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Estimating Soil Mineralizable Nitrogen under Different Management Practices

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ABSTRACT

Predicting in situ nitrogen (N) mineralization has been one of the greatest challenges to improving N management in agriculture. This study investigated the effect of tillage and residual N on soil N supplying capacity and evaluated the relationship between measured and estimated mineralizable N. The experiment was established in 1990 on a moderately well-drained Kennebec silt loam (Fine-silty, mixed, superactive mesic Cumulic Hapludoll) with continuous corn (*Zea mays* L.). The study was a split-split plot design replicated four times. The main plot treatment was tillage (no-tillage [NT] and conventional tillage [CT]), the subplot treatment was N source (manure and NH_4NO_3 fertilizer [F]), and the sub-subplot treatment was the length of residual period. Residual N was studied 1 yr after cessation of a 10-yr N application (R_1) and 6 yr after cessation of a 5-yr N application (R_6). Measured in situ N mineralization (N_{min}), laboratory potentially mineralizable N (N_o), and estimated N mineralization under field conditions ($N_{estimated}$) were evaluated. Nitrogen mineralization was studied in situ in an unplanted, sheltered area. Samples were collected from 0- to 5-, 5- to 15-, and 15- to 30-cm depths. No-tillage and manure significantly increased soil total N, N_{min}, and N_o. The combination of NT and manure significantly increased N_o in both R_1 and R_6. High correlation was observed between N_{min} and $N_{estimated}$ for 0 to 5 cm (r = 0.79) and for 0 to 30 cm (r = 0.77). No-tillage and manure sustained soil N 6 yr after discontinued N application. Potential mineralizable N, for site specific conditions could be used to estimate in situ N mineralization after adjustment to field conditions (soil water and temperature).

NITROGEN MANAGEMENT is important in efficient crop production. The main sources of N used by crops are from: (i) mineralization of soil organic N; (ii) decomposition of plant residues or organic amendments such as manure; and (iii) addition of N as inorganic fertilizer. Inefficient use of N fertilization is likely to cause undesirable environmental impacts from NO_3^- leaching or gaseous N losses by denitrification and/or volatilization. Improved estimates of the contributions to soil N to crop production are needed to minimize environmental impacts and production costs from overuse of N fertilizer, (Rice and Havlin, 1994). Soil N mineralization has been shown to provide 20 to 80% of the N required by plants (Broadbent, 1984).

Fertilizer N enters the soil organic pool via plant residue and by microbial immobilization (Stanford et al., 1973; Bengtsson et al., 2003). Mineralization of soil organic matter (SOM) and crop residue is a complex process that depends on management, soil properties, crop residue quantity/quality, and environmental conditions (Rice and Havlin, 1994; Trinsoutrot et al., 2000). Motavalli et al. (1992) reported that N furnished from SOM significantly increased corn N uptake and grain yield 7 yr after discontinuation of long-term (25 yr) N fertilizer applications.

Tillage systems affect the N mineralization rate (Rice and Havlin, 1994) and soil organic N level. No-tillage increases soil organic N as a result of accumulated crop residues at the soil surface, reduced soil disturbance, and improved soil aggregation (Mikha and Rice, 2004). Readily decomposable organic materials, such as crop residues or animal wastes, are annually added to agricultural soils (Van Kessel and Reeves, 2002). Manure is an important source of plant nutrients (Zaman et al., 2004), and has been shown to increase soil total N (Mikha and Rice, 2004) and improve the nutrient status of the soil (Zaman et al., 2004). Eghball and Power (1999) reported that 58% of beef manure N was available for plant uptake the first 2 yr after application.

During the last 30 yr, considerable research has been directed toward development of N mineralization assessment methods. These methods include both field and laboratory techniques that can be applied to estimated soil-N supply for crop production on a yearly basis (Stanford and Smith, 1972; Van Kessel and Reeves, 2002; Gurlevik et al., 2004). Measuring soil N mineralization in situ is not an easy task, and various methods exist. The buried bag method (Eno, 1960), the open-end polyvinyl chloride (PVC) tube method (Kolberg et al., 1997; Gurlevik et al., 2004) and small sheltered soil (Rice et al., 1987) are methods to determine N mineralization under field conditions. All of these methods have limitations but they attempt to capture the variations in environmental conditions that the laboratory methods for estimating the pool of mineralizable N are unable to translate to field conditions (Rice and Havlin, 1994).

A laboratory technique was proposed by Stanford and Smith (1972) to determine potentially mineralizable N (N_o), and the mineralization rate constant (k) by an incubation-leaching method, to characterize soil available N. This incubation technique has been widely used to characterize soil N mineralization and to determine the effect of management practices on soil nutrient supply capacity (Boyle and Paul, 1989; Rice and Garcia, 1994). Stanford and Smith (1972) proposed measuring net N mineralized under laboratory conditions, fitting

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Abbreviations: CT, conventional tillage; DOY, day of year; F, NH_4NO_3 fertilizer; $N_{estimated}$, estimated potentially mineralizable N from field conditions; N_{min}, measured in situ N mineralization; N_o, potentially mineralizable N; NT, no-tillage; R_1, 1 yr after cessation of a 10-yr N application; R_6, 6 yr after cessation of a 5-yr N application; SOM, soil organic matter.

the results to a first-order model to determine N_o and k, and using the model to estimate N mineralization from SOM under field conditions. To estimate N mineralization in situ ($N_{estimated}$), the k is corrected for field soil temperature using a nonlinear temperature dependence equation (Das et al., 1995) and the amount of mineralized N estimated by the first-order model is adjusted for soil water content (Myers et al., 1982).

The combination of NT and manure can increase SOM, and, thus, organic N; however, the sustained effect of these practices on the N supplying capacity of the soil and the estimated amount of in-season N mineralization have not been well quantified. There is a lack of information on the effect of management practices and manure addition on long-term N supplying capacity of the soil. Research with different soil N levels and with different tillage practices will improve our knowledge to support field N management. In this study, different residual N sources and a no-N treatment in combination with two tillage practices (NT and CT) resulted in potentially 10 levels of soil N-supplying capacity. The objectives of this study were to determine the effects of long- and short-term residual N application and source, and tillage practices on (i) potential mineralizable N and the mineralization rate constant; (ii) N_{min}; and (iii) the relationship between N_{min} and $N_{estimate}$.

