland	CCCC	0	58	60	59	3.1	3.3	3.2
		200	85	93	89	4.4	4.6	4.5
	CSCS	0	68	70	69	3.5	3.6	3.6
		200	68	71	70	3.2	3.6	3.4
LSD( <i>p</i> < 0.05)	COMM	0	89	98	94	4.0	4.7	4.4
		130	92	92	92	4.0	4.2	4.1
				21			0.8	

<sup>a</sup>R<sub>1</sub> and R<sub>2</sub> are field replicates.  
<sup>b</sup>N mineralized expressed as percentage of total organic N.  
<sup>c</sup>CCCC, continuous corn; CSCS, corn-soybean; COMM, corn-oats meadow-meadow.  
<sup>d</sup>Least significant difference.

Table 2. Effect of cropping systems on mineralizable N pools and first-order rate constants of soils incubated at 30°C for 24 weeks

Research center	Crop rotation <sup>b</sup>	N treatment kg ha <sup>-1</sup>	N <sub>o</sub> mg N kg <sup>-1</sup> soil <sup>a</sup>			<i>k</i> <sup>b</sup> × 10 <sup>3</sup> week <sup>-1</sup>		
			R <sub>1</sub>	R <sub>2</sub>	Mean	R <sub>1</sub>	R <sub>2</sub>	Mean
Clarion-Webster at Kanawha	CCCC	0	128	189	158	17	30	24
		180	—	—	—	—	—	—
	CSCS	0	467	652	560	9	14	12
		180	156	791	473	9	54	32
LSD ( <i>p</i> < 0.05) Galva-Primghar at Sutherland	COMM	0	225	333	279	10	19	14
		130	584	983	784	5	11	8
	CCCC	0	134	16	50	19	24	2
		200	272	338	151	14	16	22
LSD ( <i>p</i> < 0.05)	CSCS	0	319	382	305	12	14	15
		200	343	575	351	7	13	13
	COMM	0	174	257	459	13	22	10
		130	221	259	216	13	15	18
				240			14	
				94			3	

<sup>a</sup>N<sub>o</sub>, mineralizable N pool; *k*, first-order rate constant; R<sub>1</sub> and R<sub>2</sub> are field replicates.

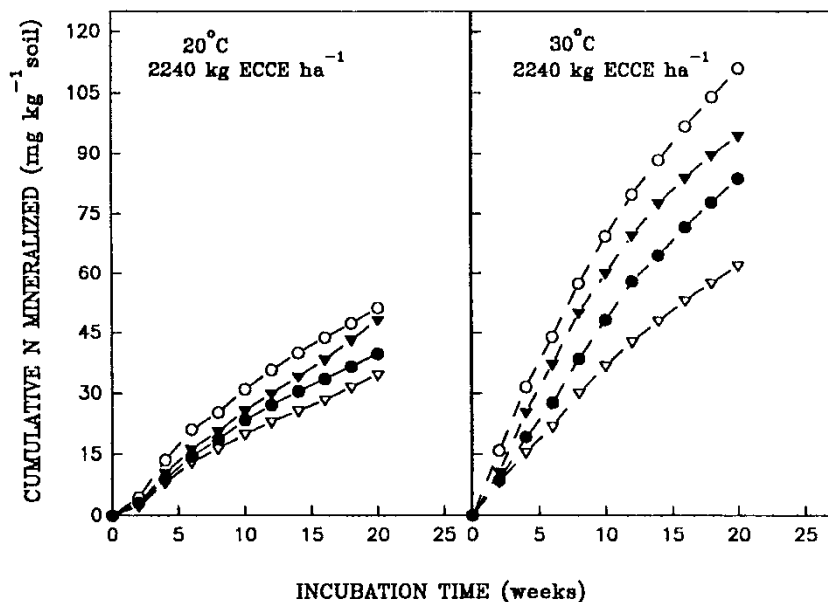
<sup>b</sup>CCCC, continuous corn; CSCS, corn-soybean; COMM, corn-oats meadow-meadow.



iterations or less. Several of the  $N_0$  and  $k$  values were significantly greater in samples from the N-treated plots than from those under untreated field plots (Table 2). These results suggest that there was abundant mineralizable N substrate in the field plots treated with N, but that mineralization rates were slower than those of the control plots.

