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.

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

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

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:

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

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

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

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):

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

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:

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

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: $\alpha = 0.035\ (cm^{-1})$, $n = 1.18$, $\theta_s = 0.45\ (m^3\ m^{-3})$, and $\theta_r = 0.0\ (m^3\ m^{-3})$. No saturated hydraulic conductivity (K_{sat}) data were available for the site so K_{sat} estimates were made from a

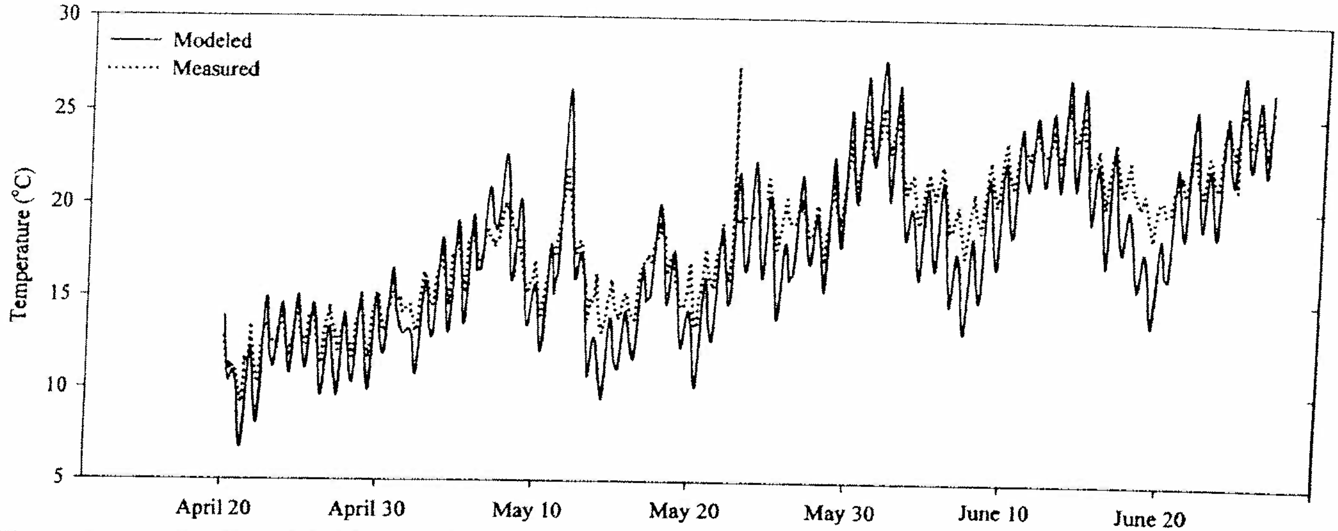

Fig. 2. The accuracy between measured and modeled soil temperature (for the Year 2000) under the shelter at the 0- to 5-cm depth using TRANSPOR model.

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.

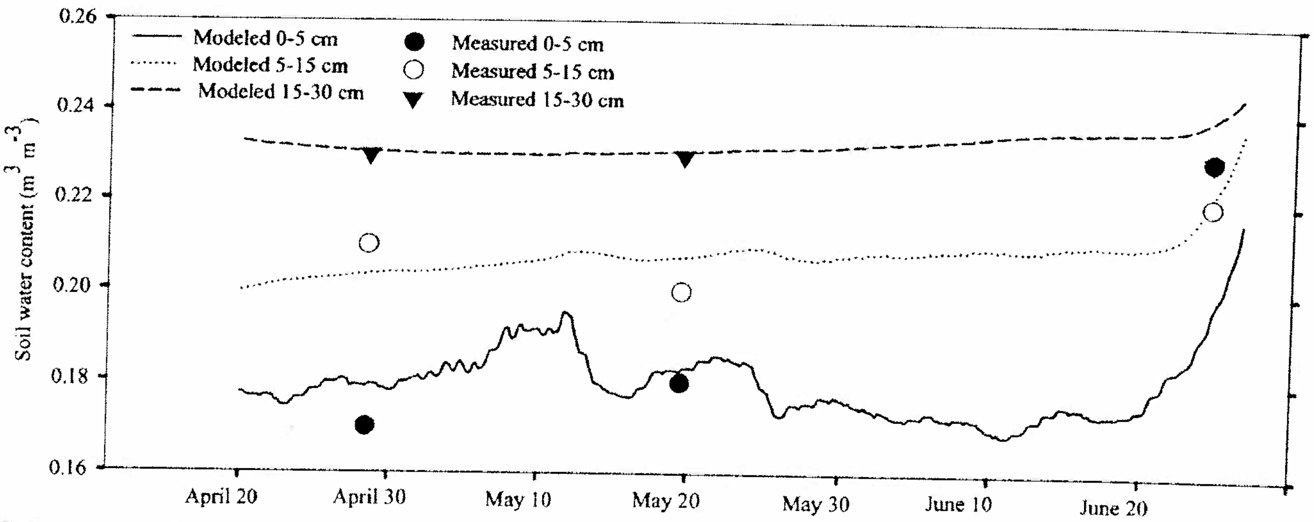

Fig. 3. Measured and modeled soil water content under the shelter for 0- to 5, 5- to 15-, and 15- to 30-cm depths for the Year 2000.

Table 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.

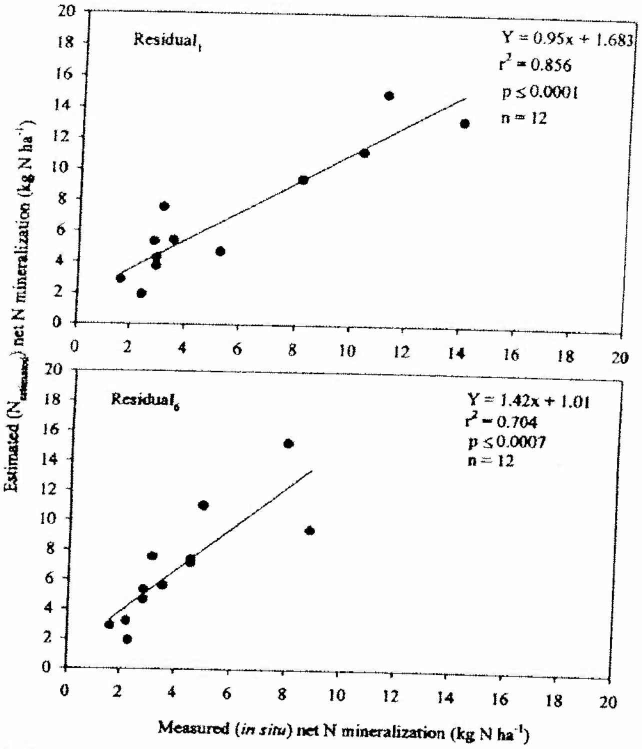

Fig. 4. Relationship between measured and predicted field N mineralization at 0- to 5-cm depth for 2000 vegetative stage of the growing season by manure application, mineral fertilizer application, and an unfertilized control. (Residual$_1$) represents 10 yr of N application and 1 yr of residual N; (Residual$_6$)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

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).

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 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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