MATERIALS AND METHODS

Site Description and Experimental Design

Our research employed soil whose properties resulted from a 10-yr continuous corn (*Zea mays* L.) tillage-N source study established in 1990 at the Kansas State University North Agronomy Farm in Manhattan, KS. The soil was a moderately well-drained Kennebec silt loam.

Long-term treatments imposed at this site included tillage and N source. The initial experiment was tillage treatments were NT and chisel-disk (fall chisel plow and spring offset disk). Nitrogen source treatments were control (C—no N applied), solid beef manure, and NH_4NO_3 fertilizer (F). The NH_4NO_3 was applied broadcast in spring before corn planting at an annual rate of 168 kg N ha^{-1}.

Each year, manure was sampled and analyzed for NH_4^+ and NO_3^- before application. The 168 kg N ha^{-1} of manure application rate was calculated assuming that 100% of the NH_4^+–N was available and 35% of the organic N was mineralized the first year (Gilbertson et al., 1979). In 1995, the plots (15 m × 6 m) were split (7.5 m × 6 m), and one half continued to receive N (applied treatments) while N application was discontinued on the other half (residual treatments).

Corn (hybrid Pioneer 33G28) was planted in the spring at a seeding rate of 50 494 seed ha^{-1}. Weeds were controlled by applying a rate of 4.76 L ha^{-1} of Bicep (Syngenta, Greensboro, NC), which is comprised of 321 g L^{-1} and 400 g L^{-1} of S-metolachlor approximately 4 wk after corn emergence. After the last manure-N applications were made in 1999, we investigated residual (R) field N mineralization 1 yr after cessation of 10 yr of N application (R_1) and 6 yr after cessation of 5 yr of N application (R_6). The experiment design was a split-plot in a completely randomized block with four replications. Tillage (NT and CT) was the main plot treatment, and N source (manure, NH_4NO_3, and 0-N control) in either R_1 or R_6 was the subplot treatment. Analysis for R_1 and R_6 as affected by tillage and fertilizer source were determined separately in a split-plot design. A split-split-plot design was employed to compare R_1 vs. R_6, where residual N was the sub-subplot treatment.

Soil Sampling

Soil cores (2-cm diam.) were taken from the R_1 and R_6 residual period at a depth of 0 to 5 cm on 29 Oct. 1999, approximately 3 wk after corn harvest for laboratory incubation and total C and N. All samples were presieved (6-mm diam.) and stored at field moisture and 4°C before analysis. In situ N mineralization was determined throughout corn vegetative stage in summer of 2000.

Soil Total Nitrogen

Air-dried soil subsamples were ground to a fine powder using a mortar and pestle after removing the roots. Soil samples were analyzed for total N content by direct combustion using a C/N Analyzer (Carlo Erba Instruments, Milano, Italy[1]).

Nitrogen Mineralization

The residual effects of 5 and 10 yr of N application, 1990–1994 and 1990–1999 respectively, were estimated in 2000 by two methods, N_{min} and N_o from laboratory incubations.

In situ Nitrogen Mineralization

In spring of 2000, shelters were used to evaluate in situ N_{min} over a fallow area previously planted to corn in 1999, as was preformed previously by Rice et al. (1987). An area (90 × 90 cm) was covered with a wooden top placed 40 cm above the soil surface to minimize denitrification and leaching from direct precipitation. No plants or weeds were allowed to grow inside the shelter and within 30 cm around the shelter to minimized water and nutrient uptake. Soil temperatures, under the shelters, were determined at 5 cm using thermocouples and recorded hourly with microprocessor-based HOBO data loggers (Onset Computer Corp., Bourne, MA) in one replicate of each treatment except the control. In previous work, the difference in soil temperature was <1°C between the sheltered and unsheltered soil (Espinoza, 1997). The soil water content under shelter was within the range of soil water outside the shelter but with less fluctuation (Mikha, 1998). The shelters were painted white to reflect solar radiation and minimize heat build up. To determine N_{min} throughout the vegetative stage, the shelters remained in the field from 17 Apr. 2000 until 23 June 2000, which corresponded to day of year (DOY) 108 to 176. Nitrogen mineralization was estimated by sampling soil for inorganic N under the shelter (near the center, two cores per sample) with a 2-cm diam. probe at 0- to 5-, 5- to 15-, and 15- to 30-cm depths once per month. Soil samples were sieved through a 6-mm sieve and stored at 4°C until analyzed. Gravimetric soil water content (SWC) was determined by weight loss at 105°C for 24 h. Field-moist soil (20 g) was extracted with 100 mL of 1 *M* KCl by shaking for 1 h on an orbital shaker at 300 RPM and filtering the supernatant through Whatman filter paper (2W). Extracts were stored at 4°C until analyzed for NH_4^+–N and NO_3^-–N on an Alpkem Autoanalyzer (Alpkem Corp., Bulletins A303-S021 and A303-S170). Net N_{min} in soils under shelters was calculated using Eq. [1]

$$N_{min} = \text{Inorganic } N_{(\text{at each sampling time})} - \text{Inorganic } N_{(\text{Planting})} \quad [1]$$

[1] Trade names are mentioned for the benefit of the reader and do not imply endorsement by USDA-ARS nor do they imply criticism of similar products not mentioned.

Nitrogen added through rainfall was not considered since this would be uniform across the study area. Nitrogen losses were not considered, thus this approach underestimates N_{min}.