### Effect of Lime Application on Nitrogen Mineralization

The cumulative amounts of N mineralized at both 20 and 30°C varied among the soil samples of the four replicated field plots treated with 2240 kg ECCE ha<sup>-1</sup> (Figure 2). The cumulative amounts of N mineralized at 20 and 30°C during 20 weeks of incubation of soils from the different lime treatments are presented in Table 3. The cumulative amounts of N mineralized at 20°C were not affected by the rate of lime application, but they were affected when the soils were incubated at 30°C (Table 3). Expressed as percentages of total organic N in soils, the cumulative amounts of mineral N produced ranged from 2.7 to 3.4% at 20°C of incubation, and from 5.8 to 7.5% at 30°C of incubation (Table 4). The  $Q_{10}$  values of N mineralization ranged from 1.9 to 2.3 and were similar in all lime treatments (Table 3). Dancer, Peterson, and Chesters (1973) also showed that liming soils to higher pH values did not affect N mineralization rates. In studies involving 40 acid



**Figure 2.** Cumulative amounts of N mineralized in soils of four replicated limed field plots at the NERC site incubated at 20 or 30°C for 20 weeks.

**Table 3.** Effect of lime application rates on N mineralization in soils during 20 weeks of incubation at 20 or 30°C

Lime applied kg ECCE ha <sup>-1</sup>	pH <sup>b</sup>	Cumulative N mineralized at temperatures specified (mg N kg <sup>-1</sup> soil) <sup>a</sup>		
		20°C	30°C	Q <sub>10</sub>
0	4.9	31.2–55.4 (41.8)	63.0–107 (79.3)	1.8–2.1 (1.9)
1,120	5.1	30.3–50.0 (35.9)	59.1–113 (75.5)	1.9–2.3 (2.1)
2,240	5.7	34.7–51.2 (43.5)	62.0–111 (87.9)	1.8–2.2 (2.2)
4,480	6.1	31.5–48.3 (40.5)	61.9–93.3 (80.6)	1.9–2.2 (2.0)
6,720	6.4	36.3–44.2 (40.6)	67.1–89.6 (78.2)	1.8–2.0 (1.9)
8,960	6.6	37.6–44.2 (41.6)	81.9–96.5 (92.0)	2.0–2.6 (2.3)
13,440	6.6	37.6–44.0 (41.6)	81.9–96.5 (92.0)	1.9–2.4 (2.1)
17,920	6.9	33.9–57.9 (43.2)	84.1–118 (96.2)	2.0–2.5 (2.2)
LSD ( $p < 0.05$ ) <sup>c</sup>		11.6	22.8	0.3

<sup>a</sup>Figures in parentheses are means of samples from four replicated field plots.<sup>b</sup>Mean of four replicated field plots (soil: 0.01 M CaCl<sub>2</sub> solution ratio, 1 : 2.5).<sup>c</sup>Least significant difference.

surface soils (pH 4.0–5.6), Nyborg and Hoyt (1978) showed, however, that the cumulative amounts of N mineralized increased twofold during a 4-week incubation when the soil pH was increased to 6.7 by liming; this effect was not permanent because no enhancement in N mineralization was observed after 1 or 2 years.

**Table 4.** Effect of lime application rates on percentage of N mineralized in savoiils incubated for 20 weeks at 20 or 30°C

Lime applied (kg ECCE ha <sup>-1</sup> )	N mineralized at temperature specified (%) <sup>a</sup>	
	20°C	30°C
0	2.3–4.4 (3.3)	4.8–8.4 (6.2)
1,120	2.3–3.8 (2.7)	4.6–8.6 (5.8)
2,240	2.9–3.6 (3.4)	5.1–7.7 (6.7)
4,480	2.5–3.8 (3.2)	4.9–7.3 (6.3)
6,720	2.8–3.6 (3.2)	5.2–7.3 (6.1)
8,960	2.6–3.6 (3.1)	6.0–7.6 (6.8)
13,440	2.7–3.5 (3.2)	6.4–7.6 (6.8)
17,920	2.8–4.2 (3.4)	6.8–8.5 (7.5)
LSD ( $p < 0.05$ ) <sup>b</sup>	0.8	1.6

<sup>a</sup>N mineralized expressed as percentage of total organic N. Figures in parentheses are means of samples from four replicated field plots.<sup>b</sup>Least significant difference.

**Table 5.** Effect of lime application rates on mineralizable N pools and first-order rate constants of soils incubated at 20°C for 20 weeks<sup>a</sup>

Lime applied (kg ECCE ha <sup>-1</sup> )	N <sub>o</sub> (mg N kg <sup>-1</sup> soil)	k × 10 <sup>3</sup> (week <sup>-1</sup> )
0	94–147 (123)	15–24 (21)
1,120	72–142 (100)	19–27 (23)
2,240	83–96 (90)	27–41 (32)
4,480	73–91 (92)	28–46 (37)
6,720	64–121 (92)	18–54 (36)
8,960	66–90 (81)	30–42 (36)
13,440	68–107 (87)	22–50 (37)
17,920	75–94 (84)	29–49 (36)
LSD ( <i>p</i> < 0.05) <sup>b</sup>	28	14

<sup>a</sup>N<sub>o</sub>, mineralizable N pool; *k*, first-order rate constant. Figures in parentheses are averages of samples from four replicated field plots.