Laboratory Nitrogen Mineralization

Potentially mineralizable N (N_o) and the rate constant (k) were determined by laboratory incubation and applying a first-order exponential model. This procedure was based on the leaching method proposed by Cabrera and Kissel (1988a) as modified by Garcia (1992). Briefly, based on soil water content and assuming a bulk density of 1.05 g cm^{-3}, 106 g soil (oven dry basis) from each field replicate was sieved through a 6-mm mesh and packed (at field moisture) into PVC cores (5.08-cm diam., 10-cm high) to a depth of 5 cm. A 149-μm polyethylene filter (Fisher Scientific, Pittsburgh, PA) was glued to the bottom of the cores to keep the soil intact inside the core. The cores were stored at 4°C until initiation of the incubation period. During leaching for mineralized N, the cores were placed on Buchner funnels (7-cm diam.) that were attached to a side-arm 500-mL Erlenmeyer flask connected to a vacuum pump. A 10-μm nylon filter (Magna, Nylon, Osmonics Inc.) with a bubble-point pressure of 0.0685 MPa was glued to the bottom of the funnels. The bubble-point pressure of the filter allowed for soil equilibration to a water potential of −0.033 MPa. A 3- to 4-mm thick layer of glass beads (solid glass spheres, 29-μm mean particle size, Potters Industries Inc., Brownwood, TX) was added to the top of the filter before leaching to maximize the contact between the filter and the soil. Each core was leached with 500 mL of 0.01 *M* $CaCl_2$. The NH_4^+ and NO_3^- concentrations were determined on an Alpkem Autoanalyzer (Alpkem Corp., Bulletin A303-S021 and A303-S170, Clackamas, OR). An N-free nutrient solution (50 mL) was added to each core and a vacuum of −0.033 MPa was applied for 6 h to adjust to a constant water content after leaching (Cabrera and Kissel, 1988a). Subsequent leachings were performed in a similar manner after 7, 14, 21, 28, 42, 56, 84, 112, 139, 167, 196, 225, 250, 275, 303, and 328 d. Between leaching events, the cores were placed in 950-mL Mason jars and incubated at 35°C.

Nitrogen Mineralization Model

The Marquardt option of SAS PROC NLIN, a nonlinear curve fitting procedure (SAS Institute, 1999) was used to fit a one-factor model (Stanford and Smith, 1972; Molina et al., 1980) to determine cumulative potentially mineralizable N (N_o). The model is

$$N_m = N_o(1 - e^{-kt}) \quad [2]$$

where N_m is mineralized N (mg N kg^{-1}); N_o is potentially mineralizable N (mg N kg^{-1}); *k* is rate constant (d^{-1}); *t* is time (d).

Field Nitrogen Mineralization Estimation ($N_{estimated}$)

Stanford and Smith (1972) proposed a method for estimating N mineralization from SOM. They proposed measuring the net N mineralized under laboratory incubation conditions and fitting the result to a first-order model of N mineralization to determine N_o and mineralization rate constant (*k*). In this study, to estimate N mineralization in the field, a model developed by Campbell et al. (1984) was used for the 2000 growing season. The amount of N mineralized estimated by the first-order model is adjusted for soil water content (Myers et al., 1982) and the *k* is corrected for field soil temperature using a nonlinear temperature dependence equation (Das et al., 1995). The mineralization rate constant (*k*) was derived from optimum temperature (35°C) and soil water content (−0.033 MPa).

The N mineralization rate was adjusted for soil water content by the relationship between relative N mineralization and relative available soil water content (Myers et al., 1982) as described below:

$$y = bx + (1 - b)x^2 \quad [3]$$

where *y* is net mineralization expressed as a fraction of the maximum rate; *b* is a coefficient

$$x = \frac{(M - M_o)}{(M_{max} - M_o)} \quad [4]$$

where *M* is actual soil moisture content (cm^3 cm^{-3}); M_{max} is soil moisture content (cm^3 cm^{-3}) at −0.03 MPa; M_o is soil moisture content (cm^3 cm^{-3}) at −10 MPa.

For the Kennebec silt loam soil used for this study, M_o was extrapolated from the moisture release curve. We calculated M_{max} = 0.26 cm^3 cm^{-3}, M_o = 0.11 cm^3 cm^{-3}, and we considered $b = 1$ according to Myers et al. (1982). To adjust the mineralization rate as affected by soil temperature (*T*), the following relationship was used as described in Das et al. (1995):

$$\frac{k_1}{k} = Q_{10}^{\frac{(T - T_o)}{10}} \quad [5]$$

where k_1 is the modified rate constant adjusted for soil temperature (in situ); *k* is the rate constant at optimum temperature (35°C); Q_{10} is the response relationship between (*k*) and (*T*); *T* is the field soil temperature (°C); T_o = Incubation temperature (35°C).

In our calculation a $Q_{10} = 2$ was used as reported in many studies (Stanford et al., 1973; Campbell et al., 1981, 1984). The adjusted model expressed by Campbell et al. (1984) was:

$$N_{estimated} = N_o\,[1 - e^{-k_1 t y}] \quad [6]$$

where $N_{estimated}$ is cumulative estimated field N mineralization (mg N kg^{-1}); N_o is potentially mineralizable N (mg N kg^{-1}); k_1 is the modified rate constant for temperature (wk^{-1}); *t* is time (wk); *y* is net mineralization as affected by soil water content.

The daily soil water content required to calculate (*y*) was measured at the initial sampling date, 17 April, then once a month throughout the 2000 growing season. The TRANSPOR model (Benjamin et al., 1990a) was used to predict daily soil water contents between the times of gravimetric water content measurements and to predict soil temperatures at soil depths (15 and 30 cm) other than those measured with the thermocouple (5-cm depth). The TRANSPOR model is a finite element model of coupled water and heat transport. A finite element grid was created to simulate one half of the protective shelter and surrounding soil (Fig. 1).

Soil hydraulic properties were determined from paired soil water pressure potential (ψ)–soil volumetric water content (θ_v) measurements determined from laboratory cores taken from the site. A nonlinear least squares fit of desorption data provided the van Genuchten coefficients (van Genuchten, 1980) to describe ψ–θ_v and hydraulic conductivity (*K*)–θ_v relationships. Least squares fit of the water desorption data grouped by tillage treatment resulted in virtually identical van Genuchten coefficients, so only one desorption curve was used to predict water contents. The values for the van Genuchten coefficients were: α = 0.035 (cm^{-1}), *n* = 1.18, θ_s = 0.45 (m^3 m^{-3}), and θ_r = 0.0 (m^3 m^{-3}). No saturated hydraulic conductivity (K_{sat}) data were available for the site so K_{sat} estimates were made from a