<sup>b</sup>Least significant difference.

The log transformation of the data in Table 3 to calculate the *N*<sub>o</sub> and *k* values showed that the data obeyed the exponential equation proposed by Stanford and Smith (1972). Increasing the lime application rate decreased the *N*<sub>o</sub> at 20°C of incubation (Table 5), but not at 30°C of incubation (Table 6). The *N*<sub>o</sub> values at 30°C of incubation were not uniform among the soil of the four replicated plots due to spatial variability (Tables 5 and 6). Even though *N*<sub>o</sub> and *k* values may provide estimates of the N-supplying power of soils, a major disadvantage in obtaining these values is that

**Table 6.** Effect of lime application rates on mineralizable N pools and first-order rate constants of soils incubated at 30°C for 20 weeks<sup>a</sup>

Lime applied (kg ECCE ha <sup>-1</sup> )	N <sub>o</sub> (mg N kg <sup>-1</sup> soil)	k × 10 <sup>3</sup> (week <sup>-1</sup> )
0	128–194 (160)	21–40 (37)
1,120	102–161 (124)	39–63 (50)
2,240	128–227 (174)	24–48 (38)
4,480	138–191 (159)	20–57 (39)
6,720	107–138 (124)	46–57 (50)
8,960	140–217 (168)	31–52 (42)
13,440	148–218 (173)	26–42 (37)
17,920	120–176 (157)	33–64 (50)
LSD ( <i>p</i> < 0.05) <sup>b</sup>	36	17

<sup>a</sup>N<sub>o</sub>, mineralizable N pool; *k*, first-order rate constant. Figures in parentheses are averages of samples from four replicated field plots.

<sup>b</sup>Least significant difference.

**Table 7.** Effect of lime application rates on nitrification in soils

Lime applied (kg ECCE ha <sup>-1</sup> )	Nitrification rate (%) <sup>a</sup>				
	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	R <sub>4</sub>	Mean
0	44	20	24	21	27
1,120	23	49	23	22	29
2,240	40	31	25	28	31
4,480	61	39	49	26	44
6,720	50	42	53	43	47
8,960	67	77	56	54	64
13,440	65	74	66	64	67
17,920	81	79	80	66	77
LSD ( $p < 0.05$ ) <sup>b</sup>					14

<sup>a</sup>R, replicates, subscript indicates replicate plot number.

<sup>b</sup>Least significant difference.

incubations are time-consuming and do not consider fluctuation in the soil environment.

### Effect of Lime Application on Nitrification

Liming soils markedly increased the nitrification rate (Table 7), suggesting that liming stimulated the microbial population and, perhaps, the enzymes responsible for nitrification in soils. Studies on oxidation of ammonium sulfate by soil organisms have shown three patterns (Morrill and Dawson 1967): 1) oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  with the formation of significant amounts of  $\text{NO}_2^-$  as an intermediate, 2) oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  with formation of trace amounts of  $\text{NO}_2^-$  during the first few days of incubation, and 3) oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  without formation of  $\text{NO}_2^-$ . Other studies by Morrill and Dawson (1967) showed that treating soils with lime to contain free phase of  $\text{CaCO}_3$  lead to changes in the  $\text{NH}_4^+$  oxidation pattern, with significant formation of  $\text{NO}_2^-$  as an intermediate. In the studies reported here, we could not detect  $\text{NO}_2^-$  by the sensitive Griess-Ilosvay colorimetric method (Mulvaney 1996) (i.e., the  $\text{NH}_4^+$ -N added was converted to  $\text{NO}_3^-$ -N). This could be the result of incubating the soils for 14 days; normally,  $\text{NO}_2^-$ -N appears within 5 and 12 days of incubation. Another reason for the lack of the detection of  $\text{NO}_2^-$ -N could be because the lime-treated soils we used did not contain a free phase of  $\text{CaCO}_3$ . The increase of  $\text{NH}_4^+$  oxidation rate with lime treatment (increasing soil pH) supports the recent findings that lime application increases many of the enzymes involved in C, N, P, and sulfur (S) cycling in soils (Acosta-Martínez and Tabatabai 2000).

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