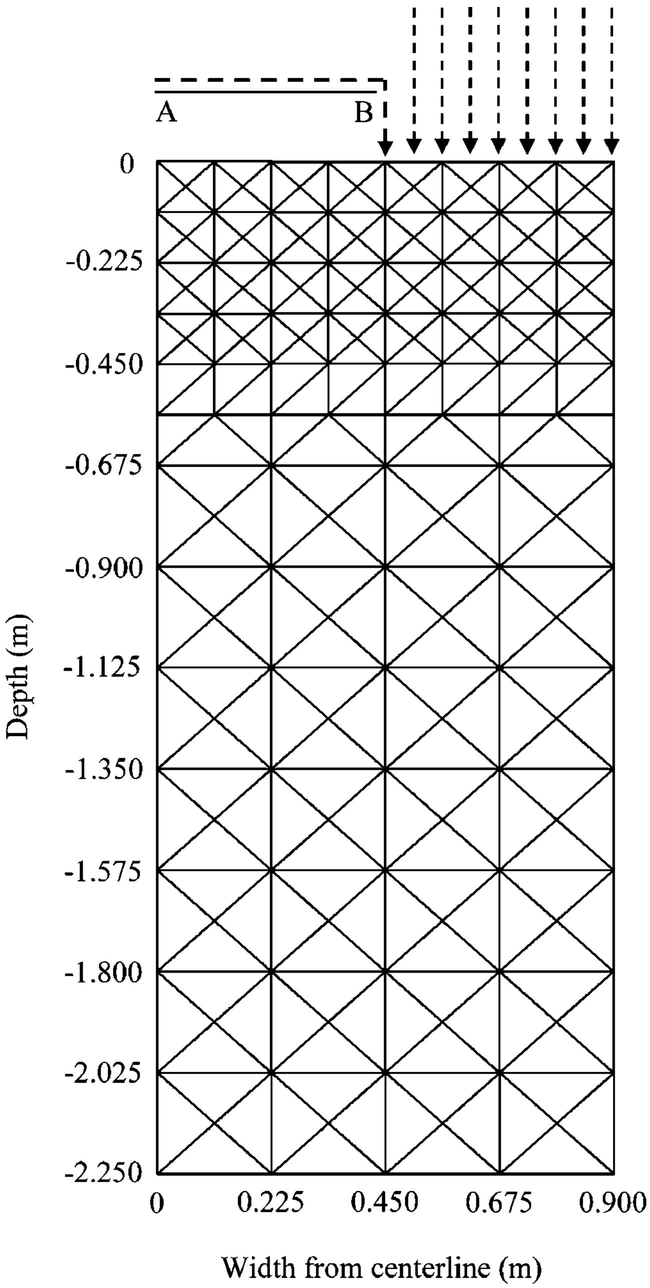

Fig. 1. Diagram showing the finite element grid for modeling water and heat movement. The line A-B represents the shelter (1/2 surface area). The dash lines represent the elements that received rainfall in the simulations. The heavy dash line indicated the runoff from the top of the shelter into the elements directly under the edge of the shelter.

similar soil in the same geographic region (Benjamin et al., 1990b) and specified at 2 cm h^{-1}.

The initial conditions for soil water and temperature distribution were based on measurements taken on April 17. The initial soil water potential was −800 kPa for the 0- to 5-cm depth, −200 kPa for the 5- to 15-cm depths, and −100 kPa for depths below 15 cm. The initial temperature was 13°C for the 0- to 5-cm depth, 15°C for the 5- to 15-cm depth, and 20°C for depths below 15 cm. The lower boundary of the simulation region was specified at −100 kPa soil water pressure potential and 20°C soil temperature for the duration of the simulation.

Weather conditions for the simulation were taken from the weather station located at Manhattan, KS. Weather data used for the model include global radiation, maximum and minimum air temperature, relative humidity, wind speed, and daily rainfall. Meteorological data was modified on the surface boundary to account for the influence of the shelter. The shelter is indicated by the line A-B (Fig. 1). Elements not underneath the shelter were subjected to the normal weather conditions as measured at the weather station. Elements under the shelter did not receive any global radiation or rainfall, but had normal air temperature and relative humidity. Wind speed under the shelter was modified by only using 1/4 of the wind measured for the day. The volume of water in rainfall that fell on the surface of the shelter was directed to the elements directly beneath the edge of the shelter. The $N_{estimated}$ was converted from mg N kg^{-1} to kg N ha^{-1} by multiplying the appropriate bulk density at the 5-cm depth. Using the bulk density at different depths, soil inorganic N was integrated to the 0- to 30-cm depth.

Statistical Analyses

Data were analyzed using a split-plot in randomized complete block design with tillage as the whole plot factor and N source as the subplot factor. A split-split-plot design was applied to compare R_1 vs. R_6 where residual N was considered the sub-subplot. The analysis of variance (ANOVA) F-test was used to test treatment factor main effects and interactions. F-protected *t* test was used to test pairwise comparisons to follow up any significant findings. The analysis of variance and mean separation difference was performed using Proc Mixed of the SAS system (SAS Institute Inc, 1999). All results were considered significantly different at $p < 0.05$ unless noted otherwise.

RESULTS

Simulation results for soil temperature at 5 cm (Fig. 2) showed that the model predicted soil temperature to within 5°C. Most of the predicted soil temperatures were within 1 to 2°C of measured values. The model was also able to capture the wide variations in soil temperature caused by changing weather conditions. The model was also used to predict soil temperature at the 15- and 30-cm depth. Comparison of measured versus modeled soil water content (Fig. 3) showed that the model was within 0.01 to 0.02 m^3 m^{-3} water content difference for each sampling period at each depth. Considering that the measured water content range at a specified pressure potential as measured in the laboratory could vary by as much as 0.06 m^3 m^{-3}, we considered this accuracy within reason. The simulation results for daily water content (0- to 30-cm depth) were used in N mineralization prediction at this depth.

Annual manure application for 10 consecutive years under NT resulted in significantly more total soil N compared with the other tillage-N treatment combinations (Table 1). The significant interaction between tillage and N source indicated soil N was conserved to a greater extent when NT was used in conjunction with manure application (Table 1). In 1999, the combination of tillage (NT and CT), N sources (manure, NH_4NO_3, and 0-N control) and residual periods (R_1 and R_6) generated 10 potential levels of soil N-supplying capacity for crop

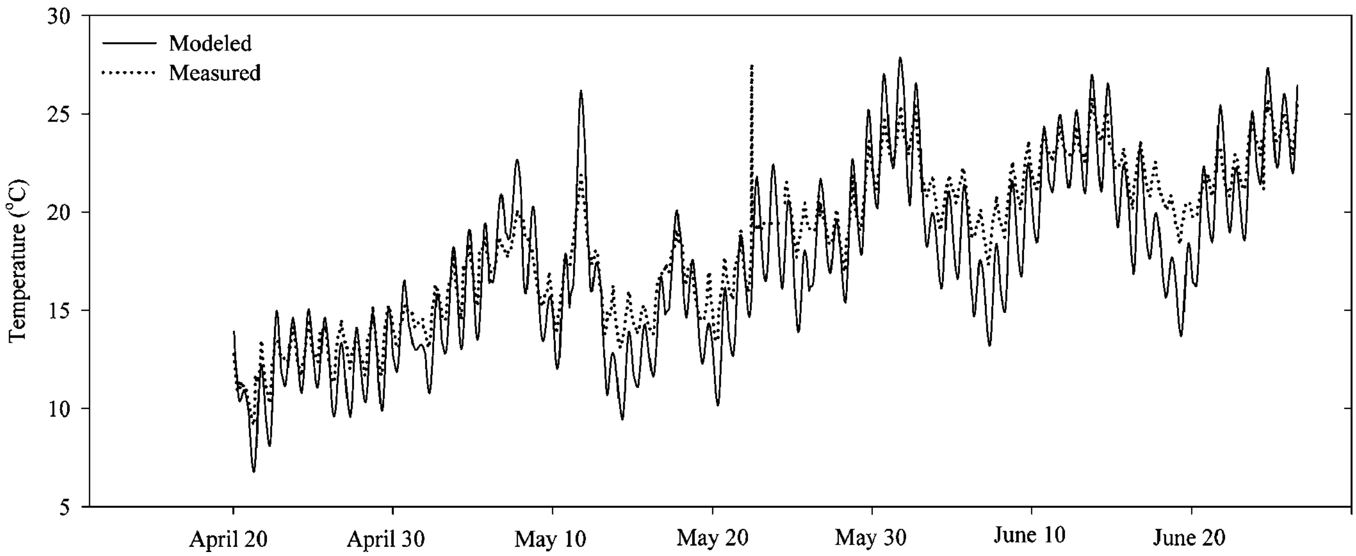

Fig. 2. The accuracy between measured and modeled soil temperature (for the Year 2000) under the shelter at the 0- to 5-cm depth using TRANSPOR model.

production. Six years after the cessation of manure application, total soil N was diminished, although total soil N remained significantly greater with NT compared with CT (Table 1). The length of the residual period (R_1 vs. R_6) did not significantly affect total soil N. However, the three-way interaction (Tillage × N-source × R-period) was significant, reflecting the loss of soil N in the NT-manure treatment over the 6 yr after N application was discontinued (Table 1).

Potentially mineralizable N in the 0- to 5-cm depth increment was significantly affected by tillage × N source interaction ($p < 0.05$) in both R_1 and R_6 periods (Table 2). Compared with NH_4NO_3 and 0-N control treatments, the combination of manure and NT significantly increased N_o in both R_1 and R_6 residual periods. The length of residual period (R_1 vs. R_6) did not significantly affect N_o; this suggests that this soil conserved SOM 6 yr after N application was discontinued. The mineralization rate constant (k) was significantly affected by N source. Averaged across tillage, k was significantly greater for NH_4NO_3 (0.00437 d^{-1}) and 0-N control (0.00455 d^{-1}) compared with manure (0.00250 d^{-1}) for R_6 residual period (Table 2). The reduction of k and the increase in N_o suggests the manure treatment had a higher substrate concentration but a lower decomposition rate compared with the NH_4NO_3 and the 0-N control treatments indicating differences in substrate quality.

To evaluate N_{min}, soil N contribution was evaluated under the shelter from DOY 108 to 176 (planting to tasseling) to a depth of 30 cm. Tillage did not significantly affect soil N availability in R_1, but NT significantly increased soil available N compared with CT in R_6 (Table 3). Soil available N was significantly affected by a time × N source interaction (Table 3). No significant differences in available N were observed between R_1 and R_6 at any sampling date.

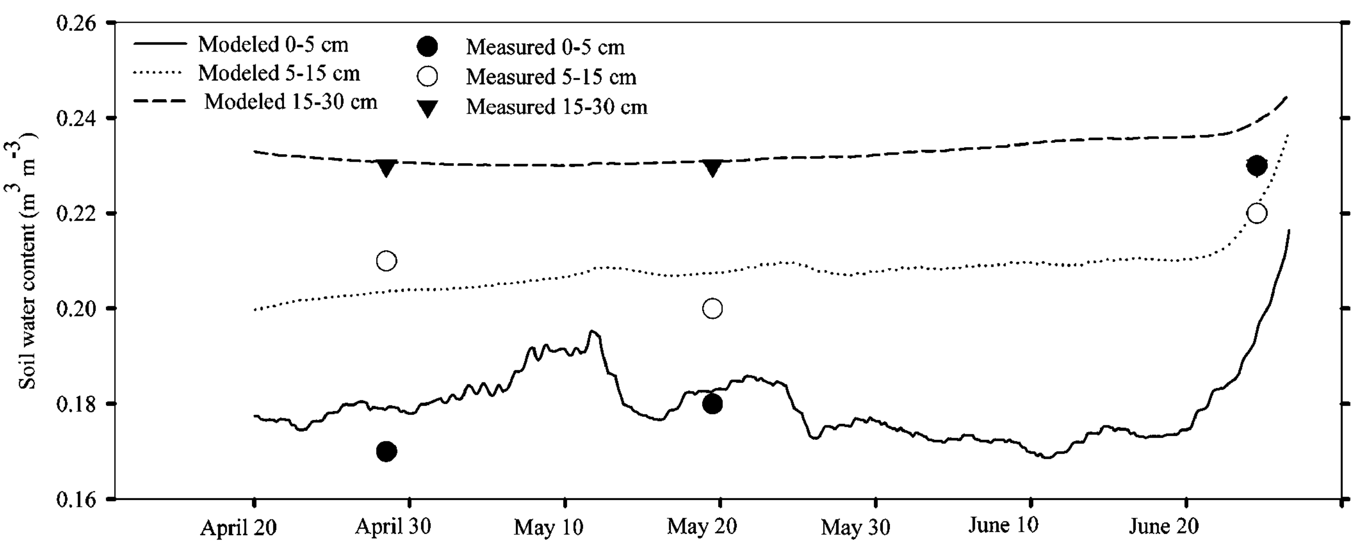

Fig. 3. Measured and modeled soil water content under the shelter for 0- to 5, 5- to 15-, and 15- to 30-cm depths for the Year 2000.

Table 1. Total N, 0 to 5 cm, as affected by no-tillage (NT), conventional tillage (CT), manure (M), NH_4NO_3 (F), and 0-N control (C) management practices after 10 yr of N application with 1 yr residual (R_1) and 5 yr of N application with 6 yr residual (R_6).

Treatment	R_1	R_6
	Total N	
	Mg ha^{-1} soil	
NT-M	2.3 a†A‡	1.9 B
NT-F	1.9 b B	1.9 B
NT-C	1.9 b B	1.9 B
NT (Mean)	2.0 ^{x}§	1.9 ^{x}
CT-M	1.7 c BC	1.8 BC
CT-F	1.7 c BC	1.6 C
CT-C	1.6 c C	1.6 C
CT (Mean)	1.6 ^{z}	1.6 ^{z}
	PR > F	
Tillage (T)	0.005	0.02
N source (NS)	0.002	0.2
T × NS	0.003	0.1
Residual period (R)	0.1	
T × NS × R	0.008	

† Mean with different lowercase letter among all management practices within each residual period (T × NS) are significantly different (ANOVA); $P < 0.05$.
‡ Mean with different uppercase letter between residual periods (T × NS × R) are significantly different (ANOVA); $P < 0.05$.
§ Mean with different in superscripts lowercase letter between tillage practices within each residual periods are significantly different (ANOVA); $P < 0.05$.

Net N mineralization under the shelter (N_{min}) at tasselling (DOY 176) was calculated by the differences between soil inorganic N at planting (DOY 108) and at tasselling (DOY 176) using Eq. [1]. Tillage did not significantly affect N_{min} in either residual period (Table 3). However, different N sources had a significant effect on N_{min} where it was significantly greater with manure than NH_4NO_3 and 0-N control (Table 4) for both residual periods.

Nitrogen mineralization at the 0- to 5-cm depth under the shelter (measured at tasselling) was compared with the result of the modified N mineralization model ($N_{estimated}$), based on laboratory N mineralization data, adjusted to field conditions (Table 5). The $N_{estimated}$ exceeded the measured values for net N_{min} for both R_1 and R_6 residual periods. Since tillage showed no significant effect on N_{min} with R_1 and R_6, the net N_{min} and $N_{estimated}$ values were averaged across tillage (Table 5). The percentage difference between N_{min} and

Table 2. Potentially mineralizable N (N_o) and mineralization rate constant (k) in 0- to 5-cm depth, as affected by no-tillage (NT), conventional tillage (CT), manure (M), NH_4NO_3 (F), and 0-N control (C) after 1 yr and 6 yr of residual N (R_1 and R_6).

	R_1	R_6	R_1	R_6
Treatment	N_o		*k*	
	kg N ha^{-1}		d^{-1}	
NT-M	560 a†	687 a	0.00260	0.00196
NT-F	280 b	241 bc	0.00545	0.00486
NT-C	182 bc	182 c	0.00447	0.00447
CT-M	227 b	371 b	0.00479	0.00303
CT-F	206 bc	215 bc	0.00562	0.00388
CT-C	152 c	152 c	0.00463	0.00463
	PR > F			
Tillage (T)	0.04	0.058	0.1	0.8
N source (NS)	0.0001	0.0001	0.02	0.005
T × NS	0.008	0.02	0.1	0.2

† Means with different lowercase letters among management practices within each residual period are significantly different (ANOVA); $P < 0.05$.

Table 3. Soil inorganic N integrated from 0- to 30-cm depth under the shelter during the vegetative stage as affected by no-tillage (NT), conventional tillage (CT), manure (M), NH_4NO_3 (F), and 0-N control (C), 1 yr after cessation of 10 yr of applied N (R_1) and 6 yr after cessation of 5 yr of applied N (R_6).

	R_1			R_6		
	DOY†					
Treatment	108	141	176	108	141	176
	kg N ha^{-1}					
NT-M	21	28	55	26	27	51
NT-F	20	29	45	27	26	35
NT-C	17	20	28	17	20	28
CT-M	19	30	53	23	26	40
CT-F	19	26	35	20	23	31
CT-C	17	17	21	17	17	21
	PR > F					
Time (Ti)	0.0001			0.001		
108 (mean)	18.6 c‡			21.5 c		
141 (mean)	24.9 b			23.0 b		
176 (mean)	39.4 a			34.3 a		
Tillage (T)	0.2			0.02		
NT (mean)	29.1			28.4 a‡		
CT (mean)	26.2			24.2 b		
N Source (NS)	0.0001			0.0001		
M (mean)	34.2 a§			31.9 a		
F (mean)	28.9 b			27.2 b		
C (mean)	19.8 c			19.8 c		
Ti × T	0.4			0.1		
Ti × NS	0.0002			0.0001		
Ti × T × NS	0.9			0.2		

† Day of year.
‡ Means with different lowercase letter among tillage (T) and time (TI) within each residual period are significantly different (ANOVA); $P < 0.05$.
§ Means with different lowercase letter among N source (NS) within each residual period are significantly different (ANOVA); $P < 0.05$.

Table 4. Field N mineralization (N_{min}†) under the shelter at tasselling stage integrated from 0- to 30-cm depth as affected by no-tillage (NT), conventional tillage (CT), manure (M), NH_4NO_3 (F), and 0-N control (C) after 10 and 5 yr of N application and 1 and 6 yr of residual N (R_1 and R_6).

	Mineralized N (N_{min})	
Treatment	R_1	R_6
	kg N ha^{-1}	
NT-M	34	25
NT-F	25	8
NT-C	11	11
CT-M	34	18
CT-F	16	10
CT-C	6	6
	PR > F	
Tillage (T)	0.4	0.2
N source (NS)	0.008	0.001
M (mean)	34 a‡	21 a
F (mean)	20 b	9 b
C (mean)	9 b	9 b
T x NS	0.8	0.3
Residual (R)	0.08	
R_1 (mean)	21 a§	
R_6 (mean)	13 b	

† Calculated using data presented in Table 3 and Eq. [1].
‡ Means with different letters among N sources (NS) within each residual period are significantly different (ANOVA); $P < 0.05$.
§ Means with different letters among residual period (*R*) are significantly different (ANOVA); $P < 0.1$.

Table 5. Field measured (N_{min}) under the shelter at 0 to 5 cm and estimated ($N_{estimated}$) averages across tillage during the 2000 vegetative stage of the growing season as affected by manure (M), NH_4NO_3 (F), and 0-N control (C) after 1 yr and 6 yr of residual N (R_1 and R_6).

Treatment	N_{min}†	$N_{estimated}$‡	Differences§
	kg N ha^{-1}		%
R_1			
Manure	12.1	12.2	0.83
Fertilizer	9.6	12.2	27.0
Control	3.0	6.4	106.0
R_6			
Manure	8.3	12.4	49.0
Fertilizer	4.7	9.1	94.0
Control	3.1	6.4	106.0

† Represents mineralized N (tasselling − planting) at 0- to 5-cm depth.
‡ Represents N mineralization prediction by adjusting the first exponential model to the field condition at tasseling stage.
§ Differences compute as $[(N_{estimated} - N_{min})/N_{min}] \times 100$.

$N_{estimated}$ was calculated as proposed by Cabrera and Kissel (1988b):

$$\% \text{ Difference} = \left[\frac{\text{Estimated } (N_{estimated})}{\text{Field measured } (N_{min})} - \frac{\text{Field measured } (N_{min})}{\text{Field measured } (N_{min})}\right] \times 100 \quad [7]$$

The difference between N_{min} and $N_{estimated}$ was lower for manure compared with NH_4NO_3 and 0-N control (Table 5). The overestimation was greater in the control treatment than where N had been previously applied (manure and NH_4NO_3) for both R_1 and R_6. High correlation ($r^2 = 0.86$ for R_1 and $r^2 = 0.70$ for R_6) between $N_{estimated}$ and N_{min} measured after planting and at tasselling at the 0- to 5-cm depth was observed (Fig. 4). When the data from R_1 and R_6 residual period were combined, there still was a high correlation ($r^2 = 0.8$, $p \leq 0.0001$) between estimated and measured net N mineralization (Fig. 5A).

Long-term laboratory incubation was preformed on soil samples taken from the 0- to 5-cm depth. The relative contribution of soil inorganic N (from planting to tasseling) at 0- to 5-cm to 0- to 30-cm depth was more than 36% at R_1 and more than 32% at R_6 (data not shown) with no differences between tillage practices. Therefore, we assume that the mineralizable N in the 0- to 5-cm depth in this study was representative of the deeper depths. Following our assumption and using the Benjamin et al. (1990b) model to estimate daily soil water content and soil temperature (at the 0- to 30-cm depth), the relationship between N_{min} and $N_{estimated}$ was evaluated. High correlation ($r^2 = 0.77$, $p \leq 0.0001$) was observed between predicted and measured net N mineralization (Fig. 5B). Although the correlation between the estimated and the measured N mineralization was almost the same for both depths, the slope of the lines indicates lower prediction accuracy of measured vs. laboratory N mineralization.

DISCUSSION

Although the quantity of plant biomass returned throughout the10 yr of the experiment was the same for NT as for CT (data not shown), total N (0 to 5 cm) was significantly greater in NT than CT with no significant differences at deeper depths (Espinoza, 1997). The increase in total N with annual addition of manure is likely due to the addition of organic material to the soil (Gerzabek et al., 1997; Aoyama et al., 1999); however NT apparently provided greater conservation of the organic N. This conservation of organic N may be due to NT fostering development and stability of macroaggregates (Six et al., 2000; Mikha and Rice, 2004) which was further enhanced by manure additions (Aoyama et al., 1999; Mikha and Rice, 2004).

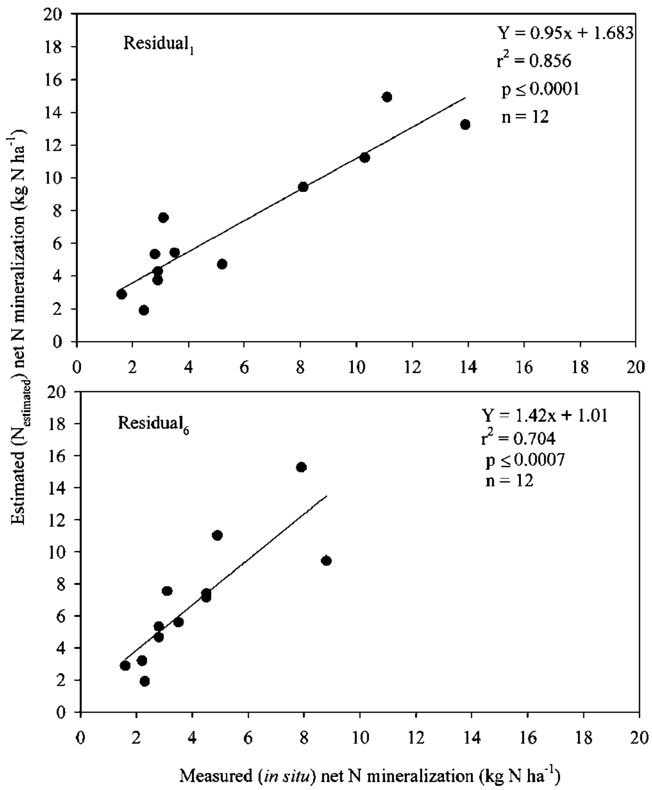

Fig. 4. Relationship between measured and predicted field N mineralization at 0- to 5-cm depth for 2000 vegetative stage of the growing season by manure application, mineral fertilizer application, and an unfertilized control. (Residual$_1$) represents 10 yr of N application and 1 yr of residual N; (Residual$_6$) represents 5 yr of N application and 6 yr of residual N.

Soil available N (0–30 cm) with the manure treatment was similar 6 yr following cessation of application as 1 yr following cessation of application. The available N with residual manure was significantly greater than residual NH_4NO_3–N. Eghball et al. (2004) also observed greater amounts of soil NO_3^-–N from previous applications of manure when compared with an unmanured treatment 4 yr after the last application. Although net N mineralization from residual N (manure and NH_4NO_3 treatments) decreased with R_6 compared with R_1, the combination of NT and manure maintained higher net N mineralization. These results suggested that greater amounts of mineralizable N were provided with the combination of NT and manure treatment. Across tillage and N source, soil available N was the same in R_6 as

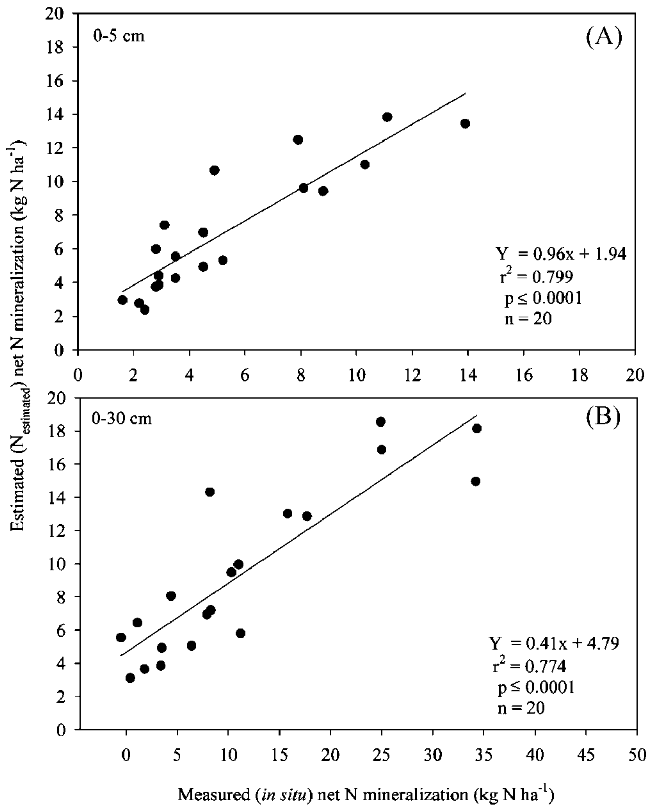

Fig. 5. Relationship between measured and predicted field N mineralization for all the treatments combination with $Residual_1$ and $Residual_6$ during the 2000 vegetative stage of growing season as affected by manure, NH_4NO_3, and 0-N control. (A) represents 0- to 5-cm depth and (B) represents 0- to 30-cm depth.

in R_1. This suggests that the portion of soil N available for mineralization was sustained in this soil even 6 yr after N application was discontinued.

In this study, the increase in N_o with manure addition was apparent even 6 yr after cessation of N applications to the same extent as with the 1-yr residual. Boyle and Paul (1989) reported similar results for sewage sludge-amended soil where they observed a substantial amount of labile N 3 yr since the last sludge addition. Averaged across tillage, N_o with manure accounted for 20 to 28% of total N for R_1 and R_6, respectively, and it was 13% with NH_4NO_3 for both R_1 and R_6 residual periods. Higher N_o with NT and manure combination implies greater conservation of organic N that could be mineralized slowly to fulfill some of the crop N need. The differences in correlation observed between R_1 and R_6 (Fig. 4) could be due to a change in substrate quality (either the size of the labile fraction or its composition) associated with R_1 treatment. Higher amounts of labile and soluble materials associated with R_1 could promote a greater amount of available N with less dependence on factors that affect residue decomposition. The slope of the line indicates the relative magnitudes of field and laboratory N mineralization. Since the environmental factors (e.g., soil temperature and soil water content) were similar, the difference in the slope of the lines between R_1 and R_6 could again suggest that field N mineralization was affected by substrate quality.

The model used in this study was a simple approach based on modifying the laboratory N_o from the first exponential model to adjust for the variation in situ soil temperature and soil water content ($N_{estimated}$). Plant residue quantity and quality as well as the degradation rate of different plant parts are not required to run this model as some other models (e.g., CERES model). Although high correlation was observed between $N_{estimated}$ and N_{min} at the 0- to 30-cm depth (Fig. 5B) and the 0- to 5-cm depth (Fig. 5A), the slope of the line was different between these depths. The difference in the slope of the lines between the 0- to 5-cm and 0- to 30-cm depth suggests lower prediction accuracy between estimated and measured N mineralization. The lower slope for 0 to 30 cm is likely due to measurement of N_o in the 0 to 5 cm; however, we were still able to capture 40% of the mineralized N with a high correlation using 0 to 5 cm. This result would make sampling and estimation for N mineralization more convenient if confirmed in future studies. Although, $N_{estimated}$ overestimated N_{min}, at 0 to 5 cm, the overestimation was lower with manure followed by NH_4NO_3 and last with 0-N control. These data suggest that treatments with high substrate quality, such as manure amendments, resulted in better agreement between $N_{estimated}$ and N_{min}.

The overestimation of $N_{estimated}$ to N_{min} agrees with other studies. Cabrera and Kissel (1988b) overestimated N_{min} by 67% in fallow plots, which they attributed to differences in soil temperature and soil disturbance. However, Campbell et al. (1988) estimated lower N mineralization compared with measured N mineralization in situ. Their explanation was that wetting and drying events caused additional N mineralization not estimated by the model. Since we have accounted for soil temperature in the field, the overestimation in this study is consistent with the explanation given by (Cabrera and Kissel, 1988b). Soil disturbance, in preparation for laboratory incubation, could cause the overestimation. However, the overestimation could also have resulted from long-term incubation that caused destruction of soil aggregates and release of protected SOM for microbial decomposition (Mikha, 2003). Laboratory incubation with intact soil cores instead of disturbed soil, and different depths could help to improve our estimation of field N mineralization. Soil hydraulic properties such as K_{sat} need to be considered for different management practices. Determining soil water content on a daily basis rather than estimated could improve the overall estimation of field N mineralization. In general, the high correlation between $N_{estimated}$ and N_{min} suggested a possibility of predicting field N mineralization from laboratory incubation under reported management practices and environmental conditions.

CONCLUSIONS

Research with soil of different N-supplying capacities is important to improve our knowledge of N management. The data generated at this site provided an opportunity to study the impact of management on N-supplying capacity and the resulting N mineralization under the same environment. No-tillage enhanced the conservation of added organic material, which released N for microbial decomposition in subsequent years. Manure improved soil N supplying capacity even 6 yr after discontinuation of application. Estimates of N supplying capacity are only potential and cannot account for environmental controls on mineralization. Therefore, a model approach that incorporates soil water and temperature may account for year to year and site changes in N mineralization in the field. Adjustment of the N mineralization model to field soil water and temperature explained almost 80% of the variability in the measured amount of net field N mineralization (0- to 5 and 0- to 30-cm depth). The prediction accuracy between estimated and measured N mineralization declined with time since last N application. Overall, N_o could be a useful tool, with model adjustment to field conditions, to estimate in situ N mineralization for site specific conditions. More research is needed to determine the effect of different management practices, soil types, and environmental conditions before a generalization can be made. Daily soil water content, sampling technique for laboratory incubation, incubation temperature, and the length of incubation period need to be taken under consideration, which could improve the estimation of in situ N mineralization.